U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Advanced High Strength Steels Manufacturing

September 2017

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.[1] The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the manufacturing of products that can be used for lightweighting applications, and provide hypothetical, technology-based estimates of potential energy savings opportunities in the manufacturing process. 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.

This study is being released as part of a series of six studies focusing on energy use in the manufacture of the following lightweight structural materials: carbon fiber reinforced polymer composites, glass fiber reinforced polymer composites, advanced high-strength steel alloys, aluminum alloys, magnesium alloys, and titanium alloys. The boundaries of these analyses were drawn based on features of the manufacturing processes that are unique to each material. Therefore, the results of the lightweight materials bandwidth studies cannot be directly compared. In a separate study, Lightweight Materials Integrating Analysis, these boundaries are redrawn to consistently include energy consumption for all phases of the product manufacturing life cycle, from the energy embodied in the raw materials through finished part fabrication (for selected applications); energy associated with end-of-life recycling is also considered. This allows the data to be integrated and compared across all six materials. This separate study, currently under development, also develops a framework for comparing manufacturing energy intensity on a material performance (e.g., effective weight) basis for illustrative applications.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure below). **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 research and development (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 theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included within the energy consumption estimates.

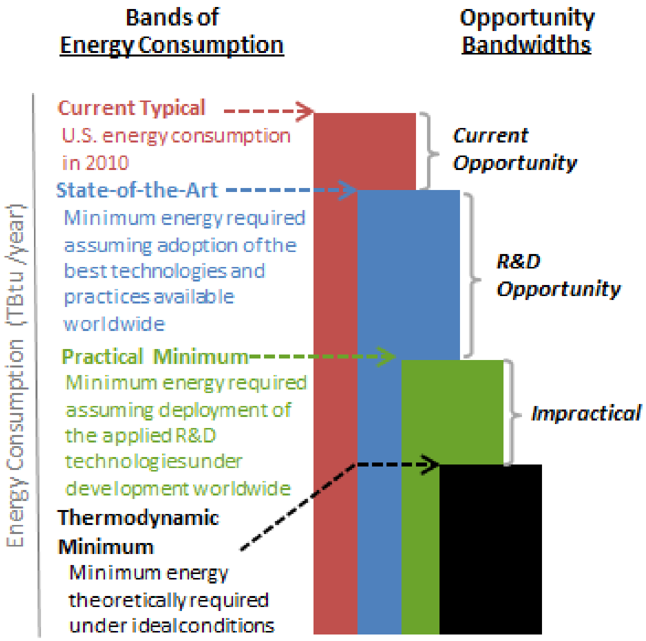

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

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[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). Most recently, revised and consistent versions of bandwidth studies for the *Chemicals, Petroleum Refining, Iron and Steel*, and *Pulp and Paper* sectors were published in 2015.

Two on-site 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. The total opportunity is the sum of the R&D and the current opportunities. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. 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.

For each lightweighting material studied in the series, the four energy bands are estimated for select individual subareas of the material manufacturing process. The estimation method involved a detailed review and analytical synthesis of data from diverse industry, governmental, and academic sources. Where published data were unavailable, best engineering judgment was used.

Acknowledgments

Joseph Cresko of DOE/AMO led the conceptual development and publication of the bandwidth study series with support from Dr. Alberta Carpenter of the National Renewable Energy Laboratory. AMO recognizes the efforts of Caroline Dollinger, Sabine Brueske, and Keith Jamison of Energetics Incorporated for conducting the research and analysis and writing this study. AMO wishes to acknowledge the contributions made by Lawrence W. Kavanagh of the Steel Market Development Institute and Mahmoud Y. Demeri for their work reviewing this study.

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List of Acronyms and Abbreviations

AHSS	Advanced High Strength Steels
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
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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Executive Summary

The United States is a significant producer of iron and steel products, especially specialty grades such as advanced high strength steels (AHSS). This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. AHSS manufacturing for lightweighting applications. Industrial, government, and academic data are used to estimate the energy consumed in six of the most energy intensive manufacturing subareas. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing subareas 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 *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 each AHSS manufacturing subarea. 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 and boundaries (Chapter 1) the 2010 production volumes (Chapter 2) and current energy consumption (current typical [CT], Chapter 3) were estimated for six select subareas. 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 4) and assuming the deployment of the applied research and development (R&D) technologies available worldwide (practical minimum [PM], Chapter 5). The minimum amount of energy theoretically required for these processes assuming ideal conditions was also estimated (thermodynamic minimum [TM)], Chapter 6); 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 7).

In this study, CT, SOA, PM, and TM energy consumption for six *individual* subareas is estimated from multiple referenced sources.

Study Results: Two energy savings opportunity *bandwidths* – current opportunity and R&D opportunity – are presented in Table ES-1 and Figure ES-1.[2] 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 U.S. advanced high strength steel manufacturing subareas studied and as a total.

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. Also, AHSS production has seen growth in the past several years, especially with increased application in the automotive sector. Therefore, it is important to note that the total energy opportunities would scale with increasing production.

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[2] 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 on-site energy use (i.e., energy consumed within the plant boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

Table ES-1. Potential Energy Savings Opportunities in the U.S. Advanced High Strength Steel Manufacturing Sector (Considering Production for Lightweighting Application Areas only)*

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Select Advanced High Strength Steel Manufacturing Subareas (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	**7.4 TBtu**[3] (52% energy savings)[4]
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	**3.22 TBtu**[5] (22% energy savings)[6]

* Calculated using the production values for lightweight structural application areas considered in this study only (see Section 1.4), and not all AHSS.

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume the successful 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" in Figure ES-1 because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, it is shown as a dashed line with color fading because emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

An estimated 22.65 TBtu of energy was consumed in 2010 to manufacture AHSS in the United States for the structural applications considered in this study. Based on the results of this study, an estimated 7.4 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide were used to upgrade the advanced high strength steel manufacturing subareas studied; an additional 3.2 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

The top three current energy savings opportunities for AHSS are as follows:

- Cold rolling – 3.3 TBtu (or 43% of the current opportunity)
- Hot rolling – 2.1 TBtu (or 29% of the current opportunity)
- Basic oxygen furnace steelmaking – 0.9 TBtu (or 13% of the current opportunity).

The top three R&D energy savings opportunities for AHSS are as follows:

- Blast furnace ironmaking – 2.0 TBtu (or 63% of the R&D opportunity)
- Cokemaking – 0.4 TBtu (or 13% of the R&D opportunity).
- Cold rolling – 0.3 TBtu (or 11% of the R&D opportunity)

DOE researchers will continue to evaluate the energy consumption and opportunity bandwidths in U.S. advanced high strength steel manufacturing, along with bandwidth study results from other manufacturing sectors.

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[3] Current opportunity = CT – SOA, as shown in Table 4-3.

[4] Current opportunity (or SOA) percentage = $\left(\frac{CT-SOA}{CT-TM}\right)x100$, as shown in Table 4-3.

[5] R&D opportunity = SOA – PM, as shown in Table 5-4.

[6] R&D opportunity percentage = $\left(\frac{SOA-PM}{CT-TM}\right)x100$, as shown in Table 5-4.

