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Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

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

September 2017

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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.[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.

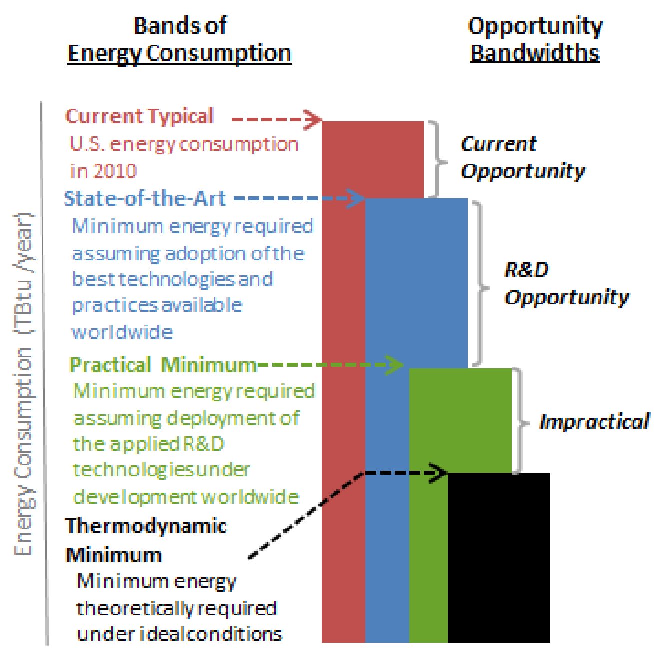

Figure P-1. Energy Consumption bands and opportunity bandwidths estimated in this study
Source: EERE

[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 Dr. Subodh Das, Caroline Dollinger, Dr. Aaron Fisher, and Sabine Brueske of Energetics Incorporated for conducting the research and analysis and writing this study. AMO wishes to acknowledge the contributions made by Alan A. Luo of the Ohio State University and Walt Brockway for their work reviewing this study.

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List of Acronyms and Abbreviations

Al	Aluminum
AMO	Advanced Manufacturing Office
Btu	British thermal unit
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
GJ	Gigajoules
IEA	International Energy Agency
K	Kelvin
kWh	Kilowatt hours
mm	Millimeter
MMBtu	Million British thermal units
MT	Metric ton (tonne)
NAICS	North American Industry Classification System
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

Both primary and secondary (recycled) aluminum are important manufactured products in the United States. This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. aluminum manufacturing for lightweighting applications. Industrial, government, and academic data are used to estimate the energy consumed in five 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 aluminum 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 five 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 five *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 for aluminum.[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 as a total and broken down by manufacturing subarea. Note that the energy savings opportunities presented reflect the estimated production of aluminum for selected application areas in baseline year 2010. Aluminum production has seen growth in the past several years, especially with increased application in areas such as the automotive sector. Therefore, it is important to note that the total energy opportunities would scale with increasing production.

[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. Aluminum Manufacturing Sector (Considering Production for Lightweighting Application Areas only)*

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Select Aluminum Manufacturing Subareas (per year)
Current Opportunity: energy savings if the best technologies and practices available are used to upgrade production	**13 TBtu**[3] (34% energy savings)[4]
R&D Opportunity: additional energy savings if the applied R&D technologies under development worldwide are deployed,	**11 TBtu**[5] (30% energy savings)[6]

* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

[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.

