U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing

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The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office works with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

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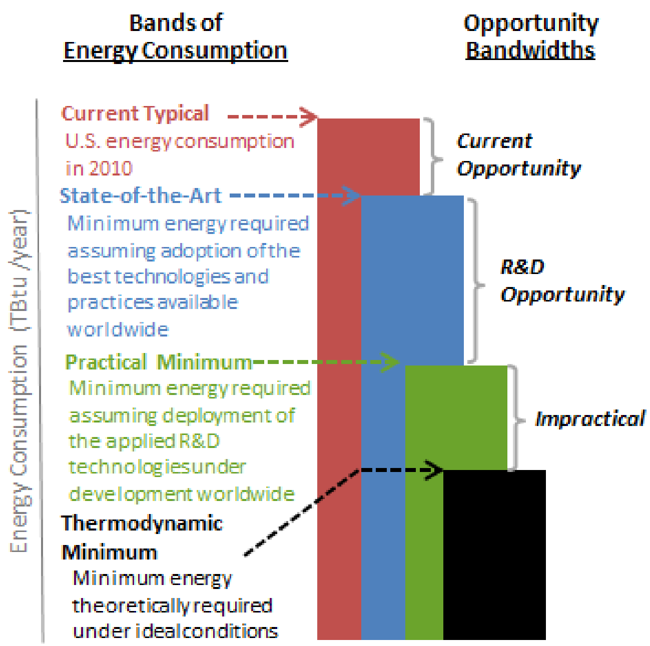
Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities. The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the processes and products that consume the most energy, and provide hypothetical, technology-based estimates of potential energy savings opportunities. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale. Bandwidth studies using the terminology and methodology outlined below were prepared for the Chemicals, Petroleum Refining, Iron and Steel, and Pulp and Paper industry sectors in 2014.[1]

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure). **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or



Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the Office of Industrial Technologies). The first two sector studies—Iron and Steel, and Metal Castings—were completed in 2004. That work was followed by Chemicals and Petroleum Refining studies in 2006, and Aluminum, Glass, and Mining in 2007. A Cement Industry analysis was conducted in 2010 and a Pulp and Paper analysis was conducted in 2011.

theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included in the energy consumption estimates.

Two onsite energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. These bandwidths are estimated for processes and products studied and for all manufacturing within a sector based on extrapolated data. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future R&D technologies was not in the scope of this study.

In each sector studied in the series, the four energy bands are estimated for select individual products or processes, subsectors, and sector-wide. The estimation method compares diverse industry, governmental, and academic data to analyses of reported plant energy consumption data from the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA). MECS is a national sample survey of U.S. manufacturing establishments conducted every four years; information is collected and reported on U.S. manufacturing energy consumption and expenditures.

Acknowledgements

AMO wishes to acknowledge the contributions made by Arvind Thekdi of E3M and David Forrest of AMO for their work reviewing this study. Appreciation is also extended to the American Iron and Steel Institute for its valuable contributions to this report.

In addition, AMO recognizes Joseph Cresko of DOE/AMO who lead the conceptual development and publication of the bandwidth study series with the support of Dr. Alberta Carpenter at the National Renewable Energy Laboratory, as well as the important contributions made by Keith Jamison, Sabine Brueske, and Caroline Kramer of Energetics Incorporated for conducting the majority of the research and analysis and drafting this study.

Executive Summary

The United States is a significant producer of iron and steel products. This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. iron and steel manufacturing. Industrial, government, and academic data are used to estimate the energy consumed in six of the most energy intensive iron and steel manufacturing processes. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing processes based on referenced energy intensities of current, state of the art, and R&D technologies. A fourth theoretical minimum energy consumption *band* is also estimated. The data from the select processes studied is also extrapolated to determine energy consumption for the entire iron and steel sector. The *bandwidth*—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The costs associated with realizing these energy savings was not in the scope of this study.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for iron and steel manufacturing processes and sector-wide. This is a step toward understanding the processes that could most benefit from technology and efficiency improvements to realize energy savings.

Study Organization and Approach: After providing an overview of the methodology (Chapter 1) and energy consumption in iron and steel manufacturing (Chapter 2), the 2010 production volumes (Chapter 3) and current energy consumption (current typical [CT], Chapter 4) were estimated for six select processes. In addition, the minimum energy consumption for these processes was estimated assuming the adoption of best technologies and practices available worldwide (state of the art [SOA], Chapter 5) and assuming the deployment of the applied research and development (R&D) technologies available worldwide (practical minimum [PM], Chapter 6). The minimum amount of energy theoretically required for these processes assuming ideal conditions was also estimated (thermodynamic minimum [TM)], Chapter 7); in some cases, this is less than zero. The difference between the energy consumption *bands* (CT, SOA, PM, TM) are the estimated energy savings opportunity *bandwidths* (Chapter 8).

The U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) provides a sector-wide estimate of energy consumption for U.S. iron and steel manufacturing; this data is referenced as sector-wide CT energy consumption. In this study, CT, SOA, PM, and TM energy consumption for six *individual* processes is estimated from multiple referenced sources. To estimate SOA, PM, and TM energy consumption for the entire sector, the CT, SOA, PM, and TM energy consumption data of the six processes studies is extrapolated estimate total sector-wide SOA, PM, and TM energy consumption. In 2010, these six processes corresponded to 82% of the industry's energy consumption.

Study Results: Two energy savings opportunity *bandwidths* – current opportunity and R&D opportunity – are presented in Table ES-1 and Figure ES-1.[1] The current opportunity is the difference between the 2010 CT energy consumption and SOA energy consumption; the R&D opportunity is the difference between SOA energy consumption and PM energy consumption. Potential energy savings opportunities are presented for the six processes studied and for all of U.S. iron and steel manufacturing based on extrapolated data. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual processes based on the sector-wide extrapolated data.

The U.S. iron and steel industry operated at relatively low capacity utilization and lower-than-typical efficiencies in 2010, due in large part to the economic downturn. While the specific impacts of the economic factors in 2010 are not directly identified in this report, it is reasonable to assume that the current opportunity is likely somewhat exaggerated, as a portion of the current savings could be achieved by simply optimizing production rates. For this reason the border between current opportunity and R&D opportunity is not explicitly defined, and a dashed line and color fading is used in Figure ES-1.

Table ES-1. Potential Energy Savings Opportunities in the U.S. Iron and Steel Manufacturing Sector[1]

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Six Select Iron and Steel Manufacturing Processes (per year)	Estimated Energy Savings Opportunity for All of the U.S. Iron and Steel Sector Based on Extrapolated Data (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	197 TBtu[2] (39% energy savings, where TM is the baseline)	240 TBtu[3] (39% energy savings, where TM is the baseline)
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	124 TBtu[4] (24% energy savings, where TM is the baseline)	150 TBtu[5] (24% energy savings, where TM is the baseline)

[1] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for onsite energy use (i.e., energy consumed within the refinery boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.
[2] 197 TBtu = 822 – 625
[3] 240 TBtu = 999 – 759
[4] 124 TBtu = 625 – 501
[5] 150 TBtu = 759 – 609

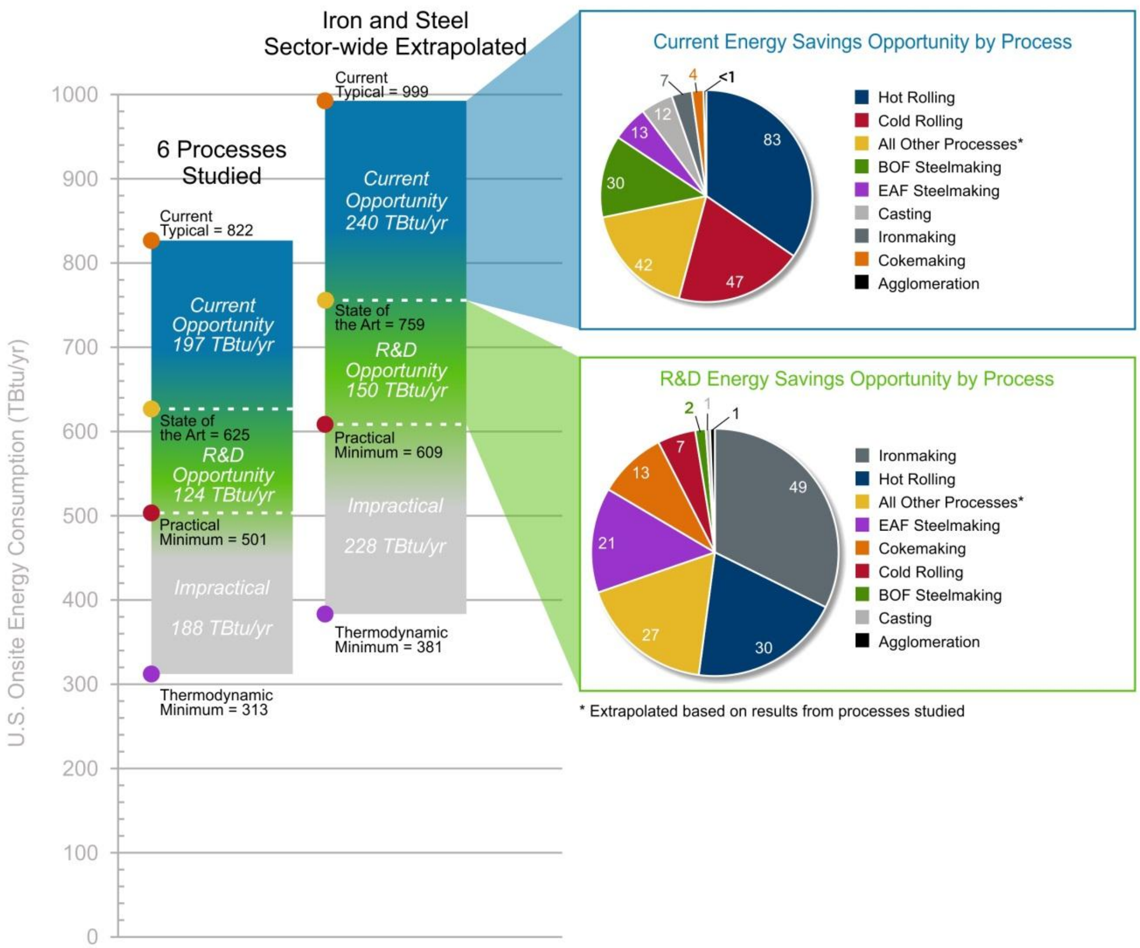


Figure ES-1. Current and R&D Energy Savings Opportunities for the Six Processes Studied and for Iron and Steel Sector-wide Based on Extrapolated Data

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” because with today’s knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

The results presented show that 197 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade six iron and steel manufacturing processes; an additional 124 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

However, if the energy savings potential is estimated for the U.S. iron and steel industry as a whole, the current energy savings opportunity is 240 TBtu per year and the R&D opportunity increases to 150 TBtu per year.

The top four Current Energy Savings Opportunities for the processes are as follows:

- Hot rolling - 83 TBtu (or 35% of current opportunity)
- Cold rolling - 47 TBtu (or 20% of current opportunity)
- All other NAICS 331111[6] processes - 42 TBtu (or 18% of the current opportunity)
- Basic oxygen furnace (BOF) steelmaking - 30 TBtu (or 13% of the current opportunity).

The top four R&D Energy Saving Opportunities for the processes are as follows:

- Ironmaking - 49 TBtu (or 32% of the R&D opportunity)
- Hot rolling - 30 TBtu (or 20% of the R&D opportunity)
- All other NAICS 331111[7] processes - 27 TBtu (or 18% of the R&D opportunity)
- Electric arc furnace (EAF) steelmaking- 21 TBtu (or 14% of the R&D opportunity),

[6] All other NAICS 331111 includes all other processes in the iron and steel sector other than the six processes studied.
[7] All other NAICS 331111 includes all other processes in the iron and steel sector other than the six processes studied.

List of Acronyms and Abbreviations

AISI	American Iron and Steel Institute
AMO	Advanced Manufacturing Office
AOD	Argon oxygen decarburization
BF	Blast furnace
BFG	Blast furnace gas
BOF	Basic oxygen furnace
Btu	British thermal unit
COE	Cost of energy
COG	Coke oven gas
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
DRI	Direct-reduced iron
EAF	Electric arc furnace
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GJ	Gigajoules
HHV	Higher heating value
IEA	International Energy Agency
K	Kelvin
kWh	Kilowatt hours
LHV	Lower heating value
MECS	Manufacturing Energy Consumption Survey
mm	Millimeter
MMBtu	Million British thermal units
MMBtu/ton	Million British thermal units per short ton
MT	Metric ton (tonne)
NAICS	North American Industry Classification System
PJ	Petajoules
PM	Practical minimum energy consumption or energy intensity
SOA	State of the art energy consumption or energy intensity
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity

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1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. iron and steel manufacturing sector, as defined by classification 331111 of the North American Industry Classification System (NAICS). The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for iron and steel manufacturing processes and iron and steel sector-wide. In this study, four different energy consumption *bands* (or measures) are estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

The United States produces a wide range of steel products using various processes; six of the most energy-intensive iron and steel manufacturing processes were studied. Together, these processes accounted for 82% of the onsite energy consumption of the U.S. iron and steel sector in 2010.

The four bands of energy consumption estimated in this report include: the onsite energy consumption associated with six iron and steel manufacturing processes in 2010 (current typical); two hypothetical energy consumption levels with progressively more advanced technologies and practices (state of the art and practical minimum); and one energy consumption level based on the minimum amount of energy needed to theoretically complete an iron and steel manufacturing process (thermodynamic minimum). The bands of energy consumption are used to calculate *current* and *R&D opportunity* bandwidths for energy savings.

1.2. Comparison to Other Bandwidth Studies

This study builds upon the 2004 DOE bandwidth report *Steel Industry Energy Bandwidth Study*. This study compares diverse industrial, academic and governmental consumption data to analyses[1] of reported plant energy consumption data in the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA) for data year 2010. This study also updates energy consumption and production values to the year 2010.

This report is one in a series of bandwidth studies commissioned by DOE's Advanced Manufacturing Office characterizing energy consumption in U.S. manufacturing using a uniform methodology and definitions of energy bands. Other manufacturing sector bandwidth studies include chemicals, petroleum refining, and pulp and paper; additional sector studies are under consideration. Collectively, these studies explore the potential energy savings opportunities in

[1] The relevant analysis was published as the *Manufacturing Energy and Carbon Footprint for the Iron and Steel Sector* (NAICS 3311, 3312), based on energy use data from 2010 EIA MECS (with adjustments) in February 2014. Hereafter, this document will be referred to as the "Energy Footprint" and listed in the References section as DOE 2014.

manufacturing that are available through existing technology and with investment in research and development (R&D) technologies.

1.3. Definitions of Energy Consumption Bands and Opportunity Bandwidths

There are four energy consumption bands referenced throughout this report: current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy consumption. These bands describe different levels of energy consumption for iron and steel manufacturing processes.

As shown in Figure 1-1, the bands progress from higher to lower levels of energy consumption, reflecting the use of increasingly more efficient manufacturing technologies and practices. The upper bound is set by a mix of new and older technologies and practices in current use (the current typical level of energy consumption). The lower bound is defined by the theoretical minimum energy requirement assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption).

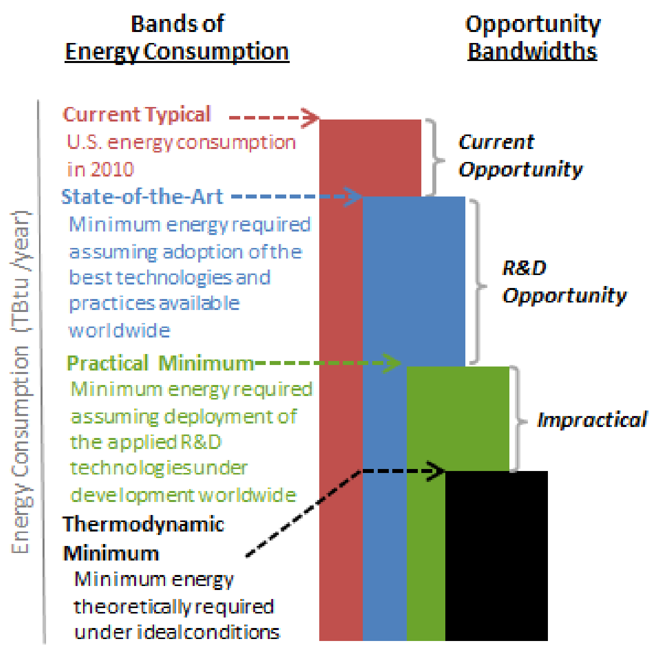


Figure 1-1. Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If manufacturers use the most efficient technologies and practices available in the world, energy consumption could decrease from the current typical to the level defined by the state of the art. Since these state of the art technologies already exist, the difference between the current typical and the state of the art energy consumption levels defines the *current opportunity* to decrease energy consumption. Given that this is an evaluation of technical potential, fully realizing the current opportunity would require investments in capital that may or not be economically viable for any given facility.

Widespread deployment of future R&D advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

Definitions of the four energy bands are provided in the inset (box at right). Definitions of the two opportunity bandwidths are provided below:

The *current opportunity* is the energy savings that is potentially attainable through capital investments in the best technologies and practices available worldwide. It is the difference between CT and SOA energy consumption.

The *R&D opportunity* is the energy savings that is potentially attainable through the applied R&D technologies under development. It is the difference between SOA and PM energy consumption. To attain this energy savings, iron and steel mills would need to manufacture products in new ways with technologies that are not commercially available.

Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption for a *specific manufacturing process industry-wide*:

Current Typical (CT) energy consumption:
U.S. energy consumption in 2010.

State of the Art (SOA) energy consumption:
The minimum amount of energy required assuming the adoption of the best technologies and practices available worldwide.

Practical Minimum (PM) energy consumption:
The minimum amount of energy required assuming the deployment of the best applied R&D technologies under development worldwide.

This measure is expressed as a range to reflect the speculative nature of the energy impacts of the unproven technologies considered.

Thermodynamic Minimum (TM) energy consumption:
The minimum amount of energy theoretically required assuming ideal conditions typically unachievable in real-world applications.

The difference between PM and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

1.4. Bandwidth Analysis Method

This Section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "onsite energy" or "primary energy" and defined as follows:

- **Onsite energy** (sometimes referred to as site or end use energy) is the energy consumed within the manufacturing plant boundary (i.e., within the plant gates). Non-fuel feedstock energy is *not* included in the onsite energy consumption values presented in this study.

- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both offsite and onsite during the manufacturing process. Offsite energy consumption includes generation and transmission losses associated with bringing electricity and steam to the plant boundary. Non-fuel feedstock energy is not included in the primary energy values. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

Four bands of energy consumption are quantified for select individual processes and iron and steel manufacturing sector-wide. **The bands of energy consumption and the opportunity bandwidths presented herein consider onsite energy consumption; feedstocks[2] are excluded.** To determine the total annual onsite CT, SOA, PM, and TM energy consumption values of the processes studied (TBtu per year), energy intensity values per unit weight (Btu per pound of product) are estimated and multiplied by the production volumes (pounds per year of product). The year 2010 is used as a base year since it is the most recent year for which consistent sector-wide energy consumption data are available. Unless otherwise noted, 2010 production data is used. Some iron and steel manufacturing processes are exothermic and are net producers of energy; the net energy was considered in the analysis.

The estimates presented are for macro-scale consideration of energy use in iron and steel manufacturing. The estimates reported herein are representative of average U.S. iron and steel manufacturing; they do not represent energy use in any specific facility or any particular region in the United States or the world.

Significant investment in technology development and implementation would be needed to fully realize the potential energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future R&D technologies was not in the scope of this study.

The calculated energy consumption values in this report are based on an examination of referenced data and extrapolation to sector-wide energy savings opportunities. The references, methodology, and assumptions employed are presented with the data in each chapter and were peer reviewed.

Overview of energy use in iron and steel manufacturing: Chapter 2 provides an **overview** of the U.S. iron and steel sector and how energy is used in iron and steel manufacturing (how much, what type, and for what end uses).

Estimating production volumes for select processes: Chapter 3 presents the relevant **production volumes** for the six processes (tons per year) in 2010 and the rationale for how the six processes were selected.

[2] Feedstock energy is the nonfuel use of combustible energy. Feedstocks are converted to iron and steel products (not used as a fuel); MECS values reported as “feedstocks” exclude feedstocks converted to other energy products.

***Estimating CT energy consumption*:** Chapter 4 presents the calculated onsite **CT energy consumption** (TBtu per year) for the six processes individually and sector-wide (along with references for the CT energy intensity data and assumptions). The CT energy consumption data is calculated based on this energy intensity data and the production volumes (identified in Chapter 3). The boundary assumptions for the industrial processes considered in this bandwidth study are presented.

MECS provides onsite CT energy consumption data sector-wide for 2010 (See Table 4-1). However, MECS does not provide CT energy consumption data for individual processes. The percent coverage of the processes studied (compared to MECS sector-wide data) is presented and used in calculations discussed later in this report.

Primary CT energy consumption (TBtu per year) estimates are calculated, which include offsite generation and transmission losses associated with bringing electricity and steam to manufacturing facilities. Primary energy consumption estimates are not provided for SOA, PM, or TM because they were outside the scope of this study.

***Estimating SOA energy consumption*:** Chapter 5 presents the estimated onsite **SOA energy consumption** for the six processes (along with the references for the SOA energy intensity data and assumptions). The sector-wide SOA energy consumption is estimated based on an extrapolation of the SOA energy consumption for the six processes studied. The *current opportunity* bandwidth, the difference between CT energy consumption and SOA energy consumption (also called the SOA energy savings), is presented along with the SOA energy savings percent.

***Estimating PM energy consumption*:** Chapter 6 presents the estimated onsite **PM energy consumption** for the six processes (along with the references for PM energy intensity data and assumptions). The range of potentially applicable applied R&D technologies to consider in the PM analysis worldwide is vast. The technologies that were considered are sorted by process and described in Appendix A4. The technologies that are considered crosscutting throughout all of iron and steel manufacturing along with the most energy-saving, process-specific R&D technologies were used to determine PM energy consumption for each process. A weighting method that includes factors such as technology readiness, cost, and environmental impact was developed for all technologies considered; the weighting analysis methodology and summary table provided in Appendix A5 is intended to serve as a resource for continued consideration of all identified R&D opportunities.

The sector-wide PM energy consumption is estimated based on an extrapolation of the PM energy consumption for the six processes studied. The *R&D opportunity* bandwidth, the difference between SOA energy consumption and PM energy consumption, is presented along with the PM energy savings percent. PM energy savings is the sum of *current* and *R&D opportunity*.

The technologies considered in the PM analysis are unproven on a commercial scale. As a result, the PM energy consumption is expressed as a range. The upper limit is assumed to be the SOA energy consumption; the lower limit is estimated and shown as a dashed line with color fading in the summary figures because the PM is speculative and depends on unproven R&D technologies. Furthermore, the potential energy savings opportunity could be greater if additional unproven technologies were considered.