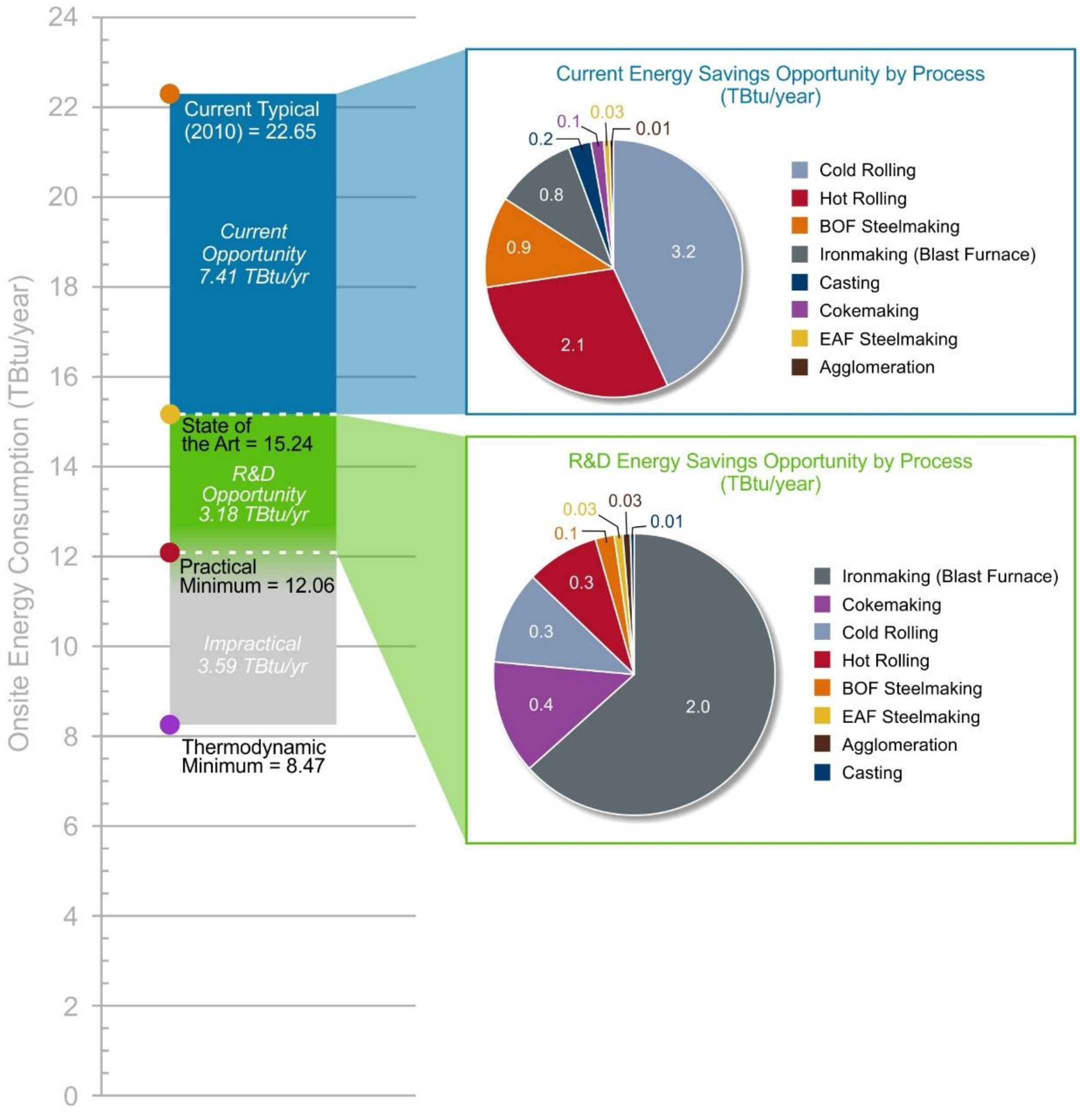

Figure ES-1. Current and R&D energy savings opportunities for the advanced high strength steel manufacturing subareas studied (considering lightweighting application area production only)
Source: EERE

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1. Introduction

1.1. Overview

The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze processes and products that are highly energy intensive, and provide hypothetical, technology-based estimates of energy savings opportunities. Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Manufacturing energy bandwidth studies serve as general data references to help understand the range (or *bandwidth*) of energy savings opportunities. DOE AMO commissioned this bandwidth study to analyze the most energy consuming processes in manufacturing advanced high strength steels (AHSS).

This study is one in a series of six bandwidth studies characterizing energy use in manufacturing lightweight structural materials in the United States. The other materials, studied in parallel, include: aluminum alloys, magnesium alloys, titanium alloys, carbon fiber reinforced composites, and glass fiber reinforced composites. Separate studies are available for these materials. As a follow-up to this work, an integrating analysis will be conducted to compare the results across all six studies.

Similar energy bandwidth studies have also been prepared for four U.S. manufacturing sectors – chemicals (DOE 2015a), iron and steel (DOE 2015b), petroleum refining (DOE 2015c), and pulp and paper (DOE 2015d). These studies follow the same analysis methodology and presentation format as the seven lightweight structural material energy bandwidth studies.

1.2. Definitions of Energy Consumption Bands and Opportunity Bandwidths

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.

As shown in the figure on the right, four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption to manufacture specific products and to compare energy savings opportunities in U.S. manufacturing facilities. **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.

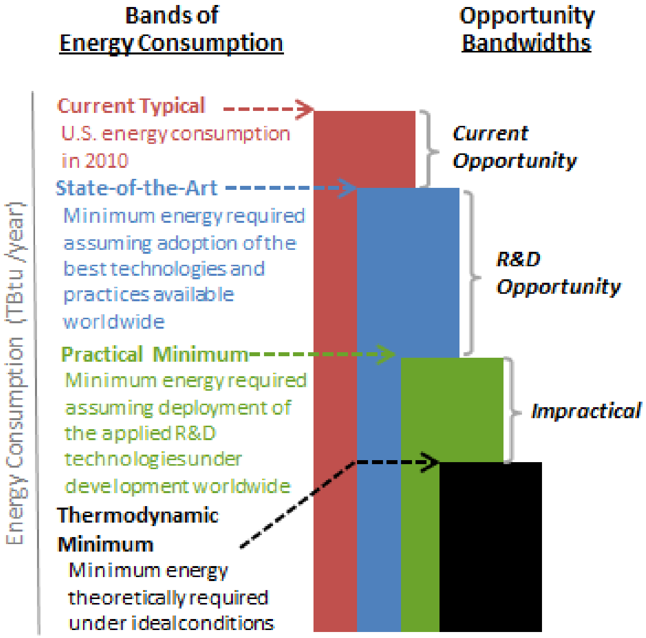

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or 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 on-site 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. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. 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 technologies was not in the scope of this study.

1.3. 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 "on-site energy" or "primary energy" and defined as follows:

- **On-site 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 on-site energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both off site and on site during the manufacturing process. Off-site 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.

The four bands of energy consumption described above are quantified for process subareas and for the material total. **The bands of energy consumption and the opportunity bandwidths presented herein consider on-site energy consumption; feedstocks[7] are excluded.** To determine the total annual on-site CT, SOA, PM, and TM energy consumption (TBtu per year), energy intensity values per unit weight (Btu per pound of material manufactured) were estimated and multiplied by the production (pounds per year of material manufactured). The year 2010 was used as a base year since it is the most recent year for which consistent energy consumption and production data were available for all six lightweight materials analyzed in this series of bandwidth studies. Unless otherwise noted, 2010 production data were used. Some production processes are exothermic and are net producers of energy; the net energy was considered in the analysis.

Chapter 2 presents the **U.S. production** (million tons per year) in 2010, including an overview of major application areas. Four structural application areas are included with the scope of this bandwidth report. The production volumes for these application areas were estimated from market data.

Chapter 3 presents the calculated on-site **CT energy intensity** (MMBtu per ton and GJ per tonne) and **CT energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources).

Chapter 4 presents the estimated on-site **SOA energy intensity** (MMBtu per ton and GJ per tonne) and **SOA energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources).

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[7] 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.

Chapter 5 presents the estimated on-site **PM energy intensity** (MMBtu per ton and GJ per tonne) and **PM energy consumption** for the process subareas studied and material total (along with sources).

Chapter 6 presents the estimated on-site **TM energy intensity** (MMBtu per ton and GJ per tonne) and **TM energy consumption** for the process subareas studied and material total (along with sources).

Chapter 7 provides a summary of **current and R&D opportunity** analysis based on bandwidth study results.

1.4. Boundaries of the AHSS Bandwidth Study

The U.S. manufacturing sector is the physical boundary of study. It is recognized that the major benefits of lightweight materials often occur *outside* of the manufacturing sector—for example, the energy benefits of a lightweight automobile component are typically realized primarily through fuel savings during the vehicle's use phase. Economic impacts may also be important: an advanced lightweight aerospace component may be more expensive than the conventional choice. While such impacts are recognized as important, they will not be quantified as this is not a life cycle assessment study. Instead, this report focuses exclusively on the energy use directly involved in the production of AHSS from the relevant input materials. The focus of this bandwidth study is thus the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to AHSS manufacturing at a production facility.

This study does not consider life cycle energy consumed during raw material extraction, off-site treatment, transportation of materials, product use, or disposal. For consistency 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.

