

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry

Ali Hasanbeigi, Lynn Price

China Energy Group
Energy Analysis and Environmental Impacts Department
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

Marlene Arens

Fraunhofer Institute for Systems and Innovation Research (ISI)

January 2013

This work was supported by the China Sustainable Energy Program of the Energy Foundation and Dow Chemical Company (through a charitable contribution) through the Department of Energy under contract No.DE-AC02-05CH11231.

Disclaimer

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

**Ernest Orlando Lawrence Berkeley National Laboratory is an equal
opportunity employer.**

Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry

Ali Hasanbeigi ^a, Marlene Arens ^b, Lynn Price ^a

^a China Energy Group, Energy Analysis and Environmental Impacts Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA, U.S.A.

^b Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe, Germany.

Abstract

Iron and steel manufacturing is among the most energy-intensive industries and accounts for the largest share, approximately 27 percent, of global carbon dioxide (CO₂) emissions from the manufacturing sector. The ongoing increase in world steel demand means that this industry's energy use and CO₂ emissions continue to grow, so there is significant incentive to develop, commercialize and adopt emerging energy-efficiency and CO₂ emissions-reduction technologies for steel production. Although studies from around the world have identified a wide range of energy-efficiency technologies applicable to the steel industry that have already been commercialized, information is limited and/or scattered regarding emerging or advanced energy-efficiency and low-carbon technologies that are not yet commercialized. This report consolidates available information on 56 emerging iron and steel industry technologies, with the intent of providing a well-structured database of information on these technologies for engineers, researchers, investors, steel companies, policy makers, and other interested parties. For each technology included, we provide information on energy savings and environmental and other benefits, costs, and commercialization status; we also identify references for more information.

Contents

Abstract	iii
1. Introduction	1
2. Description of Iron and Steel Production	5
2.1. Iron and Steel Production Process and Energy Use	5
2.1.1. Raw Materials	6
2.1.2. Ironmaking	6
2.1.3. Steelmaking	7
2.1.4. Casting, Rolling, and Finishing	8
2.2. CO ₂ Impact of Iron and Steel Production	8
3. Emerging Energy-efficiency and CO ₂ Emissions Reduction Technologies	10
3.1. Emerging Agglomeration Technology	10
3.1.1. Use of Biomass in the Sintering Process	10
3.2. Emerging Coke-Making Technologies	12
3.2.1. Single-chamber-system Coking Reactors	12
3.2.2. Coke Oven Under-firing with Advanced Diagnostics and Control	13
3.3. Emerging Technologies for Ironmaking Using Blast Furnace	15
3.3.1. Hot Oxygen Injection	15
3.3.2. Blast Furnace Optimization Using Computational Fluid Dynamics Modeling	16
3.3.3. Blast Furnace Optimization Using X-ray Diffraction Analytical Technique	18
3.3.4. Blast Furnace Heat Recuperation	20
3.3.5. Plasma Blast Furnace	21
3.3.6. Blast Furnace Slag Heat Recovery	23
3.3.7. Charging Carbon Composite Agglomerates in Blast Furnace	24
3.4. Alternative Emerging Ironmaking Technologies	26
3.4.1. COREX [®] Process	26
3.4.2. FINEX [®] process	28
3.4.3. Tecored	30
3.4.4. ITmk3 [®] Ironmaking Process	31
3.4.5. Paired Straight Hearth Furnace	33
3.4.6. Coal-Based HYL Process- A Syngas-based DRI Plant	35

3.4.7. Coal-Based MIDREX [®] Process	36
3.4.8. Fine Ore Reduction in Circulating and Bubbling Fluidized Beds	38
3.4.9. Cyclone Converter Furnace.....	40
3.4.10. Producing Iron by Electrolysis of Iron Ore (Molten Oxide Electrolysis)	41
3.4.11. Suspension Hydrogen (or H ₂ containing Gaseous mixtures) Reduction of Iron Oxide Concentrate.....	44
3.4.12. Ironmaking using Biomass and Waste Oxides.....	46
3.5. Emerging Technologies for Steelmaking Shops	49
3.5.1. Sensible Heat Recovery from Electric Arc Furnace Off Gas.....	49
3.5.2. Electrochemical Removal of Zinc from Steel Scrap.....	51
3.5.3. Continuous Horizontal Sidewall Scrap Charging	53
3.5.4. New Scrap-Based Steelmaking Process Using Predominantly Primary Energy	54
3.5.5. ECOARC [™]	55
3.5.6. Optimization of BOF and EAF Post Combustion Using CFD	57
3.5.7. Improving the Energy Efficiency of EAF through Laser-based Optimization of Post Combustion	58
3.5.8. Model-based Steel Temperature Measurement for Electric Arc Furnaces	59
3.5.9. In-Situ Real-Time Measurement of Melt Constituents	60
3.5.10. Injection of Plastic Waste in Blast Furnaces.....	63
3.5.11. Injection of Plastic Waste in Electric Arc Furnaces.....	65
3.5.12. Use of Waste Tires in Electric Arc Furnaces	66
3.5.13. Continuous Steelmaking for Electric Arc Furnace	67
3.6. Emerging Casting Technologies	69
3.6.1. Near-net-shape Casting/Strip Casting	69
3.6.3. Continuous Temperature Monitoring and Control in Continuous Casting.....	71
3.7. Emerging Rolling and Finishing Technologies.....	73
3.7.1. High-Temperature Membrane Module for Oxygen Enrichment of Combustion Air for Fuel-Fired Industrial Furnaces	73
3.7.2. Next-generation System for Scale-Free Steel Reheating	74
3.7.3. Thermochemical Recuperation for Steel Reheating Furnaces	75
3.7.4. Hot Strip Mill Model.....	77

3.7.5. Innovative Reheating Furnace Management Using a Continuous Burn-Out Measuring System	78
3.7.6. Oxygen-rich Furnace System for reduced CO and NO emissions.....	80
3.7.7. HotEye® Steel Surface Inspection System.....	81
3.7.8. Nitrogen Oxide Emission Reduction by Oscillating Combustion	83
3.8. Emerging Recycling and Waste Reduction Technologies	85
3.8.1. Recycling Basic Oxygen Furnace Slag	85
3.8.2. Rotary Hearth Furnace Dust Recycling System.....	87
3.8.3. Recycling of Stainless Steel Dust by Injection into Electric Arc Furnace.....	89
3.8.4. Regeneration of Hydrochloric Acid Pickling Liquor	90
3.8.5. Recycling of Waste Oxides in Steelmaking Furnace	92
3.9. Carbon Capture and Storage Technologies for the Iron and Steel industry.....	93
3.9.1. Top-Gas Recycling in Blast Furnaces, with Carbon Capture and Storage	93
3.9.2. Advanced Direct Reduction with Carbon Capture and Storage (ULCORED)	95
3.9.3. HISarna with Carbon Capture and Storage.....	98
3.9.4. Post-combustion Carbon Capture Using Chemical Absorption Technologies	99
3.9.5. Geological Sequestration of CO ₂ Using BOF or EAF Slag	101
3.9.6. Integrating Steel Production with Mineral Sequestration	104
Acknowledgments	106
References	106

Acronyms

AISI	American Iron and Steel Institute
AISI TR Program	AISI Technology Roadmap Program
BF	blast furnace
BOF	basic oxygen furnace
CaO	quicklime
CCF	cyclone converter furnace
CCS	carbon capture and storage
CFD	computational fluid dynamics
CO	carbon monoxide
CO ₂	carbon dioxide
DRI	direct reduced iron
EAF	electric arc furnace
g	gram
GJ	gigajoules
h	hour
H ₂	diatomic hydrogen
HBI	hot briquetted iron
HCI	hot compacted iron
IEA	International Energy Agency
JISF	Japan Iron and Steel Federation
kg	kilogram
kt	kiloton
kWh	kilowatt-hour
LMS	Ladle Metallurgy Station
mm	millimeter
MOE	molten oxide electrolysis
Mt	million tonnes
MJ	megajoule
MW	megawatt
MWel	megawatt electric
N ₂	nitrogen
Nm ³	cubic nanometer
NO _x	nitrogen oxide
O ₂	oxygen
PCI	pulverized coal injection
PCIR	pulverized coal injection rate
PHAR	Pickliq [®] Hydrochloric Acid Regeneration
PSH	paired straight hearth
PVC	polyvinyl chloride

RHF	rotary hearth furnace
RSB	rolled steel bar
SCS	single-chamber system
SO ₂	sulfur dioxide
SR	smelting reduction
SRI	smelting reduction iron
3-D	three-dimensional
t	tonne
TGR-BF	top-gas recycling blast furnace
tpd	tonnes per day
ULCOS	ultra-low-CO ₂ steelmaking
U.S. DOE	U.S. Department of Energy
VOC	volatile organic compound
XRD	X-ray diffraction

Emerging Energy-efficiency and Carbon Dioxide Emission-reduction Technologies for the Iron and Steel Industry

Ali Hasanbeigi ^a, Marlene Arens ^b, Lynn Price ^a

^a China Energy Group, Energy Analysis and Environmental Impacts Department, Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, CA, U.S.A.

^b Fraunhofer Institute for Systems and Innovation Research ISI (Fraunhofer ISI), Karlsruhe, Germany.

1. Introduction

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, use of coal as the primary fuel for iron and steel production means that iron and steel production has among the highest carbon dioxide (CO₂) emissions of any industry. According to the International Energy Agency (IEA), the iron and steel industry accounts for the largest share – approximately 27 percent – of CO₂ emissions from the global manufacturing sector (IEA 2007).

Annual world steel demand is expected to grow from approximately 1,410 million tonnes (Mt) of crude steel in 2010 (USGS 2012) to approximately 2,200 Mt in 2050 (Bellevrat and Menanteau 2008). The bulk of this growth will take place in China, India, and other developing countries in Asia (Figure 1). This significant increase in steel consumption and production will drive a significant increase in the industry's absolute energy use and CO₂ emissions.

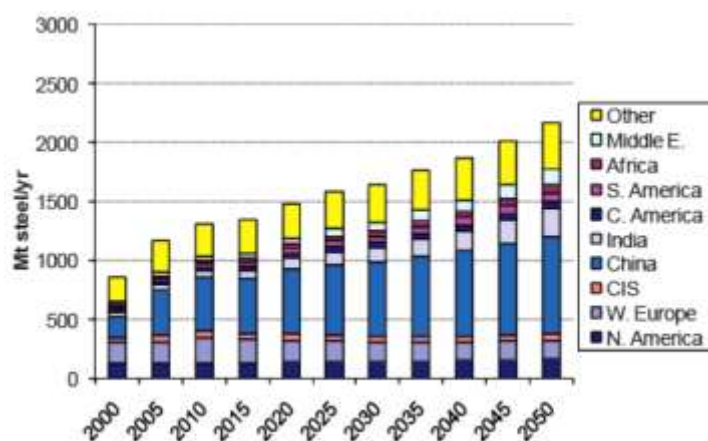


Figure 1. World steel consumption by region (Bellevrat and Menanteau 2008)

Studies have documented the potential for the worldwide iron and steel industry to save energy by adopting commercially available energy-efficiency technologies and measures (Worrell et al. 2003; Hasanbeigi et al. 2012; IEA 2007; etc.). However, in view of the projected continuing increase in absolute steel production, future reductions (e.g., by 2030 or 2050) in absolute energy

use and CO₂ emissions will require innovation beyond technologies that are available today. New developments will likely include different processes and materials as well as technologies that can economically capture and store the industry's CO₂ emissions. Deployment of these new technologies in the market will be critical to the industry's climate change mitigation strategies for the mid and long term. It should be noted that the technology adoption in regions around the world is driven by economic viability, raw materials availability, energy type used and energy cost as well as regulatory regime.

Many studies from around the world have identified sector-specific (e.g., Worrell et al. 2010; AISI 2010; EPA 2010; APP 2010; EIPPCB 2010) and cross-cutting (e.g., U.S. DOE/AMO 2012) energy-efficiency technologies for the iron and steel industry that are already commercially available. However, information is limited and not easily accessible regarding emerging or advanced energy-efficiency and low-carbon technologies for the industry that have not yet been commercialized. This report consolidates the available information on emerging technologies for the iron and steel industry to assist engineers, researchers, investors, iron and steel companies, policy makers, and other interested parties.

The information presented in this report is collected from publically available sources and covers the main emerging energy-efficiency and low-carbon technologies for the iron and steel industry; however, the list of emerging technologies addressed is not exhaustive.

The report uses a uniform structure to present information about each of the 56 technologies covered. First, we describe the technology, including background, theory, pros and cons, barriers and challenges, and case studies if available. Next, we present the energy, environmental, and other benefits of the technology as well as cost information if available. For most technologies, we include a block diagram or picture. Finally, we identify the commercialization status of each technology as well as resources for further information. The commercialization status of each technology is as of the writing of this report and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: The technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

Table 1 lists the 56 technologies covered in this report, the section of the report in which each technology is discussed, and the technology's commercialization status.

The purpose of this report is solely informational. Many emerging technologies are proprietary and/or the manufacturers who are developing a new technology are the primary sources of information about it. Thus, in some cases, we identify a company that is the source of a technology so that readers can obtain more information about the company and product.

Table 1. Emerging energy-efficiency and CO₂ emissions-reduction technologies for the iron and steel industry

No.	Report Section/Technology Name	Commercialization status
	3.1. Emerging Agglomeration Technologies	
1	3.1.1. Use of Biomass in the Sintering Process	Demonstration
	3.2. Emerging Coke-making Technologies	
2	3.2.1. Single-chamber-system Coking Reactors	Demonstration
3	3.2.2. Battery Under-firing with Advance Diagnostics and Control	Development
	3.3. Emerging Technologies for Ironmaking Using Blast Furnace	
4	3.3.1. Hot Oxygen Injection	Pilot
5	3.3.2. Blast Furnace Optimization by Using Computational Fluid Dynamics Modeling	Demonstration
6	3.3.3. Blast Furnace Optimization by Using X-ray Diffraction Analytical Technique	Demonstration
7	3.3.4. Blast Furnace Heat Recuperation	Demonstration
8	3.3.5. Plasma Blast Furnace	Development
9	3.3.6. Blast Furnace Slag Heat Recovery	Pilot/ Development
10	3.4.7. Charging Carbon Composite Agglomerates	Demonstration
	3.4. Alternative Ironmaking Technologies	
11	3.4.1. COREX® Process	Commercial with very low adoption rate
12	3.4.2. FINEX® Process	Commercial with very low adoption rate
13	3.4.3. Tecnored	Pilot
14	3.4.4. ITmk3 Ironmaking Process	Demonstration
15	3.4.5. Paired Straight Hearth Furnace	Development
16	3.4.6. Coal-Based HYL Process- A Syngas based DRI Plant	Commercial with very low adoption rate
17	3.4.7. Coal-Based MIDREX Process	Demonstration
18	3.4.8. Fine Ore Reduction in the Circulating Fluidized Bed (Circored® and Circofer®)	Demonstration/Pilot
19	3.4.9. Cyclone Converter Furnace	Pilot
20	3.4.10. Producing Iron by Electrolysis of Iron Ore (Molten Oxide Electrolysis)	Research/Development
21	3.4.11. Suspension Hydrogen Reduction of Iron Oxide Concentrate	Research/Development
22	3.4.12. Ironmaking using Biomass and Waste Oxides	Research
	3.5. Emerging Technologies for Steelmaking Shops	
23	3.5.1. Sensible Heat Recovery from Electric Arc Furnace Off Gases	Commercial with very low adoption rate/ Pilot
24	3.5.2. Electrochemical Removal of Zinc from Steel Scrap	Demonstration
25	3.5.3. Continuous Horizontal Sidewall Scrap Charging	Pilot
26	3.5.4. New Scrap-Based Steelmaking Process Predominantly Using Primary Energy	Development
27	3.5.5. ECOARC™	Demonstration
28	3.5.6. Optimization of Basic Oxygen Furnace and Electric Arc Furnace Post Combustion Using Computational Fluid Dynamics Modeling	Pilot
29	3.5.7. Improving the Energy Efficiency of Electric Arc Furnaces through Laser-	Pilot

No.	Report Section/Technology Name	Commercialization status
	based Optimization of Post Combustion	
30	3.5.8. Model-based Steel Temperature Measurement for Electric Arc Furnaces	Development
31	3.5.9. In-Situ Real-Time Measurement of Melt Constituents	Development
32	3.9.10. Injection of plastic waste in Blast Furnaces	Demonstration
33	3.9.11. Injection of Plastic Waste in the Electric Arc Furnace	Pilot
34	3.9.12. Use of Waste Tires in EAF	Commercial with very low adoption rate
35	3.6.4. Continuous Steelmaking for Electric Arc Furnace	Research
	3.6. Emerging Casting Technologies	
36	3.6.1. Near-net-shape Casting/Strip Casting	Commercial with very low adoption rate
37	3.6.2. Continuous Temperature Monitoring and Control in Continuous Casting	Development
	3.7. Emerging Rolling and Finishing Technologies	
38	3.7.1. High-Temperature Membrane Module for Oxygen Enrichment of Combustion Air for Fuel-Fired Industrial Furnaces	Pilot
39	3.7.2. Next-generation System for Scale-Free Steel Reheating	Research
40	3.7.3. Thermochemical Recuperation for Steel Reheating Furnaces	Research
41	3.7.4. Hot Strip Mill Model	Commercial with very low adoption rate
42	3.7.5. Innovative Reheating Furnace Management Using a Continuous Burn-Out Measuring System	Pilot
43	3.7.6. Oxygen-rich Furnace System for reduced CO ₂ and NO _x emissions	Development
44	3.6.2. HotEye® Steel Surface Inspection System	Commercial with very low adoption rate/ Development
45	3.7.7. NO _x Emission Reduction by Oscillating Combustion	Pilot
	3.8. Emerging Recycling and Waste Reduction Technologies	
46	3.8.1. Recycling Basic Oxygen Furnace Slag	Development
47	3.8.2. Rotary Hearth Furnace Dust Recycling System	Demonstration
48	3.8.3. Recycling of Stainless Steel Dust by Injection into Electric Arc Furnace	Pilot
49	3.8.4. Regeneration of Hydrochloric Acid Pickling Liquor	Pilot
50	3.8.5. Recycling of Waste Oxides in Steelmaking Furnace	Pilot
	3.9. Carbon Capture and Storage Technologies for the Iron and Steel industry	
51	3.9.1. Top-gas Recycling in Blast Furnaces with Carbon Capture and Storage	Pilot
52	3.9.2. Advanced Direct Reduction with Carbon Capture and Storage (ULCORED)	Development
53	3.9.3. HIsarna with Carbon Capture and Storage	Pilot
54	3.9.4. Post-combustion Carbon Capture Using Chemical Absorption Technologies	Development
55	3.9.5. Geological Sequestration of Carbon Dioxide Using Basic Oxygen Furnace and Electric Arc Furnace Slag	Research
56	3.9.6. Integrating Steel Production with Mineral Sequestration	Research

Because the nature of emerging technologies is continual and often rapid change, the information presented in this report is also subject to change. If readers are aware of a new technology that is not presented in this report or have updated information about a technology that is described in this report, please contact the authors.¹

¹ Ali Hasanbeigi: ahasanbeigi@lbl.gov; Marlene Arens: marlene.aren@isi.fraunhofer.de

2. Description of Iron and Steel Production

Iron ore is chemically reduced to produce steel by one of these three process routes: blast furnace (BF)/basic oxygen furnace (BOF), smelting reduction, or direct reduction (EIPPCB 2010). Steel is also produced by direct melting of scrap in an electric arc furnace (EAF). Each of these processes are briefly explained in the section below.

BF/BOF and EAF production are the most common today. In 2010, BF/BOF production accounted for approximately 65 percent of the steel manufactured worldwide, and EAF production accounted for approximately 30 percent (worldsteel 2011). Iron and steel can be produced at separate facilities or in an integrated steel mill, where the iron ore is reduced into pig iron or DRI and then processed into steel at the same site.

2.1. Iron and Steel Production Process and Energy Use

Figure 2 is a simplified flow diagram of steel production using BF/BOF, EAF, and direct reduction. The following subsections describe the main production steps.

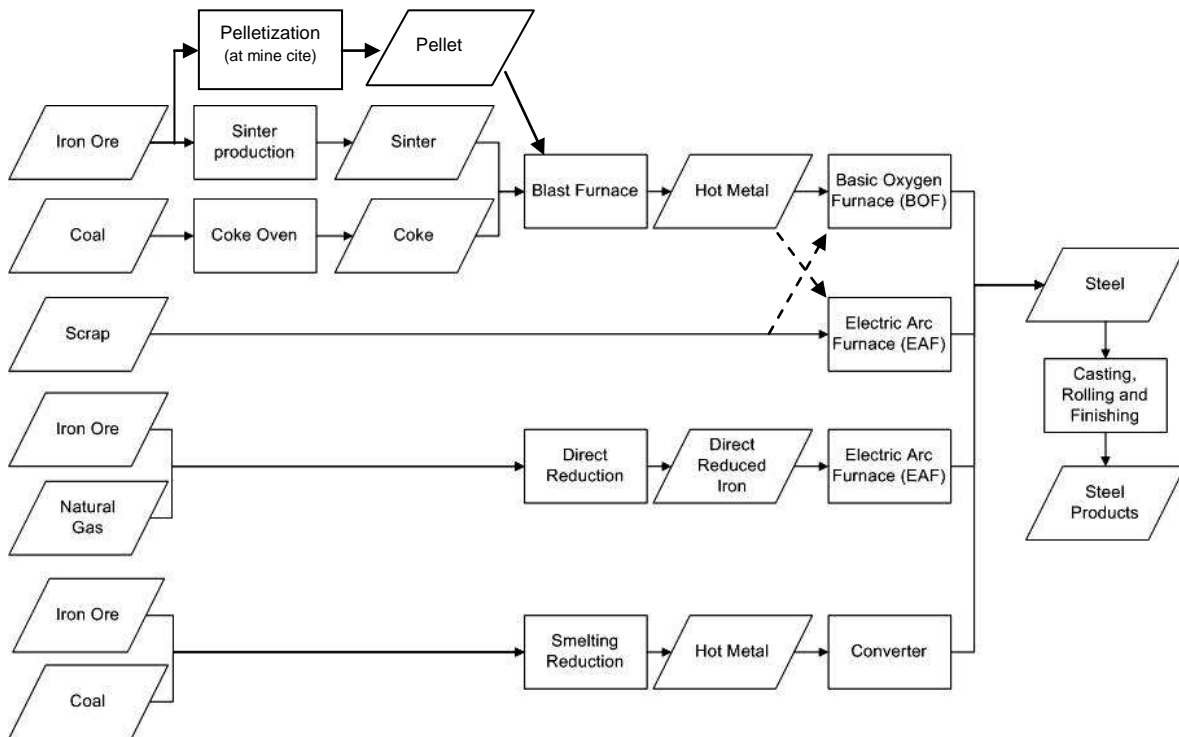


Figure 2. Flow diagram of steel production

2.1.1. Raw Materials

The subsections below describe the preparation of raw materials for iron and steel production.

Sintering

In sintering, iron ore fines, other iron-bearing wastes, and coke dust are blended and combusted; the heat induces incipient fusion to convert the fines into coarse lumps (sinter) that can be used as raw material (charge) in a BF. Sintering enables manufacturers to use iron ore fines and other iron bearing wastes but requires a large capital investment and air pollution controls (APP 2010). According to Energetics, Inc. (2004), the range of energy use for sintering is 1.5 to 1.7 gigajoules per ton (GJ/t). Sinter plants are mostly located at integrated steelworks.

Pelletizing

In pelletizing, iron ore is crushed and ground to remove impurities. The resulting beneficiated (iron-rich) ore is mixed with a binding agent and then heated to create durable, marble-sized pellets. These pellets can be used in both BF and direct reduction steel manufacturing (APP 2010). Pellet plants are mostly located at mining sites. Worldsteel (n.d.) estimates the energy consumed by pelletizing at 2.1 GJ/t pellet.

Coke Making

Coke is a carbon product formed by thermal distillation of metallurgical coal at high temperatures in the absence of air. Coke is produced in batteries of coke ovens. Coke is used to provide a reducing atmosphere in a BF and is also a source of fuel. One of the key characteristic of coke is its porosity which enables the gas exchange throughout the BF from the bottom to the top. Approximately one-third of the cleaned coke oven gas (COG) is used to fuel the coke ovens, and the remainder is used in other steel plant combustion units. Some newer coke plants use non-recovery coke ovens that burn rather than recover the byproducts. The new non-recovery coke plants capture combustion waste heat to generate steam and electricity. The primary CO₂ emissions point at coke plants is the combustion stack from the ovens (U.S. EPA 2010). Energetics, Inc. (2004) gives the range of energy use for coke making as 5.5 – 6.5 GJ/t coke ².

2.1.2. Ironmaking

The subsections below describe three ironmaking processes, i.e. the BF, direct reduction, and smelting reduction processes.

Blast Furnace

A BF is a huge shaft furnace that is top fed with iron ore, coke, and limestone. These materials form alternating layers in the furnace and are supported on a bed of incandescent coke. Hot air is blown through an opening into the bottom of the furnace and passes through the porous bed. The coke combusts, producing heat and carbon monoxide (CO) gas. The heat melts the charge, and the CO removes the oxygen from the iron ore, producing hot metal³. Hot metal is a solution of

² Full credit is taken for off-gas and by-product energy.

³ When hot metal is allowed to solidify in a pig iron casting machine, the resultant solid iron is called pig iron.

molten iron at approximately 1,480°C, which contains 4 percent carbon and some Silicon. This hot metal flows to the bottom of the furnace, through the coke bed and is periodically “tapped” from the furnace into transfer cars and transported to the BOF where it is refined into steel. The BF is the most energy-intensive step in the BF/BOF steelmaking process, generating large quantities of CO₂ (AISI 2010). Energetics, Inc. (2004) gives a range of energy use of 13.0 to 14.1 GJ/t pig iron.

Direct Reduction

Direct reduction is the removal (reduction) of oxygen from iron ore in its solid state. This technology encompasses a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, 92.6 percent of direct reduction worldwide was based on natural gas and took place in shaft furnaces, retorts, and fluidized bed reactors. The metallization rate of the end product, called Direct Reduced Iron (DRI) or ‘sponge iron’, ranges from 85 percent to 95 percent (often even higher). In 2008, 68.5 Mt of DRI was produced worldwide, using primarily MIDREX technology (58.2 percent). The MIDREX process typically consists of four stages: 1) reduction, 2) reforming, 3) heat recovery, and 4) briquette making. A mixture of pellets or lump ore, possibly including up to 10 percent fine ore, enters the furnace shaft. As the ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched with hydrogen and CO (IEA 2010). The iron is then formed into briquettes, and heat from the process is recovered.

Smelting Reduction

Smelting reduction iron (SRI) is an alternative to the BF, as it also produces liquid iron. Smelting reduction was developed to overcome the need for the energy-intensive products- coke and sinter (if sinter is used in BF). Instead smelting reduction is aimed to use coal and iron fines. Several processes are under development; some have been commercially proven (COREX, FINEX, ITmk3), others are under demonstration (e.g. Hismelt). Iron ore first undergoes a solid-state reduction in a pre-reduction unit. The resulting product at this stage - similar to DRI - is then smelted and further reduced in the smelting reduction vessel where coal is gasified, producing heat and CO-rich hot gas that can be further oxidized to generate additional heat to smelt the iron. Coal gasification is the result of a reaction with oxygen and iron ore in a liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. This process is called post-combustion and leads to a tradeoff in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting (IEA 2010). Commercial smelting reduction is still dominated by first-generation processes, notably the COREX process developed in Germany and Austria (IEA 2010).

2.1.3. Steelmaking

The subsections below describe the steelmaking process with BOF or EAF.

Basic Oxygen Furnace (BOF)

The BOF converts liquid hot metal from the BF into steel. The main operation is the addition of oxygen to remove carbon from the hot metal. In recent years, extensive ladle metallurgy processes have been developed to improve steel quality. Few energy data are available for these operations. A BOF uses virtually no energy and does not produce net energy (IEA 2007).

Electric Arc Furnace (EAF)

EAFs are mainly used to produce steel by recycling ferrous scrap. But also DRI and pig iron can be fed to the EAF as a scrap substitute. EAFs are equipped with carbon electrodes that can be raised or lowered through the furnace roof to provide the necessary energy by an electric arc. Energy consumption in EAF-steelmaking is much lower, as the energy-intensive reduction of iron ore has already been carried out in the BF (or in the DRI or SR plant). EAF steelmaking can use a wide range of scrap types, direct reduced iron (DRI), pig iron and molten iron (up to 30 percent) as the feed charge. The liquid steel from an EAF is generally sent to a Ladle Metallurgy Station (LMS) now-a-days to improve the steel quality. Recycling of scrap into steel saves virgin raw materials as well as the energy required for converting them (APP 2010). Energetics, Inc. (2004) gives a range of energy use for EAFs as 2.1 to 2.4 GJ/t crude steel.

2.1.4. Casting, Rolling, and Finishing

The molten steel produced by both BOFs and EAFs follows similar routes after leaving the furnace: it is transferred from the LMS to the continuous caster, which forms the steel into semi-finished shapes (e.g., slabs, blooms, billets, rounds, and other special sections). Steel from the continuous caster is mainly processed in rolling mills to produce the final shapes that are sold by the steel mill. These shapes include coiled strips, rails, sheets, many structural shapes, rods and bars. Because rolling mills consume electricity, they contribute to indirect greenhouse gas emissions. Fossil fuels (e.g. natural gas) are consumed in furnaces to reheat the steel before rolling. The products from the hot rolling mill may be further processed in various ways, such as annealing, hot forming, cold rolling, heat treating (tempering), pickling, galvanizing, coating, or painting. The furnaces are custom designed for the type of steel, the dimensions of the semi-finished steel pieces, and the desired temperature (U.S. EPA 2010). Energetics, Inc. (2004) gives the range of 2.0 – 2.4 GJ/t steel and 1.0 – 1.4 GJ/t steel for energy use of hot rolling (flat) and cold rolling (flat), respectively.

2.2. CO₂ Impact of Iron and Steel Production

Iron and steel production generates CO₂ emissions 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 steel plants and EAF plants) (U.S. EPA 2010).

The major process units at iron and steel facilities where raw materials, usually in combination with fuel combustion, contribute to CO₂ emissions include the sinter plant, non-recovery coke oven battery combustion stack, coke pushing, BF exhaust, BOF exhaust, and EAF exhaust (U.S. EPA 2010). The primary combustion sources of CO₂ include: byproduct recovery coke oven battery combustion stack, BF stove, boiler, process heater, reheat furnace, flame-suppression system, annealing furnace, flare; ladle reheater, and other miscellaneous (U.S. EPA 2010).

Figure 3 shows the profile of CO₂ emissions from and material flow in a typical BF/BOF integrated steel plant. It shows that total CO₂ emissions of a typical integrated steel plant are equal to 1.8 tCO₂/t rolled coil, of which 1.7 tCO₂/t rolled coil is associated with coal use, and the other 0.1 tCO₂/t rolled coil is related to lime use (Birat 2010).

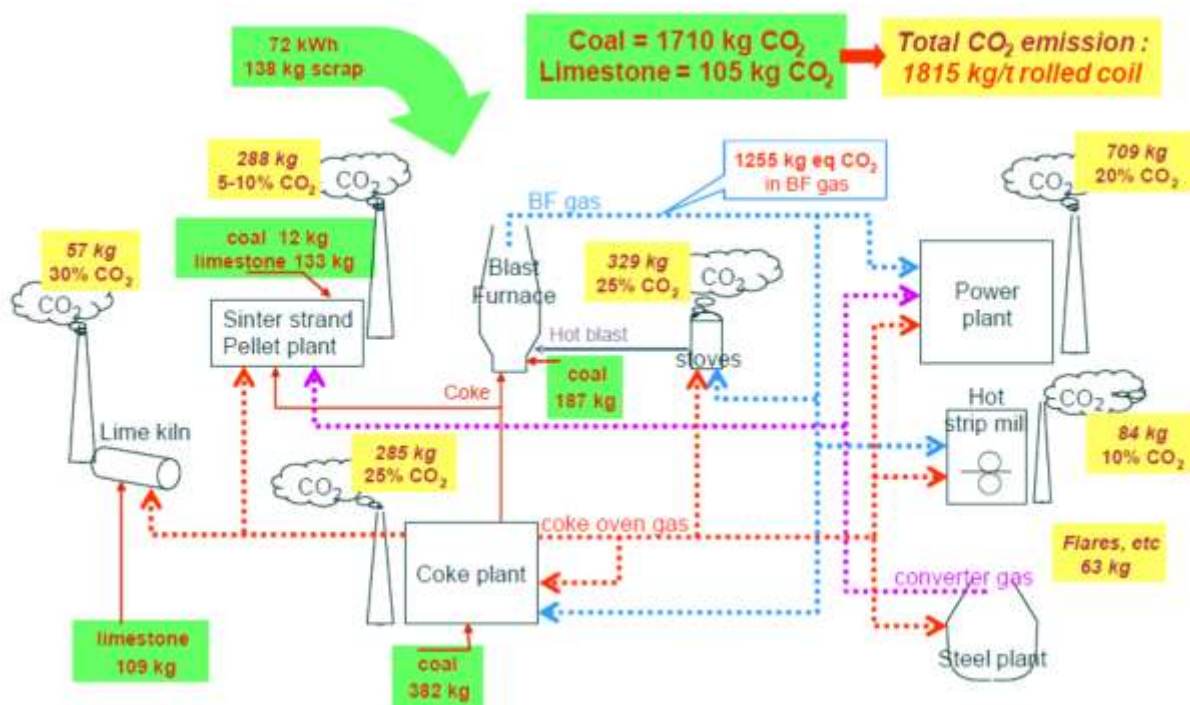


Figure 3. CO₂ emissions from typical steel mill (Birat 2010)

3. Emerging Energy-efficiency and CO₂ Emissions Reduction Technologies

The subsections below describe emerging energy-efficiency and CO₂ emissions reduction technologies for the iron- and steelmaking process.

3.1. Emerging Agglomeration Technology

Iron ore agglomeration can improve the iron content and/or physical properties of the ore. Iron feed materials from such processes usually contain between 50 percent to 70 percent iron by weight. The main agglomeration processes are sintering and pelletizing. Below an emerging technology that can be applied to this stage of iron production is presented.