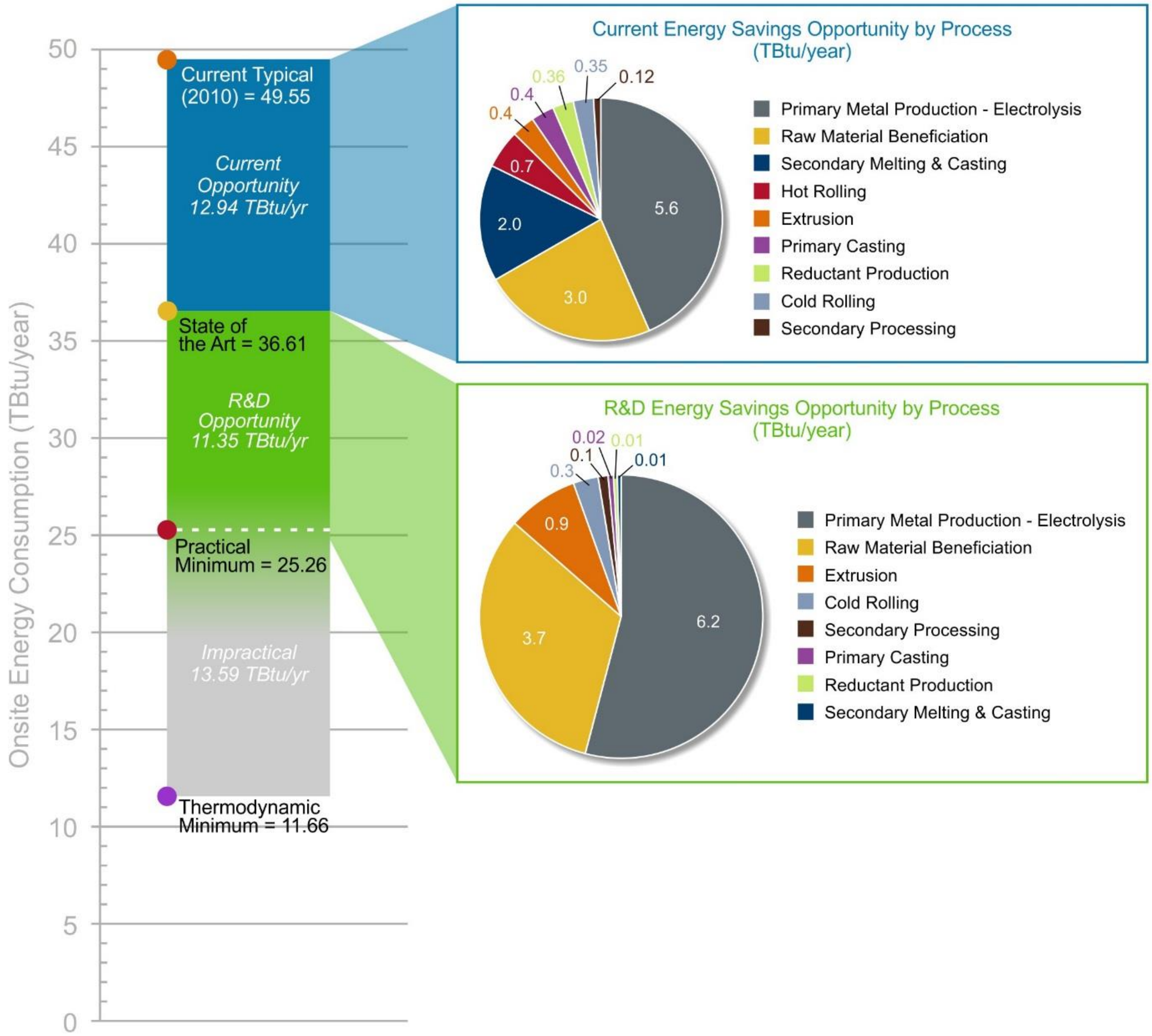

Figure ES-1. Current and R&D energy savings opportunities for the aluminum manufacturing subareas studied (considering lightweighting application area production only)
Source: EERE

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 49.55 TBtu of energy was consumed in 2010 to manufacture aluminum in the United States for the key structural applications considered in this study. Based on the results of this study, an estimated 12.94 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide were used to upgrade the aluminum manufacturing subareas studied; an additional 11.35 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

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

- Primary aluminum production (electrolysis) – 5.6 TBtu (or 43% of the current opportunity)
- Raw material beneficiation (alumina production) – 3.0 TBtu (or 23% of the current opportunity)
- Secondary aluminum production (melting and casting) – 2.0 TBtu (or 16% of the current opportunity).

The top three R&D energy saving opportunities for the processes are as follows:

- Primary aluminum production (electrolysis) – 6.2 TBtu (or 55% of the R&D opportunity)
- Raw material beneficiation (alumina production) – 3.7 TBtu (or 33% of the R&D opportunity)
- Aluminum extrusion – 0.9 TBtu (or 8% of the R&D opportunity).

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

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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 aluminum (Al).

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: magnesium, titanium, advanced high strength steel, 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 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 followed 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.

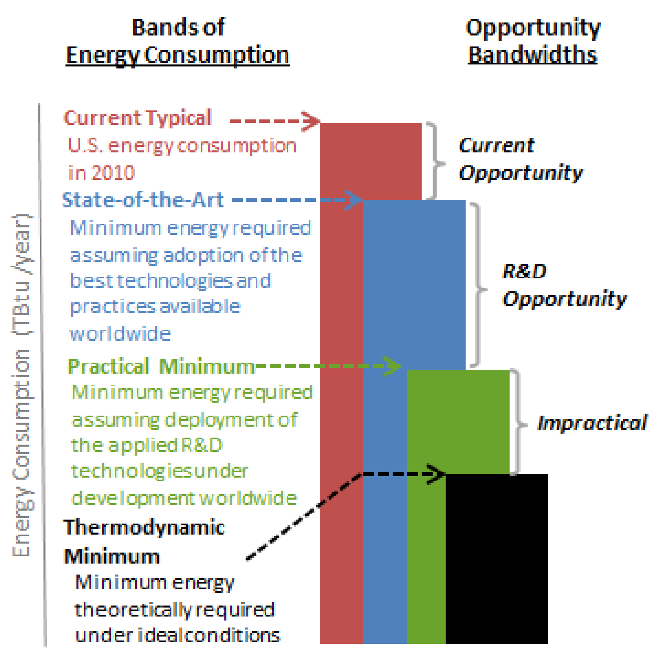

Figure 1-1. Energy Consumption bands and opportunity bandwidths estimated in this study
Source: EERE

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 amount (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 volumes** (million lb per year) for 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** (Btu per pound) 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** (Btu per pound) and **SOA energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources).

[7] Feedstock energy is the nonfuel use of combustible energy.