Steel is used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. AHSS is widely used in transportation applications, where mass reductions can provide substantial energy savings through improved fuel economy. These applications are of high relevance to the DOE because of the potential life cycle energy savings. Other applications, such as in medical, electronics and communications, computers and electrical equipment, construction and infrastructure, and consumer goods and packaging, may be less relevant to DOE. In order to focus exclusively on structural applications with strong relevance to energy use, this study was limited to four key application areas:

1) Automotive lightweighting (e.g., vehicle chassis, body, doors)
2) Compressed gas storage (e.g., hydrogen fuel tanks for electric vehicles)
3) Wind turbines (e.g., lighter and longer turbine blades)
4) Aerospace (e.g., aircraft fairings, fuselages, floor panels).

The first three of these application areas are consistent with the areas of interest outlined in the DOE *Composite Materials and Structures* Funding Opportunity Announcement (DOE 2014). The last application area (aerospace) is an additional high value-add market for lightweight structural materials. Based on the production numbers available, it was assumed that approximately 100% of overall AHSS production in the United States is for use in automotive lightweighting, as shown in Figure 1-2 (see Section 2.2 for more detail).

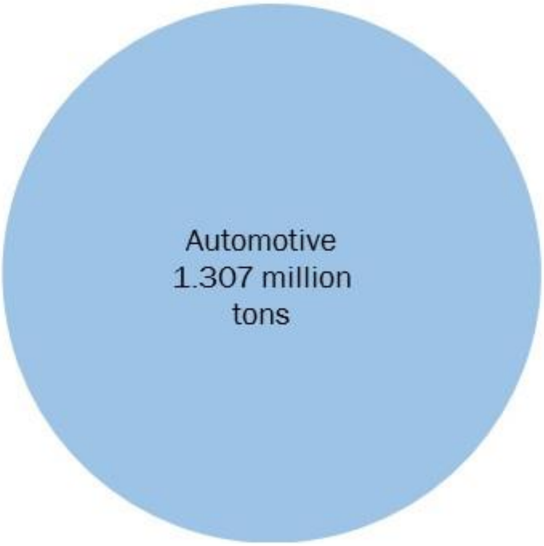


Figure 1-2. Estimated makeup of the AHSS market in 2010.
Data source: Abraham 2015, AISI 2015, Demeri 2013, and Marcus 2014

2. Advanced High Strength Steel Production

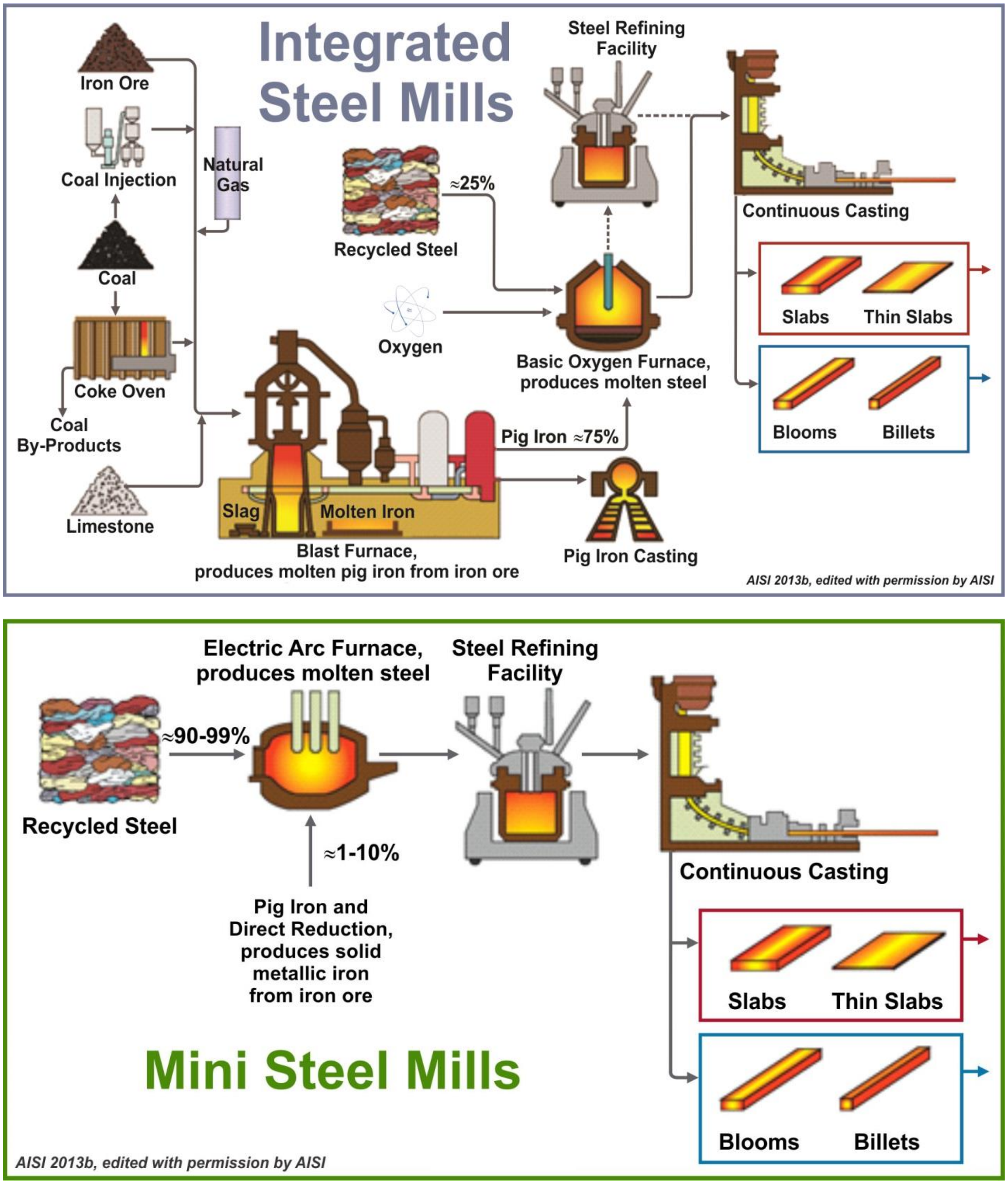
Steel is a vital domestic manufacturing product and is important for many applications including construction (residential, commercial, transportation), automotive, machinery and equipment, containers, and national security, among others. Steel is widely used in vehicles, making up over half of the composition of vehicles today (WSA 2014). Advanced high strength steel (AHSS), while also used in vehicles today, offers weight reduction possibilities of 25-39% compared to conventional steel, helping to reduce the lifecycle energy use and emissions of vehicles even further (WSA 2014). This is why steelmakers are interested in producing higher quantities and new grades of AHSS for the growing vehicle market.

2.1. Manufacturing Overview

Iron and steel operations are complex and large facilities that produce significant quantities of steel each year. Steel mills in the United States 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 for all steel (USGS 2012c)). This proportion must be lower for grades of AHSS, which require less contaminants in order to gain the resulting desired properties. There is little information on the properties of steel recycled in 2010, making it difficult to determine what amounts and types of tramp elements and alloying elements are present during the BOF and EAF steelmaking processes. Additionally, elements may be considered as tramp elements in one case or an alloying element in another case, depending upon the grade of steel being produced (Worrell & Reuter 2014). There is no commercial refining process for tramp elements available today, and it is also possible for these elements to enter the system through ore or reductants used (in addition to the steel scrap) (Worrell & Reuter 2014). To compensate for the existence of tramp elements, producers of high quality grades of steel such as AHSS must depend on a source of well sourced scrap, obsolete scrap, or the use of ore-based iron units (such as direct reduced iron or hot briquetted iron) as input to the EAF in lieu of a portion of the scrap (Worrell & Reuter 2014).

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 2-1 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 United States (USGS 2012a). Most of these steelmaking facilities in the United States 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, all 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). It is unclear which of these facilities produce AHSS grades in addition to carbon, stainless, and other types of steels, as well as the relative amounts.



AISI 2013b, edited with permission by AISI

AISI 2013b, edited with permission by AISI

Figure 2-1. Steelmaking flowlines for integrated (top) and mini mills (bottom)
Source: 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 subarea and sub-processes for CT, SOA, PM, and TM in Sections 3 through 6 of this report. Current energy intensity for pelletizing iron ore is shown for reference purpose only because this sub-process is outside the boundary of bandwidth analysis. Direct reduction ironmaking was not used in the United States in 2010, and therefore not included in the CT, SOA, PM, and TM bandwidth measures and savings summary.