3.1.1. Use of Biomass in the Sintering Process

Description:

The iron-ore sintering process contributes up to 10 percent of the CO₂ emissions from an integrated iron and steel plant (Ooi et al. 2011). This process requires the ignition of a solid fuel (usually coke breeze), which is blended into the raw feed material. A suitable alternative fuel must be solid and have downdraft combustion characteristics similar to those of coke breeze. Charcoal is an attractive alternative to coke breeze because charcoal is derived from biomass and therefore considered to be carbon neutral. Charcoal has been found to be as effective a fuel and reductant as high quality coals for the bath smelting of iron ores (Ooi et al. 2011; APP 2010).

A variety of wood char products are produced using relatively new processes such as gasification, slow pyrolysis, and fast pyrolysis (Ooi et al. 2011). Wood char has been shown to be a suitable replacement for coke breeze, improving the sintering process and reducing acid gas levels in process emissions (APP 2010). It should be noted that it is possible that only a limited amount of charcoal would be available when competition with other routes of biomass use is considered.

Ooi et al. (2011) conducted a laboratory study of the use of hardwood charcoal as a supplementary fuel in the iron-ore sintering process. The primary fuel was coke breeze; the study tested 0 percent, 20 percent, 50 percent, and 100 percent replacement with charcoal, producing raw blends with the same heat output as coke breeze. The experimental results indicate that fuel blends with 20 percent heat input provided by charcoal may improve both sinter yield and sintering productivity by up to 8 percent under normal conditions. When larger percentages of coke breeze were replaced with charcoal, reduced sintering performance was observed, which was mainly attributed to the lower fixed carbon content and higher volatile matter content of the fuel mix (Ooi et al. 2011).

Zandi et al. (2010) studied commercially available biomass materials suited to sintering: olive residues, sunflower husk pellets, almond shells, hazelnut shells, and bagasse pellets. A laboratory

sinter pot was used to study the sintering behavior of these biomass materials. The calorific values of selected biomass materials, on a dry basis, were, on average, approximately 65 percent that of dry coke breeze. However, less of this energy was available in sinter making because some of the volatile matter evaporated ahead of the flame front. Replacing 25 of coke breeze with crushed sunflower husk pellets produced a thermal profile closest to that of coke breeze alone in some size ranges of sunflower husk pellets (Zandi et al. 2010). Figure 4 shows a schematic drawing of an iron-ore sintering plant.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by replacing a portion of the coke breeze fuel with biomass fuel in sintering plants (Ooi et al. 2011; APP 2010):

- Substantial reductions in CO₂ emissions because biomass is considered carbon neutral
- Reduced acid gas emissions
- Improved carburization rates and increased product quality
- Reduced demand for fluxing agents
- Lower slag volume and levels of process wastes
- Higher productivity through use of more reactive carbon

Block Diagram or Photo:

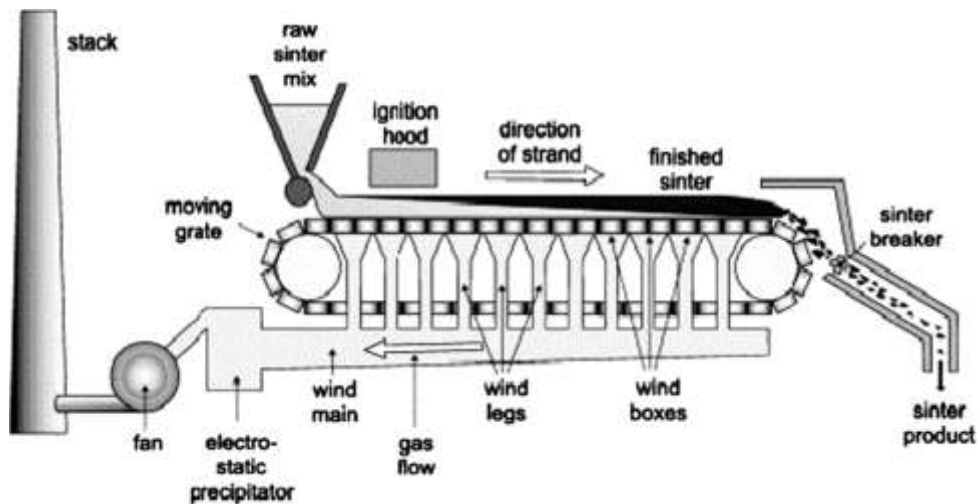


Figure 4. Schematic diagram of an iron-ore sintering plant (Ooi et al. 2011)

Commercial Status: Demonstration stage

References for further information:

Ooi et al. (2011), APP (2010), Zandi (2010)

3.2. Emerging Coke-Making Technologies

The subsections below describe the following emerging technologies to reduce the energy use and CO₂ emissions of the coke-making process: single-chamber coke reactors and battery under-firing with advanced controls.

3.2.1. Single-chamber-system Coking Reactors

Description:

Single-chamber-system (SCS) coking reactors are large-volume coke ovens that are 45 to 85 centimeters wide. Single-chamber reactors are separate, process-controlled units with rigid walls that can absorb high coking pressure. The single-chamber design allows much thinner heating walls than in other systems. This enhances heat transfer and combustion and allows for greater design flexibility in the plant (EIPPCB 2001).

The load-bearing capacity of the single-chamber reactor walls means that a greater range of coal blends can be charged than in conventional coke ovens. (Rohde and Strunk [1998] compared the coking behavior of coal blends in the single chamber system and in conventional high-capacity coke ovens.) The large-dimension oven in the SCS design reduces environmental emissions compared to those from multi-chamber reactors. SCS coke ovens are expected to take the place of current multi-chamber coke ovens whose walls have more limited flexibility. SCSs are 38- to 70-percent more thermally efficient than other coke ovens. The SCS technology is currently under development. An SCS coke reactor operating in Germany was relocated to China a few years ago (Worrell et al. 2010).

Figure 5 shows a schematic drawing of the single-chamber system.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for SCS coking reactors compared to conventional multi-chamber coking reactors (Worrell et al. 2010; Nashan 2007):

- Reduced coking time
- Improved productivity
- Increased coke strength
- Reduced space requirement, which increases design flexibility of the plant
- Ability to use wider range of coal, particularly coals containing less volatile matter, thus yielding a higher coke output
- Lower coke reactivity index values and higher coke strength after reaction values compared to those of conventional systems using similar coal
- Lower capital investment costs than for conventional ovens, particularly from implementing lean oven chambers

- Estimated capital investment of approximately \$40 million for 100,000 t of BF coke per year; estimated cost savings of 10 \$/t coke or higher
- Utilization of coke oven gas as energy carrier, reducing agent for iron ore, and synthesis gas in chemical plants
- Lower maintenance costs
- Reduced CO₂ emissions

Block Diagram or Photo:

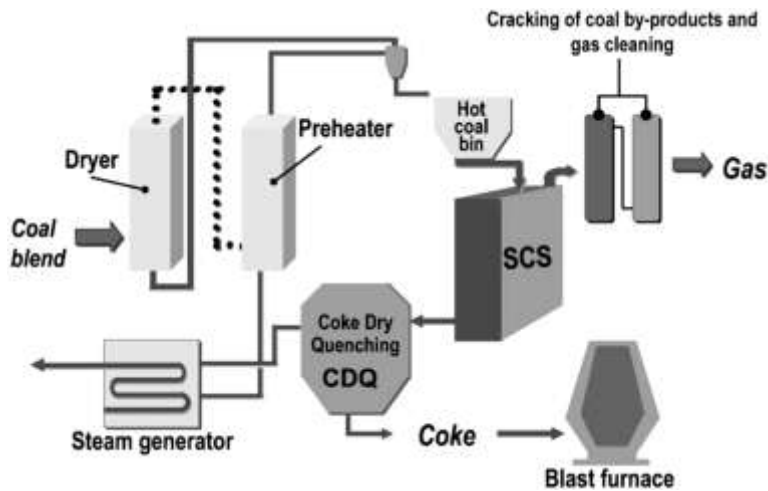


Figure 5. Schematic diagram of the single-chamber system (Díez et al. 2002)

Commercial Status:

Demonstration stage

References for further information:

EIPPCB (2001), Worrell et al. (2010), Nashan (2007)

3.2.2. Coke Oven Under-firing with Advanced Diagnostics and Control

Description:

Heating coke ovens produces significant amount of the pollutants nitrogen oxide (NO_x) and sulfur dioxide (SO₂). Therefore, improving energy efficiency of coke ovens is a cost-effective way to reduce pollutant emissions as well as energy demand (BFI 2009/2010). A VDEh-Betriebsforschungsinstitut (BFI) project developed individual control of the heating walls of coke ovens as well as innovative diagnostic systems that can detect disturbances in the heating walls (e.g., raw gas escaping from the coke wall or blockage of the combustion gas and air nozzles). A test reactor (see Figure 6) was used to study factors that influence the composition of the off gas and the temperature distribution in the heating flues; these factors include combustion gas supply

line position, combustion air/gas preheating temperature, combustion air/gas ratio, raw gas escape, and off-gas recirculation. Based on the results, the authors draw conclusions about the quality of the coke wall heating and devise measures to improve the efficiency of oven heating (BFI 2009/2010). No industrial application has been reported so far.

Energy/Environment/Cost/Other Benefits:

BFI claims that the following benefits can be achieved by coke oven under-firing with advanced diagnostics compared to conventional coke oven operation (BFI 2009/2010):

- Reduced energy consumption because of optimized wall heating
- Reduced NO_x and SO₂ emissions as a result of reduced energy use

Block Diagram or Photo:

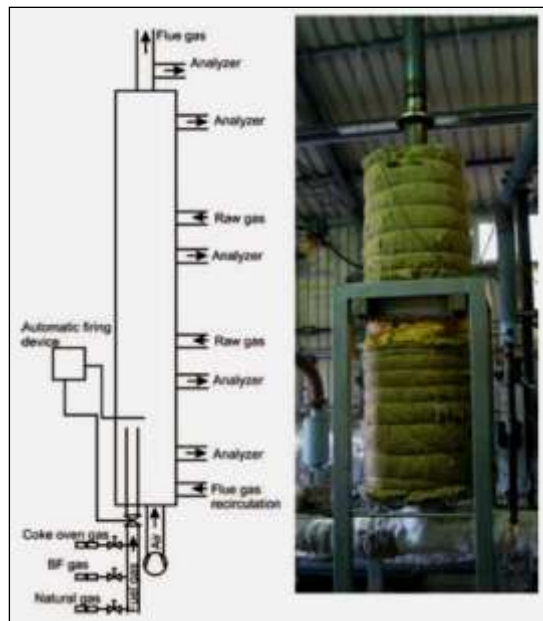


Figure 6. Coke oven heating laboratory plant schematic (left) and photograph (right) (BFI 2009/2010)

Commercial Status:

Development stage

Reference for further information:

BFI (2009/2010)

3.3. Emerging Technologies for Ironmaking Using Blast Furnace

The subsections below describe the following emerging technologies to reduce energy use and CO₂ emissions from the BF ironmaking process

3.3.1. Hot Oxygen Injection

Description:

Injection of pulverized coal directly into the BF bypasses the coke making process and injects coal directly into the BF at the tuyere level. Pulverized coal injection (PCI) is not a new technology, but, until now, the amount of coal that could be injected into the furnace was limited to 116 to 150 kilograms (kg)/t hot metal (AISI 2010) because of incomplete combustion of char in the tuyere zone and consequent disturbances in gas and burden flow in the furnace (Halder 2011). Increased coal injection is needed to further lower coke requirements and allow for more flexible furnace productivity. The direct injection of high-temperature oxygen with coal in the BF blowpipe and tuyere offers better coal dispersion at high local oxygen concentrations, which optimizes oxygen use in the BF (Riley 2002; U.S. DOE/ITP 2010a).

Praxair has developed an application in which its patented thermal nozzle technology uses oxygen to improve the combustion efficiency of injected pulverized solid fuels. This is accomplished by virtue of quicker ignition, de-volatilization of the pulverized solid fuel, and intense mixing of the solid fuel using a high-momentum, high-temperature stream of oxygen generated in situ (Halder 2011).

In a commercial-scale project, hot oxygen injection from Praxair's thermal nozzle system was demonstrated on two tuyeres of the U.S. Steel Gary Works BF. Heat loads were measured on all furnace components affected by hot oxygen. The results showed significantly higher levels of combustion in the blowpipe and tuyere with hot oxygen, along with acceptable increases in equipment temperature. The data suggest that hot oxygen increases injection of pulverized coal directly into the BF by 30 percent which reduces the amount of coke use in BF, thereby reducing the energy use in coke making (Riley 2002). For a medium-sized BF producing 4,000 t per day (tpd) with a hot oxygen replacement ratio of 0.9, coke savings would be 135 tpd, and injection of pulverized coal would increase by 150 tpd. The expected increase in oxygen consumption would be 34 kg/t hot metal, or 150 tpd. In addition, increased coal injection will increase the net heat generated from BF gas by an estimated 780 GJ/day (Riley 2002).

Figure 7 shows a schematic drawing of a hot oxygen device.

Energy/Environment/Cost/Other Benefits:

Based on pilot tests, the following benefits are reported for direct injection of high-temperature oxygen into the BF (Riley 2002):

- Increased coal injection of 37.5 kg/t hot metal

- Potential productivity increase of 15 percent
- Increase in net amount of BF gas generated
- Reduced emissions of pollutants and greenhouse gases (CO₂, SO₂, volatile organic compounds [VOCs], and NO_x) proportional to reduced coke requirements
- Estimated total capital and installation cost of \$1.05 million for a 4,000-tpd furnace
- Direct savings payback period (not including productivity benefits) of less than 11 months; including productivity benefits, payback period of 3 months.

Block Diagram or Photo:

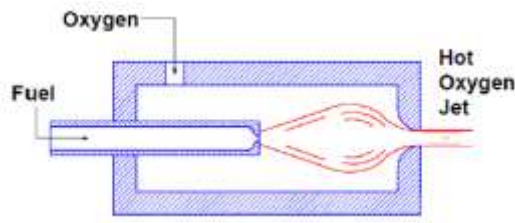


Figure 7. Schematic of hot oxygen device (Halder 2011)

Commercial Status:

Pilot stage

References for further information:

Riley (2002), U.S. DOE/ITP (2010a), Halder (2011)

3.3.2. Blast Furnace Optimization Using Computational Fluid Dynamics Modeling

Description:

One method of visualizing BF operations is by building a “virtual BF” using computational fluid dynamics (CFD) modeling. CFD uses advanced mathematical and computing concepts to simulate the behavior of high-pressure, high-temperature systems. Using the “virtual BF,” it is possible to design, optimize, and troubleshoot the system and experiment with operational improvements. CFD can be used to model increased levels of PCI. Increasing the PCI from 116–150 kg/t hot metal to 250 kg/t hot metal would save approximately 0.33 GJ of energy/t hot metal. Efforts to increase PCI to more than 250 kg/t hot metal have been frustrated because, at these levels, the permeability of the BF bed decreases, shutting off gas flow. In addition, some of the pulverized coal is wasted because it fails to combust and is blown through the BF into the gas collection system, thus increasing the apparent energy intensity of the process (AISI 2010).

The ability to increase the amount of coal injected into BFs has been limited by lack of knowledge of some key issues, so the U.S. DOE and American Iron and Steel Institute (AISI) Technology Roadmap Program (DOE/AISI TR Program) supported research at Purdue

University-Calumet to develop high-fidelity CFD numerical simulations. To date, Purdue has developed comprehensive three-dimensional (3-D) CFD models and methodologies to simulate the entire PCI process. The models were created by comparing CFD results with experimental data and were then applied to simulate the PCI process in various BFs of AISI members, using actual furnace geometries and operating practices. The effects of key parameters, such as blast temperature and flow rate, oxygen concentration, coal type, PCI rate, and tuyere diameter, have been investigated.

Because fuel economy in a BF is directly coupled to the gas and burden (raw materials or the charge) distributions in a BF, the DOE/AISI TR Program supported Purdue University-Calumet to (AISI 2010):

- Integrate all the BF CFD models developed so far, to visualize the entire BF process
- Develop a state-of-the-art 3-D CFD model for simulating the gas distribution inside a BF at given burden conditions, burden distributions, and blast parameters
- Measure top temperature and gas composition distributions and validate the CFD model
- Maximize gas utilization via optimized burden and gas distribution to produce the proper furnace permeability for given burden materials, production rates, and BFs
- Optimize the burden and gas distributions for high fuel-injection and low coke rates to produce the greatest fuel efficiency for the given burden materials, productivities, and BFs

Figure 8 shows a CFD model of a BF.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the use of CFD models for BF optimization (AISI 2010; U.S. DOE/ITP 2010a):

- Development of recommendations for design and protection of PCI lances
- Troubleshooting solutions for PCI operation
- Calculation of optimized BF operation for a given fuel injection rate and efficiency and the resulting gas distribution compared to process monitoring data; enables improved BF efficiency and productivity and lowers emissions
- Reduced emissions (e.g., CO₂, SO₂, VOCs, and NO_x) from coke making, proportional to reduced coke requirements.

Block Diagram or Photo:

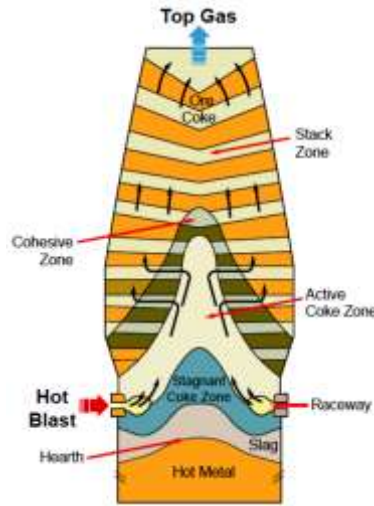


Figure 8. BF model using CFD (AISI 2010)

Commercial Status:

Demonstration stage

References for further information:

AISI (2010); U.S. DOE/ITP (2010a)

3.3.3. Blast Furnace Optimization Using X-ray Diffraction Analytical Technique

Description:

As mentioned above, in BF ironmaking, coke consumption can be decreased by increasing the pulverized coal injection rate (PCIR). This will change in-furnace reduction conditions, burden distribution, demands on raw material strength, and other factors. To maintain stable operation and minimize material losses through offgassing, it is important to understand fines generation and behavior in the BF (Leimalm et al. 2010).

PCIRs greater than 100 kg/t hot metal can result in the production and accumulation of unburned coal char in the tuyere raceways. This char is entrained in the blast and carried into the burden, reducing bed permeability, and is ultimately carried into the gas cleaning system and collected in the BF sludge. Tiny particles of coke called “fines” are also produced in the furnace and behave in a similar fashion (AISI 2010). To solve the problems related to unburned char, DOE/AISI TR Program supported research at the University of New South Wales to analyze the production of char and fines in BFs and relate this to furnace operating parameters and coal and coke properties. A novel technique using X-ray diffraction (XRD) was developed to quantify the proportion of carbon from PCIR and coke in the BF dust. XRD is used to study the microstructures of molecular and crystalline materials. The study demonstrated that blast temperature and oxygen

influenced PCI combustion and char carryover and limited coal injection rates. The results suggest that, by monitoring the carbon structure of residual char in the dust, PCI and coke quality can be optimized for various process parameters. The study further demonstrated that the carbon structure of coke fines in BF dust can be used to assess coke performance, particularly the influence of temperature on the generation of coke fines, whether they originated in the low- or high-temperature zones of the BF. Introduction of this XRD diagnostic tool in steel plants makes it possible to monitor the impact of PCI rates and coke quality and thereby further boost PCI rates (AISI 2010).

Leimalm et al. (2010) sampled the off-gas dust and shaft fines generated during operation of an experimental BF using olivine pellets and mixtures of acid pellets and sinter as iron-bearing materials. Characterization using XRD focused on fines from iron-bearing materials, coke, and slag formers. Prakash et al. also used XRD to study the effective utilization of BF flue dust from integrated steel plants (Das et al. 2002).

There are many other applications of XRD in the steel industry, including in blending of iron ores, control of sintering behavior, quality control of DRI, and analysis of converter slag. For example, König et al. (2010) describe how XRD can be used in mining for iron ore where distinguishing between hematite and magnetite has a big impact both on the refining of the ore and on the amount of coke needed in the BF (König 2010). Figure 9 shows an XRD system.

Energy/Environment/Cost/Other Benefits:

The benefits of XRD include:

- Enables use of carbon structure of BF fuels and dust emissions to select coke and optimize PCI operations
- Reduces emissions (e.g., CO₂, SO₂, VOCs, and NO_x) from coke making, proportional to reduced coke requirements

Block Diagram or Photo:



Figure 9. X-ray diffraction system (UNSW 2012)

Commercial Status: Demonstration stage

References for further information: AISI (2010), Leimalm et al. (2010), Das et al. (2002)

3.3.4. Blast Furnace Heat Recuperation

Description:

The BF flue gas exit temperature is approximately 250°C . This heat can be recovered to preheat stove combustion air. Installation of a recuperator in the furnace exhaust stream to preheat the combustion air can save considerable amount of fuel. These savings are primarily the result of the sensible heat increase of the combustion air and, to some extent, improved combustion efficiency. The amount of fuel saved will depend on the exhaust gas temperature, amount of excess air used, type of burner, and furnace control system. The cost of this technology is high and strongly dependent on BF size, estimated at \$18-20/GJ-saved, equivalent to \$1.4/t hot metal (Farla et al. 1998; Rebello et al. 1980).

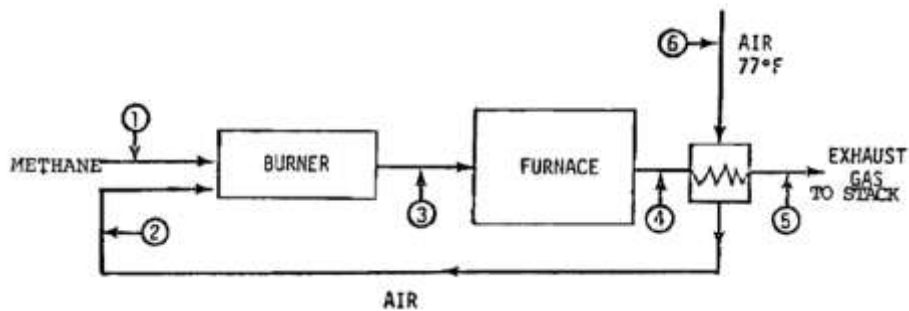
Figure 10 shows a schematic drawing of a system with a recuperator.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for BF heat recuperation through a hot blast stove (Farla et al. 1998; Stelco 1993):

- Fuel savings between 80-85 megajoules (MJ)/t hot metal (around 0.7 percent of BF energy use)
- Efficient hot blast stove operation possible without natural gas

Block Diagram or Photo:



1) mass of methane entering burner, 2) mass of air entering burner, 3) mass of products entering furnace, 4) mass of exhaust gas exiting the furnace

Figure 10. System schematic with recuperator (Rebello et al. 1980)

Commercial Status:

Demonstration stage

References for further information:

Farla et al. (1998), Rebello et al. (1980), Stelco (1993)

3.3.5. Plasma Blast Furnace

Description:

Today, plasma technology is being used successfully worldwide in a variety of industries from chemical and metallurgical to waste/environmental (asbestos vitrification, fly-ash destruction) and steel production (heat support for cupola and BF) (Solena Group, n.d.; Hacala and Michon 2009).

Plasmas are gaseous collections of electrically charged particles such as electrons and protons. These ionized particles carry energy; in a plasma BF, the plasma flow hits the metal surface, the ions release their energy, which melts the metal (BCS, Inc. 2005). Typical plasma power ranges from 1 to 4 megawatts electric (MWel). Plasma torches provide high-temperature gas streams (up to 5,000°C) (Hacala and Michon 2009). Thermal-plasma systems fall into two categories: non-transferred-arc and transferred-arc devices. In general, transferred-arc devices have been interfaced with open-bath furnaces in which melting or smelting processes are carried out, and non-transferred-arc devices have normally been applied to shaft furnaces (Birat et al. 2008).

Plasma melting can raise temperatures very rapidly and is thus more energy efficient than conventional melting technologies, for example, in non-BF applications. Plasma furnaces for melting aluminum are reported to impart heat 60-percent faster than conventional high-rate melters. Because of the rapid heat transfer in a plasma furnace, melting is also rapid. In aluminum making, the energy consumption rate is as low as 0.44 kWh/kg of aluminum compared to 0.76 kWh/kg of aluminum for induction melting (BCS, Inc. 2005). These data all are for non-steel application.

The plasma melting process also minimizes metal loss from oxidation and contamination. The plasma keeps intact a thin oxide film on the molten metal, which protects the metal from absorbing gases. A recent development in plasma heating converts ambient air to nitrogen, eliminating the need to purchase nitrogen or argon, expensive gases that are required for conventional plasma heating (BCS, Inc. 2005).

As part of the European Ultra-Low-CO₂ Steelmaking program (ULCOS) program, EUROPLASMA studied the introduction of the plasma torch in the BF top-gas recycling loop. Calculations performed for this study showed that the use of a plasma torch fed with recycled top gases reduced carbon consumption by 50 percent compared to that of a conventional BF (assuming that the plasma torch is powered with low-carbon electricity). Tests showed that a 1-megawatt (MW) plasma torch can operate with any gas mixture containing CO, diatomic hydrogen (H₂), CO₂, and nitrogen (N₂) (Hacala and Michon 2009). EUROPLASMA is now moving to the next step in its torch development: developing higher-power plasma torches. The goal is to reach 20 MWel (Hacala and Michon 2009).

The plasma technology could be used with or without carbon capture and storage (CCS), making it either a long- or short-term solution to carbon emissions where dedicated low-carbon electricity is available (Birat et al. 2008).

Figure 11 shows a schematic of plasma torch on BF.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for plasma BFs compared to conventional BFs (Hacala and Michon 2009; BCS, Inc. 2005; Birat et al. 2008):

- Reduced energy use
- Minimized metal loss from oxidation and contamination
- Carbon consumption reduced by 50 percent
- Potential to cut BF carbon consumption by 100 kg

Block Diagram or Photo:

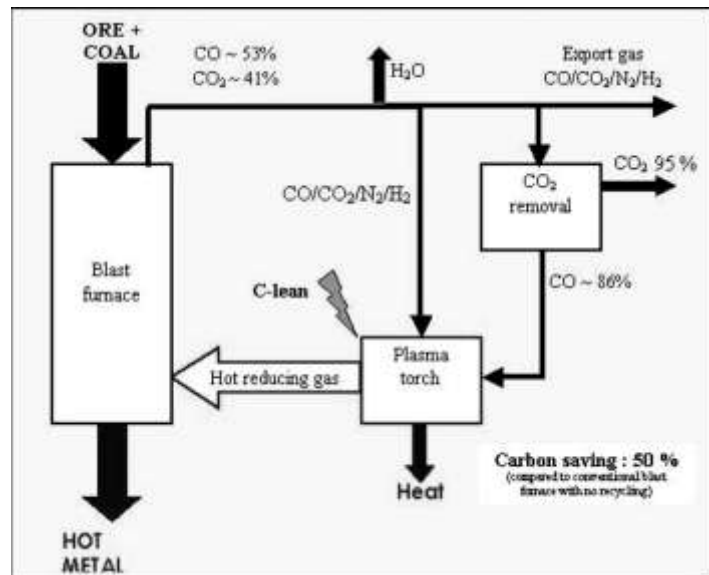


Figure 11. Plasma torch on BF (Hacala and Michon 2009)

Commercial Status:

Development stage

References for further information:

Hacala and Michon (2009); BCS, Inc. (2005); Birat et al. (2008)

3.3.6. Blast Furnace Slag Heat Recovery

Description:

In modern BFs, approximately 0.25-0.30 tonne of liquid slag with temperatures ranging from 1,200 to 1,600 °C are produced per tonne of pig iron (Worrell et al. 2010; Barati et al. 2011). Molten slag is one of the largest untapped energy sources in metal manufacturing operations. Currently, three types of technologies are under development for utilizing the thermal energy of slag: 1) recovery as hot air or steam, 2) conversion to chemical energy as fuel, and 3) thermoelectric power generation. Recovery as hot air or steam is the most developed of the three, with large-scale trials demonstrating recovery efficiencies up to 65 percent. The latter two strategies are emerging as next-generation methods of BF slag waste heat recovery (Barati et al. 2011).

Barati et al. (2011) evaluated these three technologies and found that, for both thermal and chemical energy recovery, a two-step process would yield a high efficiency with minimal technical risk. For thermoelectric power generation, the use of phase-change materials appears to solve some of the current challenges, which include the mismatch between the slag temperature and the operating range of thermoelectric materials (Barati et al. 2011). Using a second-law analysis, Bisio (1997) concludes that using air heated by slag heat recovery for combustion in the hot blast stoves of the BF is preferable to producing steam from the recovered heat.

Shimizu et al. (2010) investigated heat recovery from molten BF slag using a fluidized bed vessel. In their laboratory-scale prototype, molten slag droplets are fed into a fluidized bed vessel consisting of crushed solid slag. The heat from the resulting phase change is recovered through boiler tubes. There is no direct contact between the BF slag and the boiler tube. The solid slag is removed from the bottom (see Figure 12) (Shimizu et al. 2010).

Problems with heat recovery from melted slag include (Shimizu et al. 2010):

- Phase change from liquid to solid by cooling
- Accumulation of solid slag on heat-transfer surface
- Insufficient heat recovery if heat removal is from only liquid phase (sensible heat of liquid)
- Reduction in temperature difference if heat is recovered after solidification (cooling)

The Japan Iron and Steel Federation (JISF), under its COURSE 50 program, is also developing a process to recover sensible heat from high-temperature steelmaking slag. The heat will be used as the thermal energy to separate CO₂ from chemical absorbents in a carbon capture system, thus regenerating the absorbents (JISF 2012a). However, it should be noted that JISF technology is not for BF and is for steelmaking slag (BOF or EAF). Moreover, the slag from a BOF or EAF are different, and behave differently than the BF slag.

Energy/Environment/Cost/Other Benefits:

The main benefit of development of a commercial technique for slag heat recovery would be the energy savings, which are estimated to be approximately 0.35 GJ/t pig iron (around 2.5 percent of BF energy use) (Worrell et al. 2010).

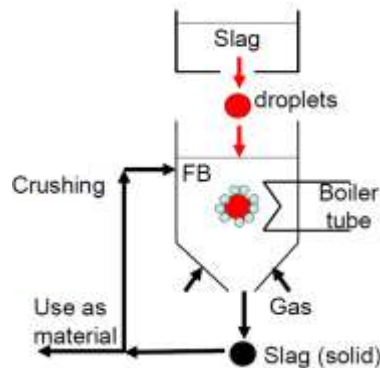
Block Diagram or Photo:

Figure 12. Sensible heat recovery from steelmaking slag (JISF 2012a)

Commercial Status:

Recovery as hot air or steam: Pilot stage

Conversion to chemical energy as fuel and thermoelectric power generation: Development stage

References for further information:

Worrell et al. (2010), JISF (2012a)

3.3.7. Charging Carbon Composite Agglomerates in Blast Furnace**Description:**

Carbon composite agglomerates are mixtures of fine iron ore (hematite, magnetite, iron-bearing ironmaking dust, and pre-reduced iron ore fines) and fine carbonaceous materials (fine coke, fine coal, charcoal, and char) along with binding agents in most cases. The composition, shape, carbon content, and physical properties of agglomerates vary widely depending on the raw materials and process conditions. In the past, carbon-bearing agglomerates were mainly used in some established or partly industrialized rotary hearth processes, such as FASTMET, INMETCO, and COMET, in which advantages such as comparatively faster reduction rates and lower fuel utilization rates were reported. Recently, application of carbon composite agglomerates in BF and EAF processes has been attracting technical and scientific interest (Yagi et al. 2003).

Regarding the method of agglomeration, it is reported that common cold-bonded carbon agglomerates have poor strength, especially during reduction. This restricts the amount of agglomerate that can be used as input to a BF. A hot briquetting process was proposed to

manufacture carbon composite iron ore briquette from a mixture of fine coal and fine iron ore; compared with the other carbon containing agglomerates, this briquette was stronger because of the thermal plasticity of coal and showed better reducing performance as well as having lower cost (Yagi et al. 2003).

If carbon composite agglomerates are charged into the furnace, the temperature of thermal reserve zone decreases, retarding the reduction of iron-bearing burden materials. However, BF energy efficiency is improved because of the decrease in heat requirements for solution loss, sinter reduction, and silicon transfer reactions as well as reduced heat loss through top gas and the furnace wall (Chu et al. 2006).

Fundamental research has been carried out on various carbon agglomerates, mainly focusing on reduction and melting behaviors (Yagi et al. 2003; Meng et al. 2001; Zhang et al. 1995), carburization mechanism (Matsumura et al. 1999), and the effect of the surrounding gas atmosphere (Ueki et al. 2001) on reduction rate. Carbon-bearing agglomerates were also tested in BFs and a BF simulator. This revealed that carbon composite agglomerate charging had no deleterious effects on gas penetration, burden descent, or smooth operation, and it can improve BF energy efficiency (Kono et al. 2000).

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the use of carbon composite agglomerates in BFs compared to conventional BF production (Yagi et al. 2003; Chu et al. 2006):

- Less sinter and coke products needed, which decreases energy consumption and environmental load
- Wider range of raw materials used, i.e., effective use of non-coking coal and iron-bearing dust and sludge in steel works; enables resource recycling
- Fine iron ore and carbonaceous materials mixed at micron scale in the agglomerates, which should produce fast reduction reaction
- Carbon gasification and iron ore reduction reactions mutually accelerated and occur at lower temperature because of the coupling effect; therefore, charging carbon composite agglomerates to BF expected to improve process performance and decrease energy consumption

Block Diagram or Photo:

N/A

Commercial Status:

Demonstration stage

References for further information:

Yagi et al. (2003), Chu et al. (2006)

3.4. Alternative Emerging Ironmaking Technologies

The subsections below describe the following alternative ironmaking processes that reduce energy use and carbon emissions: the COREX process, the FINEX process, Tecnoled, ITmk3, the paired straight hearth furnace, the coal-based HYL process, the coal-based MIDREX process⁴, molten oxide electrolysis, suspension hydrogen reduction, fine ore reduction in a circulating fluidized bed, charging carbon composite agglomerates, use of biomass and waste oxides, and the cyclone converter furnace.

3.4.1. COREX[®] Process

Description:

COREX[®] is an industrially and commercially proven SR process that allows for production of hot metal directly from iron ore and non-coking coal. The process was developed to industrial scale by Siemens VAI. COREX differs from BF production in using non-coking coal as reducing agent and energy source. In addition, iron ore can be directly charged to the process in form of lump ore, pellets, and sinter (Siemens VAI 2007).