Estimating TM energy consumption: Chapter 7 presents the estimated onsite **TM energy consumption** for the six processes (along with the references for the TM energy intensity data and assumptions). The TM energy intensities are based on the commercial process pathways. TM energy consumption assumes all of the energy is used productively and there are no energy losses. TM is the minimum amount of energy required; in some cases it is less than zero.

To determine the potential available energy savings opportunities in this bandwidth study, TM energy consumption was used as the baseline for calculating the energy savings potentials for each process studied (not zero, as is typically the case in considering energy savings opportunities). The rationale for using TM as the baseline is explained in Chapter 7.

Estimating the energy savings opportunities: Chapter 8 presents the energy savings **opportunity bandwidths** for the processes and sector-wide. The analyses used to derive these values are explained in Chapters 3 to 7.

2. U.S. Iron and Steel Manufacturing Sector Overview

This Chapter presents an overview of the U.S. iron and steel manufacturing sector, including its impact on the economy and jobs, number of establishments, types of energy consumed, and the end uses of the energy. The convention for reporting energy consumption as either onsite versus primary energy is explained. The data and information in this Chapter provide the basis for understanding the energy consumption estimates.

2.1. U.S. Iron and Steel Manufacturing Economic Overview

Steel is a vital domestic manufacturing product and is important for many applications including construction (residential, commercial, transportation), automotive, machinery and equipment, containers, and national security, among others.

In 2010, the U.S. produced 88.7 million short tons (referred to as tons in the document unless otherwise noted) of raw steel while operating at about 70.4% of estimated capacity (AISI 2011a). The U.S. was the third largest steel manufacturing country in 2010 behind China and Japan, accounting for 5.7% of world steel production (AISI 2011a). Also in 2010, the U.S. steel industry as a whole contributed $17.5 billion in GDP (Considine 2012). The value of steel shipped in the U.S. in 2010 totaled $70 billion and weighed 84 million tons (AISI 2013a).

Domestic steelmakers have improved the energy intensity per ton of steel produced by 27% between 1990 and 2010 (AISI 2012). This reduction in energy consumption and corresponding increase in production is largely due to the shift from ore-based to scrap-based steel production, although deployment of new energy efficient steelmaking technologies and innovations on the plant floor are also contributors to this improvement. Steel from a variety of products such as containers, automobiles, and appliances can be recycled once they reach the end of their useful life. In fact, steel is the most recycled material in North America, with more steel recycled annually than paper, aluminum, glass, and plastic combined (SRI 2013a). In 2012, the steel recycling rate was 88%, up from a rate of 64% in 2000 (SRI 2013b). There continues to be further savings opportunity in this energy-intensive sector through both energy consumption and production efficiency improvements.

2.2. U.S. Iron and Steel Manufacturing Products, Establishments, and Processes

Iron and steel operations are complex and large facilities that produce significant quantities of steel each year. Steel mills in the U.S. are generally either integrated mills, or mini mills; the primary difference being the proportion of recycled steel that is used (up to 99% in mini mills and was 91% in 2010 (USGS 2012c)). The distribution of many of the integrated and mini mills in the United States is shown in Figure 2-1. Integrated steel mills produce steel from iron ore via the blast furnace (BF) and basic oxygen furnace (BOF) steelmaking technology while mini steels mills produce steel mostly from recycled scrap steel via the electric arc furnace (EAF) steelmaking technology. Figure 2-2 shows the steel industry process flowlines for integrated mills and for mini mills.

In 2010, there were about 15 BF/BOF steelmaking facilities operated by five companies and 112 EAF steelmaking facilities operated by over 50 companies in the U.S. (USGS 2012a). Most of these steelmaking facilities in the U.S. are concentrated in Indiana, Ohio, Pennsylvania, Michigan, and Illinois due to the close proximity to coal and iron ore suppliers among other factors. In 2010, iron and steel manufacturing directly employed 135,000 workers and total employment (including both direct and indirect employees in other industries) was estimated at 1,080,000 (AISI 2013a).

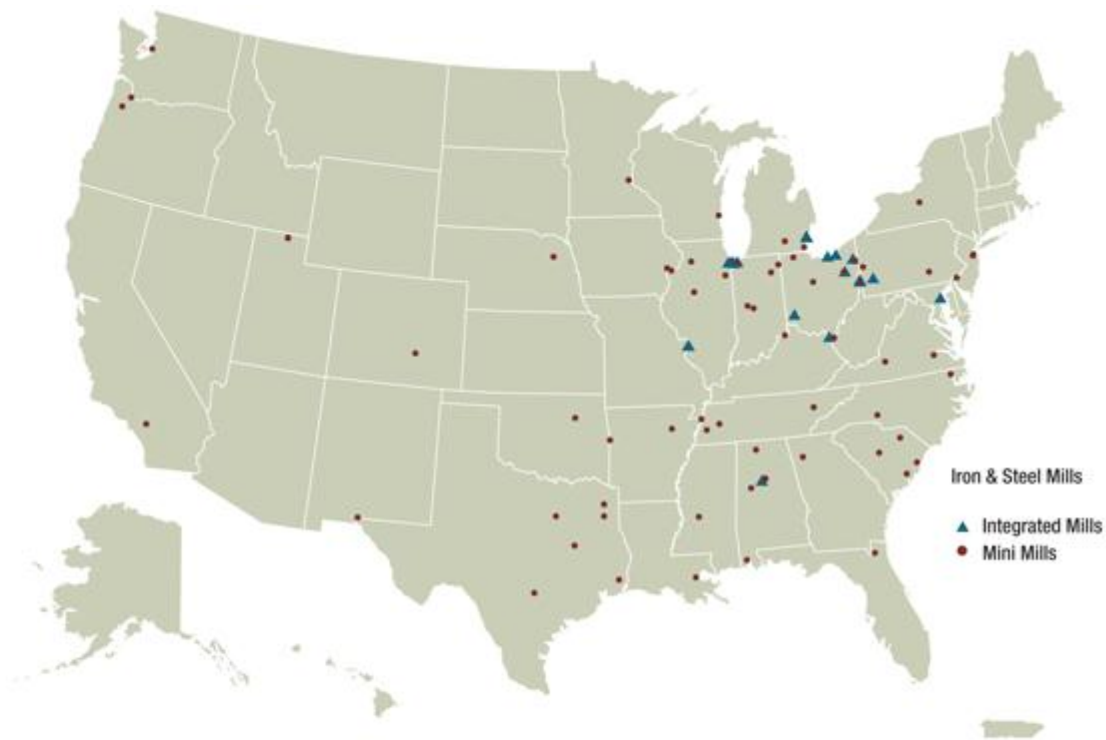
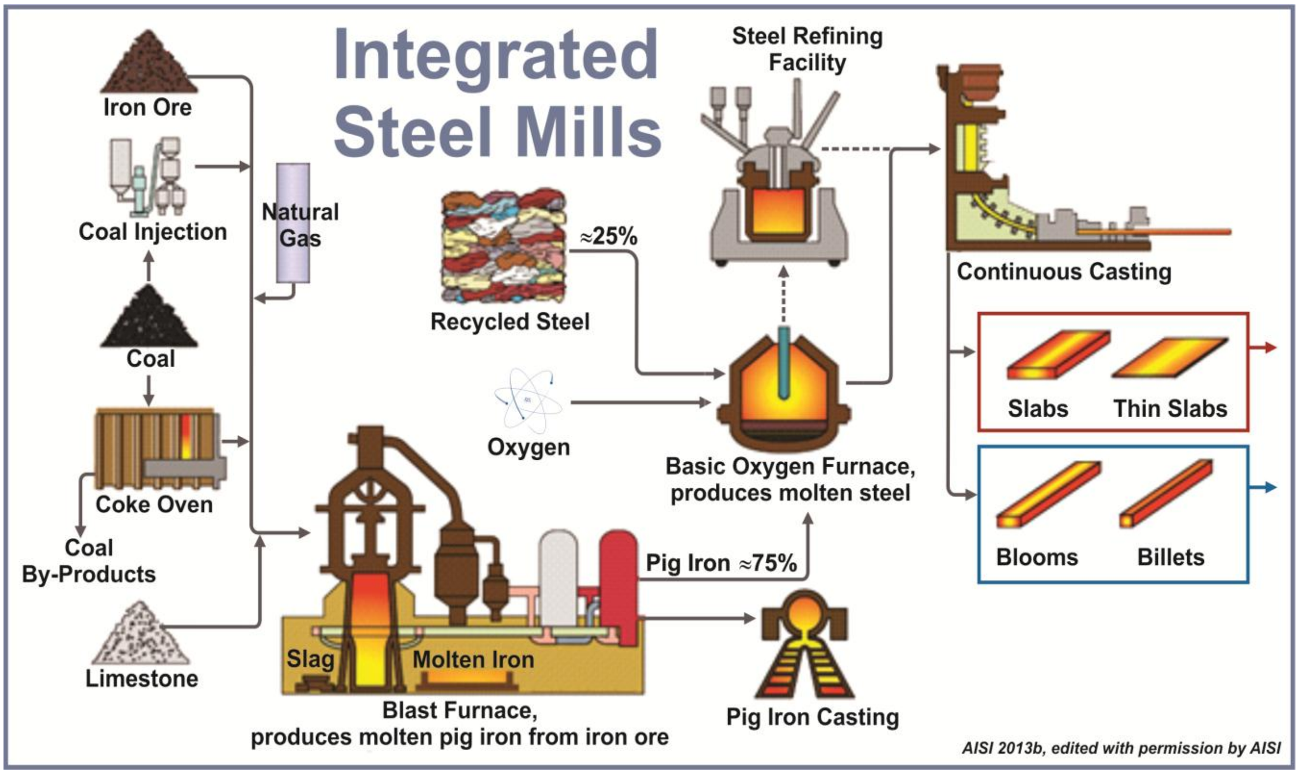


Figure 2-1. Geographic Distribution of Integrated and Mini Steel Mills in the United States *(EPA 2011)*



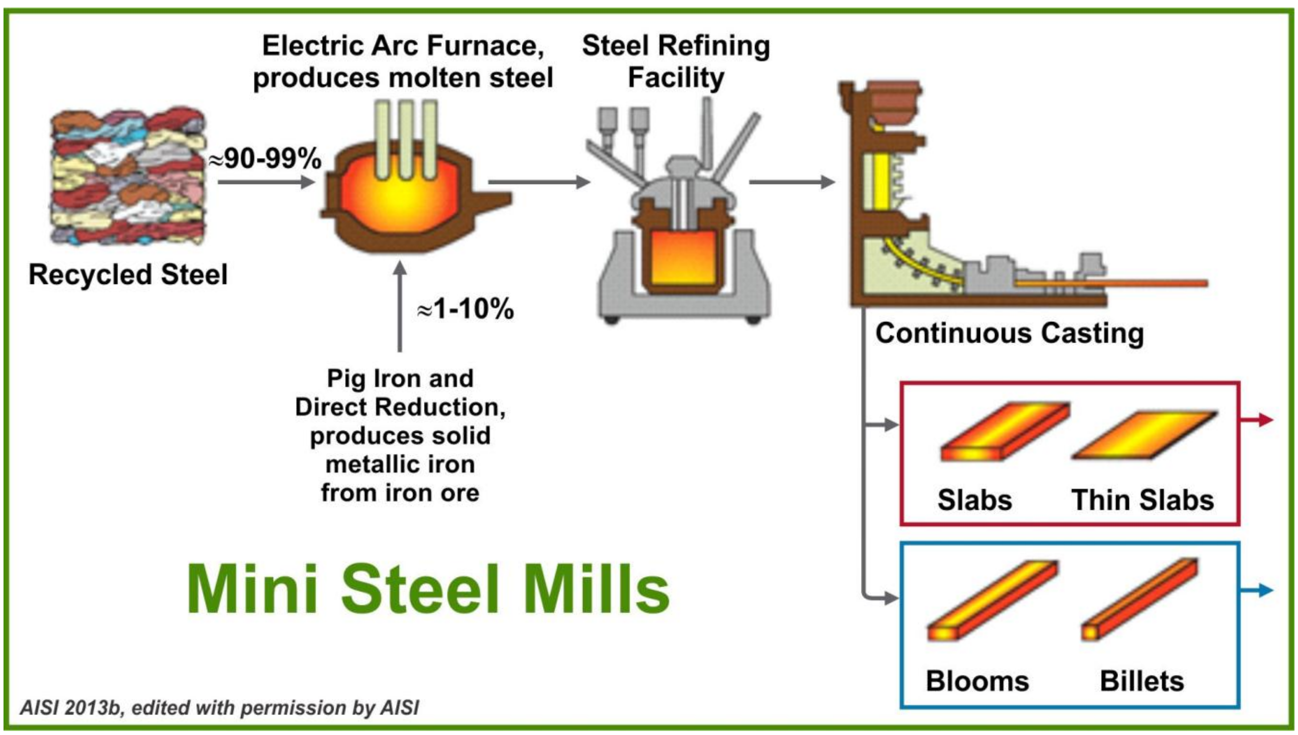


Figure 2-2. Steelmaking Flowlines for Integrated and Mini Mills *(AISI 2013b)*

This study focuses on energy consumption in six energy intensive process areas in steel manufacturing. These process areas are identified in Table 2-1, along with some of the major sub processes. Energy intensity and consumption is evaluated by process area and sub process for CT, SOA, PM, and TM in Sections 4 through 7 of this report. CT energy intensity for pelletizing iron ore is shown for reference purpose only because this sub process is outside the boundary of bandwidth analysis. Although direct reduction ironmaking was not used in the United States in 2010, and therefore not included in the bandwidth savings summary, it is likely to appear in future steel industry energy analyses and so energy intensity estimates have been included. CT, SOA and TM energy intensity for direct reduction is included for reference only in this study.

Table 2-1. Iron and Steel Process Areas Considered in the Bandwidth Analysis

Processes	Sub Processes
Agglomeration	Sintering, Pelletizing
Cokemaking	
Ironmaking	Blast Furnace, Direct Reduction
Steelmaking	Basic Oxygen Furnace, Electric Arc Furnace
Casting	
Rolling	Hot Rolling, Cold Rolling

There are two main processes for producing steel: integrated steelmaking, which combines a blast furnace with a BOF, and EAF steelmaking. These two processes are distinctly different as the integrated BOF process consumes mostly agglomerated iron ore along with some scrap steel (up to 30%; was 24% in 2010 (USGS 2012c)) while the EAF process consumes mostly scrap steel as well as reduced iron, cast iron, and other iron containing materials to produce raw steel (WCA 2013). It requires about seven times the amount of energy to produce a ton of steel from ore in a blast furnace and BOF (including the energy for cokemaking, pelletizing, and sintering), compared to remelting scrap in an electric arc furnace (not including losses for generating and transmitting electricity) (IPPC 2013; LBNL 2008). However, many other factors come in to play in the economics of ore-based versus scrap-based steelmaking. For this reason, it is useful to consider the two production pathways separately in this bandwidth study.

2.2.1. Ore Agglomeration

Ore agglomeration is used to enhance the iron content and physical properties of low-grade iron ore that will be used for ironmaking. The two main processes associated with ore agglomeration are sintering and pelletizing. Sintering involves mixing ore pellets and fines, coke breeze or coal fines, and lime (which acts as both a flux and a binder), and then heating to form hardened and porous lumps of sinter. This mixture improves the efficiency of the reduction reaction in the blast furnace and the physical shape and strength of the sinter provides support and open channels for gas flow in the vessel. Sintering is an energy intensive step in the steelmaking due to the process heating.

Pelletizing involves crushing and grinding the iron ore to remove impurities and then the forming of round, uniform size iron ore pellets and heating to harden them. Pelletizing is usually conducted near the ore mining site, and not at the steel mill. Briquetting is another type of agglomeration process, which involves the formation of iron ore briquettes from iron ore and fines and hardening at elevated temperatures. A total of 45.3 million tons of iron ore and agglomerated products were consumed in blast furnaces in 2010, while only 0.6 million tons were consumed in steelmaking furnaces. The total 45.9 million tons was composed of 86% pellets, 13% sinter, briquettes, nodules, and other, and 1% natural ore (AISI 2011a).

2.2.2. Cokemaking

Coke is an important and necessary raw material for ironmaking in a blast furnace. The process of cokemaking is an energy intensive process that involves charging coal into a coke oven, where it is heated to high temperatures in an airless environment. This drives off volatile chemicals, thus increasing the purity of the carbon. The heating process is self-sustaining and is fueled by oxidation of some of the coal. Coke oven off-gas contains high amounts of carbon monoxide which is usually recovered for its calorific value. Electricity can be produced through the combustion of coke oven off-gases to provide power for other plant operations. In 2010, integrated steel plants in the U.S. produced 9.3 million tons of coke and consumed 12 million tons (AISI 2011a). Coke is also produced at merchant plants.

2.2.3. Ironmaking

Ironmaking is the process where iron ore is converted to iron.

2.2.3.1. Blast Furnace Ironmaking

Traditional Ironmaking takes place in a blast furnace. Iron ore agglomerate, a limestone flux, and coke are fed into the furnace where the coke is reacted with preheated air in order to heat and reduce (remove oxygen from) the iron ore resulting in a high carbon molten iron product known as pig iron. The quality of the coke that is used affects energy use in the blast furnace; the lower the quality of coke, the greater the volume of coke required. Pig iron produced in the blast furnace typically contains up to 5% by weight carbon, up to 2.5% by weight manganese, up to 4% by weight silicon, and phosphorus and sulfur (Fruehan et al. 2000; McHannon 1971).

Before being tapped from the furnace, pig iron collects in a molten pool with a protective layer of slag (principally calcium oxide from the lime and silicon oxide native to the ore). After tapping, which occurs approximately every eight hours, the pig iron is typically routed to a basic oxygen furnace where oxygen is blown through the molten metal to oxidize impurities and produce steel. About 29.6 million tons of pig iron was produced in the U.S. in 2010, all of which was consumed for steelmaking (AISI 2011a). Globally, the U.S. ranked 8th in pig iron production and accounted for 3% of world production (USGS 2012b).

2.2.3.2. Direct Reduction Ironmaking

An alternative ore-based ironmaking process is a solid-state method known as direct reduction in which briquettes or nuggets of iron ore are either mixed with coal or exposed to a reducing gas (such as natural gas or hydrogen) at elevated temperature. The direct reduction process does not involve iron ore agglomeration and cokemaking, processes which are significant energy users in the integrated steelmaking process. The carbon and hydrogen in these reducing agents reacts with the iron oxide to produce approximately 96% pure solid metallic iron, often referred to as sponge iron, in the form of nuggets or briquettes primarily for use in EAF steelmaking. In 2010, 75,000 metric tons were produced by the coal-based ITmk3® process at Mesabi Nugget, LLC in their startup year (capacity 500,000 metric tons (tonnes) per year) (Steel Dynamics. Inc. n.d.). Gas-based direct reduction plants are planned or under construction in the U.S. (including a Nucor plant in Louisiana and a Voestalpine plant in Texas) and this will affect the product mix in future years (Griggs 2013; Voestalpine 2013).

2.2.4. Steelmaking

Steelmaking is the process where iron and scrap is converted to steel through the removal of impurities and incorporation of alloying elements.

2.2.4.1. Basic Oxygen Furnace Steelmaking

After the molten pig iron is produced in the blast furnace, it is fed to a basic oxygen furnace along with a maximum of 30% scrap steel to be converted to raw steel. Oxygen is injected into the BOF in order to remove carbon from the pig iron through oxidation. The sensible heat in the molten pig iron and the heat generated by burning the carbon content with oxygen provide the energy required to melt the scrap and bring the bath to the required temperature for casting. The bath temperature is adjusted either by adding small amounts of carbon and then lancing with oxygen to increase the temperature or by adding iron ore to cool the bath. In 2010, 38.7% of steel produced in the U.S. was produced using the BOF route (AISI 2011a). However, a majority (70%) of world steel is produced through the BOF method (WSA 2012).

In BOF steelmaking, energy is lost through radiation and conduction from the vessel, unrecovered heat and calorific value of the off-gases, and through yield loss (oxidized iron in the slag, steel mixed into the slag by-product, oxidized particulates in the off-gas).

2.2.4.2. Electric Arc Furnace Steelmaking

Raw steel produced via the electric arc furnace process is made from a feedstock of recycled steel and other iron scrap types, which makes this process distinctively different from BOF steelmaking. The process does not require a pig iron supply, as the energy to melt the charge is electrical and not dependent on high levels of carbon. An electric arc is produced between the feedstock and graphite electrodes to melt the recycled steel. Fuel (e.g., carbon fines plus oxygen via a side lance) is frequently used to accelerate the melting process. EAF steelmaking does not involve iron ore agglomeration, cokemaking and ironmaking, processes which are significant energy users in the integrated steelmaking. In 2010, 61.3% of steel produced in the U.S. was produced using the EAF route (AISI 2011a). The share of EAF steelmaking has steadily increased since 1980, when 28% of steel was produced through this method (ArcelorMittal 2014).

In EAF steelmaking energy is lost through radiation and conduction, cooling of the furnace shell, unrecovered heat in the off-gases, and through yield loss (oxidized iron in the slag, steel mixed into the slag by-product, oxidized particulates in the off-gas, and oxidation through exposure of the liquid metal to air during tapping).

2.2.5. Casting

From the EAF or BOF, molten steel is semi-finished through casting into various solid forms, either individual ingots or continuous slabs, beams, billets, or blooms. Nearly all steel is cast using the continuous casting process, but a small percentage is still cast by the original batch method of pouring the molten steel into molds to create ingots. In 2010, 97.4% of steel produced in the U.S. was solidified using continuous casting while the remainder (2.6%) was solidified through the ingot method (AISI 2011a).

When transporting steel from the melting furnaces to the caster in a ladle, steelmakers can make minor adjustments to the composition and temperature, stir the metal with gas to improve its uniformity, and promote the flotation of undesirable contaminants such as slag and refractory material. More sophisticated adjustments in cleanliness, temperature, composition, and removal of dissolved gases are possible at an optional ladle metallurgy station. The flow pattern of liquid steel from the ladle to the caster (for example, through a bathtub-like tundish), and within the caster itself, is controlled to promote removal of detrimental inclusions. During the casting process, heat is removed from the steel as it cools from liquid to solid form—both to the surrounding environment and to chill water in the water-cooled continuous casting process. The cooling rates and thermal gradients are controlled to prevent cracking, control chemical segregation, and control the metallurgical structure of the steel. There is some yield loss, and therefore energy loss, due to removal of unusable portions of individual ingots. The yield loss is much smaller in continuous casting because most of the product can be used, apart from remnants of steel from the ladle and tundish ("skulls"). Improved yields have led to improved energy efficiency over time, most notably due to increased use of continuous casting vs. ingot casting.