Table 2-1. Advanced High Strength Steel Manufacturing Process Areas Considered in Bandwidth Analysis

Subareas	Sub-Processes
Agglomeration	Sintering
Cokemaking	
Ironmaking	Blast Furnace
Basic Oxygen Furnace (BOF) Steelmaking	
Electric Arc Furnace (EAF) Steelmaking	
Casting/Rolling	Continuous Casting Hot Rolling Cold Rolling

There are two main processes for producing steel: integrated steelmaking, which combines a blast furnace (BF) with a basic oxygen furnace (BOF), and electric arc furnace (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 for all steel (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). Steel grades such as AHSS require specific compositions, meaning that there is less of a possibility of using an increased amount of recycled steel to produce AHSS.

It requires significantly more 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 agglomeration, pelletizing was not included in the production or energy intensity numbers because this process occurs outside of the boundary of this bandwidth analysis (pelletizing is usually conducted near the ore mining site, and not at the steel mill).

2.2. Production Values

Production data for total AHSS produced in the United States (or worldwide) is generally not available or collected as a whole. However, sector-side iron and steel manufacturing production data is available by process and sector-wide. The American Iron and Steel Institute (AISI) is the leading source for information on total steel production in North America. The AISI Statistical Summary is released annually and provides production data along with other statistical information. Total iron and steel sector production data for 2010 is summarized in Table 2-2. The amount of AHSS that is cast and rolled, 1.307 million tons (1.186 million tonnes) as shown in Table 2-2, was estimated based on the amount of AHSS that it shipped to automakers in North America. Based on expert communications and sources, it was assumed that U.S. steel was shipped to about U.S. automakers and half of the remaining North American automotive industry; the total was calculated using the reference value of 156 lb of AHSS per vehicle which was also adjusted for processing losses (Abraham 2015, AISI 2015, Demeri 2013, and Marcus 2014). Based on figures provided by AISI 2015, it is assumed that all of the AHSS produced in 2010 for the North American automotive market is cold rolled.

While AHSS would have applicability for the four applications considered for this study (automotive lightweighting, compressed gas storage, wind turbines, and aerospace and other transportation), the automotive sector is the most notable application area and for which steel consumption data was available. It was therefore assumed that this application consumes a significant majority of AHSS produced in the United States, which is small compared to the total amount of steel produced. However, the energy intensity numbers provided in this report are the basis for the total energy consumption, and can be used to calculate the consumption for various steel type production values, including AHSS.

Throughout the report, energy intensities are presented as MMBtu per ton (and GJ per tonne) of product for a specific subarea (e.g., for cokemaking the energy intensity is in MMBtu per ton (and GJ per tonne) of coke produced). This is how results are typically presented in the iron and steel industry and data available from sources was presented in this way.

Table 2-2. U.S. Advanced High Strength Steel Subarea Products and Production in 2010

Subarea	Product	**2010 Total Steel Sector Production** (1,000 tons) [1,000 tonnes]	**2010 AHSS Estimated Production** (1,000 tons) [1,000 tonnes]
Agglomeration			
Sintering*	Sinter	5,759 [5,228]	178 [161]
Cokemaking	Coke	9,292 [8,435]	287 [260]
Ironmaking**	Iron	29,590 [26,862]	914 [829]
BOF Steelmaking***	Raw Steel	34,345 [31,179]	1,061 [963]
EAF Steelmaking***	Raw Steel	54,386 [49,372]	265 [241]
Casting/Rolling			
Casting	Continuous Cast Steel	84,784 [76,968]	1,307 [1,186]
Hot Rolling	Hot Rolled Steel	84,784 [76,968]	1,307 [1,186]
Cold Rolling	Cold Rolled Steel	27,710 [25,156]	1,307 [1,186]

* Represents sinter consumption in steel mill blast furnaces; assumed to be produced domestically.
** Excludes limited production of ITmk3-produced iron nuggets.
*** Detailed data on which pathway was used to produce AHSS was unavailable for 2010; therefore, the split of 80% BOF route and 20% EAF route was assumed for this report (based on expert communications). It is recognized that the amount of scrap vs. ore used as inputs to the steelmaking process may vary depending upon the specific facility but that information is general unavailable for citation. Modifications of this assumption would result in a different total energy consumption.
Data sources: Abraham 2015, AISI 2011a, AISI 2015, Demeri 2013, Marcus 2014.

3. Current Typical Energy Intensity and Energy Consumption

This chapter presents the energy consumption data for individual advanced high strength steel manufacturing subareas in 2010 for the boundary application areas production. Energy consumption in a manufacturing process can vary for diverse reasons. The energy intensity estimates reported herein are representative of average U.S. advanced high strength steel manufacturing; they do not represent energy consumption in any specific facility or any particular region in the United States.

3.1. Sources for Current Typical Energy Intensity

Appendix A1 presents the CT energy intensities and energy consumption for the subareas studied. Table 3-1 presents a summary of the main references consulted to identify CT energy intensity by subarea. Appendix A2 provides the references used for each subarea.

Because the steel sector is diverse, covering many products, a range of data sources were considered (see Table 3-1). In most cases, multiple references were considered for each process. Each iron and steel manufacturing 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. 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 3-1. Main Sources Referenced in Identifying Current Typical Intensity by Subarea and Material Total

Source Abbreviation	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 United States; 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.

3.2. Current Typical Energy Intensity and Energy Consumption

Table 3-2 presents the energy intensities and calculated on site and primary CT energy consumption for the AHSS production subareas studied. Feedstock energy is excluded from the consumption values. The energy intensities are presented in terms of MMBtu per ton (or GJ per tonne) of subarea product (listed in parenthesis in the first column). The CT energy consumption for these subareas is estimated to account for 22.7 TBtu of on-site energy and 27.6 TBtu of primary energy in 2010.

Primary energy is calculated from on-site CT energy consumption data based on an analysis of MECS data (DOE 2014), with scaling to include off-site electricity and steam generation and transmission losses (DOE 2014). To determine primary energy, the net electricity and net steam portions of sector-wide on-site energy are scaled to account for off-site generation and transmission losses and added to on-site energy (see the footnote in Table 3-2 for details on the scaling method).

Table 3-2. On-site CT Energy Intensity and Calculated Energy Consumption and Calculated Primary CT Energy Consumption for U.S. AHSS Manufacturing: Application Areas Studied (2010)

Subarea (product)	**On-site CT Energy Intensity** (MMBtu/ton product) [GJ/tonne product]	**Production** (1,000 tons) [1,000 tonnes]	**On-site CT Energy Consumption, Calculated** (TBtu/year)	**Off-site Losses, Calculated*** (TBtu/year)	**Primary CT Energy Consumption, Calculated** (TBtu/year)
Agglomeration (sinter)	1.32 [1.54]	178 [161]	0.23	0.03	0.27
Cokemaking (coke)	3.83 [4.45]	287 [260]	1.10	0.06	1.16
BF Ironmaking (iron)	11.72 [13.63]	914 [829]	11.02	0.12	11.13
BOF Steelmaking (raw steel)	0.58 [0.67]	1,061 [963]	0.61	0.24	0.85
EAF Steelmaking (raw steel)	1.96 [2.28]	265 [241]	0.52	0.92	1.44
Casting/Rolling (cast/rolled steel)					
Casting	0.19 [0.22]	1,307 [1,186]	0.25	0.18	0.43
Hot Rolling	2.99 [3.48]	1,307 [1,186]	3.91	1. 06	5.14
Cold Rolling	3.48 [4.05]	1,307 [1,186]	5.02	2.29	7.30
Total for Process Subareas Studied			**22.65**	**4.9**	**27.55**

Current typical (CT)

* Accounts for off-site electricity and steam generation and transmission losses. Off-site 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 off-site sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Off-site steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and off-site 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).

** CT energy consumption values for blast furnace and cold rolling each exclude a portion of nonfuel feedstock natural gas (based on DOE 2014).

4. State of the Art Energy Intensity and Energy Consumption

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. AHSS producers 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.

4.1. Sources for State of the Art Energy Intensity

Appendix A1 presents the on-site SOA energy intensity and consumption for the subareas considered in this bandwidth study. The on-site 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 on-site SOA energy consumption estimates exclude feedstock energy.

Table 4-1 presents the list of published sources that were referenced to identify the SOA energy intensities. The source abbreviated as NRC 2007 was heavily referenced to determine the SOA energy intensity for many of the subareas. Technologies employed in this source 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.