The COREX process is a two-stage direct smelting process, consisting of: 1) a melter-gasifier, which melts the DRI and gasifies the coal; and 2) a DRI shaft furnace mounted above melter-gasifier, which reduces lump ore or pellets to DRI by reducing gas from the melter-gasifier. The shaft furnace is a modified MIDREX DRI counter-current reactor (see subsection 3.4.7 for more information about MIDREX) without a cooling zone in which lump ore or/and pellets are reduced to approximately 85-percent metallization. The hot DRI at a temperature of approximately 800⁰C is discharged from the shaft furnace by means of horizontal screw conveyors, to the charging pipes of the melter-gasifier. The reducing gas enters the bottom of metallization zone. The fresh reducing gas from the melter-gasifier enters the shaft furnace at approximately 800 °C and then exits from the furnace top at ~450 °C. The melter-gasifier, which completes the reduction and melting of the DRI, consists of a fluidized bed chamber resting on liquid slag and a hot metal bath. Coarse coal is charged to the top of melter-gasifier and charred in the fluidized bed. Oxygen is injected via tuyeres around the circumference of the melter-gasifier. This forms a raceway in which the oxygen reacts with charred coal to form CO. For optimum energy efficiency and economics, the process requires the following auxiliaries: 1) CO₂ stripping of the shaft top gas, which enables better utilization of the process gas (after CO₂ stripping, the rich reducing gas could be recirculated to the shaft furnace); and 2) In most cases, co-generation of the export gas, required because of the high calorific value of the gas. An additional DRI shaft furnace could be also installed to utilize the off gas and to produce an amount of DRI equivalent to the hot metal from the melter-gasifier (APP 2010).

⁴ Natural gas-based HYL and MIDREX processes are commercialized; thus, they are not included in this section as emerging technologies.

Some of the limitations of the COREX process are (Agrawal and Mathur 2011):

- It can't use ore fines directly
- There are restrictions on non-coking coal (volatile matter of carbonaceous material to be maintained at around 25%)
- Net export gas should be utilised very economically, otherwise the process becomes unviable.

There are five commercial COREX units in operation in China, Korea, India, and South Africa (Siemens VAI 2007). Figure 13 is a simplified diagram of the COREX process.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for COREX compared to a conventional BF (APP 2010; Siemens VAI 2007):

- No need for coking coal and coke
- Fuel savings of 18 percent and oxygen consumption reduction of 13 percent (reported for a low-export gas system demonstration in India)
- Approximately 20-percent lower CO₂ emissions per tonne of product
- Approximately 30-percent lower NO_x emissions per tonne of product
- No VOC emissions; significantly lower SO_x emissions
- Fuel rate significantly reduced by circulation of the shaft furnace top gas back to the shaft furnace
- Reduced investment and operation costs
- Lower slag production (18-percent slag production reduction reported in a low-export gas system demonstration in India).

Block Diagram or Photo:

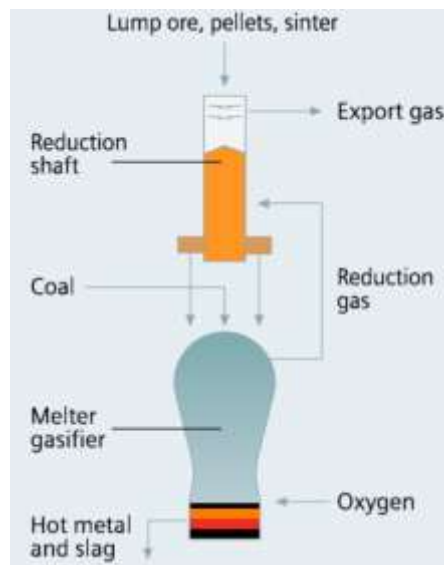


Figure 13. Simplified flow diagram of the COREX process (Siemens VAI 2007)

Commercial status:

Commercial with very low adoption rate

References for further information:

Siemens VAI (2007), APP (2010)

3.4.2. FINEX[®] process**Description:**

The FINEX[®] smelting-reduction process, developed by Siemens VAI and the Korean steel producer Posco, is based on the direct use of non-coking coal and fine ore. The major difference between the COREX and FINEX processes is that the FINEX process can directly use sinter feed iron ore (up to 12 mm) (Siemens VAI 2007), without agglomeration.

The FINEX core plant consists of a melter-gasifier and a series of successive fluidized bed reactors that form a counter-flow system in which ore fines are reduced in three or four stages to DRI. The upper reactor stage serves primarily as a preheating stage. In the succeeding stages, the iron ore is progressively reduced to fine DRI. The fine DRI is then compacted and charged in the form of hot compacted iron (HCI) into the melter-gasifier. The charged HCI is subsequently reduced to metallic iron and melted. The heat needed for the metallurgical reduction and melting is supplied by coal gasification with oxygen. The reduction gas, also produced by the coal gasification, is passed through the fluidized bed reactors. The FINEX export gas is a highly valuable product and can be further used for DRI/HBI production, electric energy generation, or heating. The hot metal and slag produced in the melter-gasifier is frequently tapped from the hearth, as is also done in BF or COREX[®] operation (Siemens VAI 2007).

Currently the Posco COREX plant is part of the FINEX demonstration, with an annual hot metal capacity of 900,000 t/year. Based on good results at the FINEX demonstration plant, Posco decided in August 2004 to construct a 1.5-million-t/year industrial FINEX plant at Posco Pohang Works, Korea which was commissioned in 2007 (Siemens VAI 2007). Siemens VAI Metals Technologies received an order from Posco Engineering & Construction Co., Ltd. (Posco E&C), a subsidiary company of the Korean steel producer Pohang Iron and Steel Co. Ltd. (Posco), for engineering and the supply of proprietary equipment for a FINEX plant with capacity of 2-million-t/year which is scheduled to commission in mid-2013 (Siemens 2011).

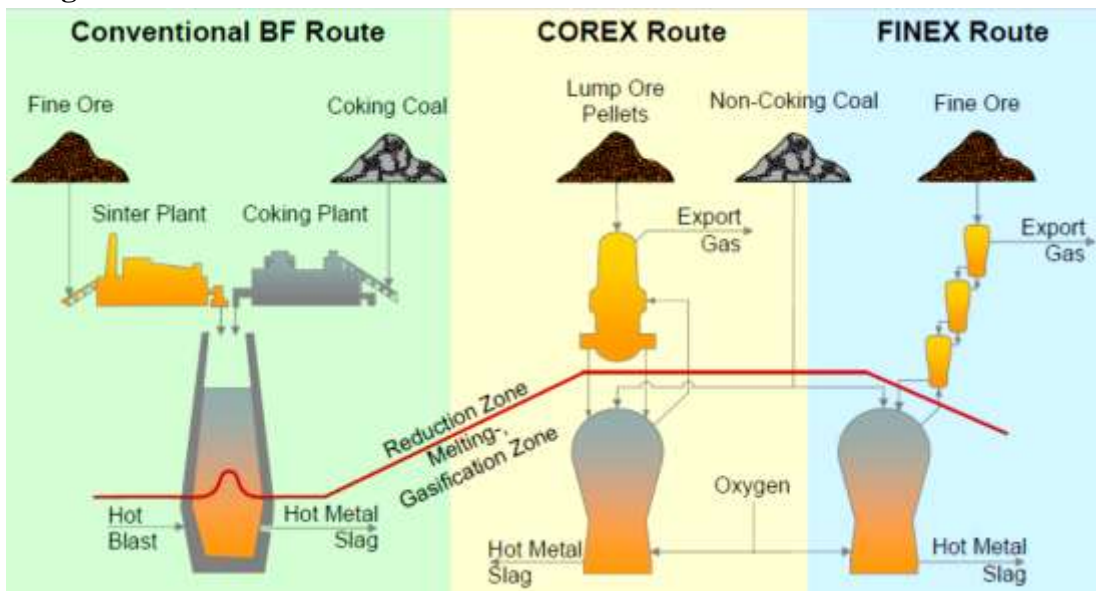
Figure 14 compares the BF, COREX, and FINEX processes.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for COREX compared to BF production (APP 2010; Siemens VAI 2007):

- No need for pelletizing, sintering, or agglomeration of iron-bearing materials
- Allows use of fine concentrates
- Capital cost claimed to be 20 percent lower than for BF, and production cost 15 percent lower
- Lower emissions because of lower energy consumption and no need for coke making
- Direct utilization of non-coking coal
- High valuable export gas for a wide range of applications in metallurgical processes and energy production
- Production of hot metal with quality similar to that produced in a BF

Block Diagram or Photo:



Note: This figure is primarily for illustration of major differences between three process. For the case of BF, however, in addition to sinter than is shown, the lump iron ore or sinter (or combinations) can be charged in BF.

Figure 14. Comparison of BF, COREX, and FINEX processes (Grill 2009)

Commercial status:

Commercial with very low adoption rate

References for further information:

Siemens VAI (2007), APP (2010)

3.4.3. Tecnored

Description:

The Tecnored process uses agglomerated pellets or briquettes containing iron ore fines and low-cost coals. Within the furnace, the pellets or briquettes are reduced to hot metal. Hot blast and other solid reductants are injected into the furnace as well. The furnace' shaft height is only 2 to 3 meters and therefore much smaller than typical BFs (Danieli Corus n.d.).

The Tecnored process starts with preparation of self-reducing pellets or briquettes, which are made from iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines are mixed and agglomerated into pellets or briquettes. After a drying process, the pellets/briquettes are fed from the top to the Tecnored furnaces. Additional lump coal and hot blast are injected into the furnace as well. The top gas is cleaned. Some of the top gas is re-fed as cold blast to the furnace. Preheated top gas is either fed as hot blast to the furnace or is used for the drying of the self-reducing pellets/briquettes. Surplus top gas is exported, for example to co-generation system or to replace fuels in other processes. Hot metal and slag are tapped at the bottom of the furnace (Danieli Corus n.d).

The Tecnored process can use low-cost materials (e.g., low grade iron ore fines, low-cost fuels). Its smaller design means it requires less power and less pressure within the furnace. It achieves full metallization (up to 99 percent). The process takes just 30 minutes compared to a typical blast furnace process, which takes up to 8 hours. However, this technology needs further development, and its capacity is smaller than typical blast furnaces.

A Vale Tecnored pilot plant reportedly started operating in 2011 in Brazil. The capacity of the test facility was intended to be 75,000 tonnes with an increase to 300,000 tonnes planned (Asmet 2011).

Figure 15 shows a flow diagram of the Tecnored process.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the Tecnored process compared to conventional BF production (Lockwood 2000, Danieli Corus n.d):

- Eliminates the need to use coke and sintering facilities, thereby reducing construction costs, energy use, pollutants, and CO₂ emissions.
- Lower power and pressure requirements because of smaller size of furnace
- Uses low-cost iron ore fines and low-cost fuels
- Achieves full metallization (up to 99 percent).

Block Diagram or Photo:

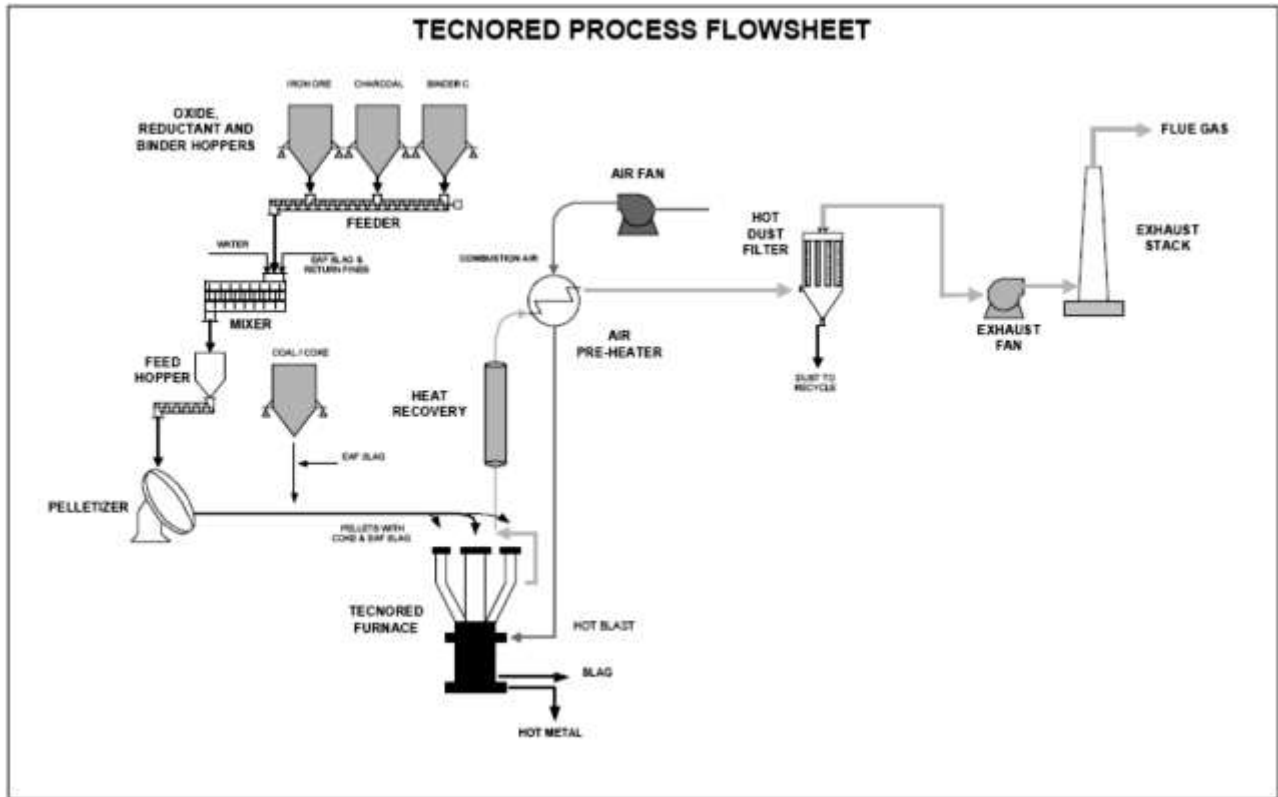


Figure 15. Flow diagram of the Tecnored process (Lockwood 2000)

Commercial Status:

Pilot stage

References for further information:

Lockwood (2000), Danieli Corus (n.d), Asmet (2011), Júniora et al. (2005)

3.4.4. ITmk3[®] Ironmaking Process

Description:

In almost all direct reduction ironmaking technologies that use a rotary hearth furnace (RHF), the RHF reduces iron ore to about 80 percent. A secondary smelting facility removes the remaining other material (gangue) from the ore. The DRI produced is usually taken to an EAF for final reduction and gangue removal. However, ITmk3[®] technology uses the RHF as a stand-alone unit that produces gangue-free metal eliminating the need for a secondary smelting process (Fruehan 2004a). The ITmk3 process uses low-grade iron ore⁵ and coal (other feedstocks can be used as

⁵ This process does not use low grade ore directly. Low grade ores are beneficiated, and the resulting fines (with >62% Fe content) are pelletized and used.

supplements) to produce iron nuggets whose quality is superior to that of DRI (97 percent iron content) but is similar to that of pig iron. The mixing, agglomeration, and feeding steps are the same as in the production of DRI or BFs, but the RHF is operated differently. In the last zone of the RHF, the temperature is raised, which melts the reduced iron ore and enables it to separate easily from the gangue. The result is a nugget containing iron and carbon with almost no oxygen or slag (Mesabi Nugget Delaware LLC and Mining Resources LLC,2011). This technology was demonstrated in a commercial scale demonstration plant co-funded by the U.S. DOE in 2006. This technology achieves reduction, melting, and slag removal in only about 10 minutes (U.S. DOE/ITP 2010a).

Kobe Steel, a Japanese steel company, developed and licensed the ITmk3 technology for production of nuggets. Mesabi Nugget, LCC, a joint venture between Steel Dynamics and Kobe Steel, began producing pig iron nuggets using ITmk3 technology in January 2010. The plant has the capacity to produce 500,000 tonnes of nuggets per year. Mesabi Nugget produces iron nuggets principally as feedstock for EAF steelmaking (Mesabi Nugget Delaware LLC and Mining Resources LLC,2011). Kobe Steel and SAIL (India’s largest steel producing company) have signed an agreement to build the second ITmk3 plant with the capacity of 500,000 tonnes in India (SAIL 2012). Figure 16 shows the ITmk3 process.

Energy/Environment/Cost/Other Benefits:

Mesabi Nugget, LLC claims the following benefits for the ITmk3[®] technology compared to conventional steel making (Mesabi Nugget Delaware and Mining Resources,2011):

- Lower capital and operation costs
- 30-percent energy savings over integrated steel making; 10 percent savings over EAF fed by DRI
- No coke oven is required
- Utilization of all chemical energy of coal; no gas exported from the system
- Reduced NO_x, sulfur oxide (SO_x), and particulate matter emissions
- Reduction, melting, and slag removal in only 10 minutes
- Reduction of iron oxide (FeO) to <2 percent, minimizing attack to refractories

Block Diagram or Photo:

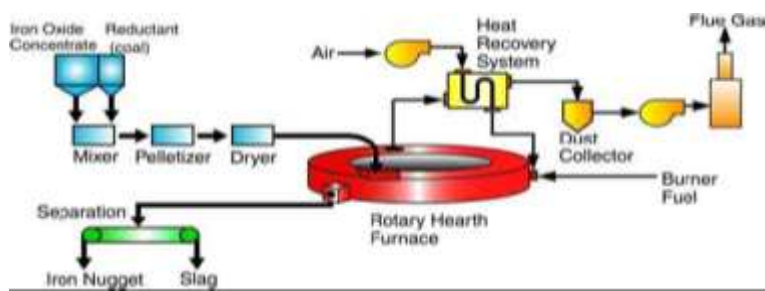


Figure 16. ITmk3[®] process (APP 2010)

Commercial Status:

Demonstration stage

Reference for further information:

Mesabi Nugget Delaware and Mining Resources (2011); Fruehan (2004a)

3.4.5. Paired Straight Hearth Furnace**Description:**

The paired straight hearth (PSH) furnace is charged with cold-bonded self-reducing pellets composed of iron oxide and coal. When the pellets are heated, the iron oxide is chemically reduced to produce a 95-percent metallized pellet suitable for use in steelmaking in an EAF. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal. As the pellets are heated on the hearth, CO gas is evolved and combusted above the pellet bed to drive the process. The bed of conventional RHF's is only two to three pellets high whereas the PSH furnace has a bed height of eight pellets (approximately 120 mm). The PSH furnace off gases are fully combusted to raise the temperature above the bed to 1,600°C. Reoxidation is prevented by the CO-rich gases rising through the bed. The PSH furnace technology is significantly more productive while using less energy than conventional furnaces (AISI 2010). The initial research program, funded by the DOE/AISI TR Program, was completed in 2002.

In 2006, DOE/AISI, through its TR Program, commissioned an engineering study by a well-known furnace builder to verify the feasibility and costs of building a PSH furnace. The study concluded that it is feasible to design, build, and continuously operate a PSH furnace to produce 46,000 t per year of DRI at 95-percent metallization for a cost of \$16,729,000. A detailed design and validation study to evaluate raw material flexibility was then initiated, and this study is scheduled to be completed in 2013. A demonstration-scale PSH furnace planned after that study is complete. The PSH furnace may be coupled to a smelter to provide a viable replacement for BF and BOF steelmaking.

Technology integration issues related to materials handling, furnace and waste treatment control systems, pellet quality, multi-layer bed stability, DRI quality, material throughput, process economics, long-term furnace performance, reliability, and stability are some of the barriers and uncertainties about this technology that need to be addressed (U.S. DOE/ITP 2011a).

The most likely point of initial entry for PSH furnaces into the mainstream market is integrated steelmaking facilities that might be looking for an alternative source of hot metal. This could include producers of coil, slab, long, or specialty steel products (U.S. DOE/ITP 2011a).

Figure 17 shows the process flow in a PSH furnace.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for PSH furnace ironmaking compared to BF ironmaking (APP 2010; U.S. DOE/ITP 2011a):

- Higher-productivity smelting operations when used as a pre-reducer with a smelter, to the degree that the combined process is a suitable replacement for a BF/coke oven
- 30 percent less energy at lower capital cost compared to BF ironmaking
- One-third fewer total CO₂ emissions per tonne of hot metal produced
- No coke oven is required.
- Coal used without requiring gasification
- For EAF operations, reduced energy intensity because of availability of hot metal on site (reduced power consumption, tap-to-tap time)
- Reduced costs (no cokemaking process needed, high-volatility coals can be used)
- Can use high-volatility coals to produce DRI pellets from virgin iron ores and steelmaking waste products, an important advantage given the scarcity of high-quality raw material

Block Diagram or Photo:

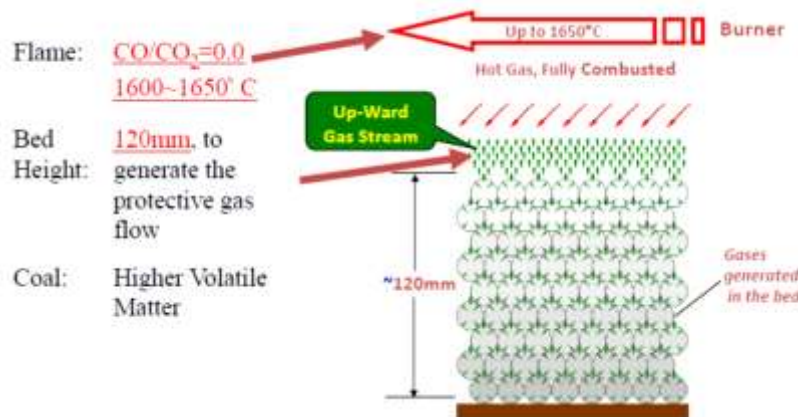


Figure 17. Process flow of paired straight hearth furnace (Lu 2008)

Commercial Status:

Development stage

References for further information:

AISI (2010), U.S. DOE/ITP (2011).

3.4.6. Coal-Based HYL Process- A Syngas-based DRI Plant

Description:

The HYL process, by Tenova HYL, is designed to directly reduce iron ores using reducing gases in a solid-gas moving bed reactor. Oxygen is removed from the iron ores by chemical reactions based on H₂ and CO to produce highly metallized DRI (Danieli and Tenova,2011).

The original HYL technology used natural gas, but Tenova HYL has built a new coal-based HYL technology (also known as Energiron HYL technology) by adding a coal gasification technology to HYL. The reactor and its peripheral systems and the principles of operation for the coal-based HYL process are same as for the gas-based HYL process in which oxide material is fed from the top and is reduced by a counter-current flow of H₂ and CO containing gas. Because this process does not use natural gas, a lower-carbon-content product (around 0.4 percent) is expected. Similar to the gas-based HYL process, in the coal-based process, the furnace top gas is cooled and cleaned, and its CO₂ is removed and then recycled into a reducing gas circuit. Reducing gas is produced in a coal gasifier that can process practically any kind of carbon-bearing material. Coal and oxygen are injected into the gasifier, and almost all carbon in the coal is gasified. The gas is dust laden and includes CO₂ and H₂O as well as other impurities. It is cleaned and cooled in a series of cyclones and H₂O, CO₂, and sulfur are removed. Because the HYL reactor is designed to work with high-H₂-content reducing gas, and the gas from the gasifier contains considerable amounts of CO, a gas shift reactor is required to convert CO into H₂ by the reaction $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. The shift reactor is installed before the CO₂ removal system. The temperature and pressure of the gas are then regulated before injection into the reactor (APP 2010).

Danieli & C. and Tenova HYL will build 4 units, each 2.75 million-t/year coal-based HYL plant for Jindal Steel and Power Limited in India. The Syngas plant will provide reducing gas for the DR plant as well as power generation facilities (Tenova HYL 2011).

Figure 18 diagrams the coal-based HYL process.

Energy/Environment/Cost/Other Benefits

Tenova HYL, Inc. claims the following benefits for coal-based HYL compared to BF production (Tenova HYL 2008; APP 2010):

- No need for coking coal and coke
- No need for natural gas
- Allows usage of low-quality coals
- Production of hot DRI that could be charged to EAF with significant energy savings

Block Diagram or Photo:

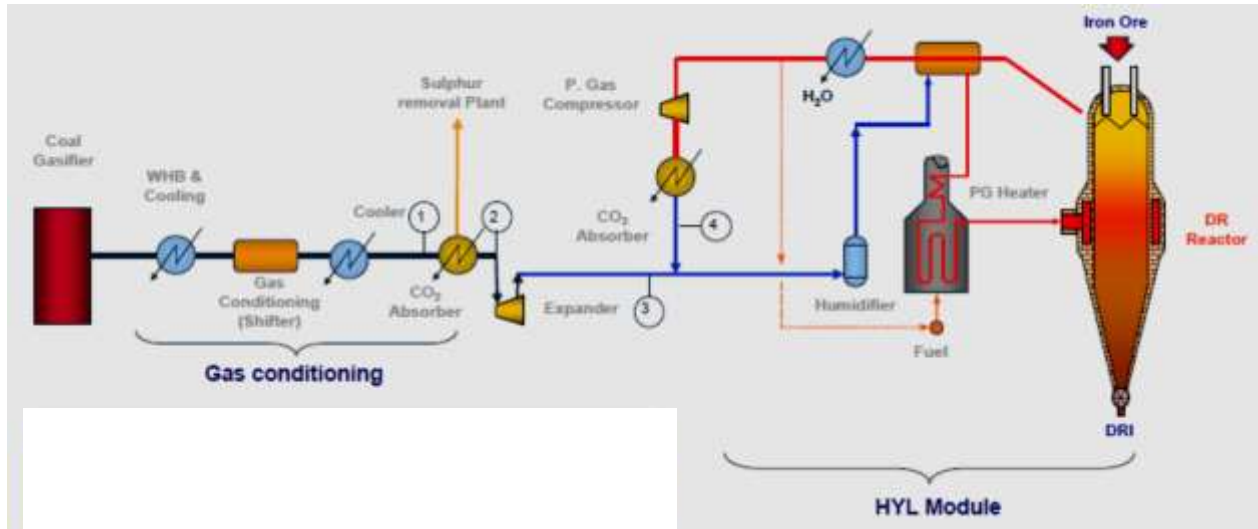


Figure 18. Coal-Based HYL Process (TenoVA HYL 2008)

Commercial status:

Commercial with very low adoption rate

References for further information:

TenoVA HYL (2008), APP (2010)

3.4.7. Coal-Based MIDREX[®] Process

Description:

The MIDREX[®] direct reduction process uses a natural-gas-based shaft furnace process that converts iron oxides (pellets or lump ore) into DRI. The MIDREX direct reduction technology has evolved during the past four decades from plant capacities of just 150,000 t/year to capacities now approaching 2 million t/year (Siemens VAI 2007). This process currently produces 60 percent of the world's DRI annually (MIDREX Technologies, Inc. 2012). However, because not all regions have abundant, inexpensive natural gas, another direct reduction alternative is needed. An alternative option is the MXCOL process, which uses synthetic gas (syngas) made from coal in combination with a MIDREX[®] direct reduction plant. Syngas options include a coal gasifier, coke oven gas, or BOF gas. The big advantage of coal gasification is that lower-grade, inexpensive domestic coals can be used to produce a high-quality reducing gas for the MIDREX shaft furnace (MIDREX Technologies, Inc.2011).

The coal-based MXCOL/MIDREX reactor and auxiliary systems are the same as those for a gas-based MIDREX plant. In the MXCOL process, the cold syngas is depressurized to about 3 bar in a turbo expander, which generates electricity. The low-pressure syngas is mixed with recycled

gas to produce the required reducing gas. The mixed gas is then heated to more than 9,00°C and enters the shaft furnace where it reacts with the iron oxide to produce DRI. The spent reducing gas (top gas) exiting the shaft furnace is scrubbed and cooled, then passed through a CO₂ removal system, which reduces the CO₂ content to 2-3 percent or less. This ensures that the mixed reducing gas (syngas from the gasification plant and recycled top gas from the MIDREX plant) has an acceptably high reductant (H₂+CO) to oxidant (H₂O+ CO₂) ratio for efficient iron oxide reduction. The CO₂ removal system will also remove the sulfur gases contained in the recycled top gas. The recycling of the top gas makes MXCOL a very efficient process. Very pure CO₂ is recovered from the gasifier cleaning and conditioning plant and the CO₂ removal system in the MIDREX plant. These streams could be sequestered or sold for enhanced oil recovery or use in a petrochemical or other operation (MIDREX Technologies, Inc.2011).

Jindal Steel and Power Limited in India has contracted with MIDREX Technologies for a 1.8 Mt/year MXCOL plant, the world's first coal gasifier-based MIDREX plant (MIDREX Technologies, Inc.2011).

Figure 19 shows a diagram of the coal-based MIDREX process.

Energy/Environment/Cost/Other Benefits

MIDREX Technologies, Inc. claims the following benefits for coal-based MIDREX compared to BF production (MIDREX Technologies, Inc.2011):

- Can use any coal gasification technology (The additional cost of coal gasification should be taken into account.)
- Fixed-bed or fluidized-bed gasifiers able to readily use the low-rank, high-ash domestic coals in India and China
- Potential to use coal syngas from other sources such as coke oven gas or BOF gas
- Uses the well-proven MIDREX direct reduction process; can readily use domestic iron oxides as feed material.
- Produces DRI with quality comparable to that produced by natural gas-based MIDREX plants
- The DRI can be hot charged into a nearby EAF to significantly reduce the EAF electricity requirement and increase productivity
- No coke, coke ovens, or sinter plant required
- Lower specific capital cost than an integrated steel works
- Lower air emissions than an integrated steel works
- Ability to capture high-purity CO₂ for sequestering or injecting into oil and gas fields

Block Diagram or Photo:

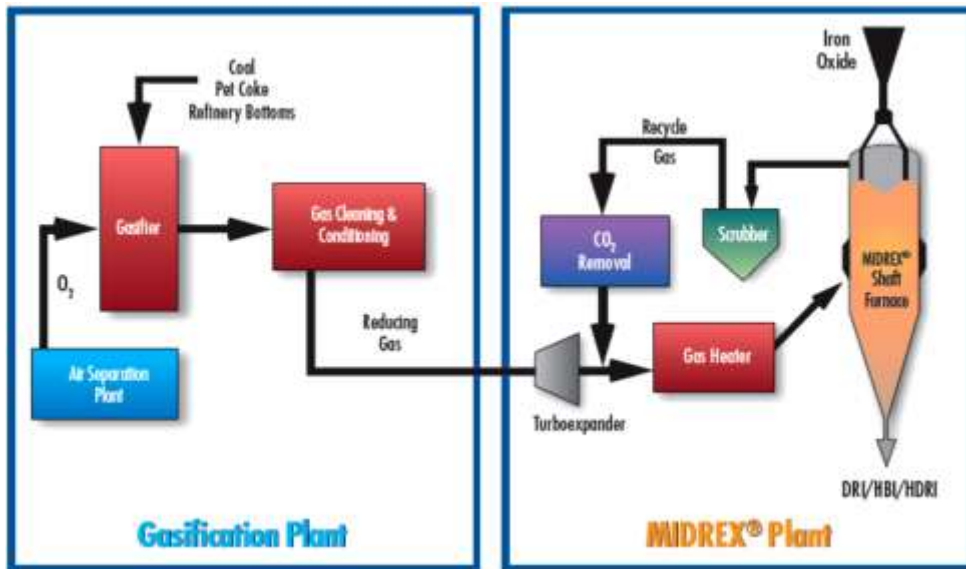


Figure 19. Coal-Based MIDREX Process (MIDREX Technologies, Inc. 2011)

Commercial status:

Demonstration stage

References for further information:

MIDREX Technologies, Inc. (2012), MIDREX Technologies, Inc. (2011)

3.4.8. Fine Ore Reduction in Circulating and Bubbling Fluidized Beds

Description:

Both Circored and Circofer are fine ore reduction processes. Circored is gas-based, and Circofer is coal-based. Both use a proven two-stage configuration, combining a circulating fluidized bed with a bubbling fluidized bed. Both are direct reduction processes utilizing iron ore fines directly to decrease DRI or HBI production costs by avoiding an expensive agglomeration step. The Circored process uses hydrogen as reductant. The first Circored plant, designed to produce 500,000 t/year of HBI, was commissioned in Trinidad in 1999. In the Circofer process, coal is used as reductant. The Circofer pilot plant at Outotec's research and development center in Frankfurt, Germany, has a capacity of 5 tpd ore fines and has demonstrated the basic principle of the process (Outotec, Inc. 2007, 2012).

In the Circofer process, coal and ore are fed into two fluid beds. The first is a circulating fluidized bed where the coal is charred, and the ore is 50-percent metallized. The second is a bubbling fluidized bed where final reduction using the char is achieved. Productivity is limited because of required high retention times in the bubbling fluidized bed. In the proposed combined process for

Circofer only the circulating fluidized bed would be used to produce char and a 50-percent metallized product which would be fed into a smelter. Smelting using char could achieve 80-percent post combustion, and final reduction is very rapid (Fruehan 2004a).

The Circofer process operates at reduction temperatures of approximately 950 °C in a closed gas circuit without producing export gas. One possible application of Circofer is as a single-stage pre-reduction step for the HIsmelt® process (see Figure 20). It is claimed that this leads to a significant increase in the throughput of the HIsmelt process (Outotec, Inc. 2007).

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for Circored and Circofer technology compared to BF production (Outotec, Inc. 2007, 2012):

- No iron ore agglomeration required
- Reduced energy use and CO₂ emissions because sintering process eliminated
- If Circofer added to the HIsmelt® process, a claimed significant increase in the throughput of the HIsmelt process

Block Diagram or Photo:

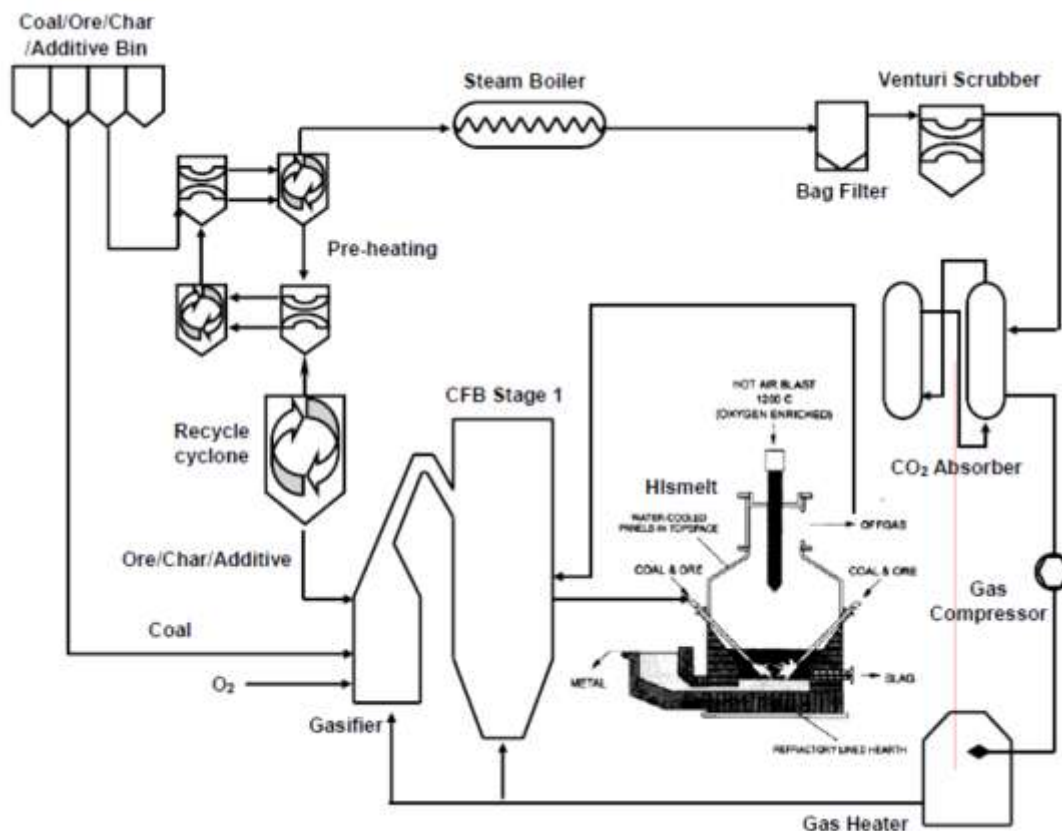


Figure 20. First-stage Circofer-smelter schematic (Fruehan 2004a).