2.2.6. Rolling

Rolling and finishing processes are used to produce the finished steel products. Steel rolling occurs in both hot and cold rolling mills. For hot rolling, the steel slabs or billets that are formed during continuous casting are reheated in furnaces to reach the necessary temperature and temperature uniformity before they are rolled to reduce their thickness. Although steel slabs or billets are sometimes directly charged from continuous casting to a reheat furnace for hot rolling, those that are cooled to air temperature require longer reheat times and this increases the energy consumption of the process. Heat treatments and controlled processing may sometimes be performed during the hot rolling operation, for example, water quenching in a hot strip mill or a controlled temperature rolling in a plate mill. Electrical energy is required for the motors and hydraulics during the rolling process, steam is used to remove scale, and combustion gases are used for heating in the reheat furnaces.

Hot rolled coils can be sent to a cold rolling mill, where the thickness is further reduced—often with multiple steps and with intermediate high temperature heat treatments when the steel gets too hard to roll further without cracking. Final heat treatments are often required—for example, annealing to soften the steel for forming applications, or a quench and temper to increase the strength of the steel.

Yield loss, and therefore energy loss, can occur through oxidation of the steel, cracking of the edges of the rolled product during both hot rolling and cold rolling, and through cropping of the ends of the bars during hot rolling.

2.3. U.S. Iron and Steel Manufacturing Energy Consumption

Onsite energy and primary energy for the U.S. iron and steel sector are provided in Table 2-2. EIA MECS provides onsite energy consumption data by end use, including onsite fuel and electricity consumption, as well as feedstock energy. Primary energy includes assumptions for offsite losses (DOE 2014).

Table 2-2. U.S. Iron and Steel Manufacturing Energy Consumption Sector-Wide, 2010	
Onsite Energy Consumption (includes electricity, steam, and fuel energy used onsite at the facility)	999 TBtu
Primary Energy Consumption (includes onsite energy consumption, and offsite energy losses associated with generating electricity and steam offsite and delivering to the facility)	1,359 TBtu

Source: DOE 2014

Iron and steel manufacturing is the 5th largest consumer of energy in U.S. manufacturing, accounting for 1,359 TBtu (7%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Offsite electricity and steam generation and transmission losses in iron and steel manufacturing totaled 347 TBtu in 2010; onsite energy consumed within the boundaries of U.S. iron and steel mills totaled 999 TBtu.

Figure 2-3 shows the total onsite energy *entering* U.S. iron and steel mills; most of the energy entering is in the form of fuel. About 26% of this fuel is used onsite in boilers and combined heat and power (CHP) to generate additional electricity and steam (DOE 2014). In contrast, Figure

2-4 shows the total onsite energy at the *point of end use*. Electricity and steam from both offsite and onsite generation are included in Figure 2-4, along with the portion of energy loss that occurs in onsite generation. The data provided in Table 2-2, Figure 2-3, and Figure 2-4 are based on MECS with adjustments to account for withheld and unreported data (DOE 2014).

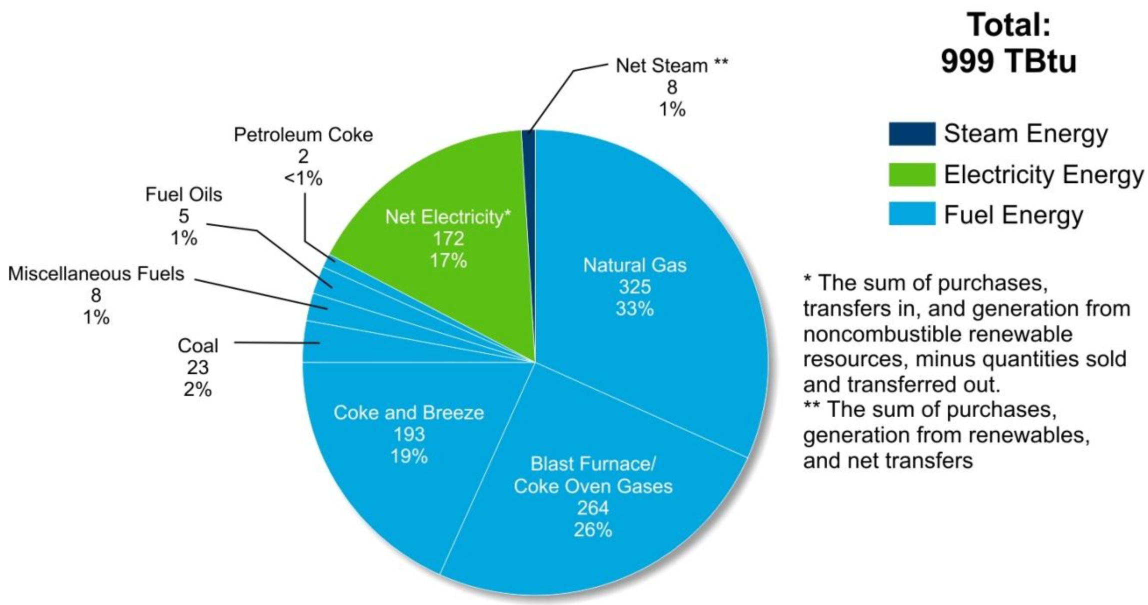


Figure 2-3. Onsite Energy Entering U.S. Iron and Steel Mills, 2010 *(DOE 2014)*

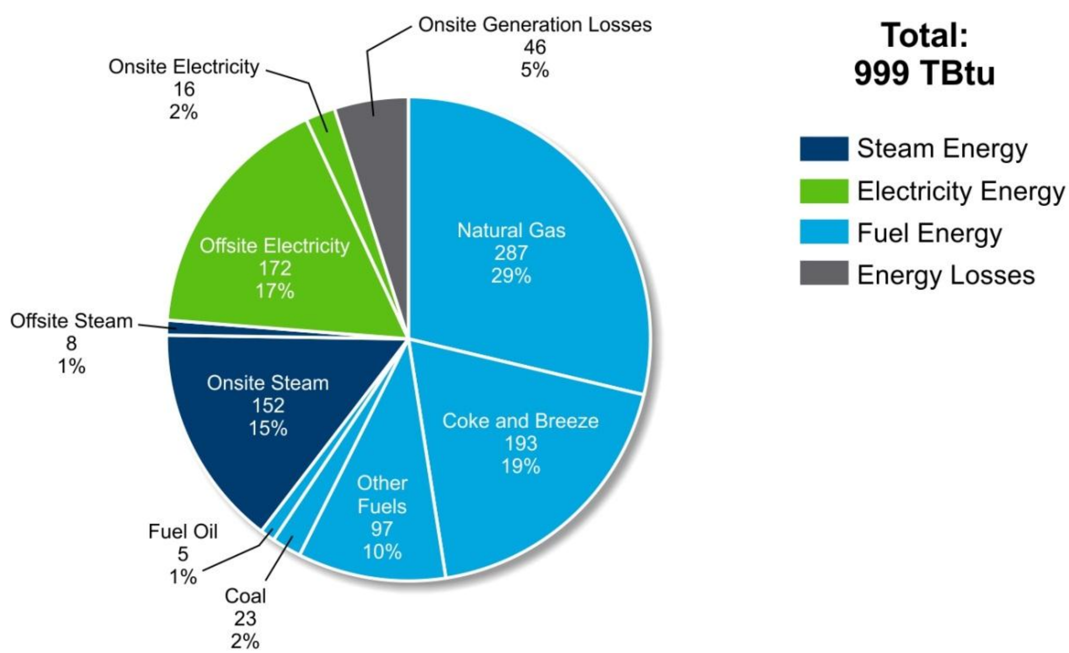


Figure 2-4. Onsite Energy Consumption at Point of End Use in U.S. Iron and Steel Mills, 2010 *(DOE 2014)*

2.3.1. Fuel and Feedstocks

As shown in Figure 2-3, onsite fuel consumption amounted to 818 TBtu in 2010, or 83% of total onsite energy entering iron and steel mills (EIA 2013). Natural gas and blast furnace/coke oven gases account for over half (59%) of the sector's fuel consumption.

Figure 2-5 provides a breakdown of fuel consumption in the iron and steel sector by end use in 2010. The categories of end use are reported by EIA in MECS. The majority of the fuel (68%) is used directly for process heating; some examples of process heating equipment include fired heaters, heated reactors, and heat exchangers. A significant portion of fuel (26%) is used indirectly in boilers and CHP to generate additional onsite electricity and steam (DOE 2014).

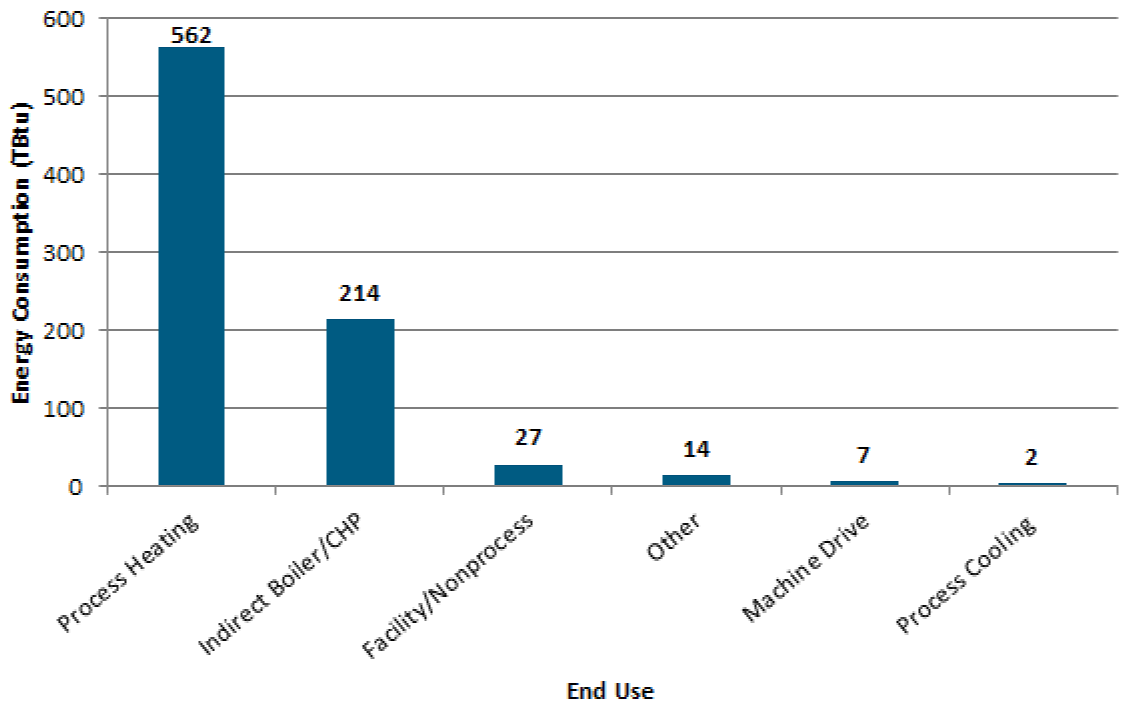


Figure 2-5. Fuel Consumption in the Iron and Steel Sector by End Use, 2010 *(DOE 2014)*

Feedstock energy is the nonfuel use of combustible energy. For iron and steel manufacturing, feedstock energy is converted to products instead of being used as a fuel. For the energy bandwidth study, only the fuel use of combustible energy is considered in the opportunity analysis; however, due to the highly connected nature of feedstock and fuel energy, it is important to provide some context around that relationship and some background information on feedstock energy in this sector.

Figure 2-6 shows feedstock energy use in the U.S. iron and steel manufacturing sector. The sector consumed 373 TBtu of feedstock energy in 2010. Coal accounts for 87% of the feedstock energy used (EIA 2013).

It should be noted that a significant proportion of energy first used as feedstock is subsequently used as byproduct process energy. Comparison of MECS Tables 1.2, 2.2, and 3.2 indicates that 307 TBtu (82%) of feedstock energy is converted to byproduct onsite energy. MECS Table 3.5 indicates that 264 TBtu of byproduct onsite energy is blast furnace gas (BFG) and coke oven gas (COG), 2 TBtu is coke, and the remainder of byproduct energy is unclear.

(373 TBtu feedstock energy = 264 TBtu BFG/COG + 2 TBtu coke + remainder unclear)

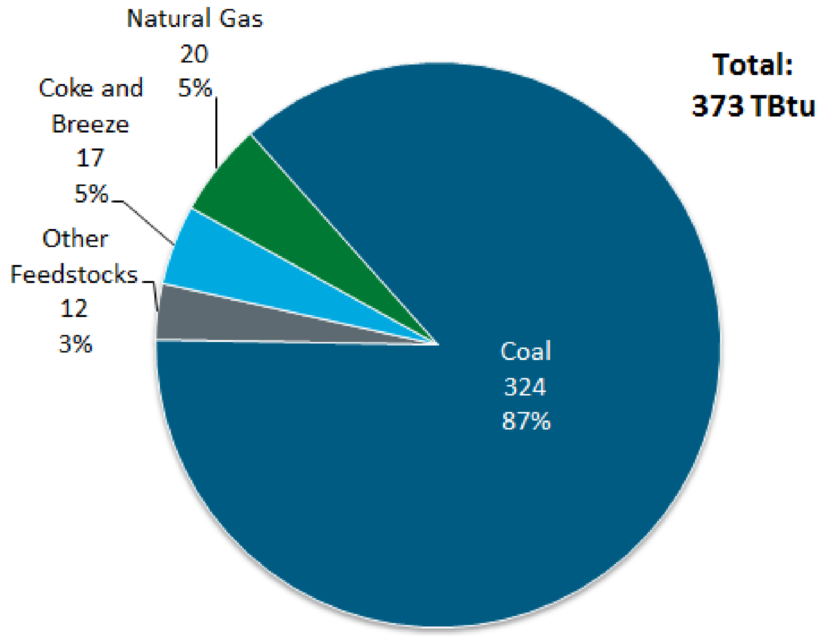


Figure 2-6. Feedstock Energy Consumption in the Iron and Steel Sector, 2010 (EIA 2013)

Feedstock energy is a significant portion of energy consumption in U.S. iron and steel manufacturing (373 TBtu) so it is important to consider when analyzing overall iron and steel sector energy use. However, **feedstock energy is not included in the onsite energy data in the energy consumption bands in this study**. Feedstock energy is excluded in order to be consistent with previous bandwidth studies and because the relative amount of feedstock energy versus fuel energy used in manufacturing is not readily available for individual processes.

2.3.2. Electricity

Figure 2-3 shows that onsite net electricity entering iron and steel mills totaled 172 TBtu in 2010. The data presented is the *net amount*, which is the sum of purchases and transfers from offsite sources as well as generation from non-combustion renewable resources (e.g., hydroelectric, geothermal, solar, or wind energy) less the amount of electricity that is sold or transferred out of the plant. Figure 2-4 shows that 188 TBtu of total electricity is consumed at the point of end use and includes 16 TBtu of electricity generated onsite.

In Figure 2-7, the breakdown of the 188 TBtu of electricity is shown by end use in 2010 (DOE 2014). There are numerous uses for electricity in iron and steel manufacturing; the most common uses are for process heating and machine driven equipment (i.e., motor-driven systems such as compressors, fans, pumps, and materials handling and processing equipment). Motors used for cooling water circulation pumps and fans, however, are accounted for in process cooling end use. Other end uses of electricity for iron and steel manufacturing are less significant, but include nonprocess facility related end uses (e.g., facility heating, ventilation, and air conditioning (HVAC), facility lighting, cooking, office equipment, etc.) and other end uses.

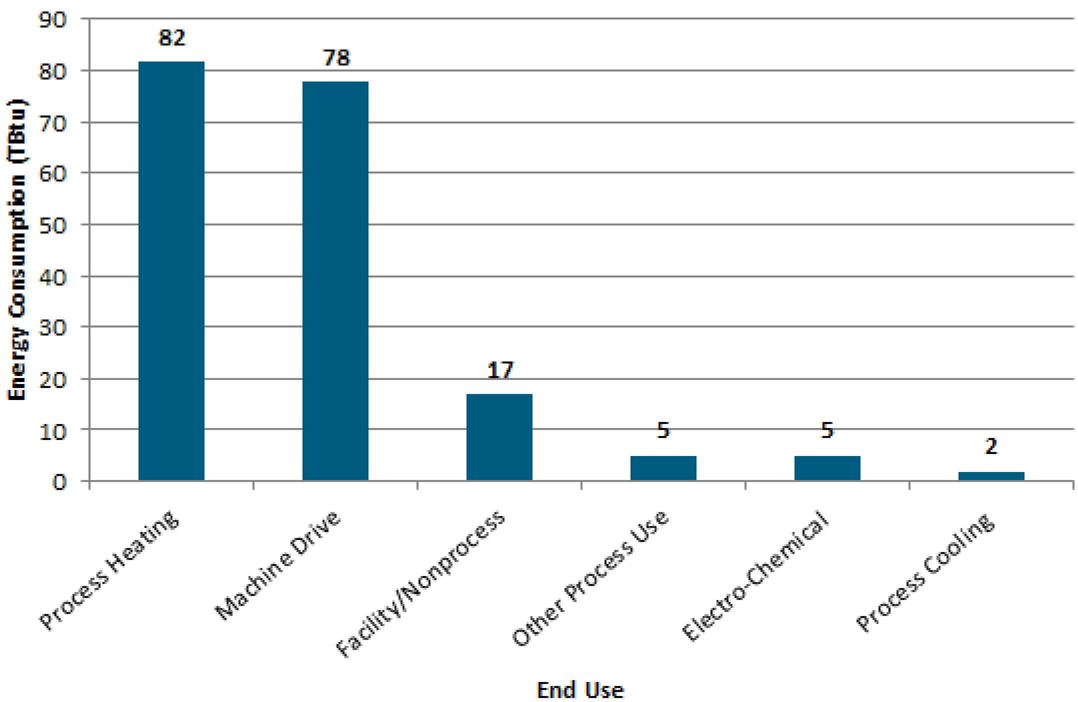


Figure 2-7. Electricity Consumption in the Iron and Steel Sector by End Use, 2010 *(DOE 2014)*

2.3.3. Steam

Figure 2-3 shows 8 TBtu of net steam entering iron and steel mills in 2010. The data presented is the *net amount*, which is the sum of purchases, generation from renewables, and net transfers. A larger amount of steam is generated onsite. Figure 2-4 shows that 161 TBtu of steam is consumed at the point of end use, including 152 TBtu of steam generated onsite (34 TBtu of purchased and generated steam is lost through distribution to end uses) (DOE 2014).

Figure 2-8 shows the breakdown of 127 TBtu of steam by end use in 2010 (DOE 2014). A majority of the offsite- and onsite-generated steam is used for process heating; other end uses for steam in iron and steel manufacturing include facility heating, ventilation, and air conditioning (HVAC), other process uses, machine driven equipment (i.e., steam turbines), , and other nonprocess end uses. Unlike fuel and electricity end use, steam end use is <u>not</u> reported in MECS. The end use distribution shown here was determined in the Energy Footprint analysis (DOE 2014) based on input from an industry-led working group.

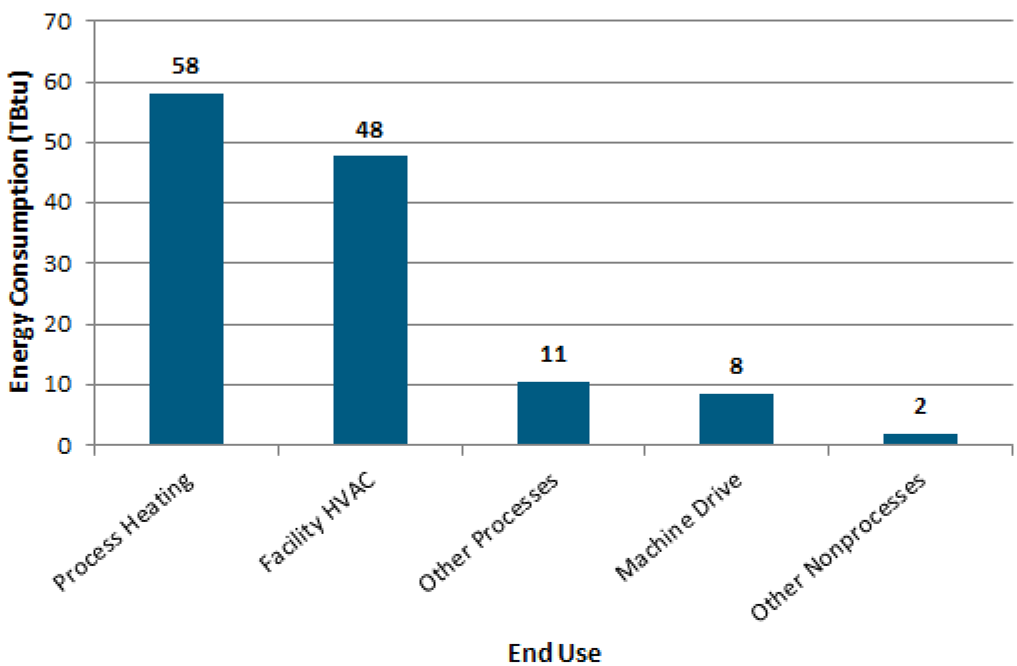


Figure 2-8. Steam Consumption in the Iron and Steel Sector by End Use, 2010 *(DOE 2014)*

3. Production Volumes in U.S. Iron and Steel Manufacturing

In this bandwidth study, six iron and steel processes were selected for individual analysis. Table 3-1 presents the U.S. production data of the six processes for the year 2010, unless otherwise noted.

Table 3-1. U.S. Iron and Steel Production Volumes for Processes Studied in 2010

Process	**Production** (1,000 tons)
Agglomeration	
Pelletizing [a]	39,728
Sintering [a]	5,759
Cokemaking [b]	9,292 (integrated only) 12,021 (integrated + offsite)
Ironmaking [c]	29,590
Steelmaking	
BOF	34,345
EAF	54,386
Casting (Continuous)	84,784
Rolled Products	
Heavy Shapes and Plates	14,899
Tin Plate and Products	2,791
Bar	14,128
Rod	4,213
Sheets and Strip	45,783

[a] Represents pellet and sinter consumption in steel mill blast furnaces; assumed to be produced domestically.

[b] The smaller value represents production of coke at integrated steel mills; the larger value represents total coke consumption including coke produced outside of integrated steel mills, e.g., merchant coke.

[c] Excludes limited production of ITmk3-produced iron nuggets.

Source: AISI 2011a.

The most energy intensive processes were selected for this study. Other, less intensive processes were added to the study to expand the representative coverage of the iron and steel sector as a whole. In general, the selection of processes was largely dependent on the availability of current production and energy consumption data.

The year 2010 was used for production values to correspond with the latest MECS data, which is also for 2010. Production data was gathered from the American Iron and Steel Institute (AISI), the leading source for information on steel production in North America. The AISI Statistical Summary is released annually and provides production data along with other statistical information.

4. Current Typical Energy Consumption for U.S. Iron and Steel Manufacturing

This Chapter presents the energy consumption data for individual iron and steel manufacturing processes and sector-wide in 2010. Energy consumption in a manufacturing process can vary for diverse reasons. The energy intensity estimates reported herein are representative of average U.S. iron and steel manufacturing; they do not represent energy consumption in any specific facility or any particular region in the United States.