Table 4-1. Main Sources Referenced in Identifying State of the Art Intensity by Process Area and Material Total

Source Abbreviation	Description
Energiron 2013	*Energiron: The Innovative Direct Reduction Technology*, Information on the direct reduction process
Giavani et al. 2012	*Consteel Evolution™ – 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.

4.2. State of the Art Energy Intensity and Energy Consumption

Table 4-2 presents the on-site SOA energy intensities and energy consumption for the AHSS manufacturing subareas studied. The SOA energy intensities are presented as MMBtu per ton and GJ per tonne subarea product and the on-site SOA energy consumption is presented as TBtu per year.

Table 4-2. SOA Energy Intensities and Calculated SOA Energy Consumption for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**On-site SOA Energy Intensity** (MMBtu/ton product) [GJ/tonne product]	**On-site SOA Energy Consumption, Calculated** (TBtu/year)
Agglomeration (sinter)	1.27 [1.47]	0.23
Cokemaking (coke)	3.37 [3.92]	0.97
BF Ironmaking (iron)	11.13 [12.94]	10.17
BOF Steelmaking (raw steel)	-0.30 [-0.35]	-0.32
EAF Steelmaking (raw steel)	1.85 [2.16]	0.49
Casting/Rolling (cast/rolled steel)		
Casting	0.05 [0.06]	0.07
Hot Rolling	1.37 [1.59]	1.78
Cold Rolling	1.42 [1.65]	1.85
Total for Process Subareas Studied		**15.24**

State of the Art (SOA)

Table 4-3 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each subarea and as a total. This is presented as the SOA energy savings (or *current opportunity*) and SOA energy savings percent. 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. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is BOF steelmaking at 72% energy savings; the greatest *current opportunity* in terms of TBtu savings is cold rolling at 3.2 TBtu per year savings.

If U.S AHSS manufacturing (for the 2010 production level of AHSS for application areas considered) were able to attain on-site SOA energy intensities, it is estimated that 7.4 TBtu per year of energy could be saved from the subareas alone, corresponding to a 52% energy savings overall (see formula below). 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.

Table 4-3. Calculated SOA Energy Consumption for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**On-site CT Energy Consumption, Calculated** (TBtu/year)	**On-site SOA Energy Consumption, Calculated** (TBtu/year)	**SOA Energy Savings*** (CT-SOA) (TBtu/year)	**SOA Energy Savings Percent**** (CT-SOA)/ (CT-TM)
Agglomeration (sinter)	0.23	0.23	<0.1	19%
Cokemaking (coke)	1.10	0.97	0.13	22%
BF Ironmaking (iron)	11.02	10.17	0.85	26%
BOF Steelmaking (raw steel)	0.61	-0.32	0.93	72%
EAF Steelmaking (raw steel)	0.52	0.49	0.03	15%
Casting/Rolling (cast/rolled steel)	9.17	3.71	5.46	63%
Casting	0.25	0.07	0.17	71%
Hot Rolling	3.91	1.78	2.12	60%
Cold Rolling	5.02	1.85	3.17	64%
Total for Process Subareas Studied	**22.65**	**15.24**	**7.41**	**52%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* SOA energy savings is also called *Current Opportunity.*
** SOA energy savings percent is the SOA energy savings opportunity from transforming AHSS production processes. Energy savings percent is calculated using TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT-SOA)/(CT-TM)

The SOA energy savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in Chapter 6, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site SOA energy savings percent is:

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

5. Practical Minimum Energy Intensity and Energy Consumption

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

5.1. Sources for Practical Minimum Energy Intensity

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific AHSS production 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 search of R&D activities in the steel industry was conducted. 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 A3 provides an example of the range of technologies considered for evaluation, and explains the calculation methodology.

Table 5-1 presents the key sources consulted to identify PM energy intensities in AHSS manufacturing.

Table 5-1. Sources Referenced in Identifying Practical Minimum Intensity by Process Area and Material Total

Source Abbreviation	Description
Birat et al. 2009	*The "CO_2 Tool": CO_2 emissions & energy consumption of existing & breakthrough steelmaking routes.*
Birat et al. 1999	*CO_2 Emissions and the Steel Industry's Available Responses to the Greenhouse Effect.*
Energetics 2005	*Steel Industry Marginal Opportunity Study.*
Gordon et al. 2010	*Ironmaking Technology Selection for Site Specific Conditions.*
LBNL 2013	*Emerging Energy-efficiency and Carbon Dioxide Emissions-reduction Technologies for the Iron and Steel Industry*.
Sadoway 2008	*Electrochemical Pathways Towards Carbon-free Metals Production.*
UNIDO 2010	*Global Technology Roadmap for CCS in Industry: Steel Sectoral Report.*

Numerous fact sheets, case studies, reports, and other sources were referenced.

5.2. Practical Minimum Energy Intensity and Energy Consumption

Table 5-2 presents the on-site PM energy intensities and energy consumption for the AHSS manufacturing subareas studied. The PM energy intensities are presented as MMBtu per ton and GJ per tonne subarea product and the on-site PM energy consumption is presented as TBtu per year.

Table 5-2. Calculated PM Energy Consumption for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**On-site PM Energy Intensity** (MMBtu/ton product) [GJ/tonne product]	**On-site PM Energy Consumption, Calculated** (TBtu/year)
Agglomeration (sinter)	1.11 [1.29]	0.20
Cokemaking (coke)	1.92 [2.23]	0.55
BF Ironmaking (iron)	8.92 [10.38]	8.15
BOF Steelmaking (raw steel)	-0.37 [-0.43]	-0.39
EAF Steelmaking (raw steel)	1.74 [2.02]	0.46
Casting/Rolling (cast/rolled steel)		
Casting	0.04 [0.05]	0.06
Hot Rolling	1.16 [1.35]	1.52
Cold Rolling	1.16 [1.35]	1.51
Total for Process Subareas Studied		**12.06**

Practical Minimum (PM)

Table 5-3 presents a comparison of the on-site CT energy consumption and PM energy consumption for each subarea and as a total. This is presented as the PM energy savings (the difference between CT energy consumption and PM energy consumption) and PM energy savings percent. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings. Table 5-4 calculates the R&D opportunity for the process subareas studied.

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. Among the processes studied, the greatest *current* plus *R&D opportunity* in terms of percent energy savings is cokemaking at 90% energy savings; the greatest *current* plus *R&D opportunity* in terms of TBtu savings is cold rolling at 3.5 TBtu per year savings.

If U.S. AHSS manufacturing (for the 2010 production level of AHSS for application areas considered) were able to attain on-site PM energy intensities, it is estimated that 10.6 TBtu per year of energy could be saved from the subareas alone, corresponding to a 75% energy savings overall. This energy savings estimate is based on adopting available PM technologies and practices. This is a simple estimate for potential savings, it is not inferred that all existing mills could achieve these PM energy intensity values or that the improvements would prove to be cost effective in all cases.

Table 5-3. Calculated PM Energy Consumption for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**On-site CT Energy Consumption, Calculated** (TBtu/year)	**On-site PM Energy Consumption, Calculated** (TBtu/year)	**PM Energy Savings*** (CT-PM) (TBtu/year)	**PM Energy Savings Percent**** (CT-PM)/ (CT-TM)
Agglomeration (sinter)	0.23	0.20	0.04	73%
Cokemaking (coke)	1.10	0.55	0.55	90%
BF Ironmaking (iron)	11.02	8.15	2.86	86%
BOF Steelmaking (raw steel)	0.61	-0.39	1.00	77%
EAF Steelmaking (raw steel)	0.52	0.46	0.06	31%
Casting/Rolling (cast/rolled steel)	9.17	3.09	6.08	70%
Casting	0.25	0.06	0.19	77%
Hot Rolling	3.91	1.52	2.39	68%
Cold Rolling	5.02	1.51	3.51	71%
Total for Process Subareas Studied	**22.65**	**12.06**	**10.59**	**75%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
* PM energy savings is the *Current Opportunity* plus the *R&D Opportunity.*
** PM energy savings percent is the PM energy savings opportunity from transforming AHSS production processes. Energy savings percent is calculated using TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT-PM)/(CT-TM)

The PM energy savings percent is the percent of energy saved with PM energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in the following section, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equations for calculating on-site R&D opportunity and PM energy savings percent are:

$$R\&D\ Opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

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

R&D opportunity represents the opportunities for energy savings from technologies currently an R&D stage of development (early TRL) and are not ready for deployment to manufacturing. It represents the energy savings opportunities that can be achieved if the R&D is put into those technologies to get them to a high enough TRL level that they can be deployed in the manufacturing sector. Table 5-4 shows the R&D opportunity total and percent for the evaluated process subareas studied.