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per pound) 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** (Btu per pound) 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 summary results.

1.4. Boundaries of the Aluminum Bandwidth Study

The U.S. manufacturing sector is the physical boundary of this 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 are also 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 aluminum 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 aluminum 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.

Aluminum is used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. Aluminum is 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. Together, the four application areas considered in this study account for approximately 28% of overall aluminum production in the United States, as shown in Figure 1-2 (see Section 2.2 for more detail).

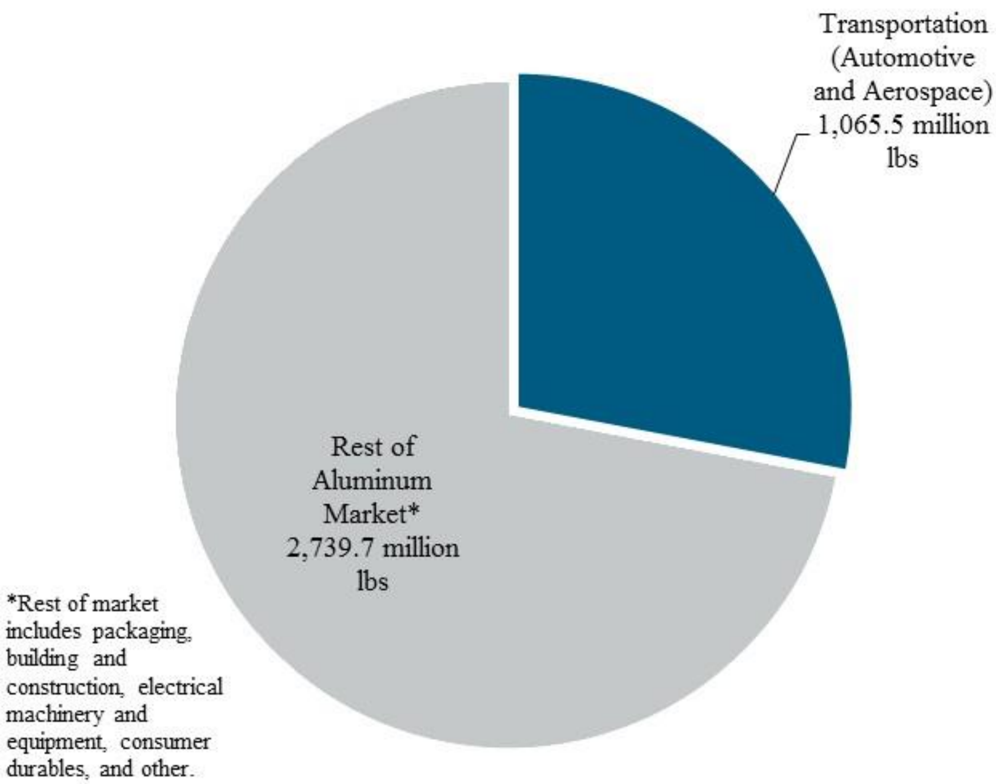

Figure 1-2. Estimated makeup of the aluminum market in 2010
Source: EERE

2. Aluminum Production

2.1. Manufacturing Overview

In 2010, the United States produced 3,805 million lb of primary aluminum, accounting for about 4% of total world production (USGS 2012). Additionally, the United States recovered 6,151 million lb of aluminum scrap to be processed into secondary aluminum (USGS 2012). During the year for this study (2010), there were nine primary aluminum smelter facilities in operation by five companies (USGS 2011c). In addition, the sector was relying upon imports as U.S. primary aluminum production was at much lower levels compared to 2008 (USGS 2011c).

This study focuses on energy consumption in five energy intensive process subareas in aluminum manufacturing. Figure 2-1 shows the aluminum manufacturing process flow diagram addressing the subareas that were considered in this bandwidth analysis. For primary aluminum production there are three main subareas: raw material preparation or beneficiation (the production of alumina), reductant production (the production of carbon anodes), and primary aluminum production (the Hall-Héroult process, involving both electrolysis and the casting of primary ingots). Secondary production involves the production of aluminum ingot from a combination of mostly recycled and processed aluminum scrap as well as some primary aluminum. Both primary and secondary cast aluminum ingots are then shipped to be further processed or used to produce rolled and extruded aluminum products in semi-finished shape production.