4.1. Boundaries of the Iron and Steel Bandwidth Study

Estimating energy requirements for an industrial process depends on the boundary assumptions; this is especially true in the iron and steel industry. The key focus of this bandwidth study is energy consumption within the plant boundary, which is the *onsite* use of process energy (including purchased energy and onsite generated steam and electricity) that is directly applied to iron and steel manufacturing.

This study does not consider lifecycle energy consumed during raw material extraction, off-site treatment, and transportation of materials. Upstream energy, such as the energy required for processing and handling materials outside of the plant is also not included. To be consistent with previous bandwidth studies, feedstock energy and the energy associated with delivering feedstocks to the plant gate (e.g., producing, conditioning, and transporting feedstocks) are *excluded* from the energy consumption bands in this analysis.

4.2. Estimated Energy Intensity for Individual Processes

Energy intensity data are needed to calculate bands of energy consumption in this study. This Section presents the estimated energy intensities of the six processes studied.

The specific energy needed to make a ton of product can vary significantly between processes, and also between facilities. Energy intensity is a common measure of energy performance in manufacturing. Energy intensity is reported in units of energy consumption (typically Btu) per unit of manufactured product (typically short tons, tons, or metric tons) and, therefore, reported as million Btu per short ton (MMBtu/ton). Energy intensity estimates are available for specific equipment performance, process unit performance, or even plant-wide performance. Energy intensity can be estimated by process, both in the United States and other global regions, based on average, representative process and plant performance.

Appendix A1 presents the CT energy intensities and energy consumption for the six processes studied. **Table 4-1** presents a summary of the references consulted to identify CT energy intensity by process. Appendix A2 provides the references used for each process. Appendix A3 provides a breakdown of CT energy intensity by energy type. In cases where energy intensity is reported in terms of lower heating value LHV (or net calorific), a ratio of higher heating value HHV to LHV was used to convert to HHV. HHV conversions by fuel type for CT and SOA energy intensity are provided in Appendix A3.

Because the iron and steel sector is diverse, covering many products, a range of data sources were considered (see Table 4-1). In most cases, multiple references were considered for each process.

Many sources were consulted in order to determine the energy intensity of the six processes selected for study. Each iron and steel facility is unique and steel is produced in different scales and by different processes; thus, it is difficult to ascertain an exact amount of energy necessary to produce a certain volume of a product. For instance, ore quality differs in chemical composition and iron content which affects the amount of energy needed for the reduction reaction to produce iron. Plant size can also impact operating practices and energy efficiency. Higher efficiency is often easier to achieve in larger plants. Consequently, the values for energy intensity provided should be regarded as estimates based on the best available information.

Table 4-1. Published Sources Reviewed to Identify Current Typical Energy Intensities for Processes Studied

Source	Description
AISI 2011a	Summary for steel industry statistics, published by the American Iron and Steel Institute. The report for year 2010 is referenced.
EIA 2013a	Manufacturing Energy Consumption Survey data released by EIA every four years; this data comes from a survey that is taken by U.S. manufacturers. The most recent year for which MECS data is published is 2010. The data is scaled up to cover the entirety of U.S. manufacturing and for individual manufacturing subsectors.
EIA 2013b	Includes documentation for the model EIA utilizes to project industrial energy use.
Energetics 2000	The *Energy and Environmental Profile of the U.S. Iron and Steel Industry*, prepared by Energetics and published by DOE in 2000 provides a detailed breakdown (including total processing energy) for key process areas.
EPA 2012	This 2012 report by the Environmental Protection Agency (EPA) provides a list of energy efficiency improvement measures for use by the iron and steel industry.
IEA 2007	This 2007 report by the International Energy Agency (IEA) includes a chapter focused on iron and steel.
IPPC 2013	While this bandwidth analysis focuses on the U.S.; specific European energy consumption values or ranges are listed for select processes in this report.
NRC 2007	Provides graphics showing actual consumption at multiple Canadian plants; also addresses best available technologies.
Stubbles 2000	This report details energy consumption in the U.S. steel industry for various processes.

When available, energy intensity values specific to the United States were used in calculating CT energy consumption for the six select processes. For certain processes, the energy intensity data was only available for non-U.S. regions, such as Canada or Western Europe. This data was used with the understanding that energy consumption can vary from country to country and from region to region. Energy intensity for the six process areas studied is summarized in Appendix A1 and detailed by process area and energy type in Appendix A3. In cases where energy intensity is reported in terms of lower heating value LHV (or net calorific), a ratio of higher heating value HHV to LHV is used to convert to HHV. HHV conversions by fuel type for CT and SOA energy intensity are provided in Tables A3-27 and A3-28.

4.2.1. Ore Agglomeration

Pelletizing energy intensity is dependent on the type and quality of iron ore and whether limestone is used to produce fluxed pellets. Pelletizing is conducted primarily at the mining site in the U.S. (NAICS 212210 Iron Ore Mining), and thus energy requirements for pelletizing are not included in U.S. government steel industry energy data. Limited data is available regarding current energy use in pelletizing. The European Union, in their Best Available Techniques reference document, reports a value of approximately 0.70 MMBtu/ton (0.82 GJ/tonne) for pelletizing using hematite ore (IPPC 2013). It should be noted that energy requirements may not be comparable to U.S. values due to differences in ores; or reflect other ore processing requirements. Also, magnetite pelletizing energy consumption would be lower, as magnetite oxidation provides a large portion of the energy required. As previously indicated, pelletizing energy is not included in the actual bandwidth calculations but this value is provided for reference.

The sintering energy intensity estimate also is derived from IPPC 2013. The estimated energy intensity of 1.32 MMBtu/ton sinter (1.54 GJ/tonne) is somewhat lower than previous values reported by others such as the International Energy Agency, which had reported a range of 1.29-1.72 MMBtu/ton sinter (1.50-2.00 GJ/tonne) (IEA 2007). However, overall energy consumption for sinter production at U.S. plants based on this value totals less than 10 TBtu, less than 1% of steel industry energy use, assuming all sinter consumption is domestically produced.

4.2.2. Cokemaking

Cokemaking energy intensity is derived from both values provided by AISI in their annual statistical report (AISI 2011a) and estimates from EIA 2013b. It should be noted that U.S. cokemaking energy values, estimated to be 3.83 MMBtu/ton coke (4.45 GJ/tonne), are specific to cokemaking facilities at integrated steel plants. In addition to process energy requirements, a moderate amount of energy ends up in cokemaking chemical by-products. Merchant coke plants, which on the whole are newer, are not accounted for in the AISI statistical report and fall under the petroleum and coal products industry within NAICS (324199 All Other Petroleum and Coal Products Manufacturing). The estimated value is also comparable to individual plant values listed in NRC 2007.

4.2.3. Ironmaking

Blast furnace ironmaking energy intensity is also derived from AISI statistical report data along with other estimates from the IPPC report (AISI 2011a, IPPC 2013). Blast furnace ironmaking energy intensity is estimated at 11.72 MMBtu/ton of hot metal (13.63 GJ/tonne). With many iron and steel plants operating at less than full capacity in 2010, this value may be slightly higher than normal.

While the traditional direct reduction route was not used in the U.S. in 2010 and data was not available for the limited production via the ITmk3® process (thus no calculated current typical), the IEA has reported that both of the gas-based direct reduction processes use around 8.9 MMBtu/ton (10.4 GJ/tonne) natural gas; with some additional electricity use required (80-90 kWh/tonne) which could be cogenerated onsite (IEA 2007).

4.2.4. Steelmaking

Steelmaking in the basic oxygen furnace (BOF) with subsequent refining operations (ladle metallurgy, vacuum treatment, slag management, etc.) can have a fairly wide range of energy use. Energy intensity for BOF steelmaking is estimated at 0.58 MMBtu/ton of liquid steel (0.67 GJ/tonne) (IPPC 2013). Of note in 2010, it was estimated that approximately 24% of U.S. BOF inputs came from scrap and not pig iron (USGS 2012c). Also, Stubbles noted that while recovery of chemical energy in the off-gas from BOF operations is possible, the economics of doing so in the U.S. were not attractive at the time of his report (Stubbles 2000). A small amount of carbon feedstock remains in the liquid steel.

Steelmaking in electric arc furnaces (EAFs) also can have a fairly wide range of energy use, and also differences in fuel mix. Overall, scrap accounts for over 90% of metal inputs, with lesser amounts of pig iron and imported direct-reduced iron (DRI) accounting for the remainder. In 2010, it was estimated that approximately 91% of U.S. EAF inputs came from scrap (USGS 2012c). While steelmakers are increasing the share of chemical energy, electricity still generally accounts for the largest share of energy consumption in the EAF. Thus for individual furnaces, a range of both chemical energy and total energy is found; and many of the smaller furnaces are significantly less efficient. For 2010, final energy intensity for EAF steelmaking is estimated at 1.86 MMBtu/ton liquid steel (2.16 GJ/tonne) using data from the Association for Iron and Steel Technology (AIST 2011). Stubbles (2000) noted that an estimated additional 100 kilowatt hours (kWh) are used for ladle heating, cranes, and other auxiliary services at EAF plants; these electric-consuming operations may not be included in the AIST-based estimates.

4.2.5. Casting and Rolling

In 2010, over 97% of raw steel in the U.S. was continuously cast, which consumes about 0.19 MMBtu/ton (0.22 GJ/tonne), based on the average of values from NRC 2007. Traditional hot rolling operations consume an estimated average of 2.58 MMBtu/ton (3.00 GJ/tonne) – this is considering both hot strip and plate as well as section mills from NRC 2007. Cold rolling mill operations consume an estimated 3.48 MMBtu/ton (4.05 GJ/tonne) (EIA 2013b), though this number will differ whether rolling strip, bar, or wire. Tinplate and galvanized steel would have higher energy requirements, but values are not estimated in this report.

4.3. Calculated Current Typical Energy Consumption for Individual Processes

Table 4-2 presents the calculated onsite CT energy consumption for the six processes studied. To calculate onsite CT energy consumption, energy intensity for each process (presented initially in Appendix A1) is multiplied by the 2010 production data (presented initially in Table 3-1 and also in Appendix A1). Feedstock energy is excluded from the consumption values. The CT energy consumption for these six processes is estimated to account for 822 TBtu of onsite energy, or 82% of the 999 TBtu of sector-wide onsite energy use in 2010. Appendix A1 also presents the onsite CT energy consumption for the six processes individually.

Calculated primary CT energy consumption by process is also reported in Table 4-2. Primary energy includes offsite energy generation and transmission losses associated with electricity and steam from offsite sources. To determine primary energy, the net electricity and net steam portions of sector-wide onsite energy are scaled to account for offsite losses and added to onsite energy (see the footnote in Table 4-2 for details on the scaling method).

Table 4-2. Calculated U.S. Onsite Current Typical Energy Consumption for Processes Studied in 2010 with Calculated Primary Energy Consumption and Offsite Losses					
Process	**Energy Intensity** (MMBtu/ton) [GJ/tonne]	**Production** (1,000 ton/year)	**Onsite CT Energy Consumption, Calculated** (TBtu/year)	**Offsite Losses, Calculated** (TBtu/year)[2]	**Primary CT Energy Consumption, Calculated** (TBtu/year)
Integrated Mills					
Agglomeration Pelletizing [b] Sintering	 0.70 [0.82] 1.32 [1.54]	 39,728 5,759	 - 8	 - 1	 - 9
Cokemaking [c]	3.83 [4.46]	9,292	36	2	37
Ironmaking Blast Furnace [d]	11.72 [13.63]	29,590	337	14	351
Steelmaking BOF [e]	0.58 [0.67]	34,345	20	8	28
Mini Mills					
Ironmaking Direct Reduction [f]	9.17 [10.71]	*negligible in 2010*	-	-	-
Steelmaking EAF [e]	1.86 [2.16]	54,386	101	155	256
Integrated and Mini Mills					
Casting	0.19 [0.22]	84,784	16	12	28
Rolling Hot Cold [d]	 2.58 [3.00] 3.48 [4.05]	 84,784 27,710	 219 86	 63 59	 282 145
Total for Processes Studied			**822**		

Current Typical (CT)

[1] Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and offsite steam transmission losses are estimated to be 10% (DOE 2007, Technical Guidelines Voluntary Reporting of Greenhouse Gases and EPA 2011, ENERGY STAR Performance Ratings Methodology).

References for production data and energy intensity data are provided by process in Appendix A2. The other values are calculated as explained in the text.

4.4. CURRENT TYPICAL ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

In this Section, the CT energy consumption estimates for nine processes studied are provided.

Table 4-3 presents the onsite CT energy consumption by process and sector-wide for U.S. iron and steel manufacturing. The six processes studied account for 82% of all onsite energy consumption by the U.S. iron and steel sector in 2010. As shown in the last column of Table 4-3, the percentage of coverage of the processes studied is calculated. This indicates how well the processes studied represent total sector-wide MECS-reported energy. The overall percentage of coverage for the processes studied (82%) is used later in this study to determine the extrapolated total sector-wide SOA, PM, and TM energy consumptions.

Table 4-3 also presents CT primary energy consumption by process. Primary energy is calculated from onsite CT energy consumption databased on an analysis of MECS data (DOE 2014), with scaling to include offsite electricity and steam generation and transmission losses (DOE 2014).

Table 4-3. Onsite and Primary Current Typical Energy Consumption for the Nine Processes Studied and Sector-Wide in 2010, with Percent of Sector Coverage			
Process	**Onsite CT Energy Consumption, calculated** (TBtu/year)	**Primary CT Energy Consumption, calculated*** (TBtu/year)	**Percent Coverage** (Onsite CT as a % of Sector-wide Total)**
Integrated Mills			
Agglomeration Pelletizing [a] Sintering	 - 8	 - 9	 - 1%
Cokemaking [b]	36	37	4%
Ironmaking Blast Furnace [c]	 337	 351	 34%
Steelmaking BOF [d]	 20	 28	 2%
Mini Mills			
Ironmaking Direct Reduction [e]	 -	 -	 -
Steelmaking EAF [d]	 101	 256	 10%
Integrated and Mini Mills			
Casting	16	28	2%
Rolling Hot Cold [c]	 219 86	 282 145	 22% 9%
Total for Processes Studied	**822**	**1,135**	**82%**
All Other Processes	176	213	18%
Total for Iron and Steel Sector-wide	**999*** **	**1,348*** **	**100%**

Current typical (CT)

** Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and offsite steam transmission losses are estimated to be 10% (DOE 2007, Technical Guidelines Voluntary Reporting of Greenhouse Gases and EPA 2011, ENERGY STAR Performance Ratings Methodology).*

*** Calculated by dividing the onsite CT energy consumption for the processes studied by sector-wide onsite CT energy consumption (999 TBtu).*

**** Source for sector-wide values is DOE 2014.*

[a] The pelletizing estimate is for a single facility, Pelletizing is not included in iron and steel mill energy consumption totals as this process takes place offsite.

[b] Cokemaking onsite and primary energy excludes approximately 300 TBtu of nonfuel feedstock coke.

[c] Blast furnace and cold rolling onsite and primary energy consumption each exclude 10 TBtu of nonfuel feedstock natural gas.
[d] In 2010, 24% of BOF inputs and 91% of EAF inputs came from scrap.

[e] As there was limited DRI production in the U.S. in 2010, the CT energy consumption values are shown for illustration only.

5. State of the Art Energy Consumption for U.S. Iron and Steel Manufacturing

As plants age, manufacturing processes and equipment are updated and replaced by newer, more energy-efficient technologies. This results in a range of energy intensities among U.S. iron and steel mills. Iron and steel mills will vary widely in size, age, efficiency, energy consumption, and types and amounts of products. Modern iron and steel mills can benefit from more energy-efficient technologies and practices.

This Chapter estimates the energy savings possible if U.S. iron and steel mills adopt the best technologies and practices available worldwide. State of the art (SOA) energy consumption is the minimum amount of energy that could be used in a specific process using existing technologies and practices.

5.1. Calculated State of the Art Energy Consumption for Individual Processes

Appendix A1 presents the onsite SOA energy intensity and consumption for the six processes considered in this bandwidth study in alphabetical order. The SOA energy consumption for each iron and steel manufacturing process is calculated by multiplying the SOA energy intensity for each process by the relevant production (all relevant data are presented in Appendix A1).

The onsite SOA energy consumption values are the net energy consumed in the process using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a pound of product. The onsite SOA energy consumption estimates exclude feedstock energy.

Table 5-1 presents the published sources referenced to identify the SOA energy intensities.

Table 5-1. Published Sources Referenced to Identify State of the Art Energy Intensities for Nine Select Processes

Source Abbreviation	Description
Energiron 2013	*Energiron: The Innovative Direct Reduction Technology*, Information on the direct reduction process
Giavani et al. 2012	*Consteel Evolution*TM *– The Second Generation of Consteel Technology*, Information regarding a specific EAF technology, the Consteel Evolution
IPPC 2013	*Best Available Techniques (BAT) Reference Document for Iron and Steel Production*, European Commission. Integrated Pollution Prevention and Control. While this bandwidth analysis focuses on the U.S., this report lists specific European energy consumption values or ranges for select processes
LBNL 2008	This Lawrence Berkeley National Laboratory report, *World Best Practice Energy Intensity Values for Selected Industrial Sector*, provides best practice values for many industrial processes, including iron and steelmaking.
NRC 2007	*Benchmarking Energy Intensity in the Canadian Steel Industry*, Natural Resources Canada. This report provides graphics and data for a variety of processes using best available technologies (energy-saving technologies that are both commercially available and economically attractive); the report also provides actual consumption at multiple Canadian plants.

NRC 2007 is heavily referenced in determining SOA intensity estimates. Technologies employed are a deviant of the International Iron and Steel Institute (IISI) EcoTech Plant which includes energy-saving technologies that are both commercially available and economically attractive, with additional inclusion of certain technologies that, while less economically attractive, were being utilized commercially in Canadian steel plants.

Technologies identified that are in a pre-commercial stage of development or that are extremely expensive were not considered in the SOA analysis (instead they were considered in Chapter 6 on the practical minimum (PM) energy consumption).

5.1.1. Ore Agglomeration

NRC 2007 does not include sintering. For sinter plants, the state of the art value of 1.27 MMBtu/ton (1.47 GJ/tonne) of sinter is derived from LBNL 2008 and IPPC 2013 has numbers that are very comparable.

5.1.2. Cokemaking

The value of 3.37 MMBtu/ton (3.92 GJ/tonne) of coke from NRC 2007 employs technologies including coke dry quenching, enhanced combustion control, and high-pressure ammonia liquor spray aspiration, among others.

5.1.3. Ironmaking

For integrated plants utilizing blast furnaces, the value of 11.13 MMBtu/ton of hot metal (12.94 GJ/tonne) from NRC 2007 includes technologies for hot stoves including waste gas heat recovery, oxygen enrichment of cold blast, high efficiency stoves, and combustion control, and top gas recovery turbine for the blast furnace.

While direct iron reduction (DRI) was not employed extensively in the U.S. in 2010, this will be changing in 2013 with the expected opening of a Nucor plant currently under construction in Louisiana. Gas-based DRI processes are generally the most efficient, with Midrex and Energiron (joint venture between Tenova, Danieli, and HYL) shaft furnaces accounting for the majority of gas-based plants. Data from Energiron indicate best values of 8.3 MMBtu/ton (9.7 GJ/tonne). CHP is an option to provide electricity demand at these plants as well.

5.1.4. Steelmaking

For integrated plants the value of -0.30 MMBtu/ton (-0.35 GJ/tonne) from NRC 2007 includes the basic oxygen furnace and secondary refining: gas recovery with dry gas cleaning system, steam recovery, ladle management, and bottom stirring.

For EAF steelmaking, two values are provided; one from NRC 2007 which utilizes more electricity; and also Consteel Evolution which has greater amount of fuel use and extensive scrap or charge preheating. Oxygen production is also assumed to utilize state of the art technology. Depending on whether one is evaluating final or primary energy as measure of efficiency will lead to different technology use. For NRC 2007, final energy intensity is calculated at 1.62 MMBtu/ton (1.89 GJ/tonne). For Consteel Evolution, with a lower share of electricity use, final energy intensity is calculated at 1.79 MMBtu/ton (2.08 GJ/tonne) but has a lower primary energy intensity. The value from NRC 2007 is used for calculations for consistency while the Consteel Evolution value is provided for comparison purposes.

5.1.5. Casting and Rolling

For continuous casting, the state of the art value is estimated at 0.05 MMBtu/ton (0.06 GJ/tonne) (NRC 2007). An estimate for thin slab casting and rolling energy intensity is also provided in Appendix A3, although not referenced in the energy consumption analysis; LBNL 2008 estimates the best value for this slab casting to be MMBtu/ton (0.20 GJ/tonne).

For a traditional hot strip mill, the best value is estimated at 1.43 MMBtu/ton (1.66 GJ/tonne) (NRC 2007), with variations for section mills (whether the product is rod, bar, or heavy) as depicted in Appendix Table A3-17. The average value of 1.60 MMBtu/ton (1.86 GJ/tonne) is used for hot rolling overall. Technologies employed to achieve the hot rolling values include recuperation and heat recovery, furnace controls, transfer bar edge heaters, energy efficient burners, and high efficiency motors.

For cold rolling mills, LBNL 2008 estimates best value for final energy of 1.42 MMBtu/ton (1.645 GJ/tonne) inclusive of pickling, cold rolling, and annealing.

5.1.6. Other Estimates of SOA Savings

DOE AMO conducted energy saving assessments at 53 plants in NAICS code 3311 between 2006 and 2011. The assessments focused primarily on process heating and steam applications, with the vast majority of assessments occurring at EAF plants. On average, existing opportunities identified in these assessments were predicted to save 6.2% of current energy consumption (DOE 2013).

EPA published a report in September 2012 (EPA 2012) that describes available and emerging technologies for reducing greenhouse gas emissions in the iron and steel industry; AISI provided input on technical feasibility and cost-effectiveness for various technology options. Technical details of energy efficiency measures are provided for specific industry processes, along with information on technology readiness and estimated payback. Overall savings potential is not provided in this report.

Lawrence Berkeley National Laboratory also published a study (separate to the study referenced in Table 5-1) that identifies energy efficiency improvement and cost saving opportunities in the iron and steel sector. This ENERGY STAR guide provides information on a range of measures, including crosscutting energy management program savings, energy systems savings (steam, motors, pumps, fans, compressed air), and process specific savings. Individual savings and paybacks are provided for some measures, combined savings is not available.

5.2. State of the Art Energy Consumption By Process and Sector-wide

Table 5-2 presents the onsite SOA energy consumption for the six U.S. iron and steel processes studied. In this table, the SOA energy consumptions for the processes studied are summed and extrapolated to provide a sector-wide onsite SOA energy consumption. Table 5-2 also presents the onsite SOA energy savings, or the *current opportunity*. The SOA energy savings is also expressed as a percent in Table 5-2. This is also shown in Figure 5-1. It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. In Figure 5-1, the percent savings is the percent of the overall energy consumption bandwidth, with CT energy consumption as the upper benchmark and TM as the lower baseline. In Figure 5-2, the *current* energy savings opportunity is shown in terms of TBtu/year savings for each process. The pie chart in Figure 5-2 captures the blue portions of the bar chart shown in Figure 5-1. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is casting at 74% energy savings; the greatest *current opportunity* in terms of TBtu savings is hot rolling at 83 TBtu per year savings.