Commercial Status:

Circored: Demonstration stage

Circofer: Pilot stage

References for further information:

Outotec, Inc. (2007, 2012), Fruehan (2004a)

3.4.9. Cyclone Converter Furnace**Description:**

In primary iron making, about one-fifth of the energy consumed is used for coke making and sintering. Smelting reduction processes avoid this energy use because they make iron directly from iron ore and coal, omitting the need for coke ovens and sinter plants. The cyclone converter furnace consists of a cyclone for pre-reduction of the iron ore; the cyclone is mounted on a converter-type vessel in which the iron ore is then reduced to iron (De Beer et al. 1998). The iron ore is pre-reduced and melted in the cyclone at the top of the furnace. From there, the molten iron ore falls into the lower part of the vessel where reduction is completed. Granular coal as well as oxygen are introduced in the lower part of vessel. Combining the pre-reduction unit and the final reduction unit avoids heating losses that occur when these two components are separated.

The cyclone converter furnace was the first smelting reduction process that combined pre-reduction and final combustion in one vessel (De Beer et al. 1998). Currently, its development is included within the HIsarna process (Van Boggelen 2012) (see subsection 3.10.3 for more information on the HIsarna process).

A 20 t/hour (h) test facility for the melting cyclone was built and successfully operated in 1994. The converter has not yet been tested on a pilot scale (De Beer et al. 1998). The cyclone has been implemented in a HIsarna pilot plant which was tested in 2011 (Van Boggelen 2012).

Figure 21 shows the converter furnace cyclone.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by use of the cyclone converter furnace (De Beer et al. 1998, EIPPCB 2010):

- Estimated specific energy consumption of 13-14 GJ/tonne hot metal (thm) as compared to about 16.1 GJ/thm for the conventional BF production (including coke making and sintering)
- Lower investment costs because the cyclone converter furnace is simple compared to other smelting reduction processes

- Total production costs estimated to be lower than those of BF

Block Diagram or Photo:

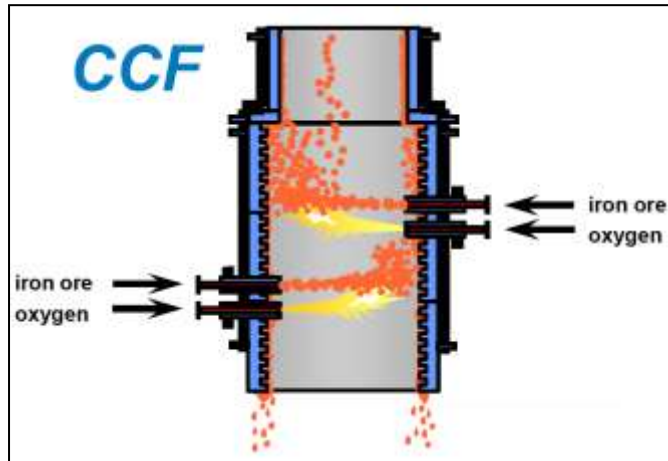


Figure 21. Converter furnace cyclone (CCF) (Van Boggelen 2012)

Commercial Status:

Pilot stage

References for further information:

Van Boggelen (2012), De Beer et al. (1998), EIPPCB (2010)

3.4.10. Producing Iron by Electrolysis of Iron Ore (Molten Oxide Electrolysis)

Description:

Electrolysis of iron ore or molten oxide electrolysis (MOE) is an emerging process. The DOE/AISI TR program funded an initial R&D project at MIT (Cambridge, MA USA) which was successfully completed in 2007. A similar technology is currently being studied in the ULCOS program. This process would allow the transformation of iron ore into metal and gaseous oxygen (O₂) using only electrical energy. Producing iron by electrolysis would eliminate the need for coke ovens and the reactors used for reducing the iron ore, such as BFs, and thereby eliminate the CO₂ created by these production methods. Although no iron is currently produced industrially by electrolysis, electrolysis is a well-established technique developed at the industrial scale for production of aluminum, zinc, and nickel (ULCOS 2012a).

MOE is an extreme form of molten salt electrolysis, a technology that has been used to produce tonnage metal – aluminum, magnesium, lithium, sodium, and the rare-earth metals – for more than 100 years. MOE is different from other molten salt electrolytic technologies because it uses carbon-free anodes, which facilitates the production of oxygen gas at the anode. MOE is totally

carbon-free, producing only O₂ and no CO or CO₂, an environmental advantage compared to conventional technology. Even including the CO₂ emissions from electricity generation related to the process, MOE ranks lowest among breakthrough technologies in terms of CO₂ emissions per unit metal product (AISI 2006a).

The most promising options for electrolysis are ULCOWIN, also called electrowinning, and iron ore ULCOLYSIS (similar to the MIT process). Both technologies have already been demonstrated at a small scale, through the research carried out during ULCOS Phase I.

In the ULCOLYSIS process, iron ore is dissolved in a molten oxide mixture at 1,600°C. This electrolyte medium can sustain a temperature above the melting point of iron metal. The anode, made of a material inert in relation to the oxide mixture, is dipped in this solution. An electric current flows between this anode and a liquid iron pool that is connected to the circuit to act as the cathode. O₂ evolves as a gas at the anode, and iron is produced as a liquid metal at the cathode. The development of ULCOWIN is, however, more advanced. A proposal has been made to further test ULCOWIN through additional scaling up of the process. A prototype plant has been proposed that could produce 5 kg/day (ULCOS 2012a).

In contrast to a conventional integrated steel mill, which requires coke ovens, BFs, and BOFs, an electrolytic cell reduces iron ore concentrates and produces molten steel in a single unit. Therefore, MOE is expected to have much lower capital costs than a conventional plant. The CO₂ reduction potential is large, depending upon the MOE plant's electricity source. An analysis by Birat in the 1990s estimated 1,750 kg CO₂/t liquid steel from benchmark BF technology compared to 345 kg CO₂/t liquid steel from MOE. This analysis assumed 90g CO₂/kWh for electric power generation⁶ and 3,500 kWh/t of molten steel in the electrolytic cell (AISI 2010).

AISI is funding Massachusetts Institute of Technology to develop and validate scale-up parameters for the design, construction, and operation of a pre-pilot-scale, self-heating MOE cell with a capacity of 4,000 amperes. This cell would operate continuously and produce iron at the rate of about 72 kg/day. If fitted with an inert anode, it could produce about 32 kg of oxygen gas per day. Long-term operation of this cell will provide the data required to design the first-generation industrial-scale cell and develop a detailed cost model to assess the commercial viability of the process (AISI 2010).

Figure 22 shows an MOE cell (MIT process) for producing iron.

⁶ This CO₂ emission factor for the electricity is very low. For instance, in 2010, the average CO₂ emission factor of the grid in China was 770 g CO₂/kWh.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for MOE compared to BF production (ULCOS 2012a; AISI 2010):

- Significantly lower CO₂ emissions
- Likely significant capital cost savings
- Lower level of air pollutant emissions (SO_x, NO_x, VOCs) because coke making, BF, and BOF are eliminated

Block Diagram or Photo:

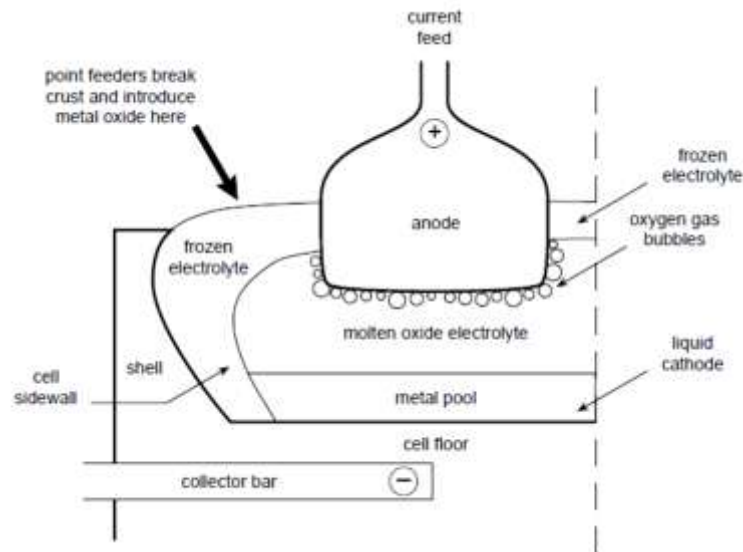


Figure 22. MOE cell for producing iron (AISI 2006a)

Commercial Status:

Research/Development stage⁷

References for further information:

ULCOS (2012a), AISI (2010)

⁷ The sizes of the prototypes are very small.

3.4.11. Suspension Hydrogen (or H₂ containing Gaseous mixtures) Reduction of Iron Oxide Concentrate

Description:

Hydrogen is currently cost prohibitive as a reducing agent or fuel. Large quantities of inexpensive hydrogen may become available in the future based on worldwide R&D work. Hydrogen produces only water vapor and no other gaseous byproducts when used as a reducing agent or fuel (AISI 2006b).

Hydrogen flash smelting would use, as a smelting vessel, a suspension or flash-type furnace similar to those used in the copper industry. Iron ore concentrates would be sprayed directly into the furnace chamber. Three reductants are suitable for this type of vessel: H₂, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics. The high temperature and lack of contact between the iron ore particles in suspension furnaces eliminates sticking and fusion of the particles (AISI 2010).

Detailed material and energy balances conducted by University of Utah in an earlier R&D project with the support of the DOE/AISI TR Program show that the proposed technology using any of the three possible reductants/fuels could use approximately 38 percent less energy than a BF. This savings results largely from eliminating coke making and the iron ore pelletizing and sintering steps. If hydrogen is used, this new technology will generate only 4 percent of the CO₂ produced in the BF process; when natural gas or coal is used, CO₂ emissions are 39 percent and 69 percent, respectively, of those from a BF. Because the residence time in a suspension furnace is only a few seconds, studies were performed to establish that full reduction could be achieved in such a short time. Kinetic studies of the reduction of iron oxide concentrates (~30 micrometer size) as a function of temperature and gas composition showed that 90- to 99-percent reduction is possible within a few seconds at temperatures of 1,300°C or higher. This was verified by larger bench-scale testing, proving that complete ore reduction is achieved in the residence time typical of industrial-size suspension vessels (AISI 2010).

Conventional BF-based steelmaking processes use CO gas to remove oxygen in iron ore. However, the molecules of CO gas are large enough that it is difficult for them to penetrate iron ore. By contrast, the much smaller molecules of H₂ gas can easily penetrate into iron ore. The penetration rate of H₂ into iron is five times as great as that of CO, so H₂ can rapidly reduce iron ore in a conventional BF (JISF 2012b).

Hydrogen reduction could be a part of an overall continuous direct steelmaking process, in which case the product from this process would be collected in its molten or solid state (e.g., reduced iron pellets or briquettes) (AISI 2006b).

Based on the success of the earlier project conducted by University of Utah, AISI had initiated a subsequent Phase II-project where a larger-scale bench reactor vessel was fabricated (AISI 2010). In 2012, a \$7.1 million award was given by the U.S. DOE to AISI/University of Utah to perform tests to determine the best vessel configuration and reductant to be used in a future industrial pilot plant⁸.

Figure 23 is a diagram of hydrogen flash smelting.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for hydrogen flash smelting compared to BF production (AISI 2010):

- Reduction or elimination of CO₂ generation in the ironmaking process
- Reduction in energy consumption; University of Utah earlier R&D study showed potential energy savings of 7.4 GJ/t hot metal (more than 50 percent of conventional BF energy use)
- Reduction of iron oxide waste

Block Diagram or Photo:

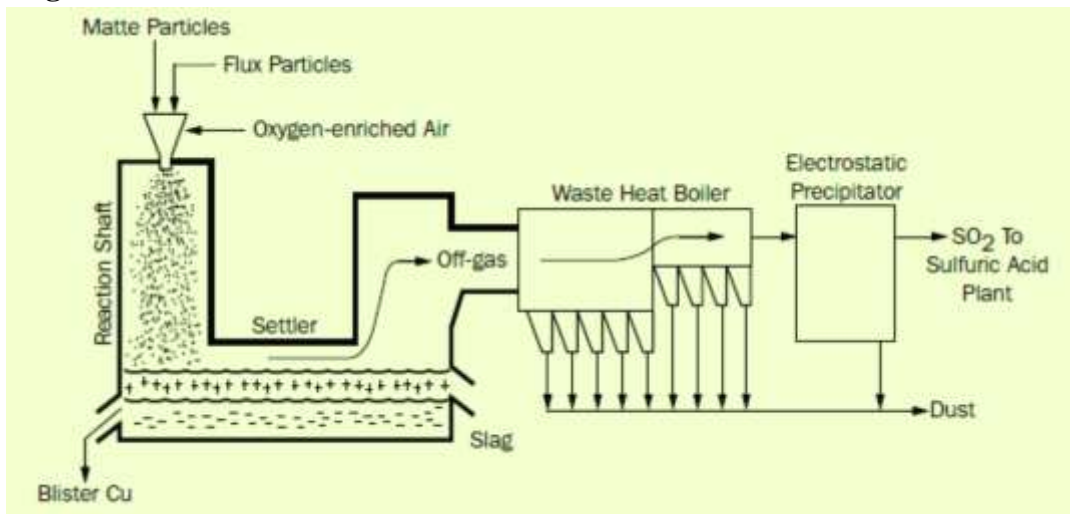


Figure 23. Hydrogen flash smelting for copper (AISI 2010)

Commercial Status:

Research/Development stage⁹

References for further information:

AISI (2010), JISF (2012b)

⁸ Personal communication, Debo Aichbhaumik and Keith Jamison of Energetics, Inc. October 2012.

⁹ The sizes of the prototypes are very small.

3.4.12. Ironmaking using Biomass and Waste Oxides

Description:

Ironmaking is the most energy-consuming and therefore CO₂-intense step in the steel industry. Replacing fossil fuels (e.g., coal) with biomass or waste oxide would reduce both energy use and CO₂ emissions. A project funded by the DOE/AISI TR program conducted preliminary research on an ironmaking process using wood charcoal in ore waste pellets (composite pellets) in a RHF. A number of processes are already under development that use composite pellets of ore or waste oxides and a carbonaceous material, such as coal or coke, which are reduced in the solid state using a rotary hearth or similar type of furnace. The product of these processes is too high in gangue and sulfur to be used effectively in the EAF. If biomass is used instead, the metal will be low in sulfur, so further processing in an EAF or a BOF should be possible. It is expected that the reduced iron ore using biomass in composite pellets would contain low percentages of gangue as well (AISI 2002, 2010).

The process combines a RHF and a smelter such as the AISI or Direct Iron Smelting Reduction (DIOS) to produce hot metal using wood charcoal in composite pellets (See Figure 24). In the RHF the reduction of the iron ore is limited to approximately 70- to 80-percent metallization. The pre-reduced material is then fed into the smelter for final reduction and gangue separation, yielding hot metal. Compared to conventional processes, this process increases RHF productivity and avoids high energy consumption for full metallization in the smelter (Fruehan 2004b).

So far, no pilot plants have been built, and only computer models have been developed. A computational model predicts productivity gains as high as 50 percent from replacing coal with wood charcoal in the composite pellets (Fruehan 2004b).

Energy/Environment/Cost/Other Benefits:

AISI (2002) claims the following benefits from using biomass and waste oxides in iron making compared to conventional BF production (AISI 2002, Fruehan 2004b):

- Reduction of more than 90 percent in greenhouse gas emissions
- Significant decrease in capital and operating costs
- Increased productivity of the rotary hearth furnace
- Increased recycling of waste oxides in steelmaking

Block Diagram or Photo:

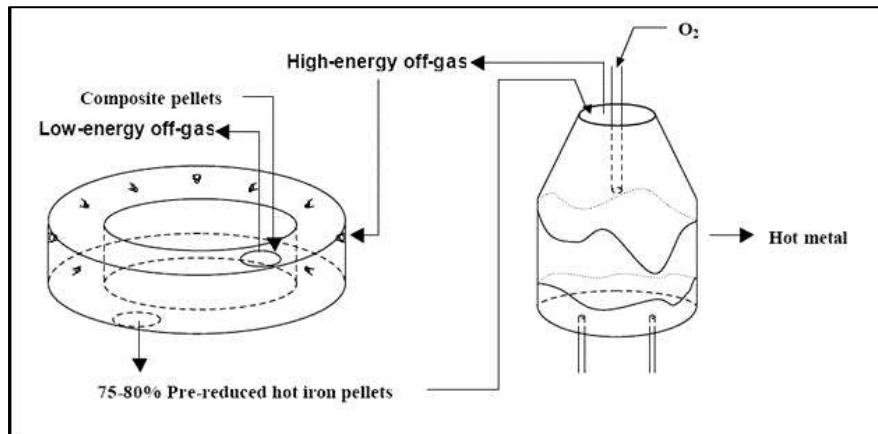


Figure 24. Schematic of the process proposed for ironmaking using biomass and waste oxides (Fruehan 2004b).

Commercial Status:

Research stage

References for further information:

Fruehan (2004b), AISI (2010), AISI (2002)

Table 2 illustrates a comparison of some of the aspects for different ironmaking technologies explained above.

Table 2. A comparison of ironmaking technologies explained in this chapter

Section No.	Ironmaking technologies	Reducing agent and energy source				Form of iron ore that can be used				Oxygen is needed	Coal gasification is needed	Commercialization status
		Non-coking Coal	Coke	NG ^a	Other	Sinter	Pellet	lump ore	Fine ore			
-	Blast Furnace		X			X	X					Commercial
3.4.1.	COREX® Process	X				X	X	X		X		Commercial with very low adoption rate
3.4.2.	FINEX® Process	X							X	X		Commercial with very low adoption rate
3.4.3.	Tecnored	X					X ^b		X ^b			Pilot
3.4.4.	ITmk3 Ironmaking Process	X					X ^c		X ^c			Demonstration
3.4.5.	Paired Straight Hearth Furnace	X					X ^d		X ^d			Development
3.4.6.	Coal-Based HYL Process- A Syngas based DRI Plant	X					X	X			X	Commercial with very low adoption rate
3.4.7.	Coal-Based MIDREX Process	X					X	X		X	X	Demonstration
3.4.8.	Fine Ore Reduction in the Circulating Fluidized Bed (Circored® and Circofer®)	X ^e		X ^e					X			Demonstration/Pilot
3.4.9.	Cyclone Converter Furnace	X					X	X		X		Pilot
3.4.10.	Producing Iron by Electrolysis of Iron Ore (Molten Oxide Electrolysis)				X ^f		X	X				Research/Development
3.4.11.	Suspension Hydrogen Reduction of Iron Oxide Concentrate			X ^g	X ^g			X	X		X ^g	Research/Development
3.4.12.	Ironmaking using Biomass and Waste Oxides				X ^h		X ^h					Research

^a NG: Natural gas

^b Pellets or briquettes used in Tecnored process are made from low-grade iron ore fines; low-cost reductants such as non-coking coals; pet-coke; biomass and briquettes of coal fines; fluxes; binders; and returned fines which are mixed and agglomerated into pellets or briquettes.

^c Low grade ores are beneficiated, and the resulting fines (with >62% Fe content) are pelletized and used.

^d Cold-bonded self-reducing pellets composed of iron oxide and coal. The sources of the iron oxide can be iron ore fines, recycled steel plant wastes, or a combination of the two. The reductant is high-volatility coal.

^e Circored is gas-based (hydrogen as reductant), and Circofer is coal-based.

^f Only electricity is used.

^g Three reductants are suitable for this process: H₂, natural gas, or synthetic gas produced from partial combustion of coal and/or waste plastics.

^h This process uses wood charcoal in ore waste pellets (composite pellets) in a RHF.

3.5. Emerging Technologies for Steelmaking Shops

The subsections below describe the following emerging technologies to reduce energy use and CO₂ emissions in the steel making shop: sensible heat recovery from EAF off gas, electrochemical de-zincing of steel scrap, continuous horizontal sidewall scrap charging, scrap-based steelmaking using predominantly primary energy, ECOARC, BOF and EAF post-combustion optimization using CFD modeling, laser-based optimization of EAF post combustion, model-based steel temperature measurement for EAFs, real-time measurement of melt constituents, and the continuous EAF steelmaking technology.

3.5.1. Sensible Heat Recovery from Electric Arc Furnace Off Gas

Description:

Because almost 70 percent of the energy losses in EAF steelmaking are associated with the off gas, through which approximately 15.5 percent of EAF energy inputs are lost as sensible heat, heat recovery could save substantial energy in EAFs. Combined with uncombusted CO that subsequently burns in the post-combustion chamber, the total thermal energy that can be recovered is more than 25 percent of EAF energy inputs. This is the amount of off-gas energy needed for viable off-gas heat recovery.

Despite the significant potential benefits, EAF off-gas heat recovery is not commonly practiced, in part because of the harsh environment in the fume system and the on-off batch nature of the process (Zuliani et al. 2010).

Tenova GmbH has adapted evaporative cooling system technology for EAF heat recovery. This system replaces conventional low-pressure water-cooled ducting with high-pressure boiler tubes designed to withstand the harsh EAF fume system conditions at pressures of 15 to 40 bar. Tenova's evaporative cooling system technology uses the heat of evaporation to produce high-pressure steam at 216°C; the off-gas temperature at the exit of the cooled part of the waste gas duct is reduced to about 600°C. The resulting high-pressure steam can be used to supplement or replace an in-plant steam generation boiler for existing applications within the plant such as for vacuum de-gassing or for in-plant DRI production using the HYL direct reduction process. With steam accumulator tanks to homogenize EAF process cycles, this technology has demonstrated continuous steam production with an average rate of 20 t/h from a 140 t/h EAF (Zuliani et al. 2010).

For a 140 t/h EAF, the EAF off-gas heat recovery technology would eliminate boiler-equivalent CO₂ emissions of almost 112,500 t CO₂/year (with coal firing) or 57,000 t CO₂/year (with natural gas firing). It is also possible to add a second stage in which the off-gas temperature is reduced from ~600°C to ~200°C with a waste heat boiler instead of the standard off-gas quench. The combined heat recovery using both the evaporative cooling system and the waste heat boiler is 75

to 80 percent of the total energy content in the waste gas, which corresponds to approximately 20 percent of primary energy input to EAF process. In cases where there is insufficient demand for steam from the EAF heat recovery, an organic rankine cycle turbine can be used for power generation. Organic rankine cycle generators are becoming commonplace in industrial heat recovery applications. They typically operate at approximately 20-percent efficiency and could be expected to generate about 4MW of electric power from an average-sized EAF. This translates to 24,000 megawatt hour (MWh)/year of electrical energy, a 7.5-percent savings in EAF net electrical energy usage (Zuliani et al. 2010).

The Goodfellow Expert Furnace System Optimization Process (Goodfellow EFSOP[®]) is a Tenova GmbH dynamic control and optimization system for EAFs, which is based on real-time measurements of off-gas composition. The system uses state-of-the-art off-gas analysis combined with process data acquisition and real-time closed loop control to optimize EAF operation (Maiolo et al. 2007). When EFSOP is combined with off-gas heat recovery, depending on the specific operating practice, direct and indirect CO₂ savings can increase by 2 to 5 times, or 40,000 to 140,000 t CO₂ annually for a 1Mt/year EAF (Zuliani et al. 2010).

Figure 25 shows the Scheme of two-stage heat recovery for an EAF steelmaking.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for sensible heat recovery from EAF off gases compared to conventional EAF production (Zuliani et al. 2010; Maiolo et al. 2007):

- Reduced energy use for steam and power generation; 75- to 80-percent recovery of total energy content in the waste gas heat using both the evaporative cooling system and waste heat boiler, which equals approximately 20 percent of EAF primary energy input
- For a 140 t/h EAF, it eliminates boiler-equivalent CO₂ emissions of almost 112,500 t/year (with coal firing) or 57,000 t/year (with natural gas firing)
- With an organic rankine cycle turbine, 7.5-percent saving in EAF electrical energy use (approximately 24,000 MWh/year for an average sized EAF)

two stages: dissolving the zinc coating from scrap in a hot, caustic solution, and recovering the zinc from the solution electrolytically. Through a galvanic process, the zinc is removed from the steel and is held in solution as sodium zincate ions rather than zinc dust. The steel is then rinsed with water and ready for re-use. Impurities are removed from the zinc solution, and a voltage is applied in order to grow metallic zinc via an oxidation-reduction reaction. All waste streams in this process are re-used. The process produces 99.8 percent pure zinc for resale (U.S. DOE/ITP 2010a).

Figure 26 shows the electrochemical de-zincing process for galvanized steel scrap.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the electrochemical de-zincing of steel scrap compared to conventional de-zincing techniques (U.S. DOE/ITP 2010a, b):

- Decreases steelmaking dust released to the air as well as pollutants in wastewater streams.
- No chemicals consumed other than drag-out losses; only a small amount of waste
- Removing zinc prior to processing of scrap saves time and money in disposal of waste dusts and water
- No extra handling, blending, or sorting required before re-melting scrap without zinc

Block Diagram or Photo:

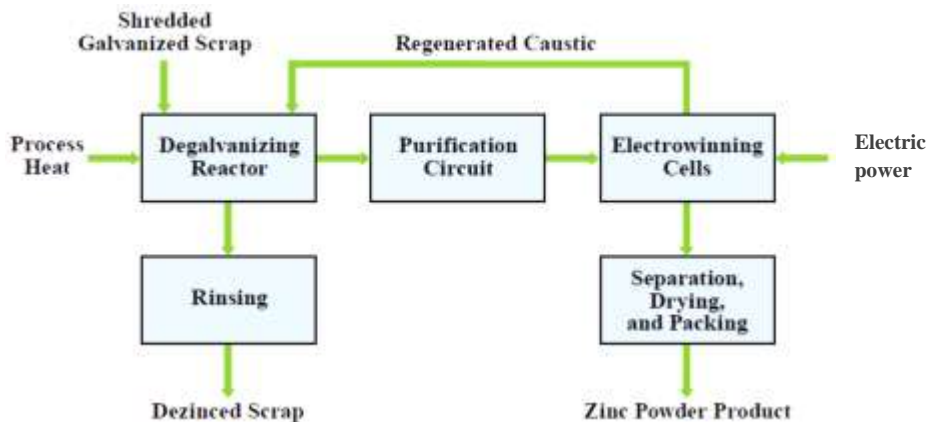


Figure 26. Electrochemical de-zincing of galvanized steel scrap (U.S. DOE/ITP 2010a)

Commercial Status:

Demonstration stage

References for further information:

U.S. DOE/ITP (2010a,b)

3.5.3. Continuous Horizontal Sidewall Scrap Charging

Description:

Scrap charging and preheating for EAFs have been used in many forms during the past 30 years. The majority of steelmakers use buckets to top charge scrap into the furnace. SMS Siemag Inc. has developed an alternative system called continuous horizontal sidewall scrap charging. The continuous horizontal sidewall scrap charger is most like a scrap baler or logger except the end open to the furnace is unconstrained, so the scrap is uncompressed and permitted to fall into the furnace. SMS Siemag Inc. claims that a continuous horizontal sidewall scrap charger provides the same performance as scrap preheaters without the typical problems such as frequent maintenance, environmental concerns, space constraints, and the need for a post-combustion burner (Cotchen and Stercho 2002).

Energy/Environment/Cost/Other Benefits:

SMS Siemag Inc. claims the following benefits of the continuous horizontal sidewall scrap charger (APP 2010):

- Lower energy consumption from elimination of open roof during charging
- Combustibles in the scrap burn in the furnace, which adds to furnace energy input
- After-burners not required, which increases overall process efficiency
- Scrap cave-ins (which break electrodes) eliminated by flat-bath operation
- Consistent foamy slag produced by bath operation, which enhances efficiency and prevents nitrogen pickup
- Reduced furnace idle time, which leads to lower electrode oxidation and consumption
- Lower losses and reduced power use from shorter tap-to-tap times
- Less restrictive scrap sizing requirements, which lowers overall production costs
- Lower refractory consumption due to less mechanical damage and thermal shock

Block Diagram or Photo:

N/A

Commercial Status:

Pilot stage

References for further information:

Cotchen and Stercho (2002), APP (2010)

3.5.4. New Scrap-Based Steelmaking Process Using Predominantly Primary Energy

Description:

Electricity is the main type of energy used in EAFs. The primary energy source is first converted to heat in a power plant; producing electrical energy is the next step. Like all conversions, these two processes entail losses whose amount is determined by the efficiency of the power plant. In an above-average power plant, this efficiency is approximately 40 to 42 percent. The electrical energy produced is transported to the EAF, with further losses incurred during transport, and then converted back to heat for steelmaking. Thus, almost two-thirds of the original primary energy is lost on the conversion route from source to EAF which makes use of on-site primary energy in the form of heat a preferable strategy for EAF (Kempgen et al. 2008).

A counter-current reactor should allow efficient use of primary energy (e.g. coal) in the scrap heating and melting steps. In such a reactor, scrap is continuously charged at the top and transformed to the liquid state with tapping temperature above what can be achieved by combustion of fossil fuels with oxygen because it is physically impossible to significantly superheat the melt in the presence of solid material. Thus, superheating occurs in a separate vessel using electricity. Thus, whereas the conventional EAF separates melting and heating in terms of time, these steps are separated spatially in the primary-energy melting process. The superheating vessel is an EAF with a power requirement comparable to that of a ladle furnace (Kempgen et al. 2008).

Figure 27 is a schematic drawing of the primary energy melter.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed by SMS Demag GmbH for the use of primary energy in the heating and melting of scrap compared to conventional EAF production (Kempgen et al. 2008):

- Approximately 32-percent reduction of primary energy intensity for liquid steel production
- Depending on the CO₂ emissions of the electricity grid, significant reduction in CO₂ emissions
- Approximately 19-percent reduction in energy costs per tonne of liquid steel produced

Block Diagram or Photo:

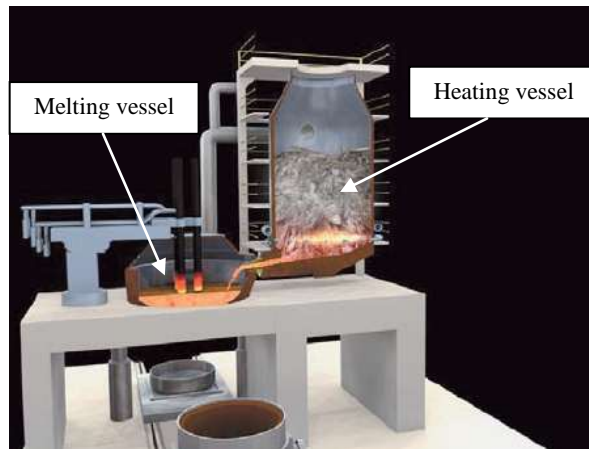


Figure 27. Schematic of the primary energy melter (Kempgen et al. 2008).

Commercial Status:

Development stage

Reference for further information:

Kempgen et al. (2008)

3.5.5. ECOARC™

Description:

JFE Engineering has developed an electric arc melting furnace called ECOARC. The ECOARC preheating shaft is connected directly to the melting chamber, so a continuous scrap charge can be maintained in the chamber and shaft at all times while melting is taking place. As a result, the furnace efficiency is extremely high. Furthermore, because the furnace as a whole has a semi-airtight structure, the oxygen concentration in the atmospheric gas can be held at a low level, suppressing oxidation of the scrap in the preheating shaft. Total exhaust gas is about half that of conventional arc furnaces. Approximately 30 percent of the CO generated in the furnace is introduced unburned into a combustion tower installed downstream from the arc furnace. The CO is burned in the tower at a temperature of more than 900°C, which is adequate to prevent emissions of white smoke, black smoke, and dioxins. Downstream from the combustion tower, the exhaust gas is quenched to 150 to 200°C by spray cooling, to prevent resynthesis of dioxins. This reduces the dioxin concentration at the dust collector exit to less than 0.1 nonogram Toxic Equivalent (ng-TEQ)/normal cubic meter (Nm³)(JFE Engineering 2004).

JFE Engineering's tests in a 5- t pilot plant indicated that the electricity consumption of 200 kWh/t or less can be expected in an actual-scale equipment. On the basis of this result, JFE Engineering received its first order for a 70-t commercial unit from Kishiwada Steel Co. in May 2000. In June 2003, electricity consumption of 233 kWh/t at an oxygen consumption of 36 Nm³/t and 196 kWh/t at an oxygen consumption of 40 Nm³/t were achieved. The technology is now being marketed by JP Steel Plantech Co. (JFE Engineering 2004). Because gasification of combustibles occurs slowly in the shaft, ECOARC is suitable for direct melting of press scraps from scrapped automobiles, which have a high plastics and other combustible content. In the 5-t pilot plant, an operation with a 20-percent press scrap ratio was possible, and, as noted above, the dioxin concentration at the bag filter exit was reduced to less than 0.1 ng-TEQ /Nm³ (JFE Engineering 2004).

Figure 28 shows the configuration of the ECOARC furnace.