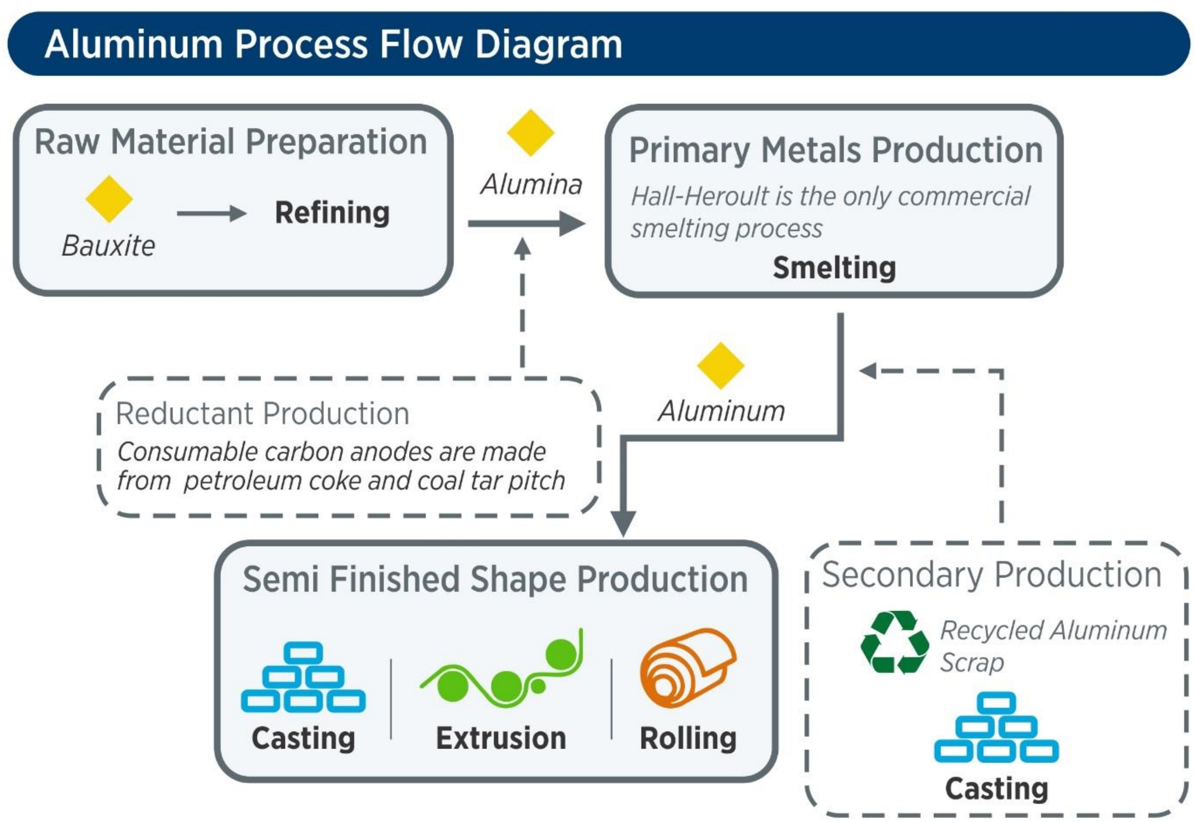

Figure 2-1. Aluminum manufacturing process flow diagram
Source: EERE

These process subareas are further 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 3 through 6 of this report. These subareas and sub-processes fall within North American Industry Classification System (NAICS) code 3313, alumina and aluminum production and processing (USCB 2012). Note that further steps, such as the production of aluminum parts (such as those for automobiles) and the die-casting of aluminum falls outside of the scope of this analysis and outside of NAICS 3313.

Table 2-1. Aluminum Manufacturing Process Areas Considered in Bandwidth Analysis

Subareas	Sub-Processes
Raw Material Beneficiation (alumina production)	
Reductant Production (carbon anode production)	
Primary Metal Production	Electrolysis Primary Ingot Casting
Secondary Metal Production	Scrap Processing Secondary Melting and Ingot Casting
Semi-Finished Shape Production	Hot Rolling Cold Rolling Extrusion

2.2. Production Values

Production data was gathered in order to calculate the annual energy consumption by process and sector-wide for aluminum manufacturing. The Aluminum Association and the U.S. Geological Survey (USGS) are the leading sources for information on alumina and aluminum production in the United States. Both of these organizations release data on aluminum production annually. The USGS provides U.S. alumina and aluminum production (as well as import and export) data and data on amounts of aluminum recycled and was used as the primary production data source (as the Aluminum Association provides value for North America as a whole). Appendix A2 provides a more detailed source listing for each subarea production value.

Production data for 2010 is summarized in Table 2-2, with both the production for the entire aluminum sector and for the boundary applications provided. See Section 1.4. for a description of the boundary application areas. The year 2010 was selected to correspond with the most current energy and production data. According to the USGS, 28% of U.S. aluminum consumption was in the transportation sector, which falls within the boundary application areas for this study (USGS 2011c). The transportation sector's consumption of aluminum increased in later years, to 34% in 2011 and 2012, 36% in 2013, and 38% in 2014 (USGS 2012b, USGS 2013, USGS 2014, USGS 2015).