To extrapolate the sector-wide data presented in Table 5-2 and Figure 5-1, the SOA energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire subsector (82%, as shown in Table 4-3). Percent coverage is the ratio of the sum of all the CT energy consumption for the individual processes studied to the CT energy consumption for the subsector provided by MECS (see Table 4-3). The extrapolated number is the estimated SOA energy consumption for the entire subsector. The SOA energy consumption for the remainder of the iron and steel sector (i.e., all processes that are not included in the six processes studied) was calculated by subtracting the total for the processes studied from the sector-wide total. These additional processes are together referred to as All Other Processes in Table 5-2).

Table 5-2 also presents the SOA energy savings percent. To calculate the onsite SOA energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with SOA technologies and practices compared to CT energy consumption, considering that the TM may not be zero. As will be explained in Chapter 7, the TM reaction energy for one iron and steel manufacturing processes is a negative value. When comparing energy savings percent from one process to another, the absolute savings is the best measure of comparison. The equation for calculating onsite SOA energy savings percent is:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

Table 5-2. Onsite State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for the Processes Studied and Sector-Wide				
Process	**Onsite CT Energy Consumption** (TBtu/year)	**Onsite SOA Energy Consumption** (TBtu/year)	**SOA Energy Savings**† (CT-SOA) (TBtu/year)	**SOA Energy Savings Percent** (CT-SOA)/ (CT-TM)*
Integrated Mills				
Agglomeration Sintering	8	7	<1	17%
Cokemaking	36	31	4	22%
Ironmaking Blast Furnace	337	329	8	9%
Steelmaking BOF	20	-10	30	72%
Mini Mills				
Steelmaking EAF	101	88	13	33%
Integrated and Mini Mills				
Casting**	16	4	12	74%
Rolling** Hot Cold	 219 86	 136 39	 83 47	 38% 55%
Total for Processes Studied	822	625	197	39%
All Other Processes	176	134	42	39%
Total for Iron and Steel Sector-wide	999	759***	240	39%

Current typical (CT), State of the art (SOA)

† SOA energy savings is also called Current Opportunity.

** SOA energy savings percent is the SOA energy savings opportunity from transforming iron and steel manufacturing processes. Energy savings percent is calculated using TM energy consumption shown in Table 7-2 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT- SOA)/(CT- TM)*

*** Does not include thin slab casting, which also replaces rolling; thin slab casting is not included in the subtotal or total values.*

**** The sector-wide SOA energy consumption was an extrapolated value, calculated by dividing the total onsite SOA energy consumption for the processes studied by the overall percent coverage from Table 4-3 (82%).*

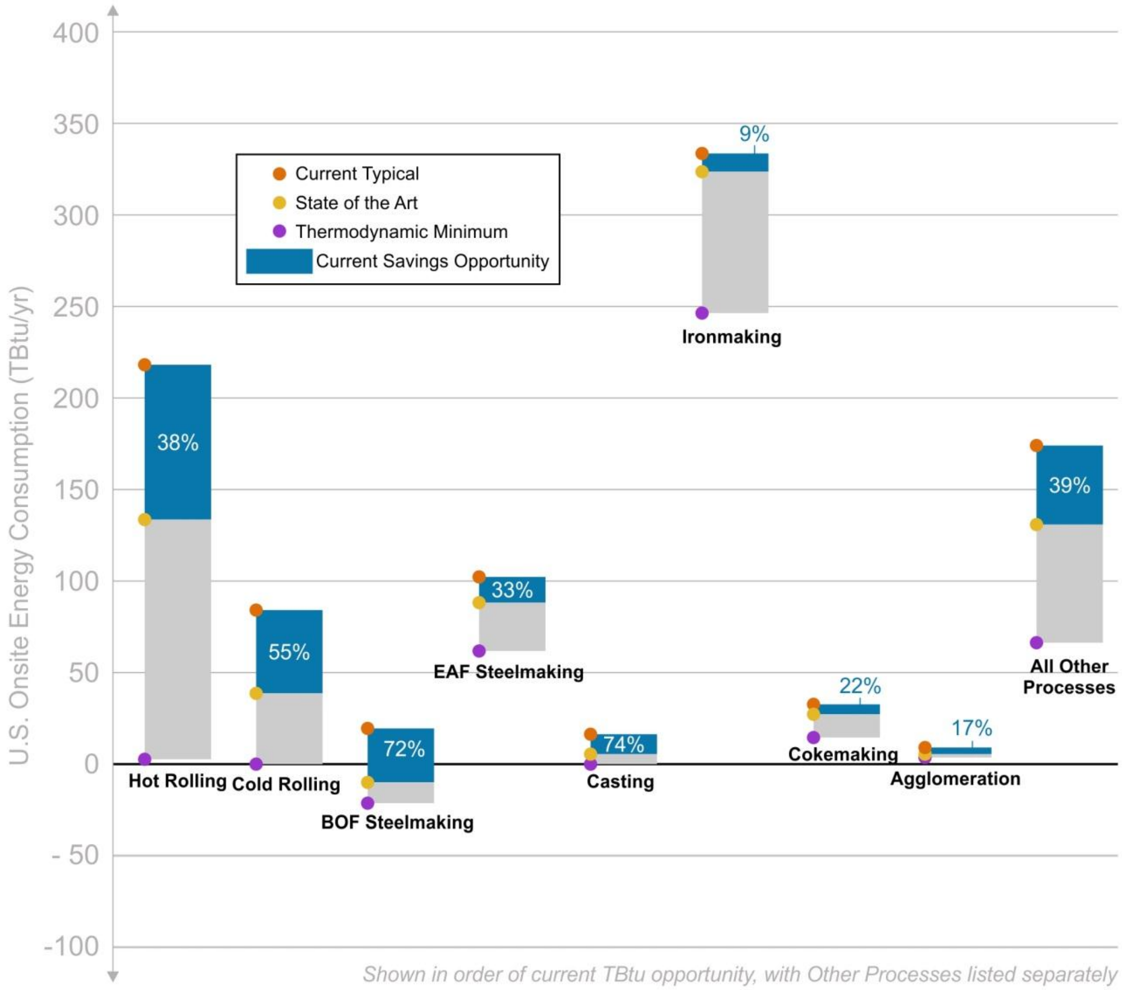


Figure 5-1. Current Opportunity Energy Savings Bandwidths for Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

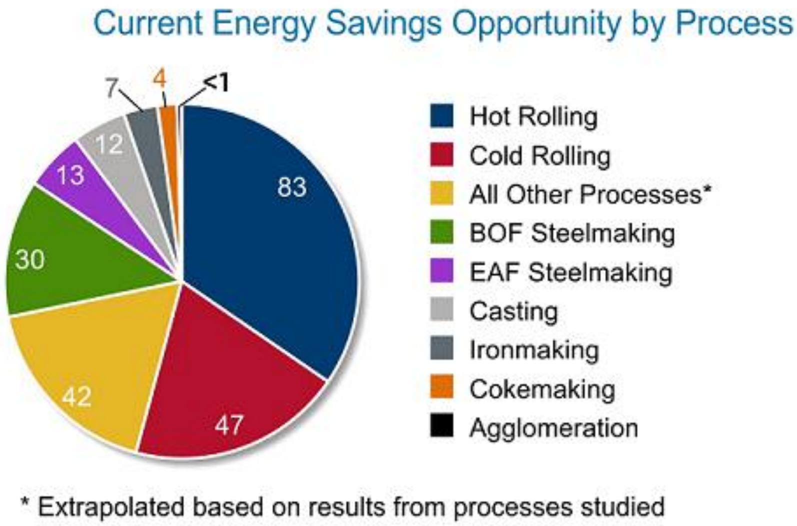


Figure 5-2. Current Energy Savings Opportunity by Process

5.2.1. Comparing State of the Art and Current Typical Energy Data

If all U.S. iron and steel mills were able to attain onsite SOA energy intensities, it is estimated that 197 TBtu per year of energy could be saved from the six processes alone, corresponding to a 39% energy savings sector-wide. This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings, it is not inferred that all existing mills could achieve these state of the art values or that the improvements would prove to be cost effective in all cases. The interactivity between savings measures is also not specifically considered. For instance, increased use of pulverized coal in the blast furnace would reduce coke requirements and associated energy use.

Noting that the energy values described in Table 5-2 are based on 2010 production values and processing routes, it is important to remember that these values are not static, but dynamic in nature. As previously discussed, steel mills operated at less than optimal capacity in 2010, negatively impacting energy efficiency to some extent as shown in an AISI chart depicting energy intensity over time as shown in Figure 5-3. In 2013, a more efficient DRI plant opened in the U.S. and the ITmk3® process is also now in commercial operation at one U.S. plant. As the supply of recycled steel (scrap) is ever-changing, the quantity of production required from virgin materials will continue to depend on market and economic conditions.

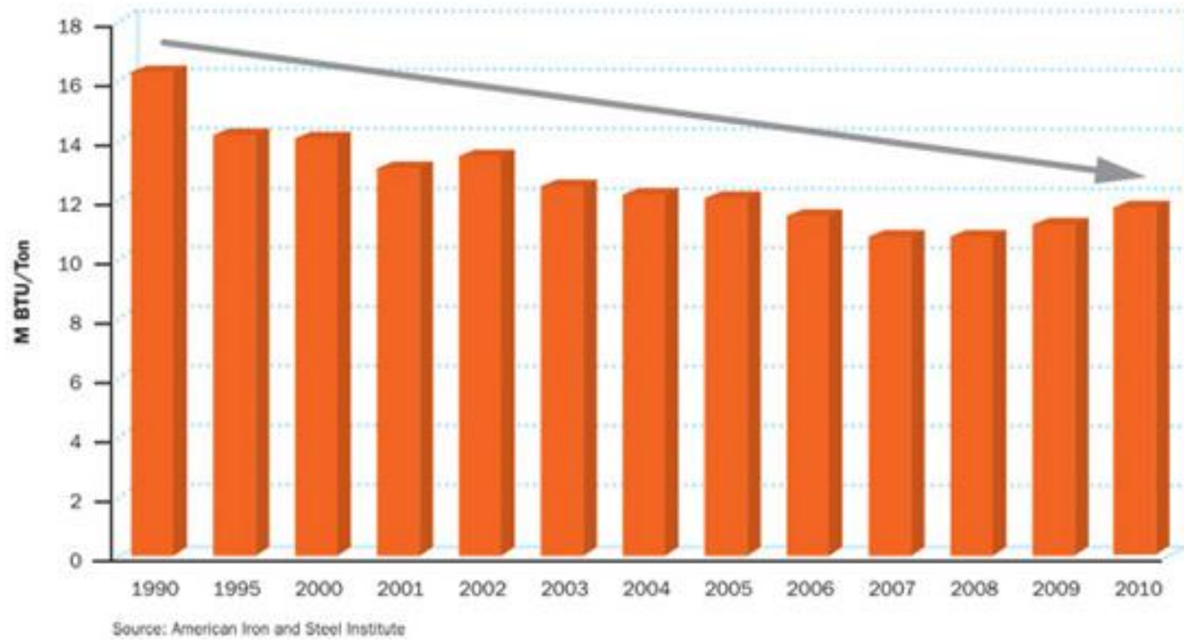


Figure 5-3. Steel energy intensity between 1990 and 2010 *(AISI 2012)*

6. Practical Minimum Energy Consumption for U.S. Iron and Steel Manufacturing

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway that can be used to make iron and steel products in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. iron and steel manufacturing. In this Chapter, the R&D energy savings made possible through R&D advancements in iron and steel manufacturing are estimated. Practical minimum (PM) is the minimum amount of energy required assuming the deployment of applied R&D technologies under development worldwide.

6.1. R&D in the Iron and Steel Industry

Investing in R&D in the short term ensures long term future prosperity. Increasing the energy efficiency of an existing process often requires capital investment and taking manufacturing equipment offline to perform the necessary updates. The risks and rewards of this type of business decision needs to be clearly assessed. As the iron and steel industry is relatively mature, most iron and steel companies (along with other primary metal producers) typically allocate less than 1% of their annual sales toward R&D (NSF 2007).

Extensive efforts have been undertaken to develop alternative approaches to making iron and steel in particular, with potential to reduce both energy intensity and carbon emissions. Various groups including the European ULCOS (Ultra–Low Carbon Dioxide Steelmaking) consortium, Hatch, and others have conducted efforts to model the energy requirements and carbon emissions from alternative ore-based process routes. One way processing route options have been depicted is within a triangle framework, with carbon, hydrogen, and electrons representing the three vertices, as can be seen in Figure 6-1. Various approaches are shown on the figure which would shift iron and steel production away from coal (decarbonizing), where carbon would be replaced by hydrogen or electricity in processes such as hydrogen reduction or electrolysis of iron ore.

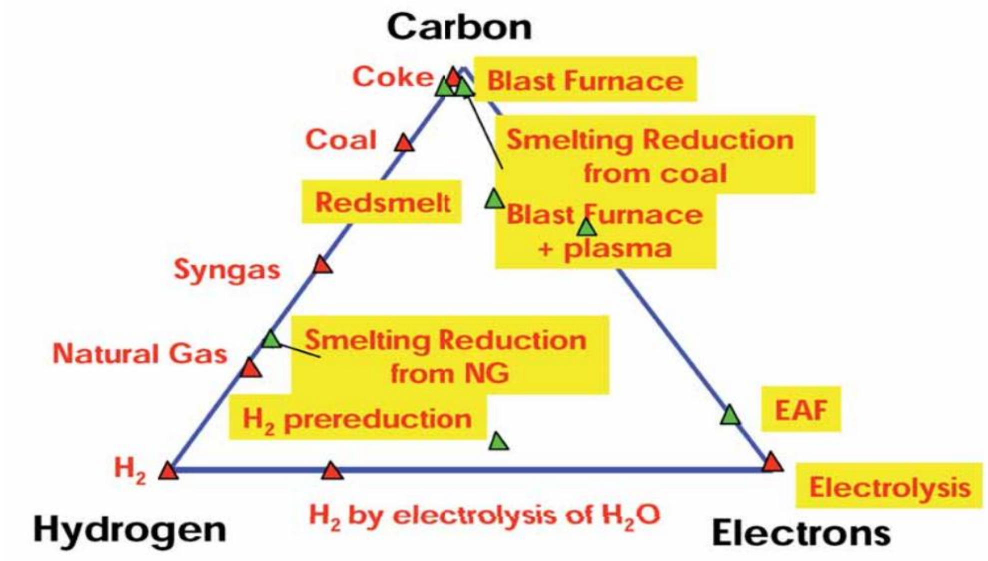


Figure 6-1. Steel Triangle Processing Route Framework *(Sadoway 2008)*

6.2. Calculated Practical Minimum Energy Consumption for Individual Processes

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific iron and steel process assuming that the most advanced technologies under research or development around the globe are deployed.

R&D progress is difficult to predict and potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a broad search of R&D activities in the iron and steel industry was conducted. A large number and range of potential technologies were identified.

The focus of this study's search was applied research, which was defined as investigating new technology with the intent of accomplishing a particular objective. Basic research, the search for unknown facts and principles without regard to commercial objectives, was not considered. Many of the technologies identified were disqualified from consideration due a lack of data from which to draw energy savings conclusions.

Appendix A1 presents the onsite PM energy consumption for the six processes considered in this bandwidth study. The PM energy consumption for each process is calculated by multiplying the estimated PM energy intensity for each process by the process's 2010 production volume (the energy intensity and production data are also presented in Appendix A1).These values exclude feedstock energy. The lower limit for onsite PM energy intensity and onsite PM energy consumption are presented in Appendix A1.The upper limit of the PM range is assumed to be the SOA energy consumption. The PM energy consumption for each process is expressed as a range because the energy savings impacts are speculative and based on unproven technologies.

Table 6-1 presents the key sources consulted to identify PM energy intensities in iron and steel manufacturing. Additionally, numerous fact sheets, case studies, reports, and award notifications were referenced; a more detailed listing of references is provided in Appendix A4 (Table A4 and References for Table A4).

Table 6-1. Key Published Sources Reviewed to Identify Practical Minimum Energy Intensities for Select Processes

Reference Abbreviation	Source
Birat et al. 2009	"The "CO_2 Tool": CO_2 emissions & energy consumption of existing & breakthrough steelmaking routes." Birat, J.-P., Lorrain, J.-P., de Lassat, Y.
Birat et al. 1999	"CO_2 Emissions and the Steel Industry's available Responses to the Greenhouse Effect." Birat, J.-P., Vizioz, J.-P., de Lassat, Y., Schneider, M., & Jeanneau, M.
Energetics 2005	*Steel Industry Marginal Opportunity Study.* Energetics, Inc. for U.S. Department of Energy, Industrial Technologies Program. 2005.
Gordon et al. 2010	Ironmaking Technology Selection for Site Specific Conditions. Gordon, Y., Freislich, M., & Els, J.
LBNL 2013	*Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry*. Hasanbeigi, A., Price, L., & Arens, M.
Sadoway 2008	"Electrochemical Pathways Towards Carbon-free Metals Production." Sadoway, D.R. Presentation.
UNIDO 2010	*Global Technology Roadmap for CCS in Industry: Steel Sectoral Report.* Birat, J.P.

Numerous fact sheets, case studies, reports, and award notifications were referenced. Details of all of the practical minimum sources consulted can be found in Appendix A4.

Appendix A4 presents details on the R&D technologies that were selected and used to estimate the PM energy intensities. Energy savings from R&D advancements were directly estimated for the six processes. In Appendix A4, technologies are aligned with the most representative process. Some of the technologies have applicability to more than one process (e.g., are crosscutting).

Analysis of the range of energy savings offered by groups of technologies is complicated in that the savings offered by multiple technologies may or may not be additive. Each technology contributes discrete or compounding savings that increase the ultimate savings of the group and some energy savings may be duplicative. As a result, all values are presented as sourced from the literature and energy savings were not aggregated for multiple technologies. A separate study of the individual technologies would be necessary to verify and validate the savings estimates and interrelationships between the technologies. If more than one technology was considered for a particular process, the technology that resulted in the lowest energy intensity was conservatively selected for the PM energy intensity.

R&D in some process areas is more broadly applicable, such as utility/power generation improvements and crosscutting technologies. Cross-cutting technologies applied during the PM analysis included new high-temperature, low-cost ceramic media for natural gas combustion burners, advanced energy and water recovery technology from low-grade waste heat, and control systems for recycling steel residues. The estimated energy savings from crosscutting improvements were assumed to be applicable to all six processes studied. To calculate PM energy consumption, the CT energy intensity and TM energy intensity were multiplied by the combined estimated savings for crosscutting improvements (1%-16%) and subtracted from the CT energy consumption.

In Appendix A4, the range of technologies considered offer a corresponding range of estimated energy savings. Brief descriptions of the technologies are followed by reported savings in terms of dollars, Btu, and percent savings. The technology developers' estimated savings were taken at face value and adjusted to represent the overall average energy savings potential.

For each technology, Appendix A4 presents a brief explanation of the energy savings and a summary of adjustments necessary to determine the overall average energy savings potential and PM energy intensity. Research savings are speculative in nature. The energy savings will vary depending on the source; they can be reported in terms of primary energy savings, plant-wide energy savings, process energy savings, or energy-type savings. In each case, the reported energy savings were adjusted to determine PM energy intensity.

6.2.1. Weighting of Technologies

The technologies described in Appendix A4 can be weighted differently depending on the audience. Plant managers may primarily be interested in productivity and quality implications; business managers may primarily be interested in relative cost and payback; technology investors may primarily be interested in market impact, technology readiness, and development risk factors; and government regulators may primarily be interested in environmental impacts. Each factor plays heavily into R&D investment considerations.

Appendix A5 (Table A5) considers how to weigh these various perspectives. Six technology weighting factors were considered for each technology:

- A Technology Readiness
- B Market Impact
- C Relative Cost and Savings Payback
- D Technical Risk
- E Productivity/Product Quality Gain
- F Environmental Impacts

Appendix A5 (Table A5) presents the PM technology weighting factors that could be applied to the technologies for specific processes (as identified in Appendix A4). Best engineering judgment was employed to rate each of the technologies with these weighting factors. A score of High, Medium, or Low was assigned to each factor along with a brief explanation for the score. The parameters referenced in scoring are detailed in Appendix A5 (Table A5). An overall importance rating for the technology was determined based on the weighting factor scores. Each weighting factor is assigned a DOE importance level of “1.”This importance level can be altered; for example, if Technology Readiness and Market Impact carry higher importance, the importance level for these factors can be changed to “2” or “3” and the resulting Overall Importance Rating would change accordingly.

The weighting factors presented in Appendix A5 can be used for further study of the R&D technologies identified in Appendix A4. The weighting factor study was part of the analysis of the R&D technologies, and serves as a guide for prioritizing the technologies. However, the weighting factors were not utilized to estimate onsite PM energy intensity or consumption.

6.3. Practical Minimum Energy Consumption By Process and Sector-wide

Table 6-2 presents the onsite PM energy consumption for the six processes studied and iron and steel sector-wide. The onsite PM energy savings is the difference between CT energy consumption and PM energy consumption. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings.

In Table 6-2, data is extrapolated to estimate the total PM subsector opportunity. PM energy consumption for the individual processes studied is summed and the data is extrapolated to estimate sector total. PM subsector energy savings is also expressed as a percent in Table 6-2. This is also shown in Figure 6-2. It is useful to consider both TBtu energy savings and energy savings percent when comparing energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same.

Table 6-2. Onsite Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for the Processes Studied and Sector-Wide				
Process	**Onsite CT Energy Consumption** (TBtu/year)	**Onsite PM Energy Consumption** (TBtu/year)	**PM Energy Savings †** (CT-PM) (TBtu/year)	**PM Energy Savings Percent** (CT-PM)/ (CT-TM)*
Integrated Mills				
Agglomeration Sintering	8	6-7	1	17-73%
Cokemaking	36	18-31	4-18	22-91%
Ironmaking Blast Furnace	337	281-329	8-56	9-64%
Steelmaking BOF	20	(-12) - (-10)	30-32	72-77%
Mini Mills				
Steelmaking EAF	101	67-88	13-34	33-86%
Integrated and Mini Mills				
Casting	16	3-4	12-13	74-79%
Rolling Hot Cold	 219 86	 106-136 32-39	 83-113 47-55	 38-52% 55-63%
Total for Processes Studied	822	501-625	197-321	39-63%
All Other Processes	176	108-134	42-69	
Total for Iron and Steel Sector-wide	999	609-759	240-390	39-63%

Current typical (CT), Practical minimum (PM), Thermodynamic Minimum (TM)

† PM energy savings is the Current Opportunity plus the R&D Opportunity.