Energy/Environment/Cost/Other Benefits:

JSP Steel Plantech Co. claims the following benefits for the ECOARC compared to conventional EAFs (APP 2010; JFE Engineering 2004; JP Steel Plantech Co. 2012):

- Reduced electricity consumption: 196 kWh/ton at an oxygen consumption of 40m³/ton oxygen
- 50-percent reduction in electrode consumption
- 1.5-percent improvement in yield
- 40-percent reduction in flicker level
- 40-percent productivity improvement
- 40-percent reduction in dust emissions
- No odor or white smoke even from scrap preheating
- Meets the dioxin emissions regulation (<0.1ng-TEQ/Nm³)
- Large volume of combustible ingredients in off gas, which minimizes the amount of fuel needed for post combustion.
- Off gas volume minimized by the use of a semi-airtight furnace and off-gas ducts

Block Diagram or Photo:

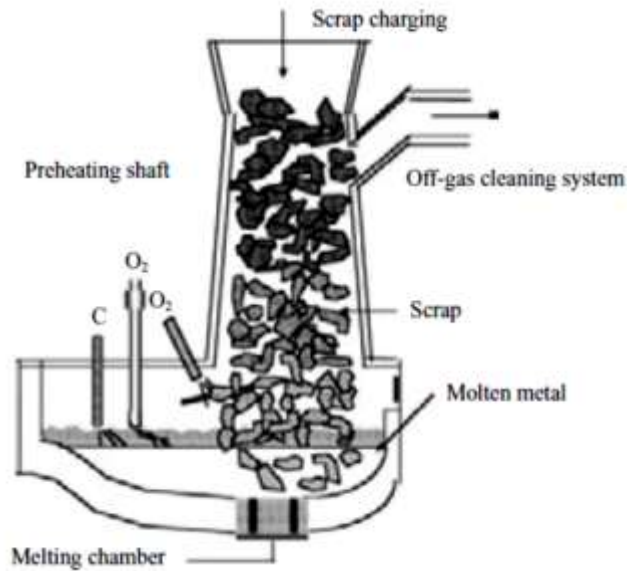


Figure 28. Schematic configuration of ECOARC (JFE Engineering 2004).

Commercial Status:

Demonstration stage

References for further information:

JFE Engineering (2004), JP Steel Plantech Co. (2012)

3.5.6. Optimization of BOF and EAF Post Combustion Using CFD

Description:

The primary off gas from EAF and BOF steel production is CO. If the CO can be combusted to CO₂, and the energy transferred to the metal, this reaction reduces the energy consumed in the EAF and allows for more scrap melting in the BOF. This reaction is referred to as post combustion and significantly reduces the energy required to produce steel (Fruehan and Matway 2004).

Researchers at Carnegie Mellon University developed Computational Fluid Dynamics (CFD) models for post combustion in EAFs and BOFs for use in optimizing these steelmaking processes. The models include all relevant phenomena, such as radiant heat transfer, accurate combustion reactions, and de-post combustion reactions. DOE/AISI's TR Program supported the project (AISI 2010).

The CFD EAF post-combustion model is a full 3-D, finite-volume technique with more than 200,000 elements. The CFX™ code was used for modeling. The software models a three-phase, 200-t alternating current electric arc furnace with a primary oxygen lance and four wall-mounted oxygen injectors for post combustion. Special models were developed to describe the combustion and de-post combustion reactions and fluid flow in the foamed slag. The model can predict the degree of post combustion and heat transfer. Based on the EAF model, the researchers developed a CFD post-combustion model for the BOF using a slice of the furnace for which there was symmetry. The program modeled a 250-t BOF with 10 post-combustion injectors located 2 to 2.5 meters above the primary oxygen jet at the bottom of the lance. The model can predict post combustion, heat transfer, temperature profiles, and the effect of operating variables such as oxygen flow rates and distribution. Instruction manuals were developed so that the models can be used by industry (AISI 2010; Fruehan and Matway 2004).

Energy/Environment/Cost/Other Benefits:

Optimized post combustion would (AISI 2010):

- Reduce the energy consumed in the EAF
- Allow for more scrap melting in the BOF, which would significantly lower the energy required to produce steel using the BF-BOF route

Block Diagram or Photo:

N/A

Commercial Status:

Pilot stage

References for further information:

AISI (2010), Fruehan and Matway (2004)

3.5.7. Improving the Energy Efficiency of EAF through Laser-based Optimization of Post Combustion

Description:

The proper melting time is crucial in EAF steelmaking. The time should be long enough to melt the scrap entirely but not longer than the time needed for post combustion from CO to CO₂. The quality of the scrap as well as the post combustion time to convert CO to CO₂ therefore determine the melting time (BFI 2009/2010).

In a project funded by BMWi (the German Federal Ministry of Economics and Technology) a laser based off-gas analysis system for EAF steelmaking was developed to analyze in detail the

conditions in the off gas, which vary considerably over time. With the help of a dynamic mass and energy balance model, the energy performance of the furnace was analyzed and evaluated as a function of the energy losses via the furnace off gas. This enabled the post-combustion oxygen feed rate to be controlled in a targeted manner, allowing improved use of the chemical energy content of the furnace off gas for the melting process. Optimizing the operating regimes for post-combustion oxygen input over time decreased the electrical energy demand of the furnace by about 17 kWh/t or 4 percent of the energy input (Figure 29) (BFI 2009/2010).

If the post-combustion oxygen feed rate is controlled dynamically based on continuous off-gas measurement and analysis, this should allow even more thorough exploitation of the chemical energy in the furnace off gas for each individual process. Further energy savings could also be achieved through on-line use of a dynamic energy balance model to check the melt temperature end point. This allows the operator to avoid overheating of the melt beyond the target tapping temperature (BFI 2009/2010).

Energy/Environment/Cost/Other Benefits:

The following benefit can be achieved when laser-based optimization of post combustion is applied to EAF steelmaking, compared to the conventional EAF production (BFI 2009/2010):

- Reduction of about 17 kWh/t or 4 percent in electrical energy demand

Block Diagram or Photo:

N/A

Commercial Status:

Pilot stage

Reference for further information:

BFI (2009/2010)

3.5.8. Model-based Steel Temperature Measurement for Electric Arc Furnaces

Description:

Maintaining the required target temperature is crucial in EAF steelmaking. Continuous monitoring of the liquid steel temperature enables optimal control of the electrical energy required to heat the melt and precise adjustment of the target temperature.

A new measurement and control concept was developed for EAFs in a project funded by BMWi (the German Federal Ministry of Economics and Technology). The temperature measurement system consists of a measuring unit, lance, and manipulator and is based on the use of an optical fiber that is immersed in the molten metal using BFI's DynTemp[®] technique. The optical

measuring system is fast and can be used to measure liquid steel either continuously or intermittently. Investigations of measurement accuracy show results comparable to those of conventional thermocouples (BFI 2012).

Figure 30 shows the EAF steel temperature measurement device.

Energy/Environment/Cost/Other Benefits:

The following benefit can be achieved when model-based steel temperature measurement is used in EAF steelmaking compared to EAF production without this feature (BFI 2012):

- Reduced electrical energy demand (amount not yet estimated)

Block Diagram or Photo:



Figure 30. Photo of the device to measure steel temperature in EAF (BFI 2012)

Commercial Status:

Development stage

Reference for further information:

BFI (2012)

3.5.9. In-Situ Real-Time Measurement of Melt Constituents

Description:

The proper composition of the melt constituents is a key factor in producing metals such as steel. The metal composition can only be controlled while the metal is molten. Therefore, in current practice, small samples of the molten material are removed and analyzed off line. This approach is expensive and time consuming, leading to excessive processing, quality control difficulties, and increased energy use and pollutant emissions (U.S. DOE/ITP 2004).

Approximately 3 percent of all steel produced is downgraded or scrapped and that 50 percent of the downgraded or scrapped material needs complete rework. In-line measurements and closed-loop control can be a key to eliminating this waste.

A new technology developed by the Energy Research Company employs a laser-induced breakdown spectroscopic (LIBS) technique to measure, in-situ and in real-time, the constituents of the melt in a process furnace (U.S. DOE/OTI 2001). A probe is placed inside the melt, and a laser is fired repetitively through a fiberoptic cable and through the probe. A small amount of melt at the probe tip absorbs the laser light, producing temperatures sufficiently high to heat and vaporize the melt sample into a gaseous plasma state. The resulting plasma emits a signal that is detected and sent to a spectrometer. This signal is spectrally resolved to uniquely identify the elements in the melt and the concentration of each element present (U.S. DOE/ITP 2004).

The system is self calibrating, and no training is required to use it. Its use enables increased production and maintenance of tighter compositional tolerances than have been possible in the past (De Saro et al. 2005b).

Two commercial installations have been completed, one in the aluminum industry and one in the glass industry. The laser-induced breakdown spectroscopic system is permanently installed in a glass manufacturing facility and is routinely used. High degrees of accuracy and repeatability are achievable with this system. The installation in the aluminum industry has shown that the laser-induced breakdown spectroscopic system is as accurate as conventional spark spectrometers (De Saro et al. 2005a). At an early stage of development, the system was also used to measure elemental concentrations of solid steel samples. Since then, the techniques have been refined. There have so far been no industrial-scale applications of this system in the steel industry, as more development work is needed for its application in the steel industry (De Saro et al. 2005b).

Figures 31 and 32 show the basic laser-induced breakdown spectroscopic system and its application to molten material.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by in-situ real-time measurement of melt constituents compared to steel production without this feature (De Saro et al. 2005b, U.S. DOE/ITP 2004):

- Energy savings and CO₂ reductions because of reduction of downgraded or scrapped material
- Increased production and tighter compositional tolerances

Block Diagram or Photo:

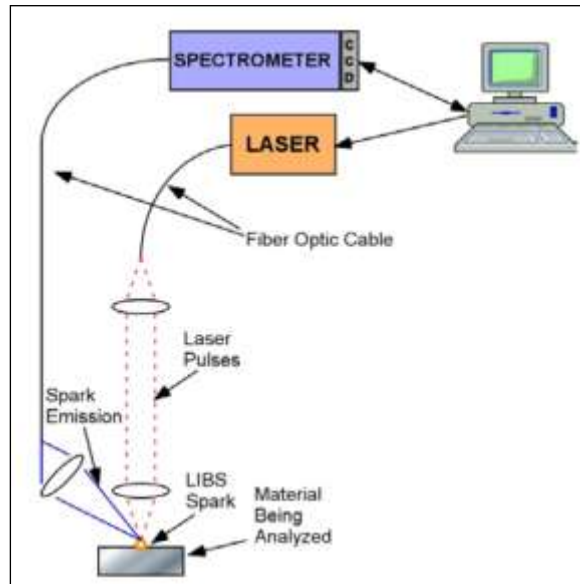


Figure 31. Schematic of basic laser-induced breakdown spectroscopic system (De Saro et al. 2005b)

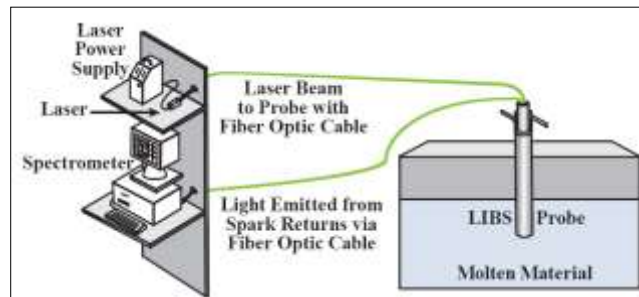


Figure 32. Example of laser-induced breakdown spectroscopic system applied to molten material (U.S. DOE/ITP 2010a)

Commercial Status:

Development stage (for the steel industry)

Demonstration stage (for the aluminum and glass industry)

References for further information:

De Saro et al. (2005a,b), U.S. DOE/ITP (2004, 2010a)

3.5.10. Injection of Plastic Waste in Blast Furnaces

Description:

Coke is traditionally used in BFs to generate CO and heat for smelting iron ore to produce hot metal. Many steel companies use pulverized coal injection in BFs to reduce the amount of Coke, and hence the cost of raw material. Plastics can replace coke or pulverized coal for the reduction reaction. Injection of plastic waste in the BF allows a reduction in coke usage¹⁰. However, coke has a special function in moving the gases, liquids, and solids within the BF. Plastics and pulverized coal cannot perform this specific function, so coke can only be replaced up to a certain limit (ICPE 2006).

The theoretical maximum for plastic injection at the tuyere level is thought to be 0.070 t/t hot metal and is determined by the thermochemical and kinetic conditions in the BF. The ratio of plastics injection depends on the relative amounts of carbon and hydrogen that can be derived from the plastic injected. A kilogram of plastic can replace about 0.75 kg of coke. When plastics are used, a reduction of the hot metal sulfur content is possible because plastics have a lower sulfur input than heavy oil or coke (Worrell et al. 2010).

Normally hydrocarbon-rich plastics are the preferred raw materials. However, chlorine-containing plastics, such as polyvinyl chloride (PVC), can also be used in the BF because the hydrogen chloride generated during the burning process is readily neutralized by the limestone used inside the BF. The high-temperature environment inside the BF (around 2,000°C) ensures that there is no possibility of dioxin formation when PVC is processed because dioxins form at lower temperatures. In addition, the reducing atmosphere in the low-temperature region at the top of the furnace contains no oxygen, so no dioxins are produced or re-synthesized in the lower-temperature zone because oxygen is necessary for dioxin formation. However, if no counter measures are taken against hydrogen chloride corrosion of the equipment used in the treatment or utilization of BF gas, use of chlorine-containing plastics like PVC should be avoided. Small amounts of paper, stones, and sand included in the plastics waste pose no problem because these are discharged as slag (ICPE 2006).

In 2004, plastic injection in a BF at Eisenhüttenstadt (Germany) averaged 0.067 t/t hot metal and in Bremen (Germany) averaged 0.052 t/t hot metal. Voestalpine Stahl GmbH (Austria) has finished trial operation of a plastics injection plant. The steel industry in Japan effectively reuses both industrial and municipal plastic waste. About 1 percent waste plastic is added to the coal charge in coke ovens in the Japanese steel industry. Waste plastic recycling processes using coke ovens began at Nippon Steel's Nagoya and Kimitsu works in 2000. The treatment capacity is 40,000 t/year. At Nippon Steel's Yawata and Muroran works, similar processes started in 2002.

¹⁰ There is a potential resource competition between injection of plastic waste in the BF and recycling of plastic waste for other uses.

(Worrell et al. 2010). JP Steel Plantech Co. has developed the plastic injection system technology for BF (JP Steel Plantech Co. 2005).

Figure 33 shows a BF waste plastics injection system.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by injecting plastic in a BF compared to using only coke or pulverized coal (Worrell et al. 2010; ICPE 2006; EIPPCB 2008):

- Reduced coke and coal use
- Reduced fuel cost because of replacement of a portion of coke and/or coal with plastic waste
- Reduced landfilling of plastic wastes
- Reduced consumption of de-sulfurization agents (e.g., lime, calcium carbide, magnesium) during pre-treatment of the hot metal because plastic has lower sulfur content.
- Cost of the plastics injection plant at Voestalpine Stahl GmbH (Austria) was about € 20 million for an injection capacity of up to 220,000 t/year

Block Diagram or Photo:

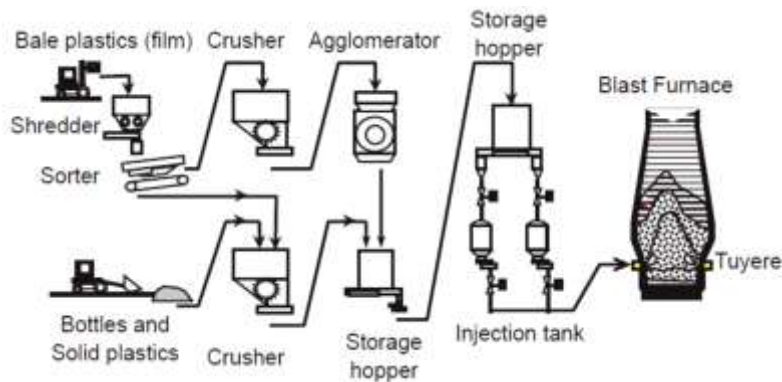


Figure 33. Waste plastics injection system for BF (JP Steel Plantech Co., 2005)

Commercial Status:

Demonstration stage

References for further information:

Worrell et al. (2010); ICPE (2006), JP Steel Plantech Co. (2005), EIPPCB (2008)

3.5.11. Injection of Plastic Waste in Electric Arc Furnaces

Description

EAF steelmaking uses carbon-based materials as slag foaming agents. Depending on cost and availability, anthracite and metallurgical coke are often used as injection materials. Because of increasing energy prices and GHG emissions, alternative carbon sources are gaining attention as replacements for conventional materials. Waste materials such as high-density polyethylene plastics can react with gas and in slag phases resulting in de-volatilization, combustion, and iron oxide reduction reactions. The addition of waste plastics in EAF steelmaking has been studied in detail by The University of New South Wales and OneSteel with the goal of developing a method for EAFs to use blends of different proportions of rubber/ high-density polyethylene plastics and coke as a slag foaming agent (Sahajwalla et al. 2011).

A prototype scale process was able to replace 30 percent of the coke and coal with polyethylene waste plastic. This new process has demonstrated the ability to accelerate the slag-foaming process at the top of the melt, thereby saving energy. Consequently, a higher productivity is achieved. In 2007, OneSteel carried out commercial trials at its Rooty Hill facility in Australia. The first trials confirmed the speed-up of the slag foaming process with reduced electricity use. The tap-to-tap time was also reduced. The technology is planned to be implemented and further developed at the OneSteel Laverton facility (Worrell et al. 2010).

Sahajwalla et al. (2010) also investigated the combustion efficiencies of blends of metallurgical coke with plastics for EAF steelmaking. Laboratory tests for coke-plastic blends indicated higher combustion efficiencies compared to coke (Sahajwalla et al. 2011).

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by injecting waste plastics in EAFs compared to using only coal (Worrell et al. 2010):

- Estimated energy savings of around 12 kWh/t of plastic charge
- Reduced CO₂ emissions
- Increased productivity by reducing tap-to-tap time
- Reduced landfilling of plastic waste

Block Diagram or Photo:

N/A

Commercial Status:

Pilot stage

References for further information:

Worrell et al. (2010), Sahajwalla et al. (2010, 2011)

3.5.12. Use of Waste Tires in Electric Arc Furnaces

Description

Steel making in an electric arc furnace is based on the principle of subjecting scrap metal to a high temperature (1,650 °C) for about 45 minutes until the metal becomes molten. An electric arc (temperature greater than 15,00 °C) provides the gradual rise in temperature. Normally in an EAF furnace, approximately 3.3t of lime and 1.15t of carbon in the form of anthracite and coke are added for every 100 t of scrap metal (Clauzade 2006).

Rubber tires contain a large amount of carbon and energy and are available at lower costs than other potential alternative fuels. Additionally, the ever-increasing use of tires poses serious disposal problems in landfills because they do not biodegrade. Tires are generally disposed of in landfills and by incineration and to some extent co-processing in cement kilns; however, landfilling and incineration are becoming unattractive because of diminishing landfill space and for legislative reasons. Scrap tires make a good carbon source for EAF steel melting. The tires are added to the EAF as a source of chemical energy, replacing coal or coke. The carbon and hydrogen in the tires provide fuel energy, and the steel belts and beads become part of the material in the furnace. Oxygen is injected into the furnaces while the tires are burning so that combustion is clean and complete. The tires are completely consumed in the process. Contrary to popular belief, there is no increase in emissions from burning tires in an EAF. A 9-kg passenger tire has a fuel value of approximately 332 MJ. Tires have a higher heating value than that of coal and coke on a per-weight basis. Two or more passenger tires can be added per tonne of steel. Tire disposal fees that steel plants may receive for tires they burn can also result in a significant revenue per tonne of steel. Scrap tires contain 1.5 percent sulfur, which compares favorably with the sulfur content of most coal and coke. When scrap tires are used in the EAF, they do not cause any noticeable change in steel chemistry other than an increase in carbon if desired (Stebbing 2005).

Under experimental conditions, Zaharia et al. (2009) showed that most of the rubber/coke blends had higher combustion efficiencies than those of constituent coke in an EAF (Zaharia et al. 2009). An industrial trial of using scrap tires in EAF, carried out by Joulazadeh (2008) at Esfahan Steel Co. in Iran, showed that coke consumption reduced from 18.0 kg/t steel to zero and electricity consumption decreased from 448 to 388 kWh/t. The study also found that the amounts of gaseous pollutants released, such as CO, NO_x, and SO₂, were far lower than the permitted limits (Joulazadeh 2008).

EAFs in the U.S. began to use scrap tires as a source of carbon and steel by introducing the whole tire into the charge bucket. Also, since 1999, rubber tires have been used as a substitute for coal and iron scraps in the scrap melting converter of Nippon Steel Corporation in its Hirohata, Japan mill. The procedure involves cutting the waste tires to smaller dimensions and charging them into the scrap melting bath along with the steel cords contained in the tires (Zaharia et al. 2009). Since

2006, the LME site at Trith-Saint-Leger in France, which is capable of processing 7,000 tonnes of scrap tires annually, has implemented the recycling of scrap tires in its EAF (Clauzade 2006).

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by injecting waste tires in an EAF compared to injecting coal (Stebbing, 2005; Clauzade 2006):

- Reduced coke and/or coal consumption
- Reduced CO₂ emissions
- Reduced landfilling of waste tires

Block Diagram or Photo:

N/A

Commercial Status:

Commercial with very low adoption rate

References for further information:

Clauzade (2006), Stebbing (2005), Joulazadeh (2008)

3.5.13. Continuous Steelmaking for Electric Arc Furnace

Description:

High-quality EAF steelmaking is currently a batch process. To improve productivity and energy efficiency, a continuous process from liquid steel to the casting mold is under development through the U.S. DOE Industrial Technologies Program (U.S. DOE/ITP 2005).

Current EAF shops consist of an EAF, a ladle metallurgy furnace, and a continuous caster. The proposed process replaces the ladle metallurgy furnace and the continuous caster with a continuous process including several vessels (oxidizer, reducer, finisher, and tundish). The process would be designed for variable production rates ranging from 70 t/h to 170 t/h (Peaslee et al. 2006).

The process has been modeled as follows: Preheated scrap is continuously charged and melted in the EAF, and final de-carbonization and de-phosphorization take place in a second vessel, the oxidizer. In the reducer, steel is continuously de-oxidized, de-sulfurized, and alloyed. Once the steel has a composition that is close to the final chemistry, it enters the fourth vessel, the finisher. The operations in the finisher include final trimming, additional de-sulfurization, inclusion floatation, and homogenization before the steel flows into the last vessel, the tundish (Peaslee et al. 2006). So far, the process has been modeled, and laboratory experiments have been conducted to validate the simulations.

Figure 36 shows the fully continuous EAF steelmaking process.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed for the proposed EAF continuous casting process compared to the conventional EAF/ladle metallurgy furnace/continuous caster process (U.S. DOE/ITP 2005, Peaslee et al. 2006):

- More productive and less capital intensive
- Reduced energy consumption because heating losses during transportation of the liquid steel from the EAF to the ladle metallurgy furnace are eliminated
- Less space required (about two-thirds of the space required for the conventional process)

Block Diagram or Photo:

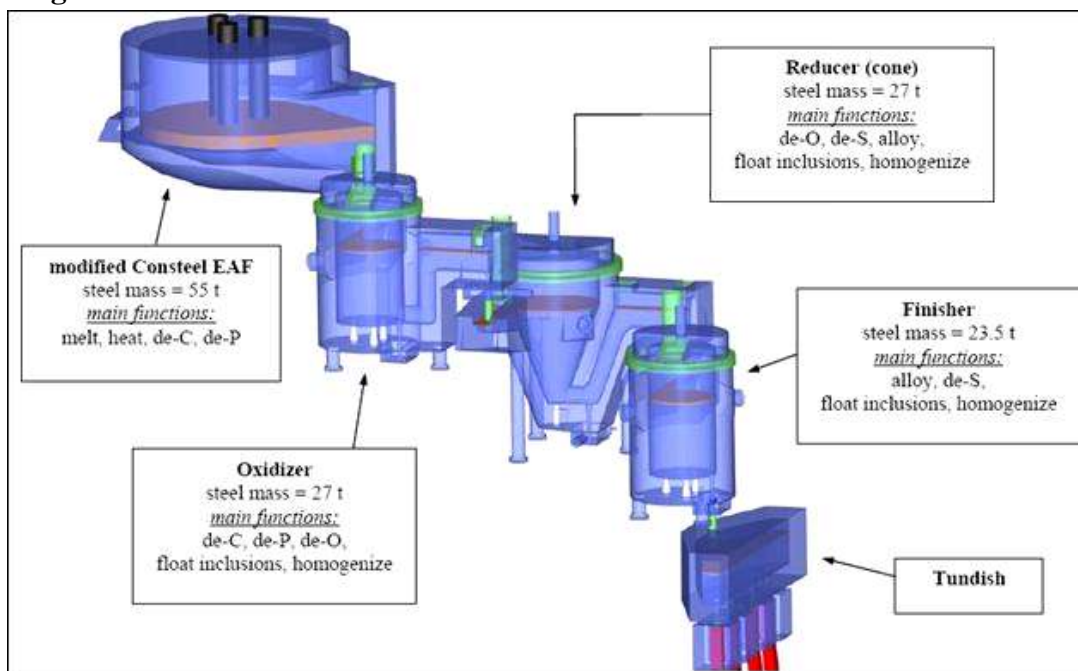


Figure 36. Side view of the fully continuous EAF steelmaking process (Peaslee et al. 2006)

Commercial Status:

Research stage

References for further information:

U.S. DOE/ITP (2005), Peaslee et al. (2006)

3.6. Emerging Casting Technologies

The subsections below describe the following emerging technologies to save energy and reduce CO₂ emissions from the steel casting process: near-net-shape casting, and continuous temperature monitoring and control.

3.6.1. Near-net-shape Casting/Strip Casting

Description:¹¹

“Near-net-shape casting entails casting metal to a form close to that required for the finished product so that less machining is required to finish the steel than in conventional production. 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, notably thin-slab casting and strip casting. In thin-slab casting, the steel is cast directly to slabs that have a thickness of 30 to 60 mm rather than the typical 120- to 300-mm thickness. Thin-slab casting has been a success in flat-product mini-mills in the U.S. (Birat et al. 2003).

In strip casting, steel is cast between two rolls that produce a strip approximately 3 mm thick. Development of near-net and strip casting started in 1975 in a number of countries: Europe, Japan, Australia, the U.S., and Canada (Luiten and Blok 2003). Since then, three commercial technologies have emerged. In all three, the steel is cast between two water-cooled rolls, which results in very rapid cooling and high production speeds. The major advantage of strip casting is a large reduction in capital costs because the process has a high productivity and integrates several production steps (Sosinsky et al. 2008). The first commercial strip casting technologies are:

1. **Castrip**[®]: The Castrip[®] consortium was formed to commercialize a product based on technology developed by BHP (Australia) and IHI Japan. The third partner is Nucor (USA). Nucor first introduced strip casting in the U.S. The first commercial strip caster was constructed at Nucor’s Crawfordsville, Indiana plant in 2002. Since then, the plant has produced ultra-thin cast strip products. The plant has a capacity of 540 kilotons (kt)/year. Nucor also commenced construction of its second strip casting plant in Blytheville, Arkansas (Sosinsky et al. 2008).
2. **Eurostrip**: Eurostrip is a consortium of ThyssenKrupp Steel, ArcelorMittal, and Voest Alpine Industries. The first pilot plant was constructed in Terni, Italy, and the first commercial plant opened in 1999 in Krefeld, Germany. The commercial plant focuses on stainless steel casting. The technology is offered at a scale of 550 kt/year (Cramb 2004).
3. **Nippon/Mitsubishi**: A strip caster commissioned in October 1997 by Nippon Steel has an output of 420 kt/year with an estimated fuel use of 0.05 GJ/t and electricity use of 42 kWh/t – considerably less than the energy used by a continuous casting process. Operations and

¹¹ Most of the text for this technology was excerpted from Worrell et al. (2010).

maintenance costs are expected to be 20 to 25 percent less than for continuous casting although this will depend strongly on the lifetime of the refractory on the rollers used in the caster and on local circumstances (Cramb 2004).

A new development in near-net-shape casting and direct rolling is endless strip production. Construction of an endless strip production plant by Arvedi started in 2008 in Cremona, Italy. The industrial production in this plant using this casting technology started in 2009. The specific energy consumption is anticipated to be 40-percent lower than that of a traditional rolling mill. For thin gauges, the suppression of the cold rolling and annealing cycle will allow energy savings of 60 percent compared to the traditional production cycle (Arvedi et al. 2008).”

A possible disadvantage of the near-net-shape casting is a loss in flexibility in the process. There are in a way no waiting periods anymore using this technology, so the process must be well controlled. This poses a problem with today’s relatively small batches of steel products with the same quality since the process parameters need to be adapted continuously which is more difficult with the near-net-shape casting process¹².

Figure 34 shows a diagram of the CASTRIP process.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the Castrip® process compared to conventional slab casting and hot rolling methods (Worrell et al. 2010, Sosinsky et al. 2008, Arvedi et al. 2008):

- Potential energy savings of 80 to 90 percent (compared to thick-slab casting -- hot rolling, pickling and cold rolling -- thin slab casting saves approximately 1 GJ/t cast steel; Compared to thin-slab casting, the Castrip® process saves approximately 1 GJ/t cast steel)
- Greater tolerance of high-residual elements without loss of quality, enabling greater flexibility in ferrous feed sourcing
- Potential for higher scrap recycling rates and less dependence on pig iron and HBI
- Lower costs for consumables (e.g., molds, rolling cylinders) and improved liquid steel yield (up to 98 percent) are reported for endless strip production

¹² Personal communication, Wolfgang Eichhammer, Fraunhofer Institute for Systems and Innovation Research ISI, November 2012.

Block Diagram or Photo:

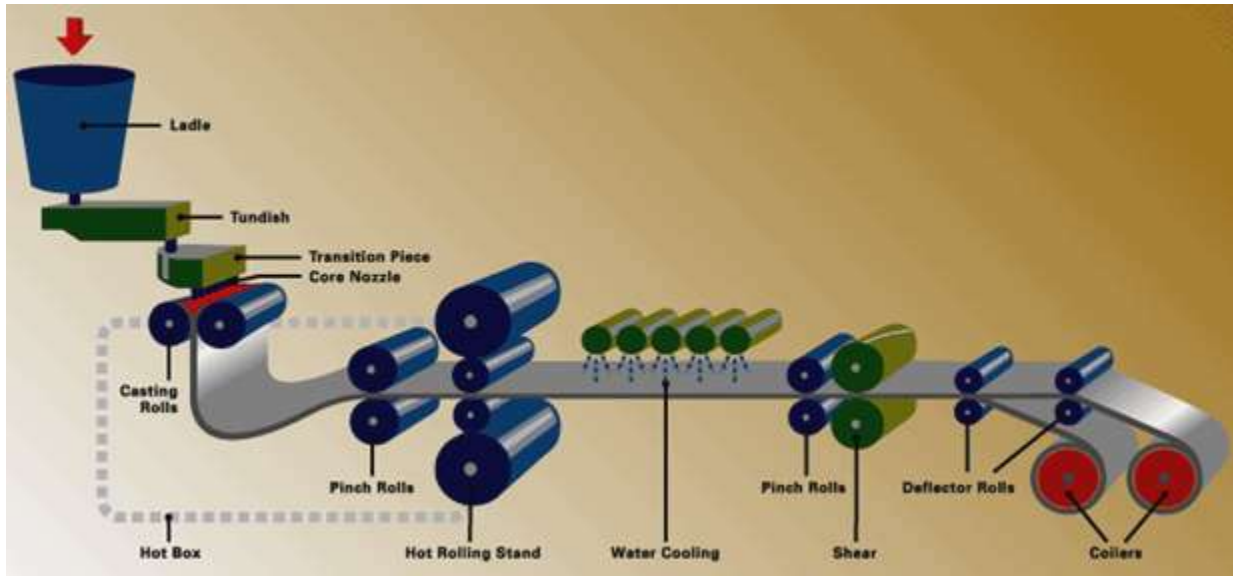


Figure 34. The Castrip® process (Castrip 2012)

Commercial Status:

Commercial with very low adoption rate

References for further information:

Worrell et al. 2010, Birat et al. (2003), Sosinsky et al. (2008), Arvedi et al. (2008)

3.6.2. Continuous Temperature Monitoring and Control in Continuous Casting

Description:

To improve the energy efficiency of producing casting melts for steel castings, continuous temperature monitoring and control are required during the melting process. Monitoring and control would ensure that the necessary melt temperature (tapping temperature) is reliably achieved, eliminating the need for subsequent, often costly, temperature adjustments (BFI 2009/2010).

VDEh-Betriebsinstitut (BFI) developed a fiberoptic temperature measuring technique called DynTemp®. The measurement device does not rely on emissivity and can be used in manual lances in foundry operations. The measuring quality equals that of conventional immersion thermocouples. An advantage of this technique is that it is insensitive to electromagnetic fields. This technique offers the potential for continuous, highly dynamic on-line melt temperature measurement. In addition to increasing the amount of time during which temperature is measured, this technique also has the benefit of multiple use of the probes in the melt. Continuous long-term measurement will be possible if a sensor with highly insulating protective coatings is developed. The inert gas required for the measurement technique can help to create a protective gas layer on

the melt bath surface which will largely prevent re-oxidization of the melt. An improvement in energy efficiency of up to 5 percent is expected from the use of the new temperature monitoring and control system. (BFI 2009/2010).

Energy/Environment/Cost/Other Benefits:

BFI claims that the following benefits can be achieved from use of the DynTemp device compared to conventional temperature measurement techniques (BFI 2009/2010):

- Longer temperature measuring times
- Energy-efficiency improvement of up to 5 percent

Commercial Status:

Development stage

Reference for further information:

BFI (2009/2010)

3.7. Emerging Rolling and Finishing Technologies

The subsections below describe the following emerging technologies that save energy and reduce CO₂ emissions in the rolling and finishing phases of steelmaking: oxygen enrichment of combustion air combined with use of low-calorific gases, scale-free steel reheating, thermochemical recuperation for reheating furnaces, the hot strip mill model, continuous burn-out measurement for management of reheating furnaces, oxygen-rich furnace system for reduced CO₂ and NO_x emissions, HotEye[®] steel surface inspection, and oscillating combustion for NO_x emissions reduction.

3.7.1. High-Temperature Membrane Module for Oxygen Enrichment of Combustion Air for Fuel-Fired Industrial Furnaces

Description:

Industrial furnaces usually are operated with high-calorific gases (e.g., natural gas, converter gas). If these gases are replaced by low-calorific gases (e.g., biogas), then the flame temperature lowers. If the combustion air is replaced by oxygen, then the flame temperature can be increased to levels of combustion that are possible with high-calorific gases (BFI 2009/2010).