Table 2-2. U.S. Aluminum Subarea Products and Production in 2010

Subarea	Product	2010 Total Aluminum Sector Production (million lb)	2010 Estimated Production for Boundary Applications (million lb)
Raw Material Beneficiation	Alumina	8,620	Not estimated*
Reductant Production	Carbon Anode	1,632	Not estimated*
Primary Metal Production	Primary Aluminum	3,805	1,065
Secondary Metal Production	Secondary Aluminum	5,247	1,469
Semi-Finished Shape Production	Hot Rolled Products Cold Rolled Products Extruded Products	9,833 5,516 3,197	2,753 1,544 895

*Because the energy intensity values for these subareas are based upon and are presented as the energy required to produce a pound of aluminum (Btu/lb aluminum) rather than to produce a pound of alumina or carbon anode, the estimated production for these subareas for the boundary applications was not needed to be calculated.
Source: USGS 2011c

When energy intensity values were presented in terms of Btu per lb alumina or Btu per lb of carbon anode produced, these values were converted to Btu per lb of aluminum in order to present the results in a consistent fashion. The Aluminum Association's 2013 report *The Environmental Footprint of Semi-Finished Aluminum Products in North America* provided the relevant production values for North America (and assumed to be the same for the United States as a whole) as follows: 0.4289 lb of carbon anode and 1.939 lb alumina is needed to produce 1 lb of primary aluminum. Additionally, 1.005 lb of processed aluminum scrap is needed to produce 1 lb of secondary aluminum ingot (Aluminum Association 2013). Global average values or regional values such as those for Europe may vary.

3. Current Typical Energy Intensity and Energy Consumption

This chapter presents the energy consumption data for individual aluminum 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. aluminum manufacturing; they do not represent energy consumption in any specific facility or any particular region in the United States.

3.1. Sources for Aluminum 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 aluminum 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 aluminum manufacturing facility is unique and aluminum 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
Aluminum Association 2013	This 2013 report from the Aluminum Association, *The Environmental Footprint of Semi-Finished Aluminum Products in North America*, was the main source for current typical energy intensity for the aluminum subareas studied. In the life cycle assessment report, detailed energy information (including fuel, electricity, and steam use) for each of the subareas is provided, based on 2010 data for North American plants (making it the most fitting source for U.S. CT energy intensity). The data provided in the report is for 2010.
EAA 2013	This report, the *Environmental Profile Report for the European Aluminum Industry,* was published by the European Aluminum Association (EAA) in 2013. The values in this report include energy use for primary aluminum production processes as well as specific semi-finished products (sheet, foil, extruded products) in Europe. The data provided in the report allowed for comparison to U.S. and North America-specific sources and is also for 2010.
World Aluminum Association 2013	Published by the World Aluminum Association in 2013, the *Global Life Cycle Inventory Data for the Primary Aluminum Industry* provides energy use information for global primary aluminum production processes. The values from this report provide a global benchmark that can be compared to U.S. and North America-specific data from other reports. The data provided in the report is also for 2010.
World Aluminum Association 2014	The World Aluminum Association provides the current energy intensity of primary aluminum smelting for individual countries. The value for North America was studied to compare to other sources.

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 aluminum production subareas studied. Feedstock energy is excluded from the consumption values. The energy intensities are presented in terms of Btu per lb aluminum produced. The CT energy consumption for these subareas is estimated to account for 50 TBtu of on-site energy and 137 TBtu of primary energy in 2010.

Primary energy is calculated from on-site CT energy consumption data based on an analysis of available data, 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. Aluminum Manufacturing: Application Areas Studied (2010)

Subarea	On-site CT Energy Intensity (Btu/lb Aluminum)	On-site CT Energy Consumption, Calculated* (TBtu/year)	Off-site Losses, Calculated*,** (TBtu/year)	Primary CT Energy Consumption, Calculated* (TBtu/year)
Raw Material Beneficiation	8,660	9.23	1.17	10.40
Reductant Production	744	0.79	0.18	0.98
Primary Metal Production			0.00	0.00
Electrolysis	23,388	24.92	52.15	77.07
Primary Casting	503	0.54	0.23	0.77
Secondary Metal Production				
Secondary Processing	567	0.83	0.55	1.38
Secondary Melting and Casting	2,229	3.28	0.52	3.80
Semi-Finished Shape Production				
Hot Rolling	1,814	4.99	1.01	6.01
Cold Rolling	1,511	2.33	1.83	4.17
Extrusion	2,948	2.64	0.57	3.21
Total for Process Subareas Studied		**49.55***	**58.23**	**107.78****

Current typical (CT)

* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

** 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).

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. aluminum manufacturing plants. These plants will vary widely in size, age, efficiency, energy consumption, and types and amounts of products. Modern aluminum plants can benefit from more energy-efficient technologies and practices.

This chapter estimates the energy savings possible if U.S. aluminum plants 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 main published sources referenced to identify the SOA energy intensities.

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

Source Abbreviation	Description
EAA 2013	This report, the *Environmental Profile Report for the European Aluminum Industry,* was published by the European Aluminum Association (EAA) in 2013. The values in this report include energy use for primary aluminum production processes as well as specific semi-finished products (sheet, foil, extruded products). The data provided in the report allowed for comparison to CT and other SOA sources to determine SOA energy intensity values.
Das 2015	In certain cases, citable data was unavailable for aluminum production subareas. In this case, estimates from one of the study's authors (Subodh Das) were used to determine the SOA energy intensity compared to CT energy intensity. These estimates were based off of discussions with experts, presentations at the Minerals, Metals, and Materials Society (TMS) 2015 annual meeting, and knowledge of the field.
IPPC 2014	This 2014 report, the *Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metal Industries*, is from the European Integrated Pollution Prevention and Control (IPPC) Bureau. This report lists specific European energy consumption and intensity values or ranges for select aluminum production subareas, providing a source for global SOA energy intensities.
Luo & Soria 2008	This 2008 report, the *Prospective Study of the World Aluminum Industry*, provides a state of the art energy intensity estimate for electrolysis. As a whole, the report discusses modeled energy consumption results for the global aluminum industry.
Worrell et al. 2008	This 2008 Lawrence Berkeley National Laboratory report, *World Best Practice Energy Intensity Values for Selected Industrial Sector*, provides best practice values for many industrial processes, including aluminum manufacturing. These energy intensity values are considered as state of the art.