** Calculated using TM from Table 7-2 as the minimum energy of production. This accounts for the energy necessary to perform the process. Potential opportunity reflects the difference between CT and TM energy consumption. Calculation: (CT- PM)/(CT- TM).*

*** The sector-wide PM energy consumption was an extrapolated value, calculated by dividing the total onsite SOA energy consumption for the processes studied by the overall percent coverage from Table 4-3 (68%).*

Figure 6-2 presents the *current opportunity* and the *R&D opportunity* for each process; the *current opportunity* is the difference between CT energy consumption and SOA energy consumption (shown in blue) and the *R&D opportunity* is the difference between the SOA energy consumption and the PM energy consumption (shown in green). In Figure 6-2, the percent savings is the percent of the overall energy consumption bandwidth where TM is the lower baseline. For the processes studied, the greatest *current opportunity* in terms of percent savings is casting at 74% energy savings; the greatest *R&D opportunity* is cokemaking at 69% energy savings. In Figure 6-3, the *current* and *R&D* savings opportunity is shown in terms of TBtu per year savings. The pie chart in Figure 6-3 captures the blue and green portions of the bar chart shown in Figure 6-2, each in a separate pie chart. For the processes studied, the greatest *current opportunity* in terms of TBtu savings is hot rolling at 83 TBtu per year savings; the greatest *R&D opportunity* in terms of TBtu savings is ironmaking at 249 TBtu per year savings.

To extrapolate the data for all other processes that is shown in Table 6-2 and Figure 6-3, the PM energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire sector (82%, see Table 4-3). The percent coverage of processes studied compared to the total CT energy consumption of the sector is shown in the last column of Table 4-3. Percent coverage is the ratio of the sum of all the CT energy consumption for the individual processes studied to the CT energy consumption for the sector provided by MECS (see Table 4-3). The PM energy consumption for the remainder of the sector (i.e., all processes that are not included in the six processes studied) was calculated by subtracting the total for the processes studied from the sector-wide total. These additional processes are together referred to as All Other Processes in Table 6-2.

Table 6-2 also presents the PM energy savings percent. To calculate the onsite PM energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with PM energy consumption (i.e., the deployment of R&D technologies under development worldwide) compared to CT energy consumption, considering that the TM energy consumption may not be zero (i.e., the TM energy consumption may be negative). As will be explained in Chapter 7, in some cases, the TM reaction energy is a negative value. When comparing energy savings percent from one process to another (or one subsector to another), the absolute savings is the best measure of comparison. The equation for calculating onsite PM energy savings percent is:

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

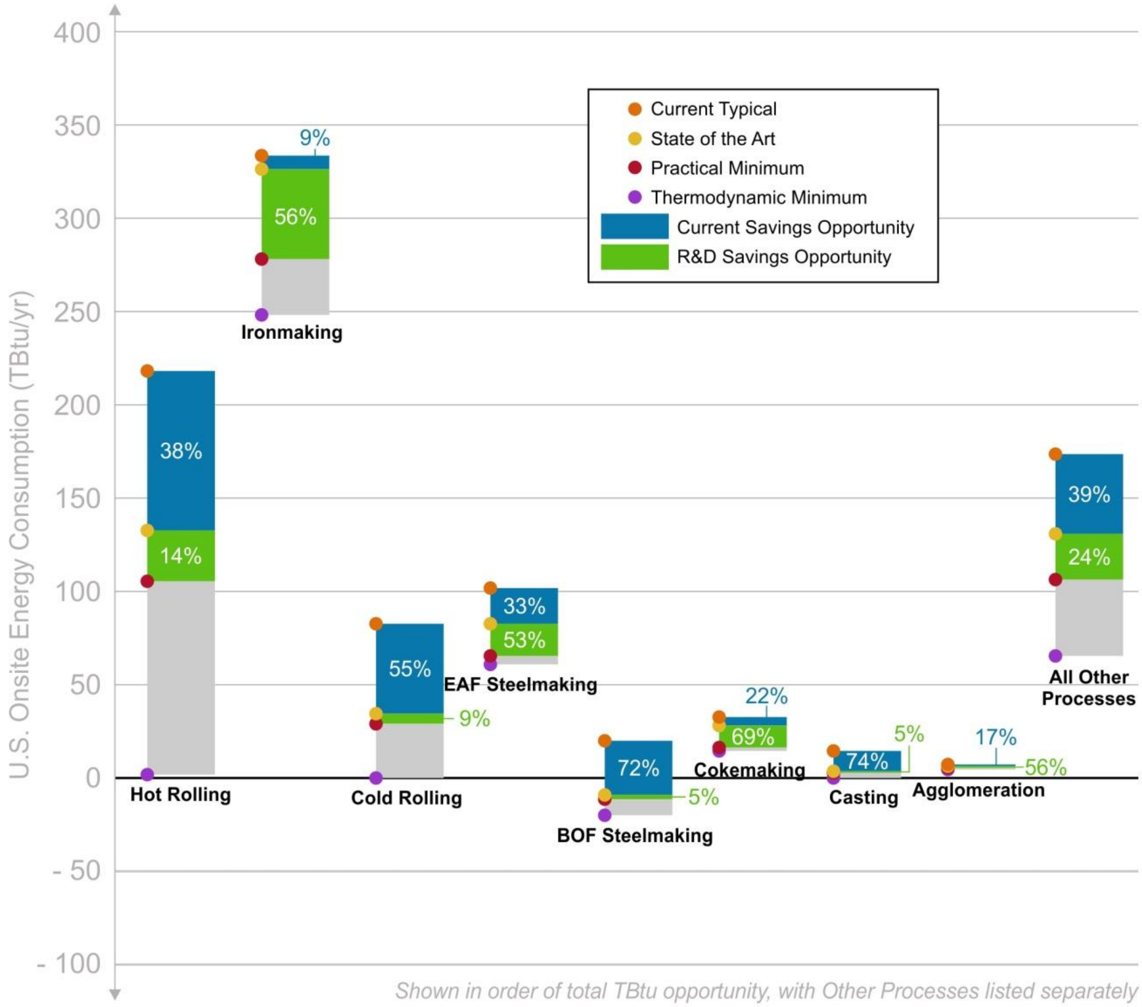


Figure 6-2. Current and R&D Opportunity Energy Savings Bandwidths for the Iron and Steel Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

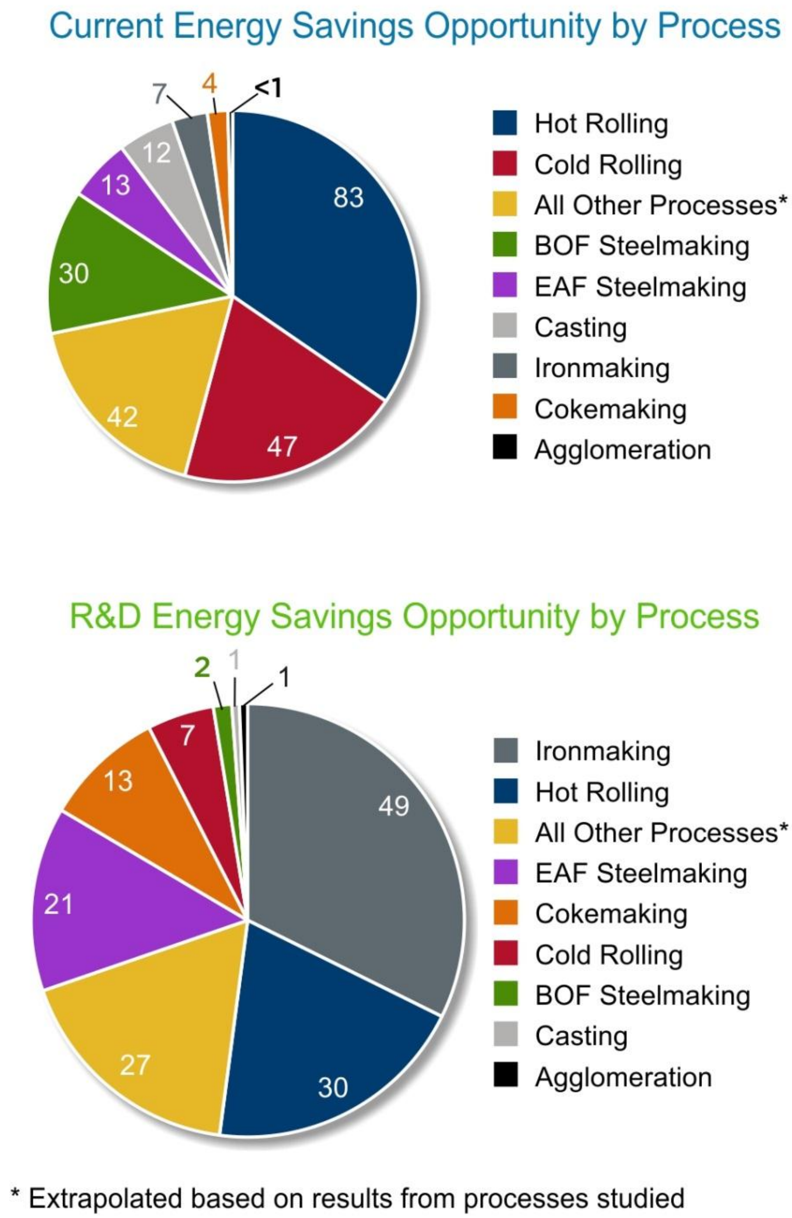


Figure 6-3. Current and R&D Energy Savings Opportunities by Iron and Steel Process Studied *(Energy Savings per Year in TBtu)*

The PM energy savings opportunity is different than SOA energy savings opportunity in that the scope of the R&D technologies contributing energy savings can essentially be boundless. Putting aside obvious financial, timing, and resource limitations, the process improvements and increased energy efficiency that can be gained through unproven technology is speculative. For this reason, a range is used to represent the potential onsite PM energy consumption, PM energy savings, and PM energy savings percent in Table 6-2. The upper limit of the PM energy consumption range is assumed to be equal to the SOA energy consumption. The lower limit of the PM energy consumption range was estimated using the method explained in Section 6.2. The lower limit is shown as a dashed line with color fading in the summary figures that present subsector and sector-wide data. This is done because the PM is speculative and depends on unproven R&D technologies; furthermore, the potential energy savings opportunity could be bigger if additional unproven technologies were considered.

7. Thermodynamic Minimum Energy Consumption for U.S. Iron and Steel Manufacturing

Real world iron and steel manufacturing does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture iron and steel can provide a more complete understanding of opportunities for energy savings. This baseline can be used to establish more realistic projections of what R&D energy savings can be achieved. This Chapter presents the thermodynamic minimum (TM) energy consumption required for the processes studied and for the entire sector.

7.1. Thermodynamic Minimum Energy

TM energy consumption is the calculated minimum amount of energy theoretically needed to complete an iron and steel manufacturing process, assuming ideal conditions that are typically unachievable in real-world applications; in some cases, it is less than zero. TM energy consumption assumes all the energy is used productively and there are no energy losses. It is based on the Gibbs Free Energy (ΔG) equation under ideal conditions for a process. One iron and steel manufacturing process (BOF steelmaking) is theoretically a net producer of energy (i.e., exothermic processes); this created energy was considered in this analysis.

7.2. Calculated Thermodynamic Minimum Energy Consumption for Individual Processes

Appendix A1 presents the onsite TM energy consumption for the six processes considered in this bandwidth study in alphabetical order. For a given process, the TM energy intensity is multiplied by the annual U.S. production or throughput to determine the total onsite TM energy consumption (the energy intensity and production/throughput data are also presented in Appendix A1). Table 7-1 presents the references for the TM energy intensity values and the applicable process. Appendix A2 also provides the references for the TM energy intensity data for each individual process. The TM values are mainly derived from earlier work conducted by Carnegie Mellon University for the DOE, and are detailed in the report, Fruehan et al. 2000.

Table 7-1. Published Sources Reviewed to Identify Thermodynamic Minimum Energy Intensities for the Processes Studied

Source	Process
de Beer et al. 1998	*Future Technologies for Energy-Efficient Iron and Steel Making*. de Beer, Worrell, & Blok provide exergy analysis of a steel plant; this report also discusses theoretical values.
Fruehan et al. 2000	*Theoretical Minimum Energies to Produce Steel for Selected Conditions*. This report highlights minimum values based on theoretical models and specific compositions.
Internal calculations	Calculations based on change in Gibbs free energy at ideal conditions.

BOF steelmaking can at times result in net energy gain through exothermic processes. For exothermic iron and steel manufacturing processes, a zero baseline would result in negative percent savings, a physical impossibility. TM energy consumption was instead referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for SOA and PM are as follows:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

For processes requiring an energy intensive transformation (e.g., ironmaking or EAF steelmaking), this percent energy savings approach results more realistic and comparable energy savings estimates. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

TM energy intensity is the least amount of energy required for each of the six process areas examined in this report – ore agglomeration, cokemaking, ironmaking, steelmaking, casting, and rolling. The full credit of off-gas chemical and thermal energy is considered. The discussion below provides a brief summary of TM results by process area from Fruehan et al. 2000. Some of the tables from Fruehan et al. 2000 are provided in Appendix A3, including some additional references not specifically sourced in this report. For further details, readers are encouraged to review the full source.

7.2.1. Ore Agglomeration and Cokemaking

Ore agglomeration consists of taking ore fines or concentrate and sintering them into sinter or pellets. Cokemaking is achieved by heating coal under pressure, driving off volatiles and increasing the strength of the material. The theoretical minimum energies for these processes were determined by calculating the energy to heat idealized coal and ore to 1100°C and 1350°C, respectively. In cokemaking the heat of devolatilization is also required but is usually accounted for in computing the energy value of coal. The coke output was taken as 0.768 per metric ton of the coal input. The volatiles represent the remainder, which is used as a fuel or for chemicals (Fruehan et al. 2000). The TM for sintering is approximately 1.03 MMBtu/ton (1.20 GJ/tonne) of sinter; and the TM for cokemaking is approximately 1.72 MMBtu/ton (2.00 GJ/tonne) of coke output.

7.2.2. Ironmaking

For iron ore reduction, Fruehan et al. 2000's base calculations considered pure Fe_2O_3 reduced at 298 Kelvin (K), heated to melting point and melted (no superheat); resulting in a TM value of

7.4 MMBtu/ton (8.6 GJ/tonne) of hot metal. In blast furnace ironmaking, the calculated TM base case is 8.43 MMBtu/ton (9.81 GJ/tonne) of hot metal – with iron nearly saturated with carbon. Other cases include effects of impurities, slags, and coke ash – with TM values ranging from 8.8-9.0 MMBtu/ton (10.2-10.4 GJ/tonne). In all cases, full credit is assumed for the energy in the off-gas.

For direct reduced iron where reduction using natural gas occurs without melting, pure Fe_2O_3 can be produced with 7.19 MMBtu/ton (8.37 GJ/tonne). Other cases presented by Fruehan et al. 2000 result in TM values ranging from 6.8-8.1 MMBtu/ton (7.9-9.3 GJ/tonne).

7.2.3. Steelmaking

Traditional integrated oxygen steelmaking produces energy as carbon and other elements are oxidized. Inputs of one ton of hot metal plus 0.29 tons of cold scrap yield 1.24 tons liquid steel with a TM energy requirement of 6.8 MMBtu/ton (7.9 GJ/tonne) of liquid steel (including ironmaking energy). Fruehan et al. 2000 notes potential energy in off gas, with a net value of 0.6 MMBtu/ton (0.8 GJ/tonne) of steel.

For producing steel from pure scrap, the metal is heated and melted (without superheat) resulting in a calculated TM value of 1.1 MMBtu/ton (1.3 GJ/tonne). Other cases presented by Fruehan et al. 2000 result in TM values ranging from 1.1-1.4 MMBtu/ton (1.3-1.6 GJ/tonne).

Fruehan et al. 2000 also provides TM values for the production of stainless steel with high chromium and nickel content. For a typical input mix in an EAF, the TM value for stainless steel of approximately 1.0 MMBtu/ton (1.2 GJ/tonne) is about 9% less than the pure iron TM value.

7.2.4. Casting and Rolling

Various estimates for hot rolling and cold rolling were provided and consider both heated and unheated slabs, normal slabs and thin slabs, as well as bars. Fruehan et al. 2000 presents values for both heat energy and deformation energy (electricity). For unheated slabs, the TM heating value for hot rolling is approximately 0.71 MMBtu/ton (0.83 GJ/tonne); and approximately 0.23 MMBtu/ton (0.27 GJ/tonne) when heating from 1173 K to 1473 K; and the deformation energy ranges from 0.01 MMBtu/ton to 0.06 MMBtu/ton (0.01 to 0.07 GJ/tonne) for rolling depending on the product and conditions. For cold rolling Fruehan et al. 2000 presents values for cold rolling process only, and does not include any additional operations (as is the case with CT, SOA, and PM cold rolling consumption estimates).

7.3. Thermodynamic Minimum Energy Consumption By Process and Sector-wide

The minimum baseline of energy consumption for an iron and steel manufacturing process is its TM energy consumption. If all the 2010 level of iron and steel production occurred at TM energy intensity, there would be 100% savings. The percentage of energy savings is determined by calculating the absolute decrease in energy consumption and dividing it by the total possible savings (CT energy consumption-TM energy consumption).

Table 7-2 provides the TM energy consumption for the six processes studied (excluding feedstock energy). In theory, if heat generating processes could be carefully coupled with heat consuming processes, this could greatly offset the energy usage in iron and steel manufacturing overall. It is an imperative to keep in mind that ideal conditions are largely unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities.

Table 7-2 also presents the extrapolated TM energy consumption for the entire sector. The extrapolation for sector-wide TM energy consumption is done with the same methodology as for SOA energy consumption and PM energy consumption (as explained in Section 5.2 and 6.4).

The TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero).

Table 7-2. Thermodynamic Minimum Energy Consumption by Process and Sector-Wide for the Six Processes Studied and Extrapolated to Sector Total

Process	Onsite TM Energy Consumption (TBtu/year)
Integrated Mills	
Agglomeration Sintering	 6
Cokemaking	16
Ironmaking Blast Furnace	 250
Steelmaking BOF	 -22
Mini Mills	
Steelmaking EAF (Pure Scrap)	 62
Integrated and Mini Mills	
Casting	<0.01
Rolling Hot Cold	 2 <1
Total for Processes Studied	313
All Other Processes	67
Total for Iron and Steel Sector-wide	381

Thermodynamic minimum (TM)

† Estimates for the entire sector were extrapolated by dividing the onsite TM energy consumption for the processes studied by the overall percent coverage of 82% (see Table 4-3).

8. U.S. Iron and Steel Manufacturing Energy Bandwidth Summary

This Chapter presents the energy savings bandwidths for the iron and steel manufacturing processes studied and sector-wide based on the analysis and data presented in the previous Chapters and the Appendices. Data is presented for the six processes studied and extrapolated to estimate the energy savings potential for all of U.S. iron and steel.

8.1. Iron and Steel Bandwidth Profile

Table 8-1 presents the *current opportunity* and *R&D opportunity* energy savings for the six processes studied and extrapolated to estimate the sector total. The process totals are summed to provide a sector-wide estimate. The energy savings data was extrapolated to account for all other processes not included in the nine processes studied, as explained in Section 5.2 (SOA) and 6.4 (PM). Each row in Table 8-1 shows the opportunity bandwidth for a specific iron and steel manufacturing process and sector-wide.

As shown in Figure 8-1, four hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). To complete the six processes studied, the analysis shows the following:

- *Current Opportunity* – 197 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 124 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

To complete all of the U.S. iron and steel sector processes (based on extrapolated data), the analysis shows the following:

- *Current Opportunity* – 240 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 150 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 8-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual iron and steel manufacturing processes. The U.S. iron and steel industry operated at relatively low capacity utilization and lower-than-typical efficiencies in 2010, due in large part to the economic downturn. While the specific impacts of the economic factors in 2010 are not directly identified in this report, it is reasonable to assume that the current opportunity is likely somewhat exaggerated, as a portion of the current savings could be achieved by simply optimizing production rates. For this reason the border between *current opportunity* and *R&D opportunity* is not explicitly defined, and a dashed line and color fading is used. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are speculative and based on unproven technologies.

Table 8-1. Current Opportunity and R&D Opportunity Energy Savings for the Nine Processes Studied and Extrapolated to Sector-Wide Total

Process	Current Opportunity (CT-SOA) (TBtu/year)	R&D Opportunity (SOA-PM) (TBtu/year)
Integrated Mills		
Agglomeration Sintering	<1	1
Cokemaking	4	13
Ironmaking Blast Furnace	7	49
Steelmaking BOF	30	2
Mini Mills		
Steelmaking EAF (Pure Scrap)	13	21
Integrated and Mini Mills		
Casting	12	1
Rolling Hot Cold	 83 47	 30 7
Total for Processes Studied	197	124
All Other Processes	42	27
Total for Iron and Steel Sector-wide	240	150

Current typical (CT), state of the art (SOA), practical minimum (PM)

From the processes studied, the greatest *current* energy savings opportunity for iron and steel manufacturing comes from upgrading production methods in hot rolling. The greatest *R&D* energy savings opportunity for iron and steel comes from blast furnace ironmaking.