The cost-efficient production of oxygen is crucial to this technique. In a project supported by the German Federal Foundation for the Environment (Deutsche Bundesstiftung Umwelt), ceramic membranes were developed in which oxygen is extracted from air with the help of waste heat from the furnaces. This project demonstrated that the necessary furnace chamber temperature can be achieved with low-calorific gases and oxygen (BFI 2009/2010).

Figure 37 shows a high-temperature membrane module on a furnace.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by the scalable high-temperature membrane modules for oxygen enrichment of combustion air in fuel-fired industrial furnaces, compared to use of high-calorific gases (BFI 2009/2010):

- Reduced CO₂ emissions (because biogas is considered carbon neutral)
- Use of waste heat from the furnaces

Block Diagram or Photo:

Figure 37. Testing of a high-temperature membrane module on a furnace; view from the stack through the module into the furnace (BFI 2009/2010)

Commercial Status:

Pilot stage

Reference for further information:

BFI (2009/2010)

3.7.2. Next-generation System for Scale-Free Steel Reheating**Description:**

Steel reheating is an important, energy-intensive process that mills and finishers use prior to rolling or forging steel.¹³ The steel slabs are heated to approximately 1150°C in reheating furnaces that often use natural gas or byproduct fuels. During this process, 1 to 2 percent of the steel is typically lost to oxidation, resulting in accumulation of scale on the steel surface as well as the furnace floor. Scale compromises steel quality because it adheres to the surface and is difficult to remove. If scale is present in the rolled product, it can result in defects or metallurgical abnormalities that require reprocessing. Scale formation also impedes gas flow and heat transfer when it accumulates on the furnace floor and so must be collected and removed frequently. In addition, the lifetime of furnace components can be negatively affected by scale. Removing scale interrupts production and results in costly down time (U.S. DOE/ITP 2007a).

A project team, led by E3M Inc. with the support of the U.S. DOE, investigated the development of a new system that reduces scale (iron oxide) formation in the steel reheating process in a laboratory furnace. The technology employs fuel-rich combustion using preheated or oxygen-enriched air to control flue gas composition. This process substantially reduces energy use and costs associated with the handling, disposal, and reprocessing of scale. Reducing scale formation

¹³ Steel reheating could be potentially eliminated is near-net-shape casting technology, which was explained earlier, is used.

increases product yield and revenue by saving high-value steel that is currently lost because of scale (U.S. DOE/ITP 2010a; Thekdi 2010).

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for scale-free reheating of steel compared to conventional reheating techniques (Thekdi 2010):

- Energy savings of approximately 0.2 GJ/t during the reheating process
- Reduction in energy use required to produce amount of steel equivalent to the amount currently lost because of scale
- Improved productivity from reduced downtime and manpower to collect and remove scale from reheating furnaces
- Estimated cost of the scale-free reheating system between \$0.75 and \$2.8 million depending on the type and capacity of the mill; estimated payback period shorter than 1 year

Block Diagram or Photo:

N/A

Commercial Status:

Research stage

References for further information:

U.S. DOE/ITP (2010a), Thekdi (2010)

3.7.3. Thermochemical Recuperation for Steel Reheating Furnaces

Description:

The conventional method for improving the efficiency of steel reheating furnaces is to preheat the ambient combustion air by recovering a fraction of the sensible heat in the flue gases leaving the furnace. This is typically accomplished by the use of metallic recuperators (air heat exchangers). Although recuperation increases reheating furnace efficiencies, there is still substantial opportunity to reduce fuel consumption of continuous reheat furnaces, including those equipped with recuperators (U.S. DOE/ITP 2011b).

One approach for utilizing the energy contained in waste heat is thermochemical recuperation. This new technique recovers sensible heat in the exhaust gas from an industrial process, furnace, or engine. That heat is then used to transform the hydrocarbon fuel into a re-formed fuel with a higher calorific heat content; this re-formed fuel is used for process heating. The technology has been demonstrated in a number of applications but has not yet been evaluated and developed for commercial adoption. U.S. DOE is supporting a project lead by the Gas Technology Institute to

validate the technical feasibility of the thermochemical recuperation concept as well as its business viability, including identification of technical, scale-up, and processing concerns (U.S. DOE/ITP 2011b).

In the first phase of the project, the Gas Technology Institute licensed simulation software that can model heat transfer and chemical reactions along with computational fluid dynamics. The evaluation focused on energy-efficiency improvements and cost benefits. Technical information developed during the first phase is being used to design, fabricate, and iteratively evaluate performance metrics in a bench-scale thermochemical recuperation unit at the Gas Technology Institute's combustion laboratory. The results will then be used for engineering design, construction, and retrofitting of a full-scale thermochemical recuperation system for prototype field tests on a steel reheating furnace (U.S. DOE/ITP 2011b).

Figure 38 shows a drawing of the thermochemical recuperation concept.

Energy/Environment/Cost/Other Benefits:

The following potential benefits could be achieved by thermochemical recuperation compared to conventional reheating techniques (U.S. DOE/ITP 2011b):

- Net reduction in continuous reheating furnace fuel use because the energy content of the fuel can be increased by more than 25 percent when the original source fuel is natural gas
- Proportional reduction in CO₂ emissions
- Reduced NO_x emissions

Block Diagram or Photo:

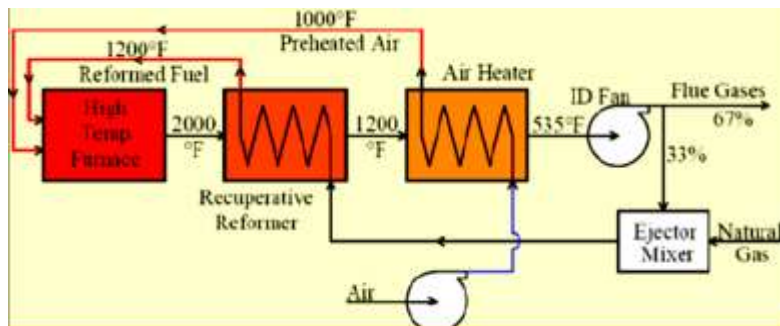


Figure 38. Thermochemical recuperation concept (U.S. DOE/ITP 2011b)

Commercial Status:

Research stage

Reference for further information:

U.S. DOE/ITP (2011b)

3.7.4. Hot Strip Mill Model

Description:

Steel from the continuous caster ranges from 1 to 25 centimeters thick. Steel is further reduced in thickness in hot and cold rolling operations. Steel products from the caster are themselves highly valuable; well over 50 percent of the cost of materials and energy is contained in these semi-finished products. Failure during the rolling operation can result in the scrapping or downgrading of this valuable commodity. During rolling, the steel undergoes numerous heating and gauging operations. This thermo-mechanical processing is as much responsible for the final properties of the steel as is its chemical composition. Furthermore, the steel produced must adhere to rigorous dimensional tolerances to satisfy the needs of the customer's forming operations. Often the "trial and error" rolling of many tons of steel is necessary to develop proper rolling practice for a given product. This is not only costly, but it also removes the rolling mill from commercial service, resulting in the loss of saleable products. To address these issues, the DOE/AISI Advanced Process Control program and TR Program supported the development of the hot strip mill model by the University of British Columbia and INTEG Process Group, Inc. (AISI 2010).

The hot strip mill model is an off-line PC-based software model originally developed by the University of British Columbia and the National Institute of Standards and Technology (Shulkosky et al. 2005). The model predicts the temperatures, deformation, microstructural evolution, and mechanical properties of steel strip or plate rolled on a hot mill. The model can be used to help locate the source of flaws introduced during rolling, to develop new rolling practices and products, and to improve existing rolling operations. It has been licensed to INTEG Corporation, which has subsequently adapted and resold the model to 32 steel mills (AISI 2010).

Users can set up their mill configurations, including number of reheat furnaces, roughing mill stands, heat retention equipment, finishing mill stands, run-out table cooling system, and mill exit area. The model can handle both strip and plate and can be configured for reversing mills, continuous mills, tandem mills, or Steckel mills utilizing a coiler or cooling bed. A variety of steel grades can be handled, including material characteristics for basic carbon grades, high-strength low-alloy grades and interstitial free grades. Dual-phase steels are being added (INTEG process group, Inc. 2004).

The hot strip mill model can be used for a variety of applications. Current users have employed it to study mill configurations, rolling schedules, and process parameters to gain detailed insight into their operations that are not available with their current models and control systems (e.g., information on temperature distribution, transformation start temperatures, and final mechanical properties) (INTEG process group, Inc. 2004).

Figure 39 shows the hot strip mill model structure.

Energy/Environment/Cost/Other Benefits:

The following potential benefits could be achieved by using the hot strip mill model compared to conventional rolling practices (AISI 2010; INTEG process group, Inc., 2004):

- Reduced energy consumption as a result of reduced failure rates in the rolling operation
- Reduced materials costs
- Improved productivity from more efficient operation of the rolling process

Block Diagram or Photo:

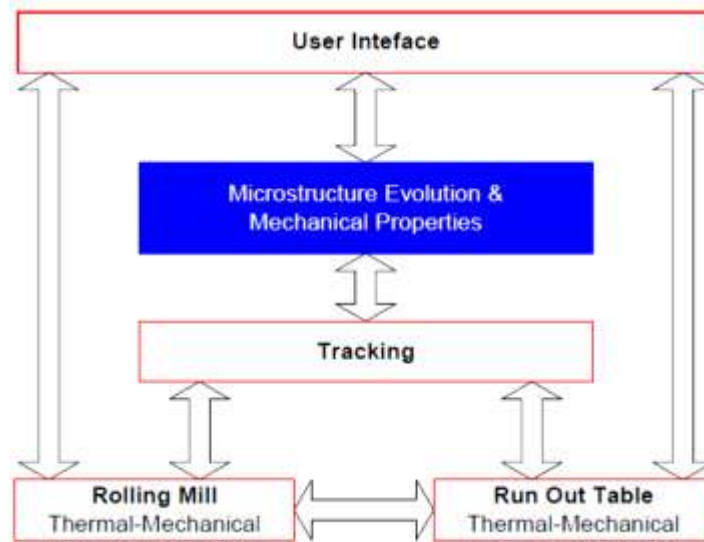


Figure 39. Hot strip mill model structure (INTEG process group, Inc. 2004)

Commercial Status:

Commercial with very low adoption rate

References for further information:

AISI (2010), Shulkosky et al. (2005), INTEG process group, Inc. (2004)

3.7.5. Innovative Reheating Furnace Management Using a Continuous Burn-Out Measuring System

Description:

In the production of high-quality metal products (e.g., auto body paneling, food packages, or shaped/molded parts), reheating and heat treatment is of critical importance. Common reheating furnaces (e.g., tunnel, bogie hearth, or continuous-throughput furnaces) need to work with a defined gas composition. To avoid surface defects through oxidation in hot-dip galvanizing lines, the gas atmosphere needs to be free of oxygen. Therefore, the furnaces are normally operated

with a fuel gas surplus resulting in excess energy consumption and CO₂ emissions (BFI 2009/2010).

VDEh-Betriebsforschungsinstitut (BFI) has developed a system to lower energy consumption and to assure product quality of preheating furnace of a hot-dip galvanizing line. The system entails (BFI 2009/2010):

- Furnace management concept via a continuous burn-out measuring system
- A new under-stoichiometric burner with forced burn-out
- Rollers made from new materials for transporting the charged stock

A burn-out measuring system for controlling the hot gas atmosphere in the individual furnace zones was modified and tested under industrial shop conditions. Figure 40 shows the modified burn-out measuring system during industrial trials on a hot-dip galvanizing line. In addition, a new burner was developed jointly with a burner manufacturer for use in under-stoichiometric operation on the burner test stand. The use of this technology in an industrial application is planned (BFI 2009/2010).

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved from reheating furnace management using a continuous burn-out measuring system compared to conventional reheating (BFI 2009/2010):

- Reduction in energy consumed for preheating furnace of a hot-dip galvanizing line
- Reduction in CO₂ emissions
- High product quality

Block Diagram or Photo:



Figure 40. Modified burn-out measuring system during industrial trials on a hot-dip galvanizing line (BFI 2009/2010)

Commercial Status:

Pilot stage

Reference for further information:

BFI (2009/2010)

3.7.6. Oxygen-rich Furnace System for reduced CO and NO emissions

Description:

Furnaces in the steel industry are one major consumer of fossil fuels. Hence, they are also key CO₂ emitters. A project was funded by the DOE/ AISI TR Program at Queen's University in Canada. The aim of the project was to develop and test the combination of a low NO_x-burner with oxygen enriched combustion air (Grandmaison et al. 2003, Poirier et al. 2003, U.S. DOE/OIT 2001).

Normally two streams are injected in reheating furnaces, natural gas and air. In this project a third stream was added to introduce oxygen into the furnace. Therefore, the furnace control system needed to be adapted in order to deal with three streams instead of two streams. A PC-based controller and oxygen valve train were used to monitor and regulate the flow of oxygen based on a flow sensing device, limiting switches and relays (Grandmaison et al. 2003). The burner was installed in a pilot reheat furnace and tested within a range of operating configurations (Poirier et al. 2003).

The burner was tested by maintaining a constant target temperature of 1100°C corresponding to firing rates of 325–365 kW at zero percent oxygen enrichment, depending on the stack oxygen concentration (excess oxidant). At 100 percent oxygen enrichment, firing rates in the range of 200–220 kW were required to maintain furnace temperature. This represents potential savings of 40–45 percent in fuel usage and a corresponding reduction in CO₂ emissions. Oxygen enrichment had little effect on NO_x emission up to an enrichment level of about 60 percent. At higher oxygen enrichment, emission levels decreased but not to zero because of nitrogen incorporated with the natural gas (Grandmaison et al. 2003, Poirier et al. 2003).

Oxygen enrichment leads to different combustion environment with significantly larger proportions of CO₂ and H₂O along with the excess oxygen commonly present in combustion systems. Hence, scale morphology was tested at samples of the 5 steel grades. The results showed that scale habit, intactness, and adhesion were not mainly affected by the stack oxygen and oxygen enrichment levels but by the steel grade. The steel scaling rates observed with oxygen enriched combustion conditions was slightly higher, but this effect was not large. A modification of an ultra-low NO_x-burner which can provide O₂ enriched combustion was installed in a pilot reheating furnace in a steel plant in Canada (Grandmaison et al. 2003).

Figure 41 shows the drawing of the research furnace.

Energy/Environment/Cost/Other Benefits:

Following benefits can be achieved by applying oxygen enrichment technology in reheating furnaces compared to conventional operation of reheating furnaces (Grandmaison et al. 2003, Poirier et al. 2003):

- Potential savings of 40–45 percent in fuel usage and a corresponding reduction in CO₂ emissions
- Reduced NO_x emissions

Block Diagram or Photo:

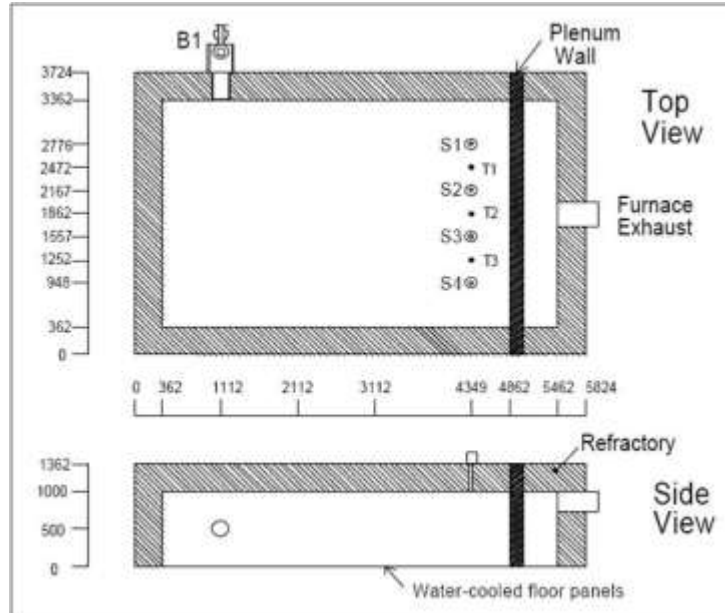


Figure 41. Drawing of the research furnace showing the location of the specimen ports, S1 --- S4, and roof thermocouples, T1 --- T3, adjacent to the ports (Grandmaison et al. 2003)

Commercial Status:

Developmental stage

Reference for further information:

Grandmaison et al. (2003), Poirier et al. (2003), U.S. DOE/OIT (2001)

3.7.7. HotEye® Steel Surface Inspection System

Description:

A new inspection system, the HotEye® Rolled Steel Bar (RSB) System, has been developed and demonstrated by OG Technologies Inc. The system integrates OG Technologies’ HotEye with a dynamic control plan for hot steel processes, mainly rolling. The HotEye system accurately and reliably measures a part’s dimensions and detects its surface features, including defects, while the part is still red hot, i.e., at temperatures of up to 1,550°C. This enables defects to be corrected before the part cools, an advantage over current measurement systems, which cannot be used until parts cool, resulting in higher scrap rates when defects are detected. The dynamic control

plan also classifies some defects that result from production, identifying their root causes and corrective actions (U.S. DOE/ITP 2010a).

The HotEye RSB System provides real-time process control, increasing yields by 2.5 percent in hot rolling steel mills and saving energy by reducing the scrap rate. The HotEye RSB System will automatically inspect 100 percent of the surface of the product in line; identify defects as small as 0.025 mm; analyze and record the size, nature, and location of the defects; measure all dimensions of the product; and generate process correction advice based on the dynamic control plan. The system can perform these inspections while the product is at temperatures up to 1,550°C and moving at a speed up to 100 m/second. This technology was developed in 2004 and has been installed in five U.S. and multiple foreign steel mills in 2009 (U.S. DOE/ITP 2010a). This technology could also be applicable for continuous casting, but more developments work is required. Figure 35 shows a drawing of the HotEye RSB sensor system.

Energy/Environment/Cost/Other Benefits:

The following benefits are reported for the HotEye RSB system compared to conventional systems (U.S. DOE/ITP 2010a):

- Detects and identifies production flaws quickly and reduces the scrap rate by 50 percent, saving energy and improving productivity
- Allows remote inspection of parts at temperatures of up to 1,550°C, reducing employee burns

Block Diagram or Photo:

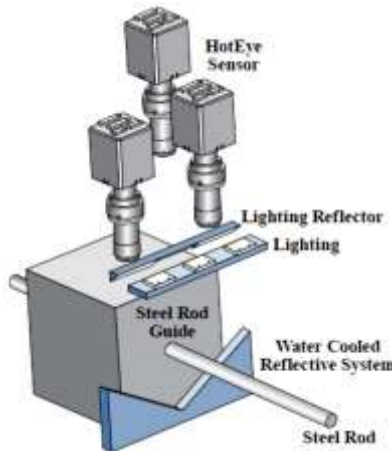


Figure 35. Design of the HotEye RSB sensor system (U.S. DOE/ITP 2010a)

Commercial Status:

For hot rolling of bars and shapes (not for flat products): Commercial with very low adoption rate

For continuous casting: Developmental stage

Reference for further information:

U.S. DOE/ITP (2010a)

3.7.8. Nitrogen Oxide Emission Reduction by Oscillating Combustion

Description:

Industrial furnaces are major consumers of fossil fuels and therefore key CO₂ emitters. If they are fired with preheated air, it can reduce CO₂ emissions but NO_x emissions will rise. A switch to oxygen injection can improve energy efficiency and reduce NO_x emissions, but its application is more cost intensive and might not always be compatible with the material being heated. By retrofitting oscillating combustion, fuel-rich and fuel-lean zones are created within the furnaces. Thereby NO_x emissions are reduced and furnace efficiency is increased for both air- and oxygen fired furnaces (U.S. DOE/ITP 2005b).

Oscillating Combustion is a retrofit technology that involves the forced oscillation of the fuel flow rate to a furnace (see figure 42). Its implementation requires that a valve is installed on the fuel supply line of each burner. The oscillating valve must be able to rapidly open and close at the frequencies, amplitudes, and duty cycles needed to optimize the heat transfer and/or reduce the NO_x emissions. Furthermore a controller must also be installed to drive all the valves on a furnace (or for each zone of the furnace) to keep the valves in proper synchronization and phasing. No modification of the burner or the furnace is necessary (Wagner 2004).

Four parameters have to be adjusted in order to optimize the performance of the oscillating combustion:

- Frequency: Number of oscillation cycles per unit time
- Amplitude: Relative change in gas flow rate during the oscillation cycle above or below the median flow rate as compared to the average flow rate, duty cycle and phasing between burners reduced NO_x emissions
- Duty cycle: Fraction of time the gas flow rate is above the average flow rate during each oscillating cycle
- Phasing between burners: Relative offset in time between the start of oscillating cycles for different burners.

It has been shown that oscillating combustion can produce substantial increases in heat transfer and reductions in NO_x emissions on many types of industrial burners. Heat transfer increases of up to 13 percent and NO_x reductions of 31 percent to 67 percent were recorded. The highest levels of NO_x emissions reduction were achieved with burners that use a nozzle-mixing approach and/or preheated or oxygen enriched combustion air, while the highest levels of heat transfer increase were achieved with burners using ambient air, although the heat transfer increase was still significant (up to 6 percent) with burners using preheated combustion. Oscillating combustion was not found suitable for burners using staging or high momentum approaches. Oscillating combustion has been field tested in many types of industrial furnaces using conventional burners (Wagner 2004).

Figure 42 shows the oscillating combustion concept.

Energy/Environment/Cost/Other Benefits:

Following benefits can be achieved by applying oscillating combustion (Wagner 2004, U.S. DOE/OIT 2001b, U.S. DOE/ITP 2005b):

- Saving of up to 5 percent of fuel use by the furnace
- Improved heat transfer by up to 13 percent
- Increased productivity by 5 percent or more
- Reduced NO_x emissions by up to 75 percent
- Simple retrofit that does not require modification of burner or furnace

Block Diagram or Photo:

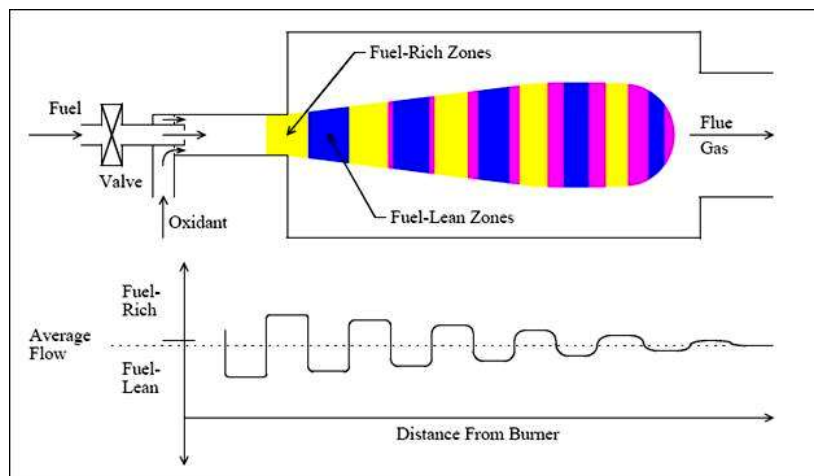


Figure 42. Oscillating combustion concept (Wagner 2004)

Commercial Status:

Pilot stage

Reference for further information:

Wagner (2004), U.S. DOE/OIT (2001b), U.S. DOE/ITP (2005b)

3.8. Emerging Recycling and Waste Reduction Technologies

The subsections below describe the following recycling and waste reduction technologies to reduce energy use and CO₂ emissions by the steel industry: BOF slag recycling, dust recycling for RHF's, recycling stainless steel dust by injection into EAF's, regeneration of hydrochloric acid pickling liquor, and recycling of waste oxides.

3.8.1. Recycling Basic Oxygen Furnace Slag

Description:

The U.S. steel industry generates about 30 million tonnes of byproducts each year, including 6 million tonnes of BOF/basic oxygen process slag. The recycling of BF slag has made significant progress, with much of the material being utilized as construction aggregate and in cementitious applications. However, the recycling of BOF/ basic oxygen process slag still faces many technical, economic, and environmental challenges. Previous efforts have focused on in-plant recycling of byproducts and have achieved limited success. As a result, large amounts of byproducts of various qualities have been stockpiled at steel mills or disposed of at landfills. However, available mill site space has diminished, and environmental constraints on disposal have increased (IMP/MTU 2006).

With support from U.S. DOE, Michigan Technological University has developed an integrated system of technologies to recover the iron value from BOF steelmaking slag and to divert the residual non-iron bearing fraction into a feedstock for the manufacture of an acid mine drainage neutralizing agent (U.S. DOE/OIT 2002).

Three products are generated from the technology developed through this research: a high-grade iron product containing about 90-percent iron, a medium-grade iron product containing about 60-percent iron, and a low-grade iron product containing less than 10-percent iron. The high-grade iron product contains primarily metallic iron and can be marketed as a replacement for pig iron or DRI for steel mills. The medium-grade iron product contains both iron oxide and metallic iron and can be utilized as a substitute for iron ore in the BF. The low-grade iron product is rich in calcium, magnesium, iron oxides, and silicates. It has sufficient lime value to be utilized for acid mine drainage treatment.

Analysis indicates that the economics of the technology are favorable. ICAN Global obtained a license agreement for the technology. This right was later transferred to the Westwood Land, Inc. A demonstration pilot plant was constructed to evaluate the technology (IMP/MTU 2006).

JFE Steel Group in Japan has also developed a new product from steelmaking slag: a large carbonated slag block called the "marine block." The marine block is intended to serve as substratum for seaweed, for improving coastline and coastal marine environments. The marine

block is manufactured by molding steelmaking slag and injecting CO₂ into the formed blocks. Figure 43 shows the microstructure of the marine block. A layer from tens to hundreds of micrometers thick and consisting mainly of calcium carbonate, which is the same material from which corals and seashells are made, coats the slag particles and forms a network that extends through the block. Beginning in 1997, marine block and concrete blocks were compared at 10 marine areas throughout Japan to test their function as seaweed bed substratum. In all the test areas, seaweed growth on the marine block exceeded the growth on concrete blocks. Seaweed grew so thickly on the marine block that it was impossible to see the block surface. In contrast, no seaweed grew the upper surface of the concrete block. This result indicated that the marine block has greater bio-affinity because of the calcium carbonate on the surface (Kazuya et al. 2006).

Energy/Environment/Cost/Other Benefits:

The following potential benefits could be achieved by recycling BOF slag using the technology developed at Michigan Technical University (IMP/MTU 2006; U.S. DOE/OIT 2002):

- Savings of 10.5 GJ/t steel by recovering iron from BOF slag (around 75 percent of conventional BF energy use)
- Higher percentage of iron units being converted to steel
- Use of slag component for acid mine drainage neutralization in abandoned coal mines
- Minimization of the potential for alkaline runoff at mill sites
- Avoided CO₂ release from lime production process

The following potential benefits could be achieved by recycling BOF slag using the technology developed by JFE Steel Group (Kazuya et al. 2006):

- Greater bio-affinity than concrete because of the calcium carbonate on the surface of the marine block
- Reduced energy use and CO₂ emissions as a result of substituting steelmaking slag-based marine blocks for concrete block

Block Diagram or Photo:

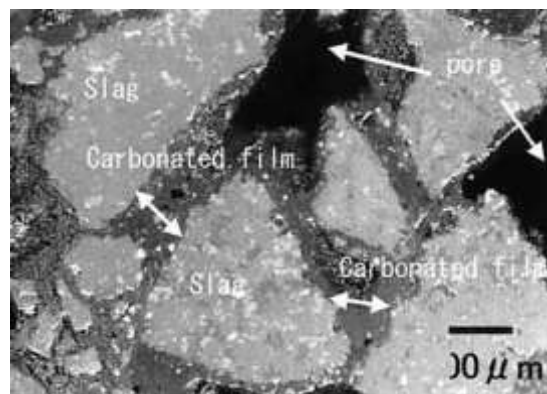


Figure 43. Microstructure of marine block (Kazuya et al. 2006)

Commercial Status:

Development stage

References for further information:

IMP/MTU (2006), U.S. DOE/OIT (2002), Kazuya et al. (2006)

3.8.2. Rotary Hearth Furnace Dust Recycling System**Description:**

In steel production, 1 to 2 percent of the raw materials charged into the steelmaking furnace end up as dust. The most valuable components of steelmaking dust are iron and zinc. In EAF steelmaking dust, zinc is present mainly in the form of zinc ferrite ($ZnFe_2O_4$) (which makes up 29 percent of the total mass of dust) and zincite (ZnO) (which makes up 2 percent) (Doronin and Svyazhin 2011).

Recycling dust and sludge is beneficial because they reduce iron ore and coke consumption, as the recycled iron which is in the dust and sludge reduces the need for virgin iron ore and avoid the coke consumption in BF for pig iron production. However, the zinc content in the dust and sludge makes it difficult to completely recycle these byproducts. Therefore, much of the surplus dust is simply discarded. To enable reuse of dust, Nippon Steel Kimitsu Works developed a RHF dust recycling technology that was used for the first time in 2000 (Nippon Steel Corp. n.d.).

The RHF process uses coal and iron-bearing material such as iron ore to produce DRI. Dust and sludge to be recycled are agglomerated to a suitable size for reduction and charged into the RHF. The RHF is heated to a high temperature by the combustion heat of burners, and the carbon content of the agglomerated raw materials acts as a reducing agent. At this time, the zinc is removed from agglomerated raw materials through reduction and gasification and is collected as secondary dust. The remaining iron (with low zinc content) can be recycled as a high-metallization DRI in a BF and melting furnace. At Kimitsu Works, one plant that uses the agglomeration method for pelletizing recycles mainly dry dust; the other plant uses the agglomeration method of extrusion and recycles mainly sludge (Oda et al. 2006).

MIDREX Technologies Inc. (U.S.) and Kobe Steel, Ltd. (Japan) have also developed a technology called FASTMET for recycling steelmaking dust. FASTMET is based on reductive melting in a RHF. Another technology developed by the Paul Wurth company for recycling steelmaking dust, called PRIMUS, is not yet widely used in the industry. This process employs two units: a multi-hearth furnace for preliminary reduction and an electric refining furnace. PRIMUS has considerable promise because it recovers more than 95 percent of the zinc from the charge materials and can be used to recycle a wide range of iron-bearing wastes (dust, scale).

However, PRIMUS also consumes a large amount of electric power (roughly 1,100 kWh per ton of recycled dust) and has high capital and operating costs (Doronin and Svyazhin 2011).

Figure 44 shows the steelmaking furnace dust recycling plant process.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by RHF dust recycling technology (Doronin and Svyazhin 2011, APP 2010; Oda et al. 2006):

- Production of DRI pellets with 70-percent metallization that are strong enough to be recycled to the BF
- Reduced energy use because of reduced coke consumption
- Reduced waste and decreased disposal costs
- Extended landfill life
- Recovery of currently unused resources (recycling iron, nickel, zinc, carbon, etc.)
- Increased productivity
- Decreased CO₂ and other pollutant emissions because of reduced energy consumption, especially reduced coke consumption

Block Diagram or Photo:

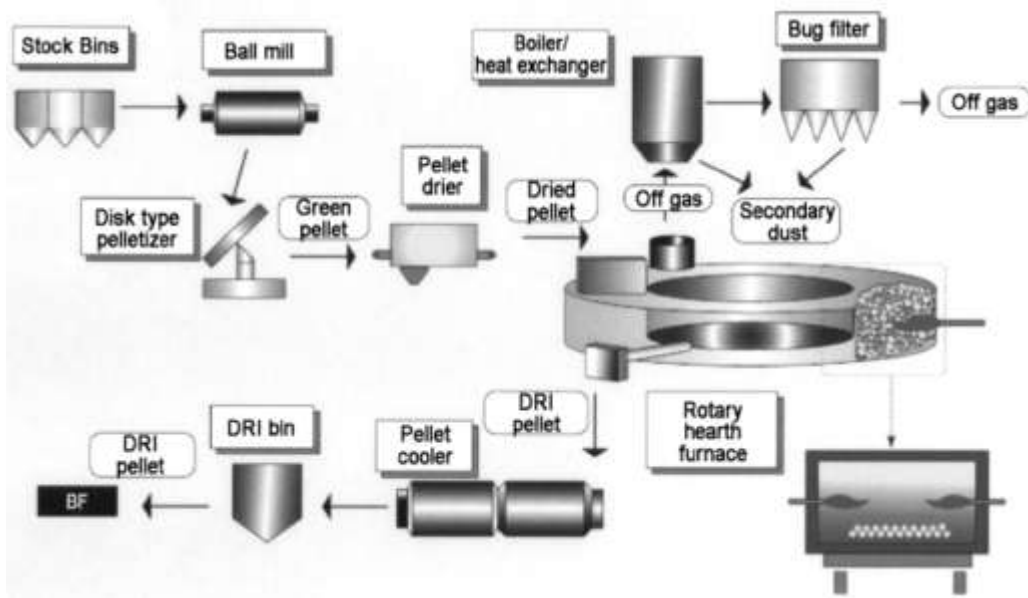


Figure 44. Configuration of steelmaking furnace dust recycling plant process (Oda et al. 2006)

Commercial Status:

Demonstration stage

References for further information:

Doronin and Svyazhin (2011), Oda et al. (2006)

3.8.3. Recycling of Stainless Steel Dust by Injection into Electric Arc Furnace

Description:

In EAF steelmaking valuable amounts of material is usually lost in the by-product dust. The dust normally consists of oxides of iron, zinc and chromium, but its content varies depending of the scrap input. The recycling of stainless steel dust by re-injection into the EAF is one opportunity for energy efficiency improvement in steelmaking.

A pilot plants project on the injection of stainless steel dust into the EAF was funded by the European Commission (Directorate-General Science, Research and Development). Tests were conducted at Ugine-Savoie Imphy at Ugine (USI), France, and Krupp Edelstahlprofile (KEP), Germany (Travernier et al. 2004). In a first step of the project, the analysis procedure for stainless steel dust was validated using dust from USI and KEP. The analysis method was proved concerning the following parameters: amount of dust, emissions flow rate, and composition (Travernier et al. 2004).

Key feature of the process is the pneumatic injection of steelmaking dust into the EAF. To allow a stable process the dust was co-injected with carbon and/or with ferro-silicon (FeSi) at KEP, or blended with coke at USI. It was shown that the recycling of the dust with this process does not alter the produced slag (Travernier et al. 2004).