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 aluminum manufacturing subareas studied. The SOA energy intensities are presented as Btu per lb aluminum 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 Aluminum Manufacturing: Application Areas Studied

Subarea	On-site SOA Energy Intensity (Btu/lb Aluminum)	On-site SOA Energy Consumption, Calculated* (TBtu/year)
Raw Material Beneficiation	5,836	6.22
Reductant Production	406	0.43
Primary Metal Production		
Electrolysis	18,109	19.29
Primary Casting	129	0.14
Secondary Metal Production		
Secondary Processing	482	0.71
Secondary Melting and Casting	860	1.26
Semi-Finished Shape Production		
Hot Rolling	1,572	4.33
Cold Rolling	1,284	1.98
Extrusion	2,506	2.24
Total for Process Subareas Studied		**36.61**

State of the Art (SOA)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

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 reductant (carbon anode) production at 94% energy savings; the greatest *current opportunity* in terms of TBtu savings is electrolysis at 5.6 TBtu per year savings.

If U.S aluminum manufacturing (for the 2010 production level of aluminum for application areas considered) were able to attain on-site SOA energy intensities, it is estimated that 13 TBtu per year of energy could be saved from the subareas alone, corresponding to a 34% energy savings overall (see equation 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 plants 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 Aluminum Manufacturing: Application Areas Studied

Subarea	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)
Raw Material Beneficiation	9.23	6.22	3.01	34%
Reductant Production	0.79	0.43	0.36	94%
Primary Metal Production				
Electrolysis	24.92	19.29	5.62	37%
Primary Casting	0.54	0.14	0.40	74%
Secondary Metal Production				
Secondary Processing	0.83	0.71	0.12	15%
Secondary Melting and Casting	3.28	1.26	2.01	83%
Semi-Finished Shape Production				
Hot Rolling	4.99	4.33	0.67	14%
Cold Rolling	2.33	1.98	0.35	15%
Extrusion	2.64	2.24	0.40	15%
Total for Process Subareas Studied	**47.60**	**35.67***	**12.94**	**34%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.
** SOA energy savings is also called *Current Opportunity.*
*** SOA energy savings percent is the SOA energy savings opportunity from transforming aluminum 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 aluminum in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. aluminum manufacturing. In this Chapter, the R&D energy savings made possible through R&D advancements in aluminum 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 aluminum 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 aluminum 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. R&D technologies investigated included (see Appendix A3 for full details):

- Vertical floatation melters
- Isothermal melting process
- Ultrahigh efficiency cells (multipolar cells)
- Carbothermic aluminum production process
- Wettable ceramic-based drained cathode technology
- Induction oven with rotating permanent magnets for energy efficient aluminumheating

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

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

Source Abbreviation	Description
Aluminum International Today	International journal of aluminum production and processing, which provided information on emerging technologies and manufacturing methodologies for consideration in the PM energy intensity analysis.
Das 2015	In certain cases, citable data was unavailable for aluminum production subareas. In this case, estimates from one of the study's authors (Subodh Das) were used to determine the PM energy intensity compared to SOA energy intensity. These estimates were based off of discussions with experts, presentations at the Minerals, Metals, and Materials Society (TMS) 2015 annual meeting, and knowledge of the field.
Luo & Soria 2008	This 2008 report, the *Prospective Study of the World Aluminum Industry*, provides some practical minimum energy intensity estimates for electrolysis. As a whole, the report discusses modeled energy consumption results for the global aluminum industry.
Recycling Today	Journal of recycling materials, including metals, useful for information on secondary production of aluminum.

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 aluminum manufacturing subareas studied. The PM energy intensities are presented as Btu per lb aluminum and the on-site PM energy consumption is presented as TBtu per year.

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

Subarea	On-site PM Energy Intensity (Btu/lb Aluminum)	On-site PM Energy Consumption, Calculated* (TBtu/year)
Raw Material Beneficiation	2,334	2.49
Reductant Production	394	0.42
Primary Metal Production		
Electrolysis	12,248	13.05
Primary Casting	110	0.12
Secondary Metal Production		
Secondary Processing	409	0.60
Secondary Melting and Casting	850	1.25
Semi-Finished Shape Production		
Hot Rolling	1,572	4.33
Cold Rolling	1,092	1.69
Extrusion	1,474	1.32
Total for Process Subareas Studied		**25.26***

Practical Minimum (PM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

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. **Error! Reference source not found.** calculates the R&D pportunity 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 reductant (carbon anode) production at 97% energy savings; the greatest *current* plus *R&D opportunity* in terms of TBtu savings is electrolysis at 11.9 TBtu per year savings.