The *impractical* bandwidth represents the energy savings potential that would require fundamental changes in iron and steel manufacturing. It is the difference between PM energy consumption and TM energy consumption. The term *impractical* is used because the significant research investment required based on today's knowledge would no longer be practical because of the thermodynamic limitations. The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

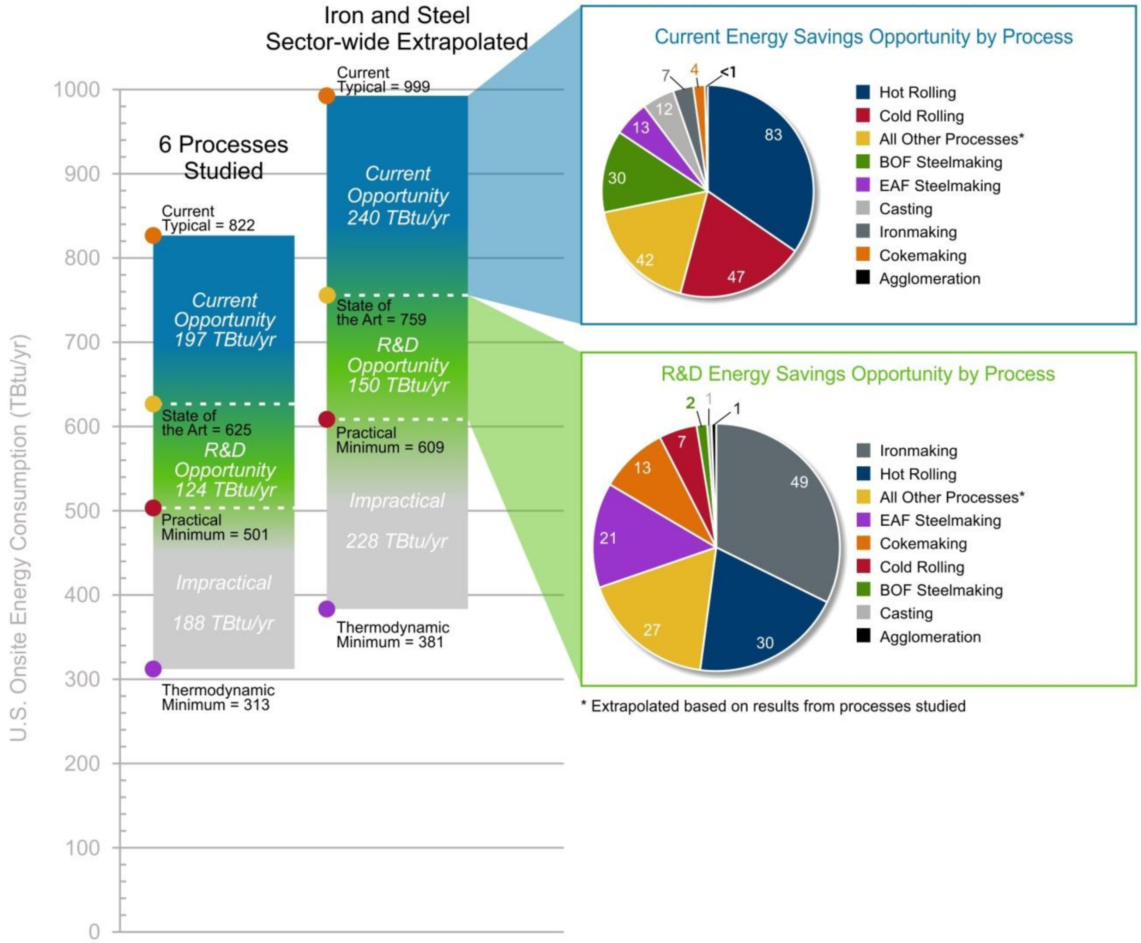


Figure 8-1. Current and R&D Energy Savings Opportunities in U.S. Iron and Steel for the Processes Studied and for Sector-Wide based on Extrapolated Data

Figure 8-2 shows the bandwidth summaries for the iron and steel processes presented in order of highest current plus R&D energy savings opportunity. Blast furnace ironmaking is the largest energy consuming process in iron and steel manufacturing. If the lower limit of PM energy consumption could be reached, this would save about 56 TBtu/year compared to CT, amounting to 6% of CT energy consumption for the entire iron and steel sector. Hot rolling, the second largest energy consuming process in iron and steel manufacturing, would save about 113 TBtu copared to CT if the lower limit of PM energy consumption could be reach; this opportunity is equal to 11% of the sector’s CT energy consumption. Other processes, such as cokemaking, casting, and agglomeration, have a much smaller difference between CT energy consumption and the PM energy consumption.

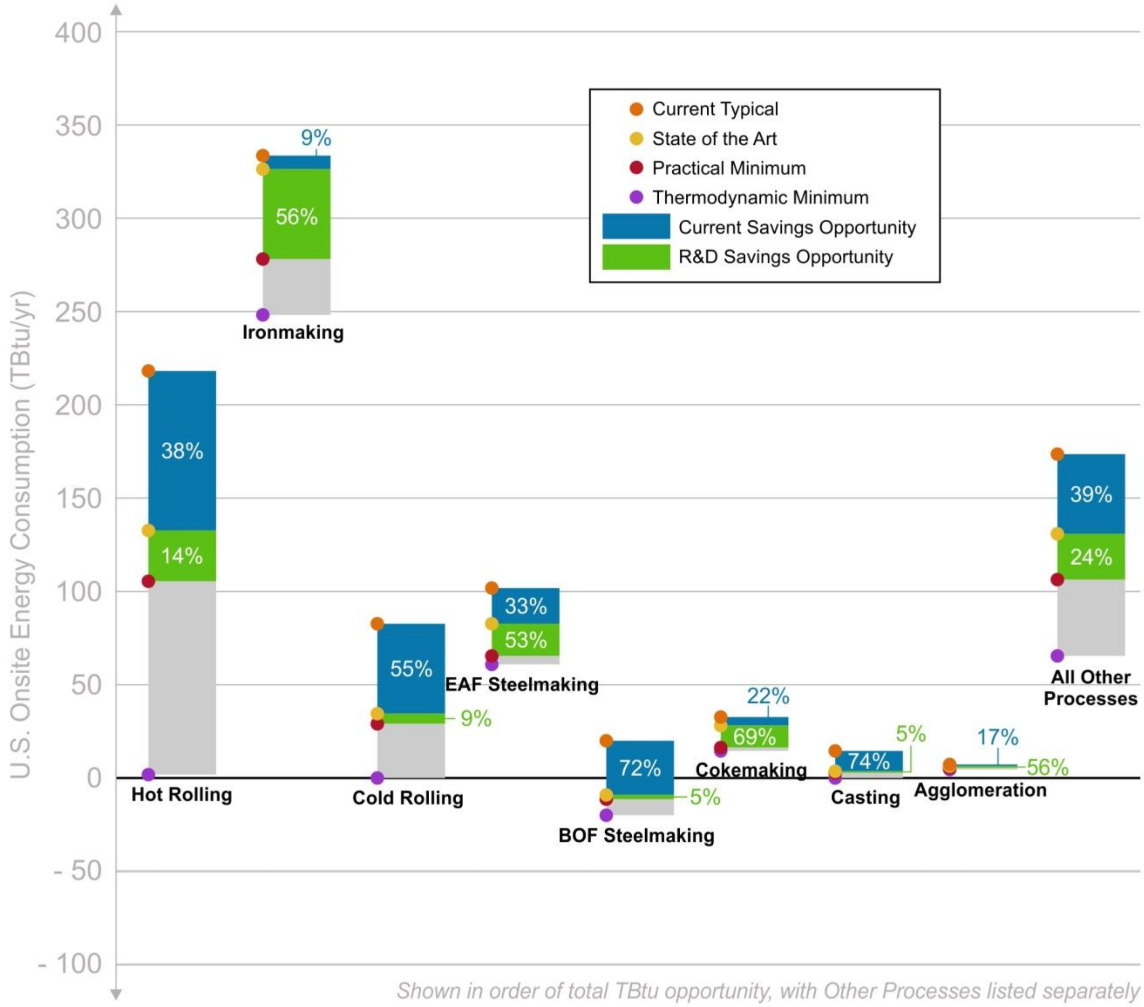


Figure 8-2. Current and R&D Opportunity Energy Savings Bandwidths for the Processes Studied
(with Percent of Overall Energy Consumption Bandwidth)

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Appendix A1: Master Iron and Steel Table

Table A1. U.S. Production Volume of Six Iron and Steel Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	2010 Production (1,000 tons)	Energy Intensity (MMBtu/ton) [GJ/tonne]				Calculated Onsite Energy Consumption (TBtu/year)			
		CY	SOA	PM Lower Limit	TM**	CY	SOA	PM Lower Limit	TM
Agglomeration									
Pelletizing [a]	39,728	0.70 [0.82]	-	-	-				
Sintering	5,759	1.32 [1.54]	1.27 [1.48]	1.11 [1.29]	1.03 [1.20]	7.60	7.31	6.39	5.94
Cokemaking	9,292	3.83 [4.46]	3.37 [3.92]	1.92 [2.23]	1.72 [2.00]	35.59	31.31	17.84	15.98
Ironmaking									
Blast Furnace	29,590	11.72 [13.63]	11.13 [12.95]	9.49 [11.04]	8.43 [9.81]	336.79[e]	329.34	280.81	249.47
Direct Reduction [b]	0	9.17 [10.71]	8.33 [9.68]	-[d]	7.19 [8.36]	0	0	0	0
Steelmaking									
BOF-based	34,345	0.58 [0.67]	-0.30 [-0.35]	-0.36 [-0.42]	-0.64 [-0.74]	19.92	-10.30	-12.36	-22.15
EAF	54,386	1.86 [2.16]	1.62 [1.88]	1.24 [1.44]	1.14 [1.33]	101.16	88.11	67.44	62.06
Casting	84,784	0.19 [0.22]	0.05 [0.06]	0.04 [0.05]	<0.01	16.11	4.24	3.39	<0.01
Rolling									
Hot [c]	84,784	2.58 [3.00]	1.60 [1.86]	1.25 [1.45]	0.02-0.25 [0.02-0.29]	218.74	135.65	105.98	1.70
Cold	27,710	3.48 [4.05]	1.42 [1.65]	1.15 [1.34]	0.02 [0.02]	86.43[e]	39.35	31.87	0.41

[a] *Conducted primarily at mining site, which is outside the scope of the analysis and thus only shown for reference*

[b] *Traditional direct reduction processes not utilized in the U.S. in 2010; a small amount of iron nuggets (approximately 75 thousand tons) were produced by the new ITmk3 process in start-up operations at the first commercial plant in Minnesota, associated energy data not available*

[c] *TM range for hot rolling depends on whether some heating is assumed or not*

[d] *No value currently available*

[e] *Current typical values for blast furnace and cold rolling each exclude 10 TBtu of nonfuel feedstock natural gas.*

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Appendix A2: References for U.S. Production Data of the 6 Processes Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

Table A2. References for U.S. Throughput Data of the Six Iron and Steel Processes Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

Process	Production Reference	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	TM Energy Intensity Reference
Agglomeration Pelletizing Sintering	AISI 2011a	Pelletizing: IPPC 2013 Sintering: IPPC 2013	Sintering: LBNL 2008	Fruehan et al. 2000
Cokemaking	AISI 2011a	AISI 2011a; EIA 2013b	NRC 2007	Fruehan et al. 2000
Ironmaking Blast Furnace Direct Reduction	AISI 2011a	AISI 2011a; IPPC 2013	Blast Furnace: NRC 2007 Direct Reduction: Energiron 2013	Fruehan et al. 2000
Steelmaking BOF-based EAF	AISI 2011a	BOF-based: IPPC 2013 EAF: AIST 2011	BOF-based: NRC 2007 EAF: NRC 2007; Giavani et al. 2012	Fruehan et al. 2000
Casting	AISI 2011a	NRC 2007	NRC 2007; LBNL 2008	Fruehan et al. 2000
Rolling Hot Cold	AISI 2011a	Hot: NRC 2007 Cold: EIA 2013b	Hot: NRC 2007 Cold: LBNL 2008	Fruehan et al. 2000

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Appendix A3: CT, SOA, and TM Energy Intensities by Process and Energy Type

Current Typical Energy Intensities

Table A3-1. Current Typical Energy Intensity Estimate for Pelletizing

Energy Source	Energy Intensity (MMBtu/ton)	Energy Intensity (GJ/MT)	Reference
Natural Gas	0.01	0.01	IPPC 2013 (Table 4.1 and text, converted to HHV, see A3-27)
COG/BFG	0.30	0.35	IPPC 2013 (Table 4.1 and text, converted to HHV)
Coke and Breeze	0.31	0.36	IPPC 2013 (Table 4.1 and text, converted to HHV)
Electricity	0.09	0.10	IPPC 2013 (Table 4.1 assumes worst case)
Total Energy/ Unit	0.70	0.82	

Table A3-2. Current Typical Energy Intensity Estimate for Sintering

Fuel Source	Energy Intensity (MMBtu/ton)	Energy Intensity (GJ/MT)	Reference
Natural Gas	0.07	0.08	IPPC 2013 (Table 3.2, converted to HHV)
Coke and Breeze	1.17	1.36	IPPC 2013 (Table 3.2, converted to HHV)
Electricity	0.09	0.10	IPPC 2013 (Table 3.2, converted to onsite energy)
Total Energy/ Unit	1.32	1.54	

Table A3-3. Current Typical Energy Intensity Estimate for Cokemaking				
Fuel Source	**Energy Intensity** (including merchant coke) **(MMBtu/ton)***	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.26	0.33	0.39	Calculated based on production and AISI 2011a Table 37
COG	2.15	2.78	3.24	Calculated based on production and AISI 2011a Table 37
BFG	0.03	0.03	0.04	Calculated based on production and AISI 2011a Table 37
Steam	0.44	0.57	0.66	Estimate based on EIA 2013b
Electricity	0.08	0.10	0.12	Estimate based on EIA 2013b
Total Energy/ Unit	2.96	3.83	4.45	

** Energy intensity per ton of total coke consumed (including offsite purchased merchant coke) is* not *referenced in determining CY. Natural gas, COG, BFG energy intensity is converted to ton of coke produced using the ratio of 9,292,000 tons coke produced to 12,021,000 coke consumed (AISI 2011a, Table 31).*

Table A3-4. Current Typical Energy Intensity Estimate for Blast Furnace Ironmaking			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Coke	10.54	12.26	Calculated based on production and AISI 2011a Table 31
Natural Gas	1.62	1.88	Calculated based on production and AISI 2011a Table 37
Oil	0.14	0.16	Calculated based on production and AISI 2011a Table 37
Coal	1.83	2.13	Calculated based on production and AISI 2011a Table 29
Steam	0.04	0.05	Based on IPPC 2013
Electricity	0.23	0.27	Based on IPPC 2013 (converted to onsite energy)
COG	0.24	0.28	Calculated based on production and AISI 2011a Table 37
BFG (Net)	-2.93	-3.40	Calculated based on production and AISI 2011a Table 37
Total Energy/ Unit	11.72	13.63	

Table A3-5. Current Typical Energy Intensity Estimate for Basic Oxygen Furnace Steelmaking			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas/ COG	0.37	0.43	Based on IPPC 2013 (converted to HHV)
BFG	0.03	0.03	Based on IPPC 2013 (converted to HHV)
Steam	0.07	0.08	Based on IPPC 2013
Electricity	0.11	0.13	Based on IPPC 2013 (converted to onsite energy)
Total Energy/ Unit	0.58	0.67	

Table A3-6. Current Typical Energy Intensity Estimate for Electric Arc Furnace Steelmaking			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.44	0.51	Estimated from AIST 2011
Electricity	1.42	1.65	Estimated from AIST 2011
Total Energy/ Unit	1.86	2.16	

Table A3-7. Current Typical Energy Intensity Estimate for Direct Reduced Ironmaking			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	8.9	10.4	IEA 2007, Chapter 5
Electricity	0.27	0.31	IEA 2007, Chapter 5
Total Energy/ Unit	9.17	10.71	

Table A3-8. Current Typical Energy Intensity Estimate for Continuous Casting			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.08	0.09	Based on NRC 2007 Figure 4-12 (converted to HHV)
Electricity	0.07	0.08	Based on NRC 2007 Figure 4-12 (converted to onsite energy)
Plant Utilities	0.04	0.05	Based on NRC 2007 Figure 4-12 (converted to onsite energy)
Total Energy/ Unit	0.19	0.22	

Table A3-9. Current Typical Energy Intensity Estimate for Hot Rolling			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Hot Strip and Plate Mills			
Natural Gas	2.55	2.96	Based on NRC 2007 Figure 4-14 (converted to HHV)
Plant Utilities	0.08	0.09	Based on NRC 2007 Figure 4-14 (electrical, converted to onsite energy)
Electricity	0.40	0.47	Based on NRC 2007 Figure 4-14 (converted to onsite energy)
Recovery (Credit)	-0.03	-0.04	Based on NRC 2007 Figure 4-14
Total Energy/ Unit	2.99	3.48	
Section Mills			
Natural Gas	1.79	2.08	Based on NRC 2007 Figure 4-16 (converted to HHV)
Plant Utilities	0.03	0.03	Based on NRC 2007 Figure 4-16 (assumed to be electrical, converted to onsite energy)
Electricity	0.34	0.40	Based on NRC 2007 Figure 4-16 (converted to onsite energy)
Total Energy/ Unit	2.16	2.51	
Average for Hot Strip, Plate and Section Mills *			
Natural Gas	2.17	2.52	
Plant Utilities, Recovery	0.03	0.04	
Electricity	0.38	0.44	
Total Energy/ Unit	2.58	3.00	

** Average referenced for Hot Rolling CA*

Table A3-10. Current Typical Energy Intensity Estimate for Cold Rolling			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	1.58	1.84	EIA 2013b Table B8
Distillate	0.01	0.01	EIA 2013b Table B8
Steam	0.85	0.99	EIA 2013b Table B8
Electricity	1.05	1.22	EIA 2013b Table B8
Total Energy/ Unit	3.48	4.05	

State of the Art Energy Intensities

Table A3-11. State of the Art Energy Intensity Estimate for Sintering			
Fuel Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.06	0.07	Based on LBNL 2008, Table 2.1.3 and text (converted to HHV, see A3-28)
Coke and Breeze	1.12	1.30	Based on LBNL 2008, Table 2.1.3 and text (converted to HHV)
Electricity	0.09	0.10	Based on LBNL 2008, Table 2.1.3 and text (converted to onsite energy)
Total Energy/ Unit	1.27	1.47	

Table A3-12. State of the Art Energy Intensity Estimate for Cokemaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.33	0.38	Based on NRC 2007 (converted to HHV)
COG	2.72	3.16	Based on NRC 2007 (converted to HHV)
BFG	0.03	0.04	Based on NRC 2007 (converted to HHV)
Steam	0.22	0.25	Based on NRC 2007
Electricity	0.09	0.10	Based on NRC 2007 (converted to onsite energy)
Total Energy/ Unit	3.37	3.92	

Table A3-13. State of the Art Energy Intensity Estimate for Blast Furnace Ironmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Coke	9.88	11.49	Based on NRC 2007 (converted to HHV)
Oil	1.21	1.41	Based on NRC 2007 (converted to HHV)
Coal	2.31	2.69	Based on NRC 2007 (converted to HHV)
Steam	0.34	0.40	Based on NRC 2007
Electricity	0.08	0.09	Based on NRC 2007 (converted to onsite energy)
COG	0.22	0.26	Based on NRC 2007 (converted to HHV)
BFG (Net)	-2.92	-3.40	Based on NRC 2007 (converted to HHV)
Total Energy/ Unit	11.13	12.94	

Table A3-14. State of the Art Energy Intensity Estimate for Basic Oxygen Furnace Steelmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Electricity	0.08	0.09	Based on NRC 2007 (converted to onsite energy)
Other	0.34	0.40	Based on NRC 2007 (assumed to be natural gas, converted to HHV)
Steam (Credit)	-0.15	-0.17	Based on NRC 2007
BOF Gas (Credit)	-0.58	-0.67	Based on NRC 2007 (converted to HHV)
Total Energy/ Unit	-0.30	-0.35	

Table A3-15. State of the Art Energy Intensity Estimates for Electric Arc Furnace Steelmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Electricity	1.47	1.71	Based on NRC 2007 (converted to onsite energy)
Natural gas	0.15	0.18	Based on NRC 2007 (converted to HHV)
Total Energy/ Unit	1.62	1.89	
Consteel Evolution Values*			
Natural gas	0.28	0.33	Giavani et al. 2012
Coal	0.52	0.60	Giavani et al. 2012
Electricity	0.92	1.07	Giavani et al. 2012
Total Energy/ Unit	1.79*	2.08*	

** Not referenced for EAF SOA, provided for additional information only.*

Table A3-16. State of the Art Energy Intensity Estimate for Direct Reduced Ironmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	8.06	9.38	Energiron 2013
Electricity	0.26	0.31	Energiron 2013
Total Energy/ Unit	8.33	9.68	

Table A3-17. State of the Art Energy Intensity Estimate for Continuous Casting			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Electricity	0.03	0.03	Based on NRC 2007 (converted to onsite energy)
Natural Gas	0.03	0.03	Based on NRC 2007 (converted to HHV)
Total Energy/ Unit	0.05	0.06	
Thin Slab Casting*			
Fuel	0.04	0.05	LBNL 2008 Table 2.1.3
Electricity	0.13	0.15	LBNL 2008 Table 2.1.3
Total Energy/ Unit	0.17	0.20	

** Not referenced for Casting SOA Energy Intensity, provided for additional information only.*

Table A3-18. State of the Art Energy Intensity Estimate for Cold Rolling Mill			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Natural Gas	0.73	0.81	Based on LBNL 2008 Section 2.1.6 (converted to HHV)
Electricity	0.41	0.48	Based on LBNL 2008 Section 2.1.6 (converted to onsite energy)
Steam	0.31	0.36	Based on LBNL 2008 Section 2.1.6
Total Energy/ Unit	1.42	1.65	

Table A3-19. State of the Art Energy Intensity Estimate for Hot Rolling			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Hot Strip Mill			
Natural Gas	1.19	1.38	Based on NRC 2007 (converted to HHV)
Electricity	0.24	0.28	Based on NRC 2007 (converted to onsite energy)
Steam	0.03	0.04	Based on NRC 2007
Other	0.01	0.01	Based on NRC 2007
Recovery (Credit)	-0.03	-0.04	Based on NRC 2007
Total Energy/ Unit	1.43	1.66	
Plate Mill			
Fuel	1.17	1.36	Based on NRC 2007 (converted to HHV)
Electricity	0.25	0.29	Based on NRC 2007 (converted to onsite energy)
Recovery (Credit)	-0.13	-0.15	Based on NRC 2007
Total Energy/ Unit	1.29	1.50	
Light Section (Rod) Mill			
Natural Gas	1.52	1.77	Based on NRC 2007 (converted to HHV)
Electricity	0.33	0.38	Based on NRC 2007 (converted to onsite energy)
Total Energy/ Unit	1.85	2.15	
Medium Section (Bar) Mill			
Natural Gas	1.43	1.66	Based on NRC 2007 (converted to HHV)
Electricity	0.25	0.29	Based on NRC 2007 (converted to onsite energy)
Total Energy/ Unit	1.68	1.95	
Heavy Section (Bloom and Structural) Mill			
Natural Gas	1.43	1.66	Based on NRC 2007 (converted to HHV)
Electricity	0.31	0.36	Based on NRC 2007 (converted to onsite energy)
Total Energy/ Unit	1.74	2.02	
Average for Hot Strip, Plate and Section Mills *			
Fuel	1.35	1.57	
Electricity	0.28	0.32	
Steam	0.01	0.01	
Recovery, Other	-0.03	-0.04	
Total Energy/ Unit	1.60	1.86	

** Average referenced for Hot Rolling SOA*

THEORETICAL MINIMUM ENERGY INTENSITIES

Table A3-20. Theoretical Minimum Energy Intensity Estimate for Sintering			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Fuel	1.03	1.20	Fruehan et al. 2000 Table 9
Total Energy/ Unit	1.03	1.20	

Table A3-21. Theoretical Minimum Energy Intensity Estimate for Cokemaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Fuel	1.72	2.00	Fruehan et al. 2000 Table 9
Total Energy/ Unit	1.72	2.00	

Table A3-22. Theoretical Minimum Energy Intensity Estimate for Blast Furnace Ironmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Ideal Case[1] Fuel	8.43	9.81	Fruehan et al. 2000 Table 2
Typical Case[2] Fuel	8.96	10.42	Fruehan et al. 2000 Table 2
Total Energy/ Unit	8.43	9.81	

[1] *Ideal Case has no gangue or ash (this value was referenced for Blast Furnace TM)*

[2] *Typical Case includes gangue and ash.*

Table A3-23. Theoretical Minimum Energy Intensity Estimate for Basic Oxygen Furnace Steelmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Exothermic (oxidation) (net value)	-0.64	-0.75	Fruehan et al. 2000 Text and Table 11 note
Total Energy/ Unit	-0.64	-0.75	