Table 5-4. Calculated PM Energy Consumption, R&D Opportunity, and R&D Opportunity for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**On-site SOA Energy Consumption, Calculated** (TBtu/year)	**On-site PM Energy Consumption, Calculated** (TBtu/year)	**R&D Opportunity** (SOA-PM) (TBtu/year)	**R&D Opportunity Savings Percent*** (SOA-PM)/ (CT-TM)
Total for Process Subareas Studied	15.24	12.06	3.18	22%

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* R&D opportunity energy savings percent is the R&D energy savings opportunity from transforming AHSS production processes. Energy savings percent is calculated using TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (SOA-PM)/(CT-TM)

6. Thermodynamic Minimum Energy Intensity and Energy Consumption

Real world iron and steel production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture AHSS can provide a more complete understanding of the realistic opportunities for energy savings. This baseline can be used to establish more realistic projections (and bounds) for the future R&D energy savings that may be achieved. This chapter presents the thermodynamic minimum (TM) energy consumption required for the subareas studied.

TM energy consumption, which is based on Gibbs free energy (ΔG) calculations, assumes ideal conditions that are unachievable in real-world applications. TM energy consumption assumes that all energy is used productively, that there are no energy losses, and that energy is ultimately perfectly conserved by the system (i.e., when cooling a material to room temperature or applying work to a process, the heat or work energy is fully recovered – perfect efficiency). It is not anticipated that any manufacturing process would ever attain this value in practice. A reasonable long-term goal for energy efficiency would be the practical minimum (see Chapter 5).

For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessary equal to zero; in some cases the change in theoretical free energy content of the material requires energy input ($TM > 0$) and in other cases the change creates a theoretical free energy gain ($TM < 0$).

6.1. Sources for Thermodynamic Minimum Energy Intensity

The thermodynamic minimum energy intensity was calculated for each sub-process by determining the Gibbs free energy associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[8] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic. [9] Changes in surface energy were not considered in the TM analysis. The change in entropy was calculated based on the relative change in the number of molecules, and the change in enthalpy was calculated based on the change in bond energy. [10]

The main source for the AHSS production subarea thermodynamic minimum energy intensities are the 2000 report *Theoretical Minimum Energies to Produce Steel for Selected Conditions* by Fruehan et al. This report highlights minimum values based on theoretical models and specific compositions, and is derived from earlier work conducted by Carnegie Mellon University for the DOE. In addition to basing the TM energy intensity values on internal calculations, the 1998 source *Future Technologies for Energy-Efficient Iron and Steel Making* by de Beer, Worrell, and Blok and which discusses theoretical values was consulted.

The TM energy intensity calculation is path independent (state function), but is directly related to the relative energy levels of the substrate reactants and the products. The reported value depends only on the starting material and the end product, and would not change if the process had greater or fewer process steps. It is important to note that a negative TM value does not imply that the reaction will occur without being forced by a manufacturing process.

BOF steelmaking can at times result in net energy gain through exothermic processes. For exergonic iron and steel manufacturing processes, a zero baseline would result in negative percent savings, a physical impossibility.

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[8] Unless otherwise noted, "ideal conditions" means a pressure of 1 atmosphere and a temperature of 77°F.

[9] Exergonic (reaction is favorable) and endergonic (reaction is not favorable) are thermodynamic terms for total change in Gibbs free energy (delta G). This differs from exothermic (reaction is favorable) and endothermic (reaction is not favorable) terminology that are used in describing change in enthalpy (delta H).

[10] Note that the bond energy values are averages, not specific to the molecule in question.

In this report, TM energy consumption is 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 current opportunity (SOA), R&D, and PM are defined below. PM savings percent is the sum of the current opportunity percent and the R&D opportunity percent.

$$Current\ opportunity\ \% = \frac{CT - SOA}{CT - TM}$$

$$R\&D\ opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

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

For processes requiring an energy intensive transformation (e.g., blast furnace ironmaking), 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, BOF steelmaking, EAF steelmaking, and casting and rolling. The full credit of off-gas chemical and thermal energy is considered.

6.2. Thermodynamic Minimum Energy Intensity and Energy Consumption

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

Table 6-1 provides the TM energy intensities and energy consumption for the subareas studied (excluding feedstock energy). It is important to keep in mind that ideal conditions are unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities. As mentioned, the TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero).

Table 6-1. Calculated TM Energy Consumption for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**TM Energy Intensity** (MMBtu/ton product) [GJ/tonne product]	**TM Energy Consumption, Calculated** (TBtu/year)
Agglomeration (sinter)	1.03 [1.20]	0.18
Cokemaking (coke)	1.72 [2.00]	0.49
BF Ironmaking (iron)	8.43 [9.80]	7.70
BOF Steelmaking (raw steel)	-0.64 [-0.75]	-0.68
EAF Steelmaking (raw steel)	1.24 [1.44]	0.33
Casting/Rolling (cast/rolled steel)		
Casting	<0.01	0.00
Hot Rolling	0.29 [0.34]	0.39
Cold Rolling	0.04 [0.05]	0.06
Total for Process Subareas Studied		**8.47**

Thermodynamic minimum (TM)

7. Current and R&D Opportunity Analysis/Bandwith Summary

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings for the subareas studied considering the AHSS production for the application area boundary considered for this study. Each row in Table 7-1 shows the opportunity bandwidth for a specific AHSS manufacturing subarea and as a total.

As shown in Figure 7-1, two hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). To complete the subareas studied, the analysis shows the following:

- *Current Opportunity* – 7.4 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 3.2 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 7-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual AHSS manufacturing subareas. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts based on today's knowledge of research tested between laboratory and demonstration scale; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

Table 7-1. Current and R&D Opportunity for AHSS Manufacturing: Application Areas Studied

Subarea (product)	**Current Opportunity** (CT-SOA) (TBtu/year)	**R&D Opportunity** (SOA-PM) (TBtu/year)
Agglomeration (sinter)	0.01	0.03
Cokemaking (coke)	0.13	0.41
BF Ironmaking (iron)	0.85	2.01
BOF Steelmaking (raw steel)	0.93	0.07
EAF Steelmaking (raw steel)	0.03	0.03
Casting/Rolling (rolled steel)		
Casting	0.17	0.01
Hot Rolling	2.12	0.27
Cold Rolling	3.17	0.34
Total for Process Subareas Studied	**7.41**	**3.18**