If U.S aluminum manufacturing (for the 2010 production level of aluminum for application areas considered) were able to attain on-site PM energy intensities, it is estimated that 24 TBtu per year of energy could be saved from the subareas alone, corresponding to a 64% 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 plants 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 Aluminum Manufacturing: Application Areas Studied

Subarea	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)
Raw Material Beneficiation	9.23	2.49	6.74	77%
Reductant Production	0.79	0.42	0.37	97%
Primary Metal Production				
Electrolysis	24.92	13.05	11.87	79%
Primary Casting	0.54	0.12	0.42	78%
Secondary Metal Production				
Secondary Processing	0.83	0.60	0.23	28%
Secondary Melting and Casting	3.28	1.25	2.03	84%
Semi-Finished Shape Production				
Hot Rolling	4.99	4.33	0.67	14%
Cold Rolling	2.33	1.69	0.65	28%
Extrusion	2.64	1.32	1.32	50%
Total for Process Subareas Studied	**49.55***	**25.26***	**24.29**	**64%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.
** PM energy savings is the *Current Opportunity* plus the *R&D Opportunity.*
*** PM energy savings percent is the PM energy savings opportunity from transforming aluminum 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. **Error! Reference source not found.** shows the &D opportunity totals and percent for the evaluated process subareas studied.

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

Subarea	On-site SOA Energy Consumption (TBtu/year)	On-site PM Energy Consumption (TBtu/year)	R&D Opportunity (SOA-PM) (TBtu/year)	R&D Opportunity Savings Percent* (SOA-PM)/ (CT-TM)
Total for Process Subareas Studied	36.61	25.26	11.35	30%

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* Energy savings percent is calculated using TM energy consumption shown in Chapter 6 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 aluminum production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture aluminum 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 source for the aluminum production subarea thermodynamic minimum energy intensity is the 2007 report produced for DOE, *U.S. Energy Requirements for Aluminum Production* as well as internal calculations. This report provides TM energy intensity values for the first steps considered in primary aluminum production: raw material beneficiation (alumina production), reductant (carbon anode) production and the Hall-Héroult process (electrolysis) using a carbon anode, under associated manufacturing conditions. For hot and cold rolling, the approach used in the 2007 report was modified to include only the deformation energy, and the thermodynamic minimum energy intensity was calculated assuming that the aluminum was rolled to 1% of its original thickness and using the material properties of the common aluminum alloy 6061-O (MatWeb 2015).

For the remaining subareas considered (primary aluminum casting, secondary aluminum production, and semi-finished shape production), a TM energy of zero was assigned. This is because the definition of TM only considers processes where a chemical transformation occurs, not where a physical transformation occurs (such as in aluminum rolling). Physical changes (i.e., shape changes) will have a TM energy intensity of zero. Changes in crystal structure and surface energy were also not considered.

The TM energy intensity calculation is path independent (state function), but is directly related to the relative energy levels of the substrates 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. Note that for

[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.

processes that involve no net chemical changes or reactions, the TM energy intensity is *zero* because all energy expended is assumed to be perfectly recovered. The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic. 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.

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., primary aluminum electrolysis), 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.

6.2. Thermodynamic Minimum Energy Intensity and Energy Consumption

The minimum baseline of energy consumption for an aluminum production subarea is its TM energy consumption. If all the 2010 level of aluminum 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 Aluminum Manufacturing: Application Areas Studied

Subarea	TM Energy Intensity (Btu/lb Aluminum)	TM Energy Consumption, Calculated* (TBtu/year)
Raw Material Beneficiation	418	0.45
Reductant Production	383	<0.01
Primary Metal Production		
Electrolysis	9,271	9.88
Primary Casting	0	0
Secondary Metal Production		
Secondary Processing	0	0
Secondary Melting and Casting	581	0.9
Semi-Finished Shape Production		
Hot/Cold Rolling	28	0.1
Extrusion	0	0
Total for Process Subareas Studied		**11.70***

Thermodynamic minimum (TM)

* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

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

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings for the subareas studied considering the aluminum production for the application area boundary considered for this study. Each row in Table 7-1 shows the opportunity bandwidth for a specific aluminum manufacturing subarea and as a total. As previously noted, the energy savings opportunities presented reflect the estimated production of aluminum for selected application areas in baseline year 2010 (including the relative amounts of primary and secondary aluminum produced).