Table A3-24. Theoretical Minimum Energy Intensity Estimate for Electric Arc Furnace Steelmaking			
Energy Source	**Energy Intensity (MMBtu/ton)**	**Energy Intensity (GJ/MT)**	**Reference**
Assuming 50/50 fuel/electric split			
Fuel	0.57	0.66	Fruehan et al. 2000 Table 5
Electricity	0.57	0.66	Fruehan et al. 2000 Table 5
Total Energy/ Unit	1.14	1.33	
Assuming all electric [a]			
Electricity	1.14	1.33	Fruehan et al. 2000 Table 5
Total Energy/ Unit	1.14	1.33	

[a] *Referenced for Blast Furnace TM*

Table A3-25. Theoretical Minimum Energy Intensity to Produce Direct Reduced Iron at 1173K (900°C or 1620°F) Reduction Temperature for Selected Conditions			
Ore	**Product**	**Energy (MMBtu/ton)**	**Energy (GJ/MT)**
Pure Fe_2O_3 *	Fe	7.188	8.360
Fe_2O_3 - 1.4% SiO_2	Fe - 2% SiO_2	7.206	8.380
Fe_2O_3 - 1.4% SiO_2	Fe - 2% SiO_2 - 8% FeO	6.793	7.900
Fe_2O_3 - 1.5% SiO_2	Fe - 2% SiO_2 - 8% FeO - 2% C	7.246	8.427
Fe_2O_3 - 1.5% SiO_2	Fe - 2% SiO_2 - 7.7% FeO - 6% C	8.110	9.432
Total Energy/ Unit		7.188	8.360

** Referenced for DRI TM*

Note: Full credit is assumed for off gas

Reference: Fruehan et al. 2000 Table 3

Table A3-26. Theoretical Minimum Energy Intensity to Roll Steel for Selected Products and Conditions						
Rolling Type	**Rolling Temperature (K)**	**Slab Temperature [a] (K)**	**Reduction (mm)**	**Energy (MMBtu/ton), [GJ/MT]**		
				Heat	**Deformation**	**Total**
Flat Carbon Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	0.709 [0.825]	0.021 [0.025]	0.731 [0.850]
Hot	1473	1173	254 to 2	0.232 [0.270]	0.021 [0.025]	0.254 [0.295]
Hot *	1473	1473	254 to 2	--	0.021 [0.025]	0.021 [0.025]
Cold **	298	298	2 to 1	--	0.015 [0.017]	0.015 [0.017]
Flat Carbon Slab (5.0 cm or 1.97 inch)						
Hot	1473	298	50 to 2	0.709 [0.825]	0.014 [0.016]	0.723 [0.841]
Hot	1473	1173	50 to 2	0.232 [0.270]	0.014 [0.016]	0.246 [0.286]
Hot	1473	1473	50 to 2	--	0.013 [0.015]	0.014 [0.016]
Cold	298	298	2 to 1	--	0.015 [0.017]	0.015 [0.017]
Flat 18-8 Stainless Steel Slab (25.4 cm or 10 inch)						
Hot	1473	298	254 to 2	0.709 [0.825]	0.062 [0.072]	0.771 [0.897]
Hot	1473	1173	254 to 2	0.233 [0.271]	0.062 [0.072]	0.294 [0.342]
Hot	1473	1473	254 to 2	--	0.062 [0.072]	0.062 [0.072]
Cold	298	298	2 to 1	--	0.044 [0.051]	0.044 [0.051]
Bar Carbon (10 cm billet to 2 cm bar)						
Hot	1473	298	10 sq to 2 sq	0.709 [0.825]	0.017 [0.020]	0.727 [0.845]
Hot	1473	1473	10 sq to 2 sq	--	0.017 [0.020]	0.017 [0.020]
Hot	1473	1173	10 sq to 2 sq	0.232 [0.270]	0.017 [0.020]	0.249 [0.290]
Hot[b]	1473	1473	10 sq to 2 sq	--	0.009 [0.011]	0.009 [0.011]
Total Energy/ Unit (Hot Rolling)						0.021 [0.025]
Total Energy/ Unit (Cold Rolling)						0.015 [0.017]

[*] Referenced for Hot Rolling TM, [**] Referenced for Cold Rolling TM

[a] Slab temperature prior to rolling

[b] Billet split into 4 pieces prior to rolling

Reference: Fruehan et al. 2000 Table 7

Table A3-27. Conversion from Lower Heating Value to Higher Heating Value for Current Typical Energy Intensity

Current Average Energy Intensity by Energy Type and Process Area																			
				Fuel															
	Intensity Source	Energy Intensity	Feed-stock [a]	Coal		Natural gas		Coke and Breeze		COG		BFG		Fuel Oil		Elect	Other (utilites, credit)	Steam	Fuel, Elec, Steam Energy Intensity (HHV)
				LHV	HHV [b]	LHV	HHV [b]	LHV	HHV [b]	LHV	HHV [c]	LHV	HHV [c]	LHV	HHV [b]				
Integrated Mills																			
Agglomeration Sintering	Table A3-2	GJ/MT sinter				0.07	0.08	1.28	1.36							0.10			1.54
		Percentage				*5%*		*88%*								*7%*			*100%*
Pelletizing	Table A3-1	GJ/MT pellets				0.01	0.01	0.34	0.36	0.31	0.35					0.10			0.82
		Percentage				*1%*		*44%*		*42%*						*12%*			*100%*
Cokemaking	Table A3-3	GJ/MT coke	33.6				0.39				3.24		0.04			0.12		0.66	4.45
		Percentage				*9%*				*73%*		*1%*				*3%*		*15%*	*100%*
Ironmaking Blast Furnace	Table A3-4	GJ/MT pig iron			2.13		1.88		12.26		0.28		-3.4		0.16	0.27		0.05	13.63
		Percentage		*16%*		*14%*		*90%*		*2%*		*-25%*		*1%*		*2%*		*0%*	*100%*
Steelmaking BOF	Table A3-5	GJ/MT steel				0.39	0.43					0.03	0.03			0.13		0.08	0.67
		Percentage				*64%*						*4%*				*19%*		*12%*	*100%*
Mini Mills																			
Steelmaking EAF	Table A3-6	GJ/MT steel					0.51									1.65			2.16
		Percentage				24%										76%			100%
Integrated and Mini Mills																			
Casting	Table A3-8	GJ/MT steel				0.08	0.09									0.08	0.05		0.22
		Percentage				*53%*										*47%*			*100%*
Rolling Hot	Table A3-9	GJ/MT steel				2.275	2.52									0.44	0.04		3.00
		Percentage				*85%*												*0%*	*85%*
Cold	Table A3-10	GJ/MT steel				1.66	1.84							0.01		1.22		0.99	4.05
		Percentage				*45%*								*0%*		*30%*		*24%*	*100%*

[a] Feedstock coal intensity based on [IPPC 2013], 1285 kg dry coal/metric ton coke produced. Energy value of coal 22.489 MMBtu/short ton (EIA form 846).

[b] Lower heating value intensity converted to higher heating value using HHV/LHV ratio, GREET 1.8d.1, The Greenhouse Gases, Regulated Emissions, and Energy Use in the Transportation Model developed by ANL, 2010, Appendix A. Coke and Breeze LHV and HHV not available, Petroleum Coke ratio used in place. Fuel Oil assumed to be Residual Oil.

[c] The Engineering Toolbox, www.engineeringtoolbox.com, Fuel Gases - Heating Values

Table A3-28. Conversion from Lower Heating Value to Higher Heating Value for State of the Art Energy Intensity

State of the Art Energy Intensity by Energy Type and Process Area																					
				Fuel																	
	Intensity Source	Energy Intensity	Feed-stock [a]	Coal		Natural gas		Coke and Breeze		COG		BFG		BOF Gas		Fuel Oil		Elect	Other (utilites, credit)	Steam	Fuel, Elec, Steam Energy Intensity (HHV)
				LHV	HHV [b]	LHV	HHV [b]	LHV	HHV [b]	LHV	HHV [c]	LHV	HHV [c]	LHV	HHV [d]	LHV	HHV [b]				
Integrated Mills																					
Agglomeration Sintering	Table A3-11	GJ/MT sinter				0.06	0.07	1.23	1.30									0.10			1.47
		Percentage				*5%*		*88%*										*7%*			*100%*
Cokemaking	Table A3-12	GJ/MT coke	33.6			0.34	0.38			2.83	3.16	0.04	0.04					0.10		0.25	3.92
		Percentage				*10%*				*81%*		*1%*						*3%*		*6%*	*100%*
Ironmaking Blast Furnace	Table A3-13	GJ/MT pig iron		2.55	2.69			10.83	11.49	0.23	0.26	-3.4	-3.40			1.32	1.41	0.09		0.40	12.94
		Percentage		*21%*				*89%*		*2%*		*-26%*				*11%*		*1%*		*3%*	*100%*
Steelmaking BOF	Table A3-14	GJ/MT steel				0.36	0.40							-0.67	-0.67			0.09		-0.17	-0.35
		Percentage				*NA*								*NA*				*NA*		*NA*	*NA*
Mini Mills																					
Steelmaking EAF	Table A3-15	GJ/MT steel				0.16	0.18											1.71			1.89
		Percentage				9%												91%			100%
Integrated and Mini Mills																					
Casting	Table A3-17	GJ/MT steel				0.03	0.03											0.03			0.06
		Percentage				*53%*												*47%*			*100%*
Rolling Hot	Table A3-18	GJ/MT steel				1.416	1.57											0.32	-0.04	0.01	1.86
		Percentage				*83%*												*17%*		*0%*	*100%*
Cold	Table A3-19	GJ/MT steel				0.73	0.81											0.48		0.36	1.65
		Percentage				*49%*										*0%*		*29%*		*22%*	*100%*

[a] Feedstock coal intensity based on [IPPC 2013], 1285 kg dry coal/metric ton coke produced. Energy value of coal 22.489 MMBtu/short ton (EIA form 846).

[b] Lower heating value intensity converted to higher heating value using HHV/LHV ratio, GREET 1.8d.1, The Greenhouse Gases, Regulated Emissions, and Energy Use in the Transportation Model developed by ANL, 2010, Appendix A. Coke and Breeze LHV and HHV not available, Petroleum Coke ratio used in place. Fuel Oil assumed to be Residual Oil.

[c] The Engineering Toolbox, www.engineeringtoolbox.com, Fuel Gases - Heating Values

[d] Institute for Industrial Productivity, Industrial Efficiency Technology Database, BOF Heat and Gas Recovery: http://ietd.iipnetwork.org/content/bof-heat-and-gas-recovery, 8.8 MJ/Nm3. Assuming equivalent LHV and HHV.

Appendix A4: Technologies Analyzed to Estimate Practical Minimum Energy Intensities with References

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Cokemaking							
Single-chamber-system coking reactors	Replace series of coking ovens with a single large volume oven	Cokemaking	Díez et al. 2002, IPPC 2001, EPA 2012, Nashan 2007, LBNL 2010	38% to 70%	Thermal efficiency improvement from 38% to 70%	CT thermal intensity for cokemaking = 5.02 MMBtu/ton . 38-70% savings claimed; assume lower (38%). 38% savings over CT = 3.83 x 0.38 = 1.46 MMBtu/ton	2.37 MMBtu/ ton
Coal Moisture Control	Drying of coal with waste heat gases	Cokemaking	APP 2010	0.3 GJ/tonne	Fuel savings of 0.3 GJ/tonne	EPA 2012 document estimates fuel savings of 0.268 MMBtu/ton (0.3 GJ/tonne). PM would be equal to 5.02-.268 = 4.75 MMBtu/ton	3.56 MMBtu/ ton
Blast Furnace Ironmaking							
Top Pressure Recovery Turbines	• Use hot high pressure gas from the furnace to power a turbine • Dust removal from blast furnace gases using dry and wet methods.	Ironmaking – Blast Furnace	APP 2010, EPA 2012, Inoue 1995, NEDO 2008, Stelco 1993	Additional 14-36 kWh/ton metal produced	Turbine could produce additional 14-36 kWh/ton of hot metal (depending on available pressure)	EPA 2012 estimates 0.095 MMBtu/ton (0.11 GJ/tonne) electricity savings.	11.63 MMBtu/ ton

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Blast Furnace Ironmaking (continued)							
Top Pressure Recovery Turbines	• Use hot high pressure gas from the furnace to power a turbine • Dust removal from blast furnace gases using dry and wet methods.	Ironmaking – Blast Furnace	APP 2010, EPA 2012, Inoue 1995, NEDO 2008, Stelco 1993	Additional 14-36 kWh/ton metal produced	Turbine could produce additional 14-36 kWh/ton of hot metal (depending on available pressure)	EPA 2012 estimates 0.095 MMBtu/ton (0.11 GJ/tonne) electricity savings.	11.63 MMBtu/ ton
Drum Chute and Segregation Slit Charging	• Use of a drum chute and segregation slit wire to control the particles dropping into the furnace	Ironmaking – Blast Furnace	EPA 2012, NEDO 2008, LBNL 2010	0.7 MMBtu/ton	Can decrease coke use by 0.7 MMBtu/ton	Reported savings of 0.7 MMBtu/ton (0.8 GJ/tonne).	11.02 MMBtu/ ton
Heat recovery from blast furnace slag	• Capture of embedded heat in blast furnace slag through recovery as hot air or steam, chemical energy, or thermoelectric power	Ironmaking – Blast Furnace	Barati et al. 2011, IPPC 2013, JISF 2012, LBNL 2010, POSCO 2010	0.35 GJ/tonne	Savings of approximately 0.35 GJ/tonne of pig iron	Reported savings of 0.3 MMBtu/ton (0.35 GJ/tonne).	11.42 MMBtu/ ton
BOF Steelmaking							
Recycling and reuse of basic oxygen furnace slag	• Separates BOF slag into three products allowing greater iron recovery and recycling • Use of low-grade iron byproduct for acid mine neutralization	BOF Steelmaking	DOE 2002a, IMP 2006, Energetics 2005	0.12 MMBtu/ton	0.12 MMBtu/ton (0.14 GJ/tonne) savings estimated	Estimated savings of 0.12 MMBtu/ton (0.14 GJ/tonne)	0.46 MMBtu/ ton

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
EAF Steelmaking							
EPC System for Side Charging and Scrap Preheating	• Design to allow continuous charging of preheated scarp into the EAF. Separation of preheating and cold scrap charging. • A design that allows movable scrap preheater to allow operation with or without use of scrap preheating • Reduction in gas flows, totally sealed system and substantial reduction in dust and other emissions.	EAF Steelmaking	KR Tec n.d., Rummler et al. n.d.	100 kWh/tonne	Preheating of scrap up to 700 °C reduces EAF energy consumption by up to 100 Kwh/tonne of molten steel.	Reported savings of up to 100 kWh/metric ton; but is similar to Consteel Evolution preheating. Assume 30 kWh/ton (0.1 MMBtu/ton - or 0.12 GJ/tonne).	1.76 MMBtu/ ton
Contiarc Furnace	Replace ladle metallurgy furnace with a continuous series of vessels	EAF Steelmaking	AEHOF 2013, EPA 2012, IPPC 2013	200 kWh/ton	Reduced energy losses (200 kWh/ton) over conventional furnace	EPA 2012 document estimates 0.62 MMBtu/ton (0.72 GJ/tonne) electricity savings.	1.24 MMBtu/ ton
Casting							
Continuous Casting for EAF	Replace ladle metallurgy furnace with a continuous series of vessels	Casting	Peaslee et al. 2006, DOE 2005	10%	Anticipated 10% decrease in energy consumption	10% savings estimate (or 0.005 MMBtu/ton - 0.006 GJ/tonne)	0.19 MMBtu/ ton
Tundish Heating Technologies (Cold Tundish)	• Using a cold tundish • Heating a tundish inductively and not by combustion	Casting	Beraldo et al. 2003, EPA 2012, LBNL 2010	78% (natural gas)	78% decrease in natural gas usage	While impact may vary by plant, EPA 2012 document estimates 0.017 MMBtu/ton (0.02 GJ/tonne) savings.	0.17 MMBtu/ ton

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Rolling							
Endless Rolling	New development in thin slab casting and direct rolling	Rolling	Arvedi et al. 2008, EPA 2012	40%	Anticipated 40% lower energy than a traditional rolling mill	40% savings estimate	1.55 – 2.09 MMBtu/ ton
Next-Generation System for Scale-free Steel Reheating	• Use of preheated or oxygen-enriched air to control flue gas • Improves the quality and yield of steel while increasing energy and production efficiency	Rolling	Thekdi 2010, DOE 2010	0.2 GJ/tonne	• 22-32% of current energy used for reheating • 0.2 GJ/tonne during reheating	Estimated savings of 0.17 MMBtu/ton (0.2 GJ/tonne).	2.41 - 3.31 MMBtu/ ton
High temperature insulation materials	Innovative insulating materials will limit their consumption in a furnace	Rolling	BMWi 2008, EPA 2012	30-35% possible	• Energy savings of 30-35% are possible • Likely savings of 2-5% on furnaces	EPA 2012 document estimates fuel savings of 0.14 MMBtu/ton (0.16 GJ/tonne).	2.44 – 3.34 MMBtu/ ton
Crosscutting Technologies							
New High-Temperature, Low-Cost Ceramic Media for Natural Gas Combustion Burners	Combining four different technologies into a single radiant burner package that functions as both a burner and a catalyst support.	Could potentially apply when electric or natural gas radiant heaters used in process heating.	DOE 2011	25% reduction in energy for process heat	Potential to reduce energy consumption by 25% for process heat.	From MECS data, 626 TBtu of direct end use for process heating. This equates to 64% of direct end use. 25% savings of 83% energy use results in 16% average savings. Practical minimum specific energy savings of 16% over CT applied to all process areas.	16% savings over CT for all process areas

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Crosscutting Technologies (continued)							
Advanced Energy and Water Recovery Technology from Low-Grade Waste Heat	Recovery of high purity water and energy from low grade heat, high moisture waste streams using nanoporous membranes. Will prove concept in laboratory and evaluate in "two different types of industrial environments.	Applies to any process step that produces sufficient low-grade waste heat to make the process viable	DOE 2011c; GTI 2011	20-30% greater energy efficiency in recovery from low grade waste heat.	The amount of energy savings would depend on the amount of waste heat could be recovered. Using the nanoporous membrane technology could increase heat recovery by 20-30% it would appear.	There will be an estimated 5.7 TBtu/year energy savings for the iron and steel industry with wet scrubbers. Compared to the overall CT energy consumption of 981 TBtu/year, this represents a 1% energy savings. Practical minimum energy savings of 1% over CT is applied to all processes.	1% savings over CT for all process areas
Control Systems for Energy-efficient Recycling of Steel Residues	By utilizing computer-aided control of the process conditions, changes can be made in the prevailing conditions to reduce recycling energy consumption. In practical trials this software helped reduce energy consumption by 10%. The modular design of this software also enables changes to the processing conditions to reflect the desired product quality.	Crosscutting	BMWi 2008	10% reduction in energy consumption	Opportunity reduced to 2%.	2% reduction in energy consumption assumed	2% savings over CT for all process areas

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

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Appendix A5: Practical Minimum Technology Weighting Factors

Methodology to Determine Weighting Factors

In this section the practical minimum technology weighting factors methodology is explained. The application of this methodology is presented in Table A4.

Six Weighting Factors, A through F, are considered for each technology and scored as shown (High (H) = 3, Medium (M) = 2, Low (L) = 1, Not Available (NA) = 0). The factors are also scaled according to DOE Importance Level, e.g., an importance level of 2 carries twice the weight of an importance level of 1. For the iron and steel bandwidth, factors A-F each carried a DOE Importance Level of 1.

The DOE Importance Level is multiplied by the score for each factor and divided by the total possible score to determine overall weighting of technology. The NA score of 0 is excluded from overall weighting.

Factor A - Technology Readiness

- High = Technology Readiness Level (TRL) 7-9
- Medium = TRL 4-6
- Low = TRL 1-3

Factor B - Market Impact

- High = widely applicable to all establishments
- Medium = applicable to many establishments
- Low = applicable to select few establishments or unique process

Factor C - Relative Cost and Savings Payback

- High = implementation cost >90% of reference technology, or payback > 10 years
- Medium = cost <90% and >40% of reference technology, payback <10 years
- Low = cost <40% of reference, payback < 2 years

Note: the score is reversed such that H = 1 and L = 3

Factor D – Technical Risk

- High = high likelihood of technology success and deployment, minimal risk factors
- Medium = insufficient evidence of technology success, some risk factors
- Low = low likelihood of success, multiple and significant risk factors

Note: the score is reversed such that H = 1 and L = 3

Factor E – Productivity/Product Quality Gain

- High = significant gain in productivity, either quantity or quality of product produced
- Medium = moderate gain in productivity
- Low = no gain in productivity

Factor F – Environmental Benefits

- High = multiple and significant environmental benefits,
- Medium = some environmental benefits,
- Low = little or no environmental benefit

Table A5. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Cokemaking													
Single-chamber-system Coking Reactors	M	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	H	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	72%
Coal Moisture Control	M	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	H	Engineering Judgment	M	Engineering Judgment	89%
Blast Furnace Ironmaking													
Top Pressure Recovery Turbines	H	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	H	Engineering Judgment	72%
Drum Chute and Segregation Slit Charging	H	Engineering Judgment	M	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	M	Engineering Judgment	L	Engineering Judgment	78%
Heat Recovery From Blast Furnace Slag	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	M	Engineering Judgment	67%
BOF Steelmaking													
Recycling and Reuse of Basic Oxygen Furnace Slag	H	Engineering Judgment	H	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	L	Engineering Judgment	H	Engineering Judgment	78%

Table A5. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
EAF Steelmaking													
EPC System for Side Charging and Scrap Preheating	H	Engineering Judgment	M	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	83%
Contiarc Furnace	H	Engineering Judgment	H	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	H	Engineering Judgment	M	Engineering Judgment	83%
Casting													
Continuous Casting for EAF	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	67%
Tundish Heating Technologies (Cold Tundish)	H	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	56%
Rolling													
Endless Rolling	H	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	H	Engineering Judgment	80%
Next-Generation System for Scale-free Steel Reheating	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	72%

Table A5. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
High Temperature Insulation Materials	M	Engineering Judgment	H	Engineering Judgment	H	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	L	Engineering Judgment	61%
Crosscutting Technologies													
New High-Temperature, Low-Cost Ceramic Media for Natural Gas Combustion Burners	H	Engineering Judgment - TRL 7	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	M	Better heating	H	Large energy savings	83%
Advanced Energy and Water Recovery Technology from Low-Grade Waste Heat	M	Engineering Judgment - TRL 4	H	Wide ranging applications	H	Major capital investment	H	Large process change	L	Engineering Judgment	H	Waste water recovery	61%
Control Systems for Energy-efficient Recycling of Steel Residues	H	Engineering Judgment - TRL 7	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	H	Engineering Judgment	H	Engineering Judgment	83%

Appendix A4 provides the methodology used to identify the weighting factors and the definitions for the abbreviations.

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