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

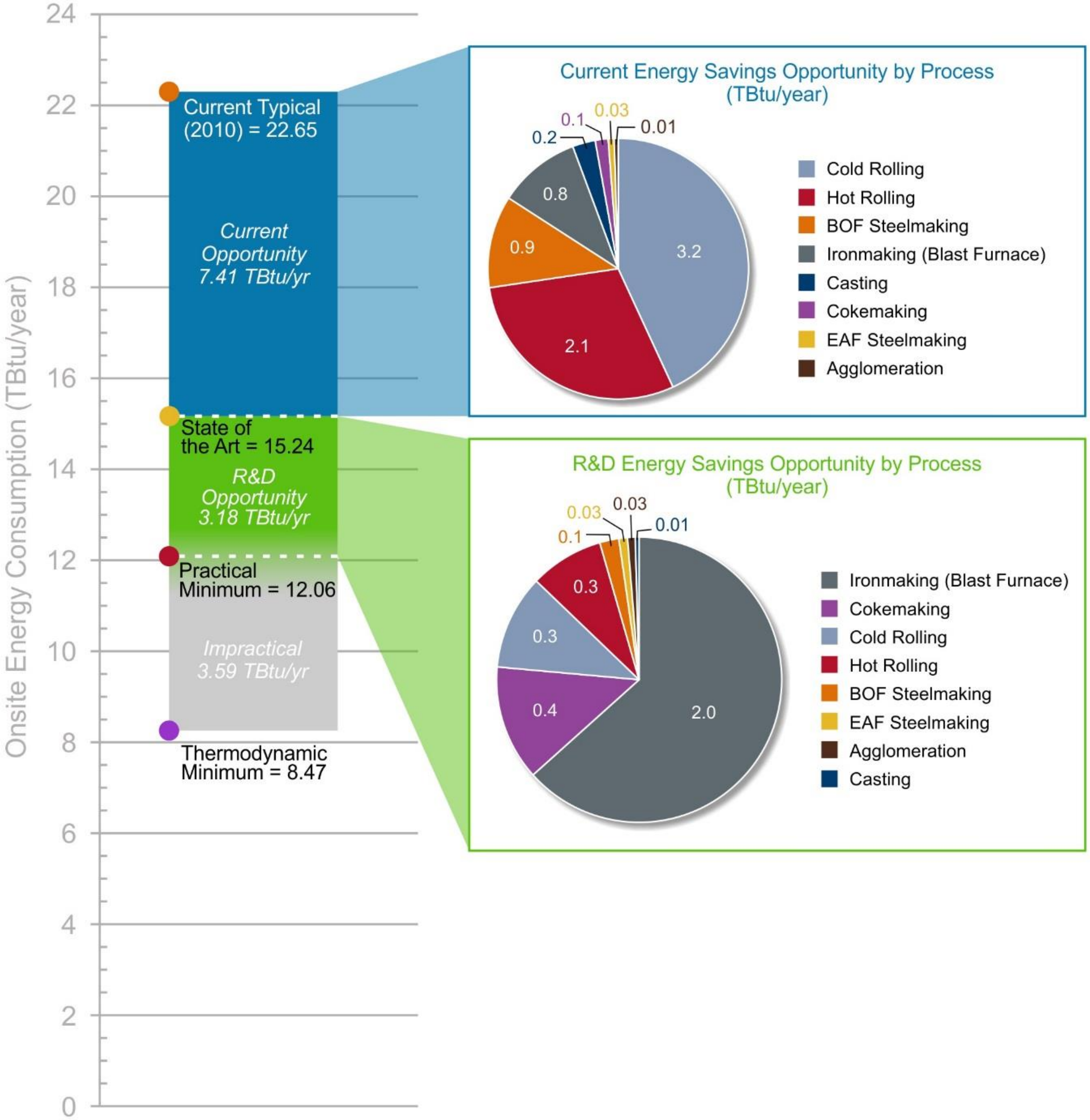

Figure 7-1. Current and R&D energy savings opportunities in U.S. AHSS manufacturing for the subareas and application areas studied
Source: EERE

The top three current energy savings opportunities for AHSS in the subareas studied are as follows:

- Cold rolling – 3.3 TBtu (or 43% of the current opportunity)
- Hot rolling – 2.1 TBtu (or 29% of the current opportunity)
- Basic oxygen furnace steelmaking – 0.9 TBtu (or 13% of the current opportunity).

The top three R&D energy savings opportunities for AHSS in the subareas studied are as follows:

- Blast furnace ironmaking – 2.0 TBtu (or 63% of the R&D opportunity)
- Cokemaking – 0.4 TBtu (or 13% of the R&D opportunity).
- Cold rolling – 0.3 TBtu (or 11% of the R&D opportunity)

The *impractical* bandwidth, or the difference between PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in AHSS manufacturing. The term *impractical* is used because the PM energy consumption is based on current knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale 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.

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Appendix A1. Master AHSS Summary Table

Table A1-1. U.S. Production Volume of AHSS Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Subarea (product)	**2010 Application Area Production** (1,000 tons) [1,000 tonnes]	**On-site Energy Intensity** (MMBtu/ton product) [GJ/tonne product]				**Calculated On-site Energy Consumption** (TBtu/year)			
		CT	**SOA**	**PM**	**TM**	**CT**	**SOA**	**PM**	**TM**
Agglomeration (sinter)	178 [161]	1.32 [1.54]	1.27 [1.47]	1.11 [1.29]	1.03 [1.20]	0.23	0.23	0.20	0.18
Cokemaking (coke)	287 [260]	3.83 [4.45]	3.37 [3.92]	1.92 [2.23]	1.72 [2.00]	1.10	0.97	0.55	0.49
BF Ironmaking (iron)	914 [829]	11.72 [13.63]	11.13 [12.94]	8.92 [10.38]	8.43 [9.80]	11.02*	10.17	8.15	7.70
BOF Steelmaking (raw steel)	1,061 [963]	0.58 [0.67]	-0.30 [-0.35]	-0.37 [-0.43]	-0.64 [-0.75]	0.61	-0.32	-0.39	-0.68
EAF Steelmaking (raw steel)	265 [241]	1.96 [2.28]	1.85 [2.16]	1.74 [2.02]	1.24 [1.44]	0.52	0.49	0.46	0.33
Casting/Rolling (cast/rolled steel)						*9.17**	*3.71*	*3.09*	*0.44*
Casting	1,307 [1,186]	0.19 [0.22]	0.05 [0.06]	0.04 [0.05]	<0.01	0.25	0.07	0.06	0.00
Hot Rolling	1,307 [1,186]	2.99 [3.48]	1.37 [1.59]	1.16 [1.35]	0.29 [0.34]	3.91	1.78	1.52	0.39
Cold Rolling	1,307 [1,186]	3.48 [4.05]	1.42 [1.65]	1.16 [1.35]	0.04 [0.05]	5.02*	1.85	1.51	0.06

* Current typical values for blast furnace ironmaking and cold rolling each exclude a portion 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 Production, CT, SOA, PM, TM

Table A2-1. U.S. Production Volume of AHSS Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Agglomeration (sinter)	Estimated based on AISI 2011a, Abraham 2015, expert communications	IPPC 2013	LBNL 2008	Fruehan et al. 2000
Cokemaking (coke)	Estimated based on AISI 2011a, Demeri 2013, Abraham 2015, expert communications	AISI 2011a; EIA 2013b	NRC 2007	Fruehan et al. 2000
BF Ironmaking (iron)	Estimated based on AISI 2011a, Demeri 2013, Abraham 2015, expert communications	AISI 2011a; IPPC 2013	NRC 2007	Fruehan et al. 2000
BOF Steelmaking (raw steel)	Estimated based on AISI 2011a, Abraham 2015, expert communications	IPPC 2013	NRC 2007	Fruehan et al. 2000
EAF Steelmaking (raw steel)	Estimated based on AISI 2011a, Abraham 2015, expert communications	AIST 2011	NRC 2007; Giavani et al. 2012	Fruehan et al. 2000
Casting/Rolling (cast/rolled steel)				
Casting	Estimated based on AISI 2011a, Abraham 2015, expert communications	NRC 2007	NRC 2007; LBNL 2008	Fruehan et al. 2000
Hot Rolling	Estimated based on AISI 2011a, Abraham 2015, expert communications	NRC 2007	NRC 2007	Fruehan et al. 2000
Cold Rolling	Estimated based on AISI 2011a, Abraham 2015, expert communications	EIA 2013b	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: Practical Minimum Energy Intensity Calculation and Technologies Considered

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. 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. The on-site PM energy intensity and consumption values are shown in Table A3-1 below.

Table A3-1. Calculated PM Energy Consumption for AHSS Manufacturing: Application Areas Considered

Subarea (product)	**On-site PM Energy Intensity** (MMBtu/ton product) [GJ/tonne product]	**On-site PM Energy Consumption, Calculated** (TBtu/year)
Agglomeration (sinter)	1.11 [1.29]	0.10
Cokemaking (coke)	1.92 [2.23]	0.28
BF Ironmaking (iron)	8.92 [10.38]	4.08
BOF Steelmaking (raw steel)	-0.37 [-0.43]	-0.19
EAF Steelmaking (raw steel)	1.74 [2.02]	1.46
Casting/Rolling (cast/rolled steel)		
Casting	0.04 [0.05]	0.06
Hot Rolling	1.16 [1.35]	1.57
Cold Rolling	1.16 [1.35]	1.56
Total for Process Subareas Studied		**8.91**

Practical Minimum (PM)

The PM energy intensity for AHSS manufacturing was determined based on the technologies outlined in Table A3-2. The applicability column indicates the subarea/sub-process where the technology is considered for application. The percent savings over the PM baseline is estimated, along with a brief explanation. Some technologies in Table A3-2 were considered but not included in the final PM model (in most of the cases the savings estimates were too conservative). In some cases, likely due to the conservative estimates of researchers, the estimated PM energy intensity was higher than the SOA energy intensity. For these cases, the crosscutting technology savings estimates were utilized. 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 intensity, the SOA energy intensity and TM energy intensity were multiplied by the combined estimated savings for crosscutting improvements (19%) and subtracted from the SOA energy consumption:

$$PM = SOA - (SOA - TM) * (19\%)$$

Table A3-3 provides a more comprehensive list of some of the technologies considered in studying R&D technology opportunities for AHSS manufacturing.