Energy/Environment/Cost/Other Benefits:

Following benefits are reported that can be achieved by recycling stainless steel dust in EAFs (Travernier et al. 2004, EIPPCB 2009):

- Use of ferro-silicon as a further reducing agent allowed reaching recovery ratio of 81 percent, 38 percent, 97 percent and 93 percent for Cr, Mn, Ni and Fe, respectively
- Annual operating costs can be reduced by 9 percent

Block Diagram or Photo:

Not available

Commercial Status:

Pilot stage

Reference for further information:

Travernier et al. (2004), EIPPCB (2009)

3.8.4. Regeneration of Hydrochloric Acid Pickling Liquor

Description:

Pickling is the chemical removal of surface oxides (scale) and other contaminants such as dirt from metal by immersion in an aqueous acid solution. Acid reacts with the oxides and base metal to produce dissolved metal salts, thereby neutralizing the acid. The pickling process generates a considerable quantity of spent pickle liquor containing the dissolved metal salts as well as residual free acid. This liquor must be regenerated or disposed of by chemical neutralization with alkali. Although carbon steel can be pickled in either sulfuric or hydrochloric acid, hydrochloric acid is the acid of choice, particularly for large, continuous, strip lines (Brown and Olsen 2006). Conventional pickling technology generates around 5.7 million cubic meters of spent pickle liquor in the U.S. alone each year; this liquor requires costly and energy-intensive handling, treatment, and disposal (U.S. DOE/ ITP 2010a).

Green Technology Group with support from U.S. DOE developed the Pickliq[®] hydrochloric acid regeneration system to regenerate spent hydrochloric acid from steel pickling. The Pickliq[®] hydrochloric acid regeneration system recycles tainted hydrochloric acid/spent pickling liquor by sending it to a reactor where sulfuric acid is added. Iron and other pickling byproducts are then removed using a filter or centrifuge. The solution is chilled to between -24°C and -18°C, causing formation of crystallized ferrous sulfate heptahydrate for easy removal from the hydrochloric acid. The purified liquid is then ready for reuse as a steel pickling agent at a fraction of the cost of replacing the hydrochloric acid with fresh. The byproduct of this process, sulfate heptahydrate, is a marketable commodity with a conservative price estimate of about \$50/t. This material would be generated at the rate of 4.74 kg/kg of metal dissolved. The process does not generate wastewater or other residual wastes that require additional treatment or disposal. Portable prototype and full-scale pickle regeneration systems were installed at U.S. Steel Corporation's Irwin Works Sheet Mill in Pittsburgh, Pennsylvania in 2000 (U.S. DOE/ OIT 2000).

The Pickliq[®] hydrochloric acid regeneration process consumes approximately 0.92 kwh of electrical energy per kg of dissolved iron, assuming a reasonably well-designed heat exchanger to reclaim heat from spent liquor for reheating. The economics of the process depend on the pickle liquor composition as well as the rate of metal dissolution from the strip as the scale is removed. For a system processing 100 kg/h of dissolved iron from about 200,000 t/ year of production, Brown and Olsen (2006) estimate the annual savings, excluding amortization of capital cost, at \$1.3 million. Although capital costs have not been fully defined and will vary with the size of the system, it is expected that the simple payback on capital would be in the range of 1 to 2 years (Brown and Olsen 2006).

Tenova Key Technologies Industriebau GmbH (2009) describes another method for hydrochloric acid regeneration using pyrohydrolysis, which provides total recovery (up to 99.9 percent) of a spent acid solution into a metal-free product. Operators not only recover hydrochloric acid in its

free and bonded state but also obtain high-quality iron oxide, either as pellets or fine powder, which is in demand by the ferrite, pigment, and other industries. Pyrohydrolysis is the chemical conversion of metal salts using steam and oxygen at high temperatures (Tenova Key Technologies Industriebau GmbH 2009).

Figure 45 shows a hydrochloric acid regeneration system.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed for hydrochloric acid regeneration using Pickliq[®] hydrochloric acid regeneration technology compared to conventional techniques for a 730,000 t/year steel pickling operation (U.S. DOE/ OIT 2000):

- Energy savings of around 240 MJ/t pickled steel
- Transport energy savings
- Reduced CO₂ and other emissions as a result of reduced energy use
- Savings in plant operation costs of \$1.3 million per year (For a system processing 100 kg/h of dissolved iron from about 200,000 t/ year of production, excluding amortization of capital cost)
- Raw materials savings totaling \$3.3 million per year
- Enabling of on-site, closed-loop pickling and regeneration
- Elimination of the need for transport of spent pickle liquor and off-site processing
- Cost effective for small mills for which regeneration has been too expensive
- Produces a marketable byproduct

Block Diagram or Photo:

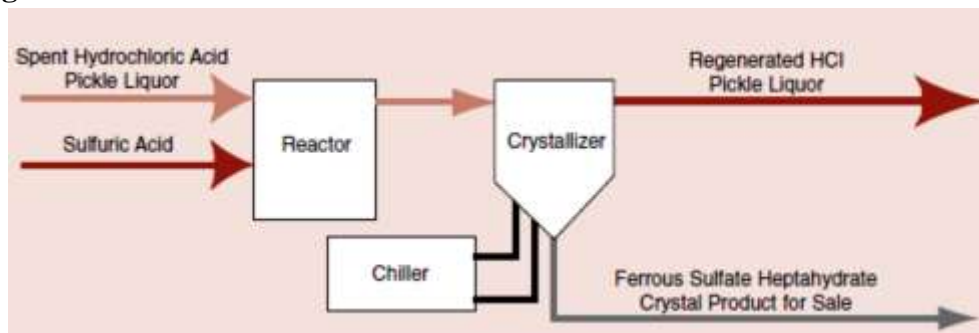


Figure 45. Hydrochloric acid regeneration system (U.S. DOE/ OIT 2000)

Commercial Status:

Pilot stage

References for further information:

Brown and Olsen (2006), U.S. DOE/ OIT (2000), Tenova Key Technologies Industriebau GmbH, (2009)

3.8.5. Recycling of Waste Oxides in Steelmaking Furnace

Description:

Major sources of waste oxides originate from BF, BOF, EAF, and mill scale from rolling in the form of waste oxide briquettes (WOBs). In most countries, BF and BOF dusts are recycled in sinter plants and used in the BF. However, in the US, most sinter plants have been closed and considerable amounts of dust are simply being land-filled (U.S. DOE 2001).

WOBs are often used in the BF. However, their use in the BF is limited because they soften at lower temperatures than sinter or pellets causing an increased pressure drop in the furnace and thus reducing productivity. They also cause excessive zinc build-up in the furnace, which can cause scaffolding. WOBs can also be used in the BOF, but they reduce scrap melting, increase the zinc content of the dust, and cause excessive slopping (U.S. DOE 2001).

Slopping is the critical issue when using WOBs. Plant trials were conducted by Carnegie Mellon University in Pittsburgh, USA, in which the ferro-oxide (FeO) and basicity of the slag were measured during the BOF process with and without WOB additions. Slopping occurs when there is an increase in gas evolution into a highly foamable slag. Excessive gas generation occurs when over-oxidized slag with high FeO contents reacts with carbon in iron drops producing carbon monoxide (CO). High foamable slags are those with high viscosity. These slags have a low basicity and temperature and are present in the first 50 percent of the blow when slopping occurs. It was found that slopping is promoted at a critical FeO content in the slag when metal drops emulsify increasing the reaction area and rate drastically. It was concluded to delay the build-up of FeO in the slag to this critical value, thus reducing slopping (U.S. DOE 2001).

Energy/Environment/Cost/Other Benefits:

Following benefits can be achieved by recycling waste oxides in steelmaking furnaces (U.S. DOE 2001, AISI 2012, U.S. DOE/OIT 2001c):

- Eliminating the need to landfill waste oxide
- Recovery of iron units from the waste oxides
- Reduction of operating costs by understanding the mechanism of slopping

Block Diagram or Photo:

Not available

Commercial Status:

Pilot stage

Reference for further information:

U.S. DOE (2001), AISI (2012), U.S. DOE/OIT (2001)

3.9. Carbon Capture and Storage Technologies for the Iron and Steel industry

In the iron and steel sector, the main sources of CO₂ emissions are power production, iron ore reduction in either a BF or a DRI plant, and coke and sinter production. Selection of carbon capture equipment will depend on factors including CO₂ capture rate, possible requirements for secondary gas treatment, energy consumption, reliability, and operational and capital costs. The BF production process can be equipped with CO₂ capture. There are also several alternatives to BF technology that have lower carbon emissions, including advanced smelting reduction technologies, e.g., Hisarna and FINEX, and DRI technology. Research is under way to identify the most energy-efficient capture technique for removing CO₂ from the BF gas recycling system. Biomass-based DRI processes are also under development and could become an important low-carbon iron production pathway (IEA/UNIDO 2011).

Unlike in the power generation sector, in the steel industry much of the generation of CO₂ is related to the reduction of the iron oxides that constitute iron ore. Oxyfuel combustion and pre- or post-combustion capture chemical looping do not mean much in a steel industry context where there is neither combustion nor oxidation except very locally inside the reactors (Birat 2010).

ULCOS is currently the largest initiative to reduce CO₂ emissions from the iron and steel industry, including through the use of carbon capture and storage. ULCOS is funded roughly equally by industry partners and the European Union. Despite the evidence of significant interest in carbon capture and storage (CCS) in the iron and steel sector, no large scale demonstration plants have yet been developed (UNIDO 2010).

The subsections below describe emerging CCS technologies for the iron and steel industry.

3.9.1. Top-Gas Recycling in Blast Furnaces, with Carbon Capture and Storage

Description:

Perhaps the most advanced potential CCS technology for the iron and steel sector is the top-gas recycling BF (TGR-BF) (UNIDO 2010). The TGR-BF relies on separation of the off gases so that the useful components can be recycled back into the furnace and used as reducing agents. This reduces the amount of coke needed in the furnace. In addition, the concept of injecting oxygen into the furnace instead of preheated air removes unwanted nitrogen from the off gas, which will be rich in CO (40 to 50 percent by volume), facilitating CCS. To experimentally test this concept, a gas separation plant was constructed next to LKAB's Experimental BF in Luleå, Sweden. At the experimental BF, facilities were installed to operate with pure oxygen and with re-injection of CO gas. The combination of the modified BF and the gas separation plant was successfully tested in 2007. Plans are currently being developed to test this principle in a commercial-scale BF (ULCOS 2012b; Kuramochi et al. 2011).

A number of approaches to carbon capture have the potential to be deployed in iron and steel making, depending on the production process being used. These include chemical adsorption technologies such as amine scrubbing, physical adsorption technologies such as pressure swing adsorption and vacuum pressure swing adsorption, and cryogenics. Detailed studies, carried out under the ULCOS project, have shown that the most effective approach in any circumstance will depend on a number of factors, including the concentration of CO₂ in the stream of gas being treated (UNIDO 2010). TGR-BF can be retrofitted to conventional BFs although major modifications to the furnace may be required (Kuramochi et al. 2011).

At the levels of concentration found in TGR-BF, physical adsorption technologies are likely to be most effective in terms of technical performance and operating and capital costs. Although pressure swing and vacuum swing adsorption have low energy requirements, they are only able to produce gases with CO₂ concentrations of approximately 80 and 88 percent respectively. Therefore, additional treatment may be required to remove impurities from the resultant gas stream, which will increase cost and energy usage (UNIDO 2010).

The relative advantages of individual technologies will vary over time. For example, the amine washing considered in the ULCOS program is based on the present state of the art of this fairly common technology, i.e., on the use of commercial MDEA amines that currently require 3.2 GJ/t CO₂ to restore the sorbent. The Japanese COURSE 50 national program aims to reduce the energy needed for carbon capture to 1.8 GJ/t CO₂, to make the process work at lower temperatures, and to use wasted heat (UNIDO 2010).

Figure 46 shows a conventional and a top-gas recycling BF process.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed for TGR-BF compared to conventional BF production (UNIDO 2010; Kuramochi et al. 2011):

- Reduction of up to 30 percent in coke consumption compared to what is needed in a conventional air-blown BF.
- Estimated emissions reduction of approximately 35 percent compared to emissions from a benchmark steel mill. With CO₂ capture from an additional stack, for example from a sinter plant, estimated emission reductions of 75 percent.
- Somewhat smaller overall CO₂ emissions reduction than what is mentioned above because reduced BF gas export needs to be compensated for, and a large amount of electricity is required to produce high-purity oxygen

Block Diagram or Photo:

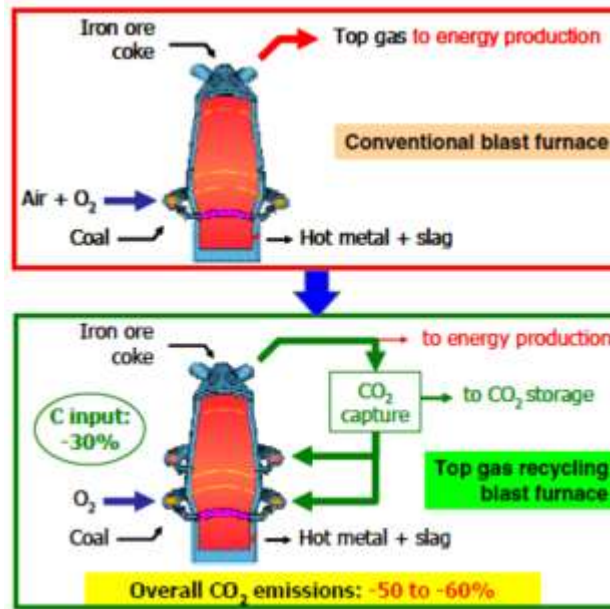


Figure 46. Schematics of conventional (top) and top-gas recycling (bottom) BF process (Borlée 2007)

Commercial Status:

Pilot stage

References for further information:

ULCOS (2012b), Kuramochi et al.(2011), UNIDO (2010)

3.9.2. Advanced Direct Reduction with Carbon Capture and Storage (ULCORED)

Description:

Production of DRI entails exposing iron ore (in the form of lumps or pellets) to a reducing gas that is produced predominantly from natural gas. The reduced iron is in a solid state, and electric energy is required to melt it in an EAF. Currently, this process is more expensive than reducing the ore in a conventional BF and it also requires better-quality iron ore than is needed for a BF. The amount of electricity required for melting DRI means this EAF process also uses more energy than a BF. However, EAFs have the advantage of eliminating the need for the coke ovens on which a BF depends. As part of the ULCOS project, a new DRI process, ULCORED, was designed by a team led by LKAB, Voestalpine, and MEFOS. This process reduces the amount of natural gas needed to produce DRI. This is partly achieved by replacing the traditional technology, reforming, by partial oxidation of the natural gas. This substitution will substantially reduce capital costs. In the new layout there will be a single source of CO₂, which will be sufficiently clean for geological storage (ULCOS 2012c).

During the past decade, a small number of DRI installations have been combined with coal gasification installations and the coal-derived syngas used as the reducing gas. This process may be particularly important for countries that have limited gas supplies but large coal reserves, such as India, China, and South Africa. CO₂ from the gasification process can be captured using pre-combustion technologies (UNIDO 2010). ULCORED could also be used with syngas from coal and biomass, and it could be used to produce CO₂-free hydrogen for use in other parts of a steel plant (Knop et al. 2008).

The main features of ULCORED are (Knop et al. 2008):

- 100-percent use of oxygen instead of air
- Use of a partial oxidation reactor instead of a reformer
- Use of shifters to transform CO in the top gas into hydrogen and CO₂
- CO₂ cleaning of the off gas stream after shifter by pressure swing adsorption / vacuum pressure swing adsorption or amine washers to produce clean CO₂ for storage and a hydrogen stream to be recycled to the reactor
- Feeding of the majority of the hydrogen, together with makeup natural gas, to the cooling zone of the DR reactor, so the latent cooling heat is used to preheat the gas to the partial oxidation reactor

When syngas from coal is used instead of natural gas, the syngas from the coal gasifier is cleaned before it is fed to the DR reactor. The gas can also be bypassed directly to the shifter to produce a CO₂- free gas for use in rolling mills, the lime plant, and even for production of electricity.

Figure 47 is a flow diagram of the ULCORED process using natural gas, and Figure 48 shows the ULCORED process using coal syngas.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed for use of ULCORED compared to conventional DRI production (Knop et al. 2008; ULCOS 2012c):

- Estimated reduction in energy use of 20 percent compared to state-of-the-art DR processes
- Only one stream of CO₂ for compression and storage
- Flexibility to make CO₂-free hydrogen for other users
- Reduced capital expenditure

3.9.3. HIsarna with Carbon Capture and Storage

Description:

HIsarna is a smelting reduction process based on bath-smelting. It combines coal preheating and partial pyrolysis in a reactor, a cyclone for ore melting, and a smelter vessel for final ore reduction and iron production. This technology requires significantly less coal than conventional production and thus reduces CO₂ emissions. The process allows partial replacement of coal with biomass, natural gas or even hydrogen. The three separate technologies associated with HIsarna have been proven independently at a small scale (ULCOS 2012d).

The HIsarna process offers a longer-term strategy for reducing CO₂ from the iron and steel industry. HIsarna uses pure oxygen and generates an off gas that is almost ready for storage. It is based on the combination of a hot cyclone developed by Corus and a bath smelter called HIsarna licensed by Rio Tinto. It incorporates some of the technology of the HIs melt process. The HIsarna process is an alternative for the BF/BOF steelmaking route. As a result, it can reduce CO₂ emissions from steel production by 20 percent. In combination with CCS, the process can reduce CO₂ emissions by 80 percent (UNIDO 2010; EPA 2010). Capture technologies for HIsarna process are pressure swing adsorption / vacuum pressure swing adsorption (IEA/UNIDO 2011).

Within the ULCOS project, a HIsarna pilot plant was commissioned in Corus's IJmuiden steelworks in the Netherlands. In this plant, the main technologies that make up the process can be tested up to a capacity of 65,000 t/year, in coupled operation. Additional work is continuing on using CCS and biomass in combination with HIsarna. If successful, the plant will be further extended to a semi-industrial scale that will have a capacity of 700,000 t/year (ULCOS 2012d).

Figure 49 shows a HIsarna reactor.

Energy/Environment/Cost/Other Benefits:

The following benefits are claimed for HIsarna compared to conventional BF production (ULCOS 2012d; UNIDO 2010):

- Lower coal consumption
- Reduction of 20 percent in CO₂ emissions, or 80 percent if combined with CCS
- Allows partial replacement of coal with biomass, natural gas, or hydrogen

Block Diagram or Photo:

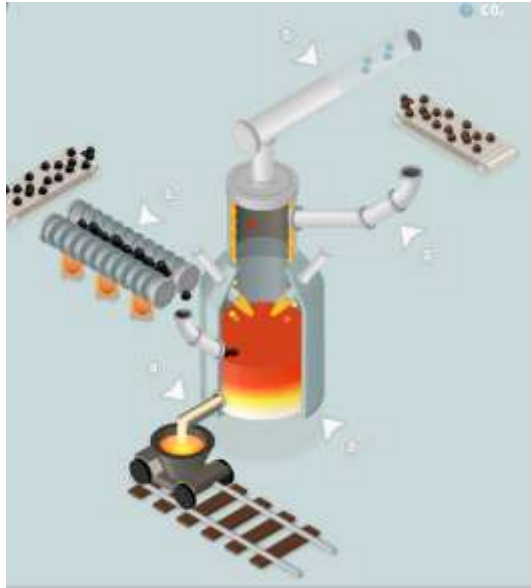


Figure 49. HIsarna reactor (ULCOS 2012d)

Commercial Status:

Pilot stage

References for further information:

ULCOS (2012d), UNIDO (2010), IEA/UNIDO (2011)

3.9.4. Post-combustion Carbon Capture Using Chemical Absorption Technologies

Description:

Chemical absorption (amine scrubbing) has been used to separate CO₂ in chemical industry exhaust streams (Bosoago et al. 2009). Post-combustion carbon capture takes advantage of this commercially mature technology and applies a common solvent, monoethanolamine, for CO₂ scrubbing. Because of the high cost of this solvent, it has to be regenerated and re-used, an energy-consuming process that results in additional CO₂ emissions. SO₂, NO₂, and oxygen play an important role in solvent-degradation mechanisms. Therefore, the SO₂, NO_x, and particulate matter concentrations in flue gases need to be reduced to a minimum before the flue gases go through the solvent scrubbing CO₂ capture system (CSI/ECRA 2009).

Chemical absorption CO₂ capture is generally considered a short-term technology. A major limitation of capturing CO₂ directly from BF gas is that less than 50 percent of the total carbon contained in the BF gas is captured because about half of the carbon is in the form of CO. In addition, the capture of CO₂ directly from BF gas is deemed more expensive compared to other options. A potentially feasible technology for BFs in the short or medium term is to capture CO₂

after CO in the BF gas is converted to CO₂ via a shift reaction, enabling a higher carbon removal rate (85 to 99.5 percent of the carbon in the BF gas). After shift reaction and CO₂ removal, the BF gas is hydrogen rich. The main advantage of the shift reaction is that higher power generation efficiency can be achieved when hydrogen-rich BF gases are used in a power plant. The major disadvantage is that the power plant using the BF gas might require important modifications in the gas turbines (Kuramochi et al. 2011).

In the shift reactor, CO reacts with steam: $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$. The pressure loss in the shift reactor amounts to 1 bar. The shift reaction is basically exothermic. The reaction enthalpy is about 0.92 GJ/t of CO₂ generated. The shift reactor needs high-temperature steam (350°C). Steam is recovered from the off-gas of the second reactor, and some of the residual heat is used to pre-heat the feedstock and steam for the first reactor. Surplus steam may be available for other uses (Gielen 2003).

Other more advanced yet longer-term CCS technologies for BF, such as top-gas recycling, ULCORED, and HISarna, are explained in previous sections. If CCS needs to be applied to the stacks of the steel mill other than BF, then an amine scrubbing unit would be the best solution (Birat 2010).

Absorption technologies are currently being used at only a pilot scale in the energy sector. Demonstration plants are in the planning phase (ECRA 2009) with the first industrial application expected in 2020. With modifications, these technologies should then be available for the steel industry. Availability of a transport (pipeline) grid and storage sites is an important factor necessary to support this CO₂-capture technology.

Figure 50 shows post-combustion CO₂ capture from a conventional BF.

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by amine scrubbing CCS compared to production without this technology (Kuramochi et al. 2011):

- CO₂ emissions reduced by less than 50 percent of the total carbon contained in the BF gas without shift reaction technology, and by 85 to 99.5 percent of the carbon in the BF gas with shift reaction

Block Diagram or Photo:

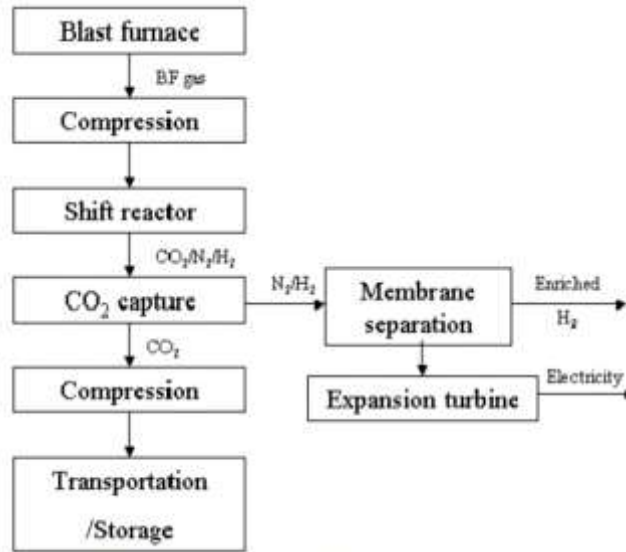


Figure 50. Post-combustion CO₂ capture from a conventional BF (Gupta et al. 2003).

Commercial Status:

Development stage

References for Further Information:

Kuramochi et al. (2011), Birat (2010), Gielen (2003), Gupta et al. (2003)

3.9.5. Geological Sequestration of CO₂ Using BOF or EAF Slag

Description:

The major mineral phases of BOF steelmaking slag are calcium silicate (Ca₂SiO₄), tricalcium silicate (Ca₃SiO₅), iron calcium (Ca₃Fe₂O₅), periclase (MgO), free calcium oxide or quicklime (CaO) and RO (R=Fe, Mn, Mg, and Ca). In addition, chemical analysis of BOF steelmaking slag shows that it contains around 40 percent CaO. Therefore, it could be used for long-term storage of CO₂. Typically, CO₂ sequestration by steelmaking slag can be divided into direct and indirect carbonation processes. The direct carbonation process can be further divided into dry and aqueous processes. The dry process uses the Ca- and Mg-containing mineral particles to react with CO₂ to form carbonated minerals, permanently fixing CO₂ gas. In the aqueous process, however, water is added to form carbonic acid, and alkaline earth metals as well as other ions are dissolved into water. This reacts with CO₂ gas to precipitate carbonated minerals. In the indirect carbonation process, solvents such as acetic acid are used to first extract alkaline earth metals and other ions from the minerals, which are then carbonated with CO₂ gas (Ma et al. 2011).

Although the direct carbonation process is simple, the carbonation reaction at room temperature is slow, and the Ca-leaching ratio from the waste slag is also lower than in the indirect process. The advantages of the indirect carbonation process include a higher Ca-extraction ratio, leaching reaction, and carbonation reaction rates; recyclability of the leaching agent, and no secondary pollution (Ma et al. 2011).

A project led by the University of Missouri and supported by U.S. DOE/AISI focused on developing a process that improves the kinetics of the hydrous carbonate formation reaction to allow steelmakers to remove CO₂ directly from their furnace exhaust gas. The proposal was to bring the CO₂-containing furnace exhaust stream in contact with reclaimed steelmaking slag in a reactor whose environment was near unit activity of water¹⁴. This reaction would produce carbonate products that are suitable for polymer fillers and agricultural and construction applications. In addition to removing CO₂, the process could recover some sensible heat for process or plant services applications, reducing the plant's overall CO₂ emissions footprint (U.S. DOE/ITP 2007b).

Ma et al. (2011) studied the leaching process, removal of impurities, and carbonation of steelmaking plant waste slag at ambient pressure. Their results showed that ionic solutions of calcium (Ca²⁺) leaching mainly occurs during the first 60 minutes of the leaching process. Moreover, adding small amounts of Sodium hydroxide (NaOH) and triethanolamine in the leaching solution allows effective removal of Mg²⁺, Al³⁺ and Fe³⁺ so that high-purity CaCO₃ products can be obtained through the carbonation process (Ma et al. 2011).

Bao et al. (2010) also investigated the extraction of calcium ions from steelmaking slag using a novel leaching medium, which involves the organic solvent tributyl phosphate, acetic acid, and ultra-pure water.

Rawlins (2008) studied the process conditions that would increase the kinetics of carbonate formation process under hydrous conditions, enabling direct removal of CO₂ from steelmaking off gas. This study showed that the carbonate formation rate is primarily governed by particle size. Slag grinding will increase the reaction surface area and is itself CO₂ sequestration net positive. The grinding cost can be recouped by recovering liberated steel particles. The critical (economic) grind size for BOF and EAF slag is 100-150 micrometers. Aqueous processing proceeds much faster than dry processing because of separate leaching and carbonation processes in the latter. The best results from this project show that 47 percent of the theoretical amount of carbonation can be achieved at 24 hours in a reactor using 100-micrometer slag particles. This amount is equal to 0.5 percent and 2.4 percent of the CO₂ emitted by integrated and EAF mills, respectively (Rawlins 2008).

¹⁴ Water activity was developed to account for the intensity with which water associates with various non-aqueous constituents and solids.

The CO₂ concentration also has an effect on the Ca use of slag. At higher temperatures, a larger Ca use appears at a lower CO₂ concentration (<10 percent) or higher CO₂ concentration (>75 percent). As the CO₂ concentration decreases, the carbonization reaction rate increases, regardless of the kind of slag used. With regard to the type of steel slag, EAF steel slag has better reactivity and Ca use than BOF steel slag (Yu and Wang 2011).

Energy/Environment/Cost/Other Benefits:

The following benefits can be achieved by using steel slag to sequester carbon (U.S. DOE/ITP 2007b; Richards 2008):

- The total sequestration potential for steelmaking slag is 6-11 percent of the CO₂ emitted from integrated mills and 35-45 percent emitted from scrap-based steelmakers.
-
- Conversion of slag and exhaust gas to potentially saleable products
- Capture and concentration of environmentally undesirable trace elements that are present in slag
- Recuperation of sensible heat for process or plant services application

Block Diagram or Photo:

N/A

Commercial Status:

Research stage

References for further information:

Ma et al. (2011), U.S. DOE/ITP (2007b), Rawlins (2008)

3.9.6. Integrating Steel Production with Mineral Sequestration

Description:

Mineral sequestration, the disposal of CO₂ in the form of benign solid carbonate, is a permanent and safe method of CO₂ disposal with virtually unlimited capacity. This method of CO₂ disposal could greatly benefit from collaboration with the steel industry as the hydrometallurgical processing of the mineral ore (peridotite rock) results in the generation of virtually pure iron oxides. This would provide new sources of iron oxide from peridotite ores and would sequester CO₂ from the BF and other combustion operations including power plants. The steel industry is accustomed to pre-processing iron ores prior to introducing them to the BF. If the gangue materials could be used to chemically bind CO₂, this would develop a niche market for the steel industry, allowing it to dispose of its own CO₂ (AISI 2006c).

U.S. DOE/AISI Technology Roadmap Program supported a project led by Columbia University to develop a combination iron reduction and carbon sequestration plant that will use serpentine ores as the source of iron and dispose of the iron-industry CO₂ (as well as additional CO₂ from other sources) in the mineral tailings that remain at the end of the iron reduction process. Using the same ore-processing steps for carbon sequestration and iron ore production increases the value of the carbon sequestration process and reduces the cost of sequestration (AISI 2006c).

A viable mineral carbon sequestration process utilizing serpentine has never been demonstrated because of slow reaction times with CO₂ in aqueous solutions. Experiments were performed exploring the catalytic effect that sodium chloride and ammonium chloride might have on serpentine dissolution, which is the rate-limiting step in the overall carbonation process. It was found that although initial dissolution rates appear to be enhanced by the presence of the salts, long-term dissolution rates remain unaffected; therefore, these salts will not help lower the costs of a mineral carbonation process. More research is needed to develop a viable carbon sequestration technology using serpentine or similar minerals (Lackner et al. 2008).

Figure 51 shows an integrated mineral CO₂ sequestration plant.

Energy/Environment/Cost/Other Benefits:

The following benefits could be achieved by integrating steel production with mineral sequestration (Lackner et al. 2008):

- Significant reduction of CO₂ emissions
- Creation of a carbon sink within the steel industry that could be sold as CO₂ credits to other industries
- Production of valuable iron oxide from peridotite ores

Block Diagram or Photo:

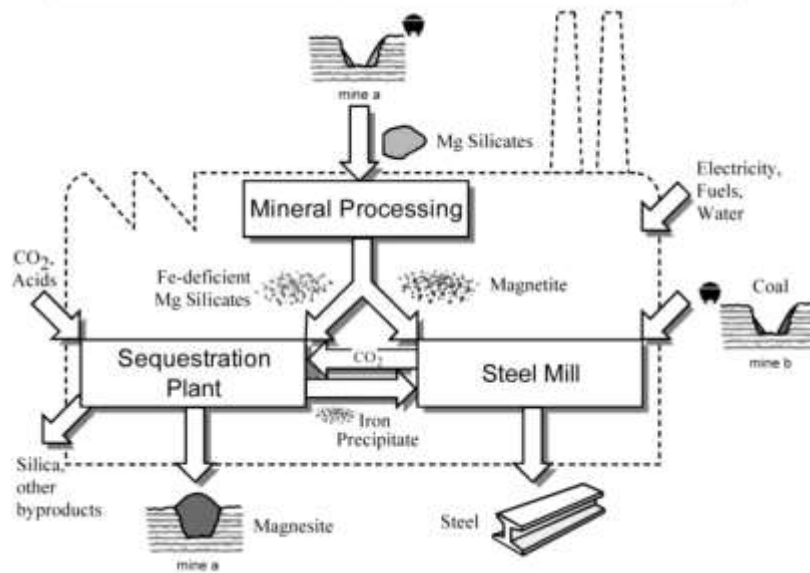


Figure 51. Integrated mineral CO₂ sequestration plant/steel mill (Lackner et al. 2008).

Commercial Status:

Research stage

References for further information:

Lackner et al. (2008), AISI (2006c)

Acknowledgments

This work was supported by the China Sustainable Energy Program of the Energy Foundation through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. The contribution of Marlene Arens to this report was funded by Fraunhofer ISI. We are thankful (in no particular order) to Debo Aichbhaumik and Keith Jamison of Energetics, Inc., Isaac Chan of U.S. DOE's Advanced Manufacturing Office, B.V. Lakshminarayana, Joe Vehec, and Peter Pagano of American Iron and Steel Institute, and Wolfgang Eichhammer of Fraunhofer Institute for Systems and Innovation Research for their valuable comments on the earlier version of the report. We also would like to thank Nan Wishner for editing the report.