Table A3-2. Details of PM Technologies Considered

Technology Name	Description	Applicability	Explanation of energy savings assumptions	PM Energy Intensity (Btu/lb) or Percent savings (over baseline energy)	Included in PM model?	Reason for excluding (if applicable)	Reference
Single-chamber-system coking reactors	Replace series of coking ovens with a single large volume oven	Cokemaking	Thermal efficiency improvement from 38% to 70%	1,186 Btu/lb	Yes		Díez et al. 2002, IPPC 2001, EPA 2012, Nashan 2007, LBNL 2010b
Coal Moisture Control	Drying of coal with waste heat gases	Cokemaking	Fuel savings of 0.3 GJ/tonne	1,778 Btu/lb	No	Single-chamber-system coking reactors provides a lower baseline energy use.	APP 2010
Top Pressure Recovery Turbines	Uses hot high pressure gas from the furnace to power a turbine; dust removal from blast furnace gases using dry and wet methods.	BF Ironmaking	Turbine could produce additional 14-36 kWh/ton of hot metal (depending on available pressure)	5,811 Btu/lb	No	Drum chute and segregation slit charging provides a lower baseline energy use.	APP 2010, EPA 2012, Inoue 1995, NEDO 2008, Stelco 1993

Technology Name	Description	Applicability	Explanation of energy savings assumptions	PM Energy Intensity (Btu/lb) or Percent savings (over baseline energy)	Included in PM model?	Reason for excluding (if applicable)	Reference
Drum Chute and Segregation Slit Charging	Use of a drum chute and segregation slit wire to control the particles dropping into the furnace	BF Ironmaking	Can decrease coke use by 0.7 MMBtu/ton	5,509 Btu/lb	Yes		EPA 2012, NEDO 2008, LBNL 2010b
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.	BF Ironmaking	Savings of approximately 0.35 GJ/tonne of pig iron	5,709 Btu/lb	No	Drum chute and segregation slit charging provides a lower baseline energy use.	Barati et al. 2011, IPPC 2013, JISF 2012, LBNL 2010b, POSCO 2010
Recycling and reuse of basic oxygen furnace slag	Separates BOF slag into three products allowing greater iron recovery and recycling and uses low-grade iron byproduct for acid mine neutralization.	BOF Steelmaking	Estimated savings of 0.12 MMBtu/ton (0.14 GJ/tonne)	229 Btu/lb	No	Value is higher than SOA energy intensity	DOE 2002, IMP 2006, Energetics 2005
EPC System for Side Charging and Scrap Preheating	Design to allow continuous charging of preheated scarp into the EAF, including separation of preheating and cold scrap charging. Reduces gas flows, uses a totally sealed system and provides substantial reduction in dust and other emissions.	EAF Steelmaking	Preheating of scrap up to 700 °C reduces EAF energy consumption by up to 100 kWh/tonne of molten steel.	930 Btu/lb	No	Contiarc furnace provides a lower baseline energy use.	KR Tec n.d., Rummler et al. n.d.
Contiac Furnace	Replaces the ladle metallurgy furnace with a continuous series of vessels,	EAF Steelmaking	Reduced energy losses (200 kWh/ton) over conventional furnace	636 Btu/lb	No	PM energy intensity only just above TM energy intensity	AEHOF 2013, EPA 2012, IPPC 2013
Continuous casting for EAF		Casting	Anticipated 10% decrease in energy consumption	85 Btu/lb	No	Value is higher than SOA energy intensity	Peaslee et al. 2006, DOE 2005

Technology Name	Description	Applicability	Explanation of energy savings assumptions	PM Energy Intensity (Btu/lb) or Percent savings (over baseline energy)	Included in PM model?	Reason for excluding (if applicable)	Reference
Tundish heating technologies (cold tundish)	Using a cold tundish (heating a tundish inductively and not by combustion)	Casting	78% decrease in natural gas usage	85 Btu/lb	No	Value is higher than SOA energy intensity	Beraldo et al. 2003, EPA 2012, LBNL 2010b
Endless rolling	New development in thin slab casting and direct rolling	Rolling	Anticipated 40% lower energy than a traditional rolling mill	897 Btu/lb (hot rolling) 1,044 Btu/lb (cold rolling)	No	Value is higher than SOA energy intensity	Arvedi et al. 2008, EPA 2012
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	Consumes 22-32% of current energy used for reheating; 0.2 GJ/tonne during reheating	1,410 Btu/lb (hot rolling) 1,655 Btu/lb (cold rolling)	No	Endless rolling provides a lower baseline energy use;	Thekdi 2010, DOE 2010
High temperature insulation materials	Innovative insulating materials that will limit their consumption in a furnace.	Rolling	Energy savings of 30-35% are possible; likely savings of 2-5% on furnaces	1,425 Btu/lb (hot rolling) 1,670 Btu/lb (cold rolling)	No	Endless rolling provides a lower baseline energy use.	BMWi 2008, EPA 2012
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.	Crosscutting	Potential to reduce energy consumption by 25% for process heat.	16%	Yes		DOE 2011

Technology Name	Description	Applicability	Explanation of energy savings assumptions	PM Energy Intensity (Btu/lb) or Percent savings (over baseline energy)	Included in PM model?	Reason for excluding (if applicable)	Reference
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.	Crosscutting	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.	1%	Yes		DOE 2011c; GTI 2011
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	Opportunity reduced to 2%.	2%	Yes		BMWi 2008

Table A3-3. Example Steel and AHSS R&D Technologies Considered for PM Energy Intensity Analysis

Subarea	Technology Name
Cokemaking	Single-chamber-system coking reactors
Cokemaking	Coal Moisture Control
Traditional Ironmaking	Top Pressure Recovery Turbines
Traditional Ironmaking	Drum Chute and Segregation Slit Charging
Traditional Ironmaking	Heat recovery from blast furnace slag
Steelmaking (BOF)	Recycling and reuse of basic oxygen furnace slag
Steelmaking (EAF)	EPC System for Side Charging and Scrap Preheating
Steelmaking (EAF)	Contiarc Furnace
Steelmaking (EAF)	Waste Heat Recovery for EAF
Casting	Continuous casting for EAF
Casting	Tundish heating technologies (cold tundish)
Rolling	Endless rolling
Rolling	Next-generation system for scale-free steel reheating
Rolling	High temperature insulation materials
Cokemaking	Production of Carbonite product to replace metallurgical coke for foundries and blast furnace
Steelmaking (BOF)	Aluminum-Bronze Alloy to Improve Hood Roof and Sidewall Life
Steelmaking (EAF)	ECOARC
Steelmaking (EAF)	Continuous Horizontal Sidewall Scrapping
Steelmaking (EAF)	Optical EAF Sensors
Steelmaking (EAF)	Nitrogen control in EAF by DRI fines injection
Steelmaking (EAF)	Electric arc furnace off-gas heat recovery
Steelmaking (EAF)	Rotary regenerators
Alternative Ironmaking/ Steelmaking	Plasma blast furnace
Alternative Ironmaking/ Steelmaking	IronArc plasma technology
Alternative Ironmaking/ Steelmaking	Molten Oxide Electrolysis
Alternative Ironmaking/ Steelmaking	Suspension hydrogen reduction of iron oxide concentrate
Alternative Ironmaking/ Steelmaking	FASTMET/FASTMELT
Alternative Ironmaking/ Steelmaking	Paired straight hearth furnace
Alternative Ironmaking/ Steelmaking	Tecnored process
Alternative Ironmaking/ Steelmaking	Microwave Electric Arc Furnaces

Table A3-3. Example Steel and AHSS R&D Technologies Considered for PM Energy Intensity Analysis

Subarea	Technology Name
Alternative Ironmaking/ Steelmaking	Cyclone converter Furnace
Alternative Ironmaking/ Steelmaking	Coal and natural gas based HYL process for DRI
Alternative Ironmaking/ Steelmaking	FINEX Process
Casting	Near-net-shape casting [thin slab or strip casting]
Rolling	Thermochemical recuperation for steel reheating

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DOE/EE-1661 • September 2017