References

- Agrawal, B.B. and A. S. Mathur, 2011. *New Ironmaking Processes:Relevance to India*. Available at http://www.iim-delhi.com/upload_events/01NewIronmakingProcessRelevanceIndia_RDCIS.pdf
- American Iron and Steel Institute (AISI). 2012. *Recycling of Waste Oxides in Steelmaking Furnaces*. Steel Works – The online resource for steel. Available at: <http://www.steel.org/en/Making%20Steel/Research%20and%20Development/R%20and%20D/Recycling%20of%20Waste%20Oxides%20in%20Steelmaking%20Furnaces.aspx>
- American Iron and Steel Institute (AISI). 2010. *Technology Roadmap Research Program for the Steel Industry*. Available at <http://www.steel.org/en/sitecore/content/Global/Document%20Types/News/2011/AISI%20Releases%20Final%20Report%20Of%20The%20Technology%20Roadmap%20Research%20Program%20Describing.aspx>
- American Iron and Steel Institute (AISI).2006a. *Technical Feasibility Study of Steelmaking by Molten Oxide Electrolysis*. (2006 TR program book, page 24-25) Available at <http://www.steel.org/Sustainability.aspx>
- American Iron and Steel Institute (AISI).2006b. "Suspension Hydrogen Reduction of Iron Oxide Concentrate." (2006 TR program book, page 20-21) Available at <http://www.steel.org/Sustainability.aspx>
- American Iron and Steel Institute (AISI). 2006c. "Integrating Steel Production with Mineral Sequestration." (2006 TR program book, page 26-27) Available at <http://www.steel.org/Sustainability.aspx>
- American Iron and Steel Institute (AISI).2002. "Evaluation of Sustainable Steelmaking Using Biomass and Waste Oxides." Brochure. (2002 TR program book, page 35-36) Available at <http://steeltrp.com/PDFs/9902.pdf>
- Asia Pacific Partnership on Clean Development and Climate (APP). 2010. *The State-of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook*. (2nd Edition). Available at <http://asiapacificpartnership.org/english/soact2nd.aspx>
- Asmet. 2011. "New Pig Iron Process 'Tecnored Technology' Tested by Vale." September 27. Available at <http://www.asmet.com/news/new-pig-iron-process-tecnored-technology-tested-by-vale>

- Arvedi, G., F. Mazzolari, A. Bianchi, G. Holleis, J. Siegl, and A. Angerbauer. 2008. "The Arvedi endless strip production line (ESP) from liquid steel to hot-rolled coil in seven minutes." *La Revue de Métallurgie-CIT*, July/August, pp. 398-407.
- Bao, W., H. Li, Y. Zhang. 2010. "Selective Leaching of Steelmaking Slag for Indirect CO₂ Mineral Sequestration." *Ind. Eng. Chem. Res.* 49: 2055–2063.
- Barati, M., S. Esfahani, T.A. Utigard. 2011. "Energy recovery from high temperature slags." *Energy*. Volume 36, Issue 9, September, pp, 5440–5449.
- Belleprat, E., P. Menanteau. 2008. "Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modeling." *Proceedings of the 4th Ulcoss seminar*, 1-2 October. Available at www.ulcos.org/en/docs/.../Ref01%20-%20SP9_Belleprat_Essen.pdf
- Bergman, L., M. Larsson. 2008. "HSC Simulations of coal based DR in ULCORED." *Proceedings of the 4th Ulcoss seminar*, 1-2 October.
- BFI (VDEh-Betriebsforschungsinstitut/Institute for Applied Research). 2012. *Steel temperature measurement in electric steel plants (EAF/LF)*. Available at http://www.bfi.de/en/fields_of_activity/process_analysis_techniques/steel_temperature_electric_steelmaking.htm
- BFI. 2009/2010. Tätigkeitsbericht/Activity Report 2009/2010. *Von der Idee zur betrieblichen Lösung/ From the idea to the industrial solution*. Düsseldorf, Germany. Available at <http://www.bfi.de/de/betriebsforschungsinstitut/BFI-Taetigkeitsbericht-2009-2010.pdf>
- Bisio, G. 1997. "Energy recovery from molten slag and exploitation of the recovered energy." *Energy*. Volume 22, Issue 5, May, pp. 501–509.
- BCS, Incorporated. 2005. "Advanced Melting Technologies: Energy Saving Concepts and Opportunities for the Metal Casting Industry." Available at http://www.eere.energy.gov/manufacturing/industries_technologies/metalcasting/pdfs/advancedmeltingtechnologies.pdf
- Birat, J.P., 2010. "Steel sectoral report - Contribution to the UNIDO roadmap on CCS1 - fifth draft." Available at www.unido.org/fileadmin/user.../Stee_sectoral_%20report.pdf
- Birat, J.P., J. Borlée, B. Korthis, J. van der Stel, K. Meijer, C. Günther, M. Halin, T. Bürgler, H. Lavelaine, C. Treadgold, I. Millar, D. Sert, T. Torp, F. Patisson, B. Paya, E. Burstrom. 2008. *ULCOS program: a progress report in the Spring of 2008*. 3rd International Conference on Process Development in Iron and Steelmaking. Available at www.ulcos.org/en/docs/Ref09%20-%20ULCOS_Scanmet%20III.pdf
- Birat J.P., F. Hanrot, G. Danloy. 2003. "CO₂ Mitigation Technologies in the Steel Industry: a Benchmarking Study Based on Process Calculations." *Stahl und Eisen*, 123 (9), 2003: 69-72.
- Birat, J.P., C. Grisvard, J.C. Hubert, B. Gros, J.J. Almon. 2001. "Charging tires in the EAF as a substitute to carbon." *Journées Sidérurgiques Internationales*, Paris, France, 12-13 December.
- Borlée, J. 2007. "Low CO₂ steels - ULCOS project (Ultra Low CO₂ Steelmaking)." Presented in IEA Deployment workshop, October 9.
- Bosoago, A., M. Ondrej, J.E. Oakey. 2009. "CO₂ Capture Technologies for Cement Industry". *Energy Procedia*, Vol. 1:133-140.
- Brown, C.J., D.R. Olsen. 2006. "Regeneration of Hydrochloric Acid Pickle Liquors by Crystallization." Third International Symposium in Iron Control in Hydrometallurgy, Montreal, Canada, October 1-4.

- Castrip. 2012. The Castrip® process. Available at <http://www.castrip.com/Process/process.html>
- Cement Sustainability Initiative (CSI) and European Cement Research Academy (ECRA). 2009. *Development of State-of-the-Art Techniques in Cement Manufacturing: Trying to Look Ahead* (CSI/ECRA-Technology Papers). Available at <http://www.wbcscement.org/pdf/technology/Technology%20papers.pdf>
- Chu M., X., Yang, F. Shen, J. Yagi, H. Nogami. 2006. “Numerical Simulation of Innovative Operation of Blast Furnace Based on Multi-Fluid Model.” *Journal of Iron and Steel Research, International*. 2006, 13(6): 8-15.
- Clauzade, C. 2006. End-of-life tires in electric arc furnaces: an industrial success story. Available at <http://www.coprochem.org/documents/Tyres%20in%20Electric%20Arc%20furnaces.pdf>
- Cotchen, J.K. and M. J. Stercho., 2002. “Continuous Horizontal Sidewall (CHS) scrap charging.” Available at <http://cat.inist.fr/?aModele=afficheN&cpsid=14418054>
- Cramb, A.W. 2004. “Strip Casting of Steels: Current Developments.” *Encyclopedia of Materials: Science and Technology*. New York: Elsevier Ltd, pp. 1-4. <http://www1.elsevier.com/emsat/pdf/300102.pdf>
- Danieli Corus. No date (n.d.). “The TecnoRed Process. A New Route For Producing Low Cost Liquid Iron.” Available at <ftp://ftp.cefetes.br/Cursos/EngenhariaMetalurgica/Marcelolucas/Disciplinas/Reducao/Material%20TecnoRed/Brochure.pdf>
- Danieli and Tenova. 2011. “HYL Process Description.” Available at <http://www.energiron.com/default.htm>
- Das, B., S. Prakash, P. S. R. Reddy, S. K. Biswal, B. K. Mohapatra, V. N. Misra. 2002. “Effective Utilization of Blast Furnace Flue Dust of Integrated Steel Plants.” *The European Journal of Mineral Processing and Environmental Protection*. Vol. 2, No. 2: 61-68.
- De Beer, J., K. Blok, E. Worrell. 1998a. “Future Technologies for Energy-Efficient Iron and Steelmaking.” *Annual Review of Energy and the Environment*. Vol. 23: 123-205;
- De Beer, J., K. Blok, E. Worrell. 1998b. “Long-term energy-efficiency improvements in the paper and board industry.” *Energy*. 23 (1): 21-42.
- De Saro R., A. Weisberg, J. Craparo. 2005a. “In Situ, Real Time Measurement of Aluminum, Steel, and Glass Melt Chemistries Using Laser Induced Breakdown Spectroscopy.” Energy Research Company. Conference Paper at the ACEEE Summer Study on Energy Efficiency in Industry. Available at http://www.eceee.org/conference_proceedings/ACEEE_industry/2005/Panel_1/p1_3/paper
- De Saro R., A. Weisberg, J. Craparo. 2005b. *In Situ, Real Time Measurement of Melt Constituents in the Aluminum, Glass, and Steel Industries. Final Report*. Energy Research Co. Available at <http://www.osti.gov/bridge/servlets/purl/902660-IOsPpB/902660.pdf>
- Díez, M. A., R. Alvarez, C. Barriocanal. 2002. “Coal for metallurgical coke production: predictions of coke quality and future requirements for cokemaking.” *International Journal of Coal Geology*. Volume 50, Issues 1–4, May 2002, pp. 389–412.
- Doronin, I. E., A. G. Svyazhin. 2011. “Commercial methods of recycling dust from steelmaking.” *Metallurgist*, Volume 54, Numbers 9-10 (2011), 673-681, DOI: 10.1007/s11015-011-9356-z

- European Integrated Pollution Prevention and Control Bureau (EIPPCB). 2010. *Best Available Techniques (BAT) Reference Document for Iron and Steel Production Industrial Emissions Directive 2010/75/EU*. Available at http://eippcb.jrc.es/reference/BREF/IS_Adopted_03_2012.pdf
- European Cement Research Academy GmbH (ECRA). 2009. *ECRA CCS Project - Report about Phase II*. Available at <http://www.cement.org/bookstore/profile.asp?id=16950>
- EIPPCB. 2008. *Best Available Techniques- Reference Document on the Production of Iron and Steel*, (draft version February 2008), European Commission, Directorate-General JRC, Institute for Prospective Technology Studies, Seville, Spain.
- EIPPCB. 2001. *Reference Document on Best Available Techniques for the Production of Iron and Steel*. European Commission.
- Energetics, Inc. 2004. *Steel Industry- Energy Bandwidth Study*. Available at www1.eere.energy.gov/industry/steel/pdfs/steelbandwidthstudy.pdf
- Farla, J.C.M., E. Worrell, L. Hein, and K. Blok. 1998. *Actual Implementation of Energy Conservation Measures in the Manufacturing Industry 1980-1994*. The Netherlands: Utrecht University Dept. of Science, Technology & Society.
- Fruehan, R. J. 2004a. *Future Steelmaking Processes: Final Report*. United States Department of Energy (U.S. DOE). Available at www.osti.gov/bridge/servlets/purl/840930
- Fruehan, R. J. 2004b. *Sustainable Steelmaking Using Biomass and Waste Oxides: Final Technical Report*. U.S. DOE, Office of Industrial Technologies (OIT). Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/steel/pdfs/report_trp_9902.pdf
- Fruehan R.J. and R.J. Matway. 2004. "Optimization of Post Combustion In Steelmaking." Available at www1.eere.energy.gov/manufacturing/.../post_combustion.pdf
- Gielen, D. 2003. "CO₂ removal in the iron and steel industry." *Energy Conversion and Management* 44: 1027–1037.
- Grandmaison, E.W., D Poirier.J., E. Boyd. 2003. "Development Of An Oxygen-enriched Furnace System For Reduced CO₂ and NO_x Emissions For The Steel Industry." Prepared for U.S. Department of Energy. Available at: <http://steeltrp.com/finalreports/finalreports/9806NonPropFinalReport.pdf>
- Grill, W. 2009. "The SIMETALCIS Corex / Finex Process." Convention on clean, green and sustainable technologies in iron and steel making. 15 – 17 July. Bhubaneswar, India.
- Gupta, M., I. Coyle, K. Thambimuthu. 2003. "CO₂ Capture Technologies and Opportunities in Canada - Strawman Document for CO₂ capture and Storage (CC&S) Technology Roadmap." 1st Canadian CC&S Technology Roadmap Workshop, 18-19 September, Calgary, Alberta, Canada.
- Hacala, A., U. Michon. 2009. "Innovative industrial plasma torch for converting biomass into high purity syngas." ISPC19 - 2009, Bochum, Germany. Available at www.ispc-conference.org/ispcproc/papers/39.pdf
- Halder, S. 2011. "An Experimental Perspective on Praxair's Hot Oxygen Technology to Enhance Pulverized Solid Fuel Combustion for Ironmaking Blast Furnaces." Praxair Inc. Technical Paper. Available at <http://www.praxair.com/praxair.nsf/AllContent/31B770CF22B3FBBF8525799F0075226F?OpenDocument>

- Hasanbeigi, A., W. Morrow, J. Sathaye, E. Masanet, T. Xu. 2012. *Assessment of Energy Efficiency Improvement and CO₂ Emission Reduction Potentials in the Iron and steel Industry in China. Report*. Berkeley, CA: Lawrence Berkeley National Laboratory Report LBNL- LBNL-5535E.
- Indian Centre for Plastic in the Environment (ICPE). 2006. Management of plastics, polymer wastes and Bio-polymers and impact of plastic on the eco-system.
- Institute of Materials Processing (IMP)/Michigan Technological University (MTU). 2006. *Verification Of Steelmaking Slag Iron Content. Final technical progress report*. Available at www1.eere.energy.gov/industry/steel/pdfs/report_trp_slag.pdf
- INTEG process group, Inc. 2004. "Hot Strip Mill Model." Available at www.integpg.com/hsmm/files/HSMM_Overview_Rel_2_0.pdf
- International Energy Agency (IEA). 2010. "The Energy Technology Systems Analysis Program (ETSAP)-Technology Brief: Iron and Steel." Available at <http://www.iea-etsap.org/web/E-TechDS/Technology.asp>
- IEA. 2007. *Tracking Industrial Energy Efficiency and CO₂ Emissions*. Available at: <http://www.iea.org/w/bookshop/add.aspx?id=298>
- IEA/ United Nations Industrial Development Organization (UNIDO). 2011. "Technology Roadmaps: Carbon Capture and Storage in Industrial Applications." Available at www.iea.org/papers/roadmaps/ccs_industry.pdf
- Japan Iron and Steel Federation (JISF). 2012a. Technologies to support COURSE 50. Available at http://www.jisf.or.jp/course50/tecnology03/index_en.html
- JISF. 2012b. COURSE 50 - Technologies to reduce CO₂ emissions. Available at http://www.jisf.or.jp/course50/tecnology01/index_en.html
- JFE Engineering. 2004. "Ecologically-Friendly and Economical Arc Furnace 'ECOARC.'" JFE Technical report. No. 3, July. Available at www.jfe-steel.co.jp/en/research/report/003/pdf/003-16.pdf
- Joulazadeh, M. H. 2008. "Using Scrap Tires in EAFs as a Substitute for Carbon." *International Journal of ISSI*, Vol.5, No. 1, pp. 36-40.
- JP Steel Plantech Co. 2012. "ECOARC." Available at <http://www.steelplantech.co.jp/english/products/steelmaking/eaf/ecoarc/>
- JP Steel Plantech Co. 2005. "Waste Plastics Injection System for BF." Available at http://www.jase-w.eccj.or.jp/technologies/pdf/iron_steel/S-02.pdf Júniora, J.H.N., M.A. Contruccib, J.C D'Abreuc. 2005. "Tecnoed Process - High Potential in Using Different Kinds of Solid Fuels." *Materials Research*, Vol. 8, No. 4, pp. 447-451. Available at http://www.scielo.br/scielo.php?pid=S1516-14392005000400016&script=sci_arttext
- Kazuya, Y., T. Hirokazu, T. Tatsuhito. 2006. "New Applications of Iron and Steelmaking Slag Contributing to a Recycling-oriented Society." JFE Technical report. No. 8. October..
- Kempgen, J., J. Schlüter, U. Falkenreck, W. Weisedel. 2008. "New scrap-based steelmaking process predominantly using primary energy." *Millenium Steel* 2008. Available at www.millennium-steel.com/articles/pdf/2008/pp96-98%20MS08.pdf
- Knop, K., M. Hallin, E. Burström. 2008. "ULCORED SP 12- Concept for minimized CO₂ emission." *Proceedings of the 4th Ulcoss seminar*, 1-2 October.
- König, U., J. Hållstedt, J. Noreland, K. Vallo, L. Gobbo, T. Füllmann, K. Macchiarola, J. Nieminen. 2010. "Using X-ray diffraction." *Nordic Steel and Mining Review*.

- Kono, Y., Y. Iguchi, M. Shimizu. 2000. "The Basis and Application for Carbon Reduction of Iron Oxide", ISIJ, Tokyo, Japan, 31-36.
- Kuramochi, T., A. Ramírez, W. Turkenburg, A. Faaij. 2011. "Techno-economic assessment and comparison of CO₂ capture technologies for industrial processes: preliminary results for the iron and steel sector." *Energy Procedia* 4: 1981–1988.
- Lackner, K.S., P. F. Duby, T. Yegulalp, S. Krevor, C. Graves. 2008. *Integrating Steel Production with Mineral Carbon Sequestration*. Available at steeltrp.com/finalreports/finalreports/9957NonPropFinal.pdf
- Leimalm, U., M. Lundgren, L. Sundqvist Ökvist, B. Bjorkman. 2010. "Off-gas Dust in an Experimental Blast Furnace Part 1: Characterization of Flue Dust, Sludge and Shaft Fines." *ISIJ International*, Vol. 50, No. 11, pp. 1560–1569.
- Lockwood G2000. *Ironmaking Process Alternatives Screening Study - Volume I: Summary Report*. Available at www1.eere.energy.gov/manufacturing/.../ironmaking_process.pdf
- Lu, W.K., 2008. "The Search for a New Ironmaking Process Towards Sustainable Development." GCEP "Industry" Workshop, Stanford University, April 15-16. Available at gcep.stanford.edu/pdfs/.../Lu_New_Sustainable_Ironmaking.pdf
- Luiten, E. and K. Blok. 2003. "Stimulating R&D of Industrial Energy-Efficient Technology; the Effect of Government Intervention on the Development of Strip Casting Technology." *Energy Policy* 31, pp. 1339-1356.
- Ma, G.J, H. Tangb, Y. Jin. 2011. "Mineral Sequestration of CO₂ Using Basic Oxygen Furnace (BOF) Steelmaking Slag." *Advanced Materials Research*, Vols. 194-196, pp 2140-2144.
- Maiolo, J., M. Boutazakhti, C.W. Li, C. Williams. 2007. "Developments towards an Intelligent Electric Arc Furnace at CMC Texas using Goodfellow EFSOP® Technology." AISTech, Indianapolis,IN, May 7-10.
- Matsumura, T., Y. Takenaka, M. Shimizu. 1999. "Effect of the carbon content on the reduction and melting behavior of carbon composite iron ore pellet." *Tetsu-to-Hagane* 85: 652-657.
- Meng, F., Y. Iguchi, I. Kojima. 2001. "Reduction, carburization and melting behavior of iron ore pellets containing coal char or graphite on heating." *Tetsu-to-Hagane* 87: 585-592.
- Mesabi Nugget Delaware, LLC and Mining Resources, LLC. 2011. "The Mesabi Nugget Story." Available at <http://www.mesabinuggetmn.com/>
- MIDREX Technologies, Inc. 2012. "Direct Reduction- Shaft Furnace and Rotary Hearth Furnace (RHF)." Available at http://www.midrex.com/handler.cfm/cat_id/17/section/technology
- MIDREX Technologies, Inc. 2011. "MXCOL®: A breakthrough in coal-based direct reduction." Available at <http://www.midrex.com/uploads/documents/MXCOL-English%20article%20US.pdf>
- Nashan, G. 2007. "Strategies to increase the technical and economic efficiency of the blast furnace ironmaking process by using new advanced cokemaking technologies." Available at www.coke-oven-managers.org/PDFs/2007/2007%20-%20Nashan.pdf
- Nippon Steel Corp. No date (n.d.). *Dust and Sludge Recycling with the Rotary Hearth Furnace*. Available at www.nsc.co.jp/en/tech/report/pdf/n9215.pdf
- Oda, H., T. Ibarikai, Y. Abe. 2006. *Dust Recycling System by the Rotary Hearth Furnace*. Nippon Steel Technical Report No. 94 July 2006. Available at www.nsc.co.jp/en/tech/report/pdf/n9424.pdf

- Ooi, T.C., D. Thompson, D. R. Anderson, R. Fisher, T. Fray, M. Zandi. 2011. "The effect of charcoal combustion on iron-ore sintering performance and emission of persistent organic pollutants." *Combustion and Flame* 158: 979–987.
- Outotec, Inc. 2012. "Circored® and Circofer®: Fine Ore Reduction in the Circulating Fluidized Bed." Available at <http://www.outotec.com/pages/Page.aspx?id=7250&epslanguage=EN>
- Outotec, Inc. 2007. "Fluidization technology." Available at www.outotec.com/36280.epibrw
- Peaslee K.D., V.L. Richards, D. G.C. Robertson, J. D. Smith. 2006. *Development of a Process to Continuously Melt, Refine and Cast High Quality Steel. Final Technical Report*. Project funded by the U. S. Department of Energy under Award No. DE-FC36-03ID14279. Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/steel/pdfs/finaltechreport.pdf
- Poirier D., E.W. Grandmaison, A.D. Lawrence, M.D. Matovic, E. Boyd. 2003. "Oxygen-enriched Combustion Studies with the Low NO_x CGRI Burner." Combustion Canada 2003 Conference – Vancouver, BC Sept. 22-24, 2003. Available at: <http://chemeng.queensu.ca/people/faculty/grandmaison/publications/Poirier%20et%20al%20-%20Combustion%20Canada%202003.pdf>
- Rawlins, C.H. 2008. *Geological Sequestration of Carbon Dioxide by Hydrous Carbonate Formation in Steelmaking Slag*. PhD dissertation. Missouri University of Science and Technology. Available at scholarsmine.mst.edu/thesis/pdf/Rawlins_09007dcc804d4f95.pdf
- Rebello, W.J., K. H. Kohnken, H. R. Phipps Jr. 1980. "Estimation of Fuel Savings by Recuperation of Furnace Exhausts to Preheat Combustion Air." *Proceedings from the Second Industrial Energy Technology Conference*, Houston TX, April 13-16,.
- Richards, V.L. 2008. *Geological Sequestration of CO₂ by Hydrous Carbonate Formation With Reclaimed Slag*. AISI/DOE Technology Roadmap Program for the Steel Industry. Available at <http://steeltrp.com/finalreports/finalreports/9955NonPropFinalReport.pdf>
- Riley, M.F. 2002. *Hot Oxygen Injection Into The Blast Furnace. Final Report*. AISI/DOE Technology Roadmap Program. Available at steeltrp.com/finalreports/finalreports/9718NonPropFinalReport.pdf
- Rohde W., J. Strunk. 1998. "Comparison of coking behavior of coal blends in the single chamber system and in conventional high capacity coke ovens." *Fuel and Energy Abstracts*, Volume 39, Number 1, January, pp. 10-10(1)
- Shimizu, T., D. Haga, G. Mikami, T. Takahashi, K. Horinouchi. 2010. "Heat recovery from melted blast furnace slag using fluidized bed." 61st IEA-FBC Meeting. October 28-29, Salerno, Italy. Available at <http://www.processeng.biz/iea-fbc.org/index.php?site=event/61th+IEA-FBC+MeetingOctober+28-29%2C+2010&u=p>
- Siemens VAI. 2007. "Competence in Ironmaking." Available at www.industry.siemens.com/.../Competence-in-Ironmaking-en.pdf
- Sahajwalla, V., M. Zaharia, M. Rahman, R. Khanna, N. Saha-Chaudhury, P. O'Kane, J. Dicker, C. Skidmore, D. Knights. 2011. "Recycling Rubber Tyres and Waste Plastics in EAF Steelmaking." *steel research international*, Volume 82, Issue 5, pp. 566–572, May,
- Sahajwalla, V., M. Zaharia, S. Kongkarat, R. Khanna, N. Saha-Chaudhury, P. O'Kane. 2010. "Recycling Plastics as a Resource for Electric Arc Furnace (EAF) Steelmaking: Combustion and Structural Transformations of Metallurgical Coke and Plastic Blends." *Energy Fuels*, 2010, 24 (1): 379–391.
- SAIL, 2012. Press Release: SAIL, Kobe Steel seal pact to bring environment-friendly steel making to India. Available at <http://www.sail.co.in/showpressrelease.php?id=305>

- Schliephake, H., C. Born, R. Granderath, F. Memoli, J. Simmons. 2011. Heat Recovery for the EAF of Georgsmarienhütte, Germany. Tenova technical article, Iron & Steel Technology 02/05/2011. Available at http://www.tenovagroup.com/technical_articles.php?page=1&id_product_line=1&data=
- Shulkosky, R.A., D. L. Rosburg, J. D. Chapman. 2005. "Validation of the Hot Strip Mill Model." Available at steeltrp.com/PDFs/0040.pdf
- Siemens, 2011. *Press release: Siemens receives third FINEX order from POSCO*. Available at http://www.siemens.com/press/en/pressrelease/?press=/en/pressrelease/2011/industry_solutions/iis201109998.htm
- Solena Group. No date (n.d.). "The Commercial Viability of Plasma Technology- A White Paper." Available at sgibiopower.com/files/plasma.pdf
- Sosinsky, D., P. Campbell., R. Mahapatra, W. Blejde, and F. Fischer. 2008. "The CASTRIP® process – recent developments at Nucor Steel’s commercial strip casting plant." *Metallurgist* 52, pp. 691 - 699.
- Stebbing, L. 2005. "Using Scrap Tires as an Alternative Fuel Source." Available at: http://www.acceleratedtech.com/tire_info.htm
- Stelco. 1993. "Present and Future Use of Energy in the Canadian Steel Industry." Ottawa, Canada: CANMET.
- Tenova Key Technologies Industriebau GmbH. 2009. "Recovery of acid and oxide by-products from spent pickling liquor." *Metallurgical Plant and Technology* 1: 52–53.
- Tenova HYL. 2011. "Press Release May 2011: JSPL Selects Energiron for Four New DR Plants". Available at <http://www.tenovagroup.com/pdf/press/60-Jindal%20press%20release.pdf>
- Tenova HYL. 2008. "Improved Technologies for Cost Effective Steelmaking." Metal Bulletin/MJunction. Indian Steel 2008 Conference. Mumbai, India. Feb.
- Thekdi, A. 2010. *Development of Next Generation Heating System For Scale Free Steel Reheating-Final Technical report*. Available at www1.eere.energy.gov/industry/steel/pdfs/scale_free_reheat.pdf
- Travernier, H., C. Grisvard , H.P. Jung, P. Drissen. 2004. Foaming of the slag and recycling of stainless steel dusts by injection into the electric arc furnace for stainless steels. Final Report. European Commission. Research Directorate-General, European Commission. Directorate-General Science, Research and Development. Abstract available at <http://cat.inist.fr/?aModele=afficheN&cpsidt=15438513>
- Ueki, Y., H. Maeda, H. Nakagawa, M. Shimizu. 2001. "Effect of atmospheric gas composition on reduction of high density carbon composite pellet." *CAMP-ISIJ*, 14, 82Ultra - low CO₂ Steelmaking (ULCOS), 2012a. "ULCOWIN: Alkaline Electrolysis." Available at <http://www.ulcos.org/en/research/electrolysis.php>
- ULCOS. 2012a. "Alkaline Electrolysis." Available at <http://www.ulcos.org/en/research/electrolysis.php>
- ULCOS. 2012b. "Top Gas Recycling." Available at http://www.ulcos.org/en/research/blast_furnace.php
- ULCOS. 2012c. "ULCORED." Available at http://www.ulcos.org/en/research/advanced_direct_reduction.php
- ULCOS. 2012d. "Hisarna smelter technology." Available at <http://www.ulcos.org/en/research/isarna.php#>
- United Nations Industrial Development Organization (UNIDO). 2010. *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report*. Available at www.unido.org/.../CCS_%20industry_%20synthesis_final.pdf

- University of New South Wales (UNSW). 2012. Solid State & Elemental Analysis Unit. Available at <http://www.sseau.unsw.edu.au/xrd/xrdlab.htm>
- U.S. Department of Energy (DOE). 2001. *Recycling of Waste Oxides in Steelmaking*. Notice of Energy RD&D Project. Available at: <http://steeltrp.com/finalreports/finalreports/9760NonPropFinalReport.pdf>
- U.S. Department of Energy (U.S. DOE), Advanced Manufacturing Office (AMO). 2012. “Industries and Technologies.” Available at http://www1.eere.energy.gov/industry/industries_technologies/index.html
- U.S. DOE/ Industrial Technologies Program (ITP). 2011a. *Paired Straight Hearth Furnace*. Available at www1.eere.energy.gov/.../steel/.../paired_straight_hearth_furnace.pdf
- U.S. DOE/ ITP. 2011b. *Thermochemical Recuperation for High Temperature Furnaces*. Available at www1.eere.energy.gov/.../steel/.../thermochemical_recuperation.pdf
- U.S. DOE/ Industrial Technologies Program (ITP). 2010a. *IMPACTS: Industrial Technologies Program: Summary of Program Results for CY 2009*. Available at <https://www1.eere.energy.gov/manufacturing/>
- U.S. DOE/ ITP. 2010b. *Energy Technology Solutions: Public-Private Partnerships Transforming Industry*. Available at www1.eere.energy.gov/industry/pdfs/itp_successes.pdf
- U.S. DOE/ ITP. 2007a. *Next Generation Heating System for Scale-Free Steel Reheating*. Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/steel.html
- U.S. DOE/ ITP. 2007b. *Geological Sequestration of CO₂ by Hydrogen. Carbonate Formation with Reclaimed Slag*. Available at http://www1.eere.energy.gov/manufacturing/resources/steel/pdfs/geo_co2seq.pdf
- U.S. DOE/ ITP. 2005. *Process to Continuously Melt, Refine, and Cast High Quality Steel. Continuous transfer process could replace current ladle operations*. Energy Efficiency and Renewable Energy Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/steel/pdfs/dev_of_process.pdf
- U.S. DOE/ITP. 2005b. *NO_x Emission Reduction by Oscillating Combustion*. Available at: http://www1.eere.energy.gov/manufacturing/industries_technologies/steel/pdfs/nox_reduction2.pdf
- U.S. DOE/ ITP. 2004. *In-Situ, Real-Time Measurement of Melt Constituents. Laser-Induced Breakdown Spectroscopy (LIBS) Provides Real-Time Analysis of Elemental Constituents to Improve Product Quality*. Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/aluminum/pdfs/real_time_measurement.pdf
- U.S. DOE/Office of Industrial Technologies (OIT). 2002. *Recycling and Reuse of Basic Oxygen Furnace (BOF)/ Basic Oxygen Process (BOP) Steelmaking Slag*. Available at www1.eere.energy.gov/manufacturing/industries.../recycling_bof.pdf
- U.S. DOE/ OIT. 2001a. *In-Situ, Real-Time Measurement of Melt Constituents. Steel Project Fact Sheet*. Available at http://www1.eere.energy.gov/manufacturing/industries_technologies/aluminum/pdfs/real_time_measurement.pdf
- U.S. DOE/OIT. 2001b. *NO_x Emission Reduction By Oscillating Combustion*. Available at: [http://eelndom1.ee.doe.gov/OIT/oitpdf.nsf/Files/oscillsteel.pdf/\\$file/oscillsteel.pdf](http://eelndom1.ee.doe.gov/OIT/oitpdf.nsf/Files/oscillsteel.pdf/$file/oscillsteel.pdf)

- U.S. DOE/OIT. 2001c. *Recycling of Waste Oxides in Steelmaking Furnaces*. Available at: http://www1.eere.energy.gov/manufacturing/industries_technologies/mining/pdfs/waste_oxides.pdf
- U.S. DOE/ OIT. 2000. *Energy Saving Regeneration of Hydrochloric Acid Pickling Liquor*. Available at www.nrel.gov/docs/fy00osti/28232.pdf
- U.S. DOE/OIT. 1999. *Development of an O₂-Enriched Furnace System For Reduced CO₂ and NO₂ Emissions*. Washington, D.C. 20585. Available at: http://www1.eere.energy.gov/manufacturing/industries_technologies/steel/pdfs/o2_furnace.pdf
- U.S. Environmental Protection Agency (U.S. EPA). 2010. *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry*. Available at www.epa.gov/nsr/ghgdocs/ironsteel.pdf
- U.S. Geological Survey (USGS). 2012. *Mineral Commodity Summaries- Iron and Steel*. Available at http://minerals.usgs.gov/minerals/pubs/commodity/iron_&_steel/mcs-2012-feste.pdf
- van Boggelen, J. 2012. "Hisarna, a Low CO₂ Ironmaking Process." Presentation at Cleveland Institution of Engineers, Middlesbrough, UK. Available at <http://www.cieng.org/events/lectures%202011%20-%202012%20session/2012-01-10%20hisarna/2012%2001%2010%20for%20publication%20v3.pdf>
- Wagner, J.C. 2004. *NO_x Emission Reduction By Oscillating Combustion. Final Report*. U.S. Department of Energy Contract No. DE-FC36-96EE41260. Available at: <http://www.osti.gov/bridge/servlets/purl/828180-IWZ8O8/native/828180.pdf>
- World Steel Association (worldsteel). 2011. *Steel Statistical Yearbook 2011*. <http://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html>
- worldsteel. No date (n.d.). *CO₂ Emissions Data Collection – User Guide, Version 6*. <http://www.worldsteel.org/climatechange/files/2/2/Data%20collection%20user%20guide.pdf>
- Worrell, E., P. Blinde, M. Neelis, E. Blomen, E. Masanet. 2010. *Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry: An ENERGY STAR Guide for Energy and Plant Managers*. Available at www.energystar.gov/ia/business/industry/Iron_Steel_Guide.pdf
- Worrell, E., J.A. Laitner, M. Ruth, M., and H. Finman. 2003, "Productivity Benefits of Industrial Energy Efficiency Measures." *Energy* 11, 28:1081-1098.
- Yagi, J.I., H. Nogami, M. Chu. 2003. "Numerical analysis on blast furnace performance by multi-dimensional transient simulator based on multi-fluid theory." Third International Conference on CFD in the Minerals and Process Industries, CSIRO, Melbourne, Australia, 10-12 December. Available at www.cfd.com.au/cfd_conf03/papers/037Yag.pdf
- Yu, J., K. Wang. 2011. "Study on Characteristics of Steel Slag for CO₂ Capture." *Energy Fuels* 2011, 25: 5483–5492.
- Zaharia, M., V. Sahajwalla, B. ChulKim, R. Khanna, N. Saha-Chaudhury, P. O’Kane, J. Dicker, C. Skidmore, D. Knights. 2009. "Recycling of Rubber Tires in Electric Arc Furnace Steelmaking: Simultaneous Combustion of Metallurgical Coke and Rubber Tires Blends." *Energy & Fuels* 2009, 23, :2467–2474.
- Zandi, M., M. Martinez-Pacheco, T. A.T. Fray. 2010. Biomass for iron ore sintering. *Minerals Engineering*. Volume 23, Issue 14, November 2010, Pages 1139–1145
- Zhang, X., R. Takahashi, J. Yagi., 1995. "Reaction rates of oxidized iron-scrap briquette with pulverized coke in nitrogen atmosphere." *Tetsu-to-Hagane* 81: 1043-1048.

Zuliani, D.J., V. Scipolo, C. Born. 2010. "Opportunities for increasing productivity, lowering operating costs and reducing greenhouse gas emissions in EAF and BOF steelmaking." Millennium Steel India 2010. Available at www.millennium-steel.com/articles/pdf/.../pp35-42%20MSI10.pdf