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* – 13 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 11 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 aluminum 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 are 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 Aluminum Manufacturing: Application Areas Studied

Subarea	Current Opportunity* (CT-SOA) (TBtu/year)	R&D Opportunity* (SOA-PM) (TBtu/year)
Raw Material Beneficiation	3.01	3.73
Reductant Production	0.36	0.01
Primary Metal Production		
Electrolysis	5.62	6.24
Primary Casting	0.40	0.02
Secondary Metal Production		
Secondary Processing	0.12	0.11
Secondary Melting and Casting	2.01	0.01
Semi-Finished Shape Production		
Hot Rolling	0.67	0
Cold Rolling	0.35	0.30
Extrusion	0.40	0.92
Total for Process Subareas Studied	**12.94**	**11.35**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

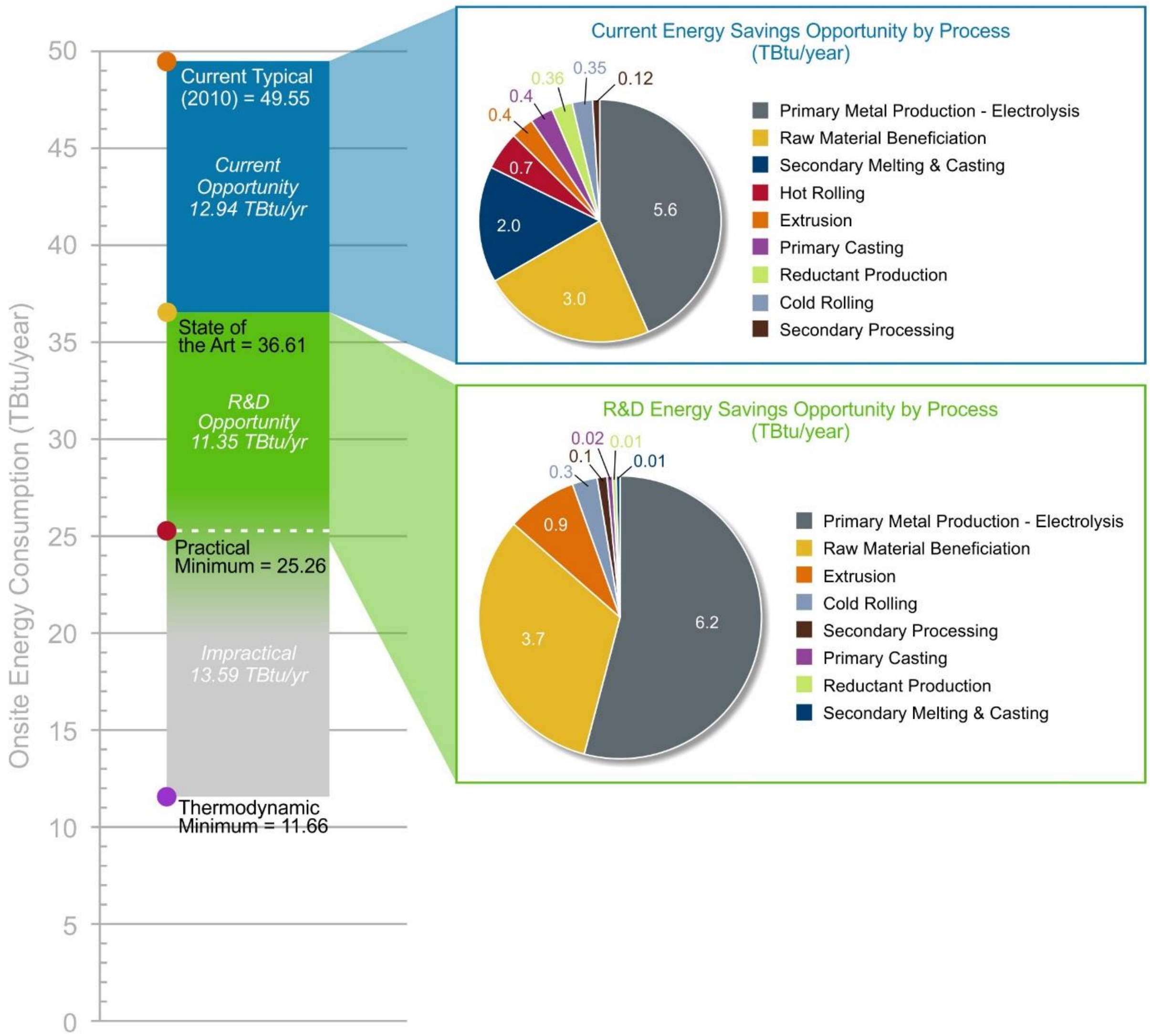

Figure 7-1. Current and R&D energy savings opportunities in U.S. aluminum manufacturing for the subareas and application areas studied
Source: EERE

From the subareas studied, the greatest *current* and *R&D* energy savings opportunity for aluminum manufacturing comes from upgrading electrolysis production for primary aluminum—this is largely due to the fact that a significant amount of energy consumed in the aluminum sector occurs in this step.

The *impractical* bandwidth, or the difference between PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in aluminum 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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Das 2015	Engineering estimates from S. Das. 2015.
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Appendix A1. Master Aluminum Summary Table

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

Subarea	2010 Application Area Production (million lb)	On-site Energy Intensity (Btu/lb Aluminum)				Calculated On-site Energy Consumption[a] (TBtu/year)			
		CT	SOA	PM	TM[b]	CT[a]	SOA[a]	PM[a]	TM[a]
Raw Material Beneficiation	N/A	8,660	5,863	2,334	418	9.23 [a]	6.22 [a]	2.49 [a]	0.4 [a]
Reductant Production	N/A	744	406	394	383	0.79 [a]	0.43 [a]	0.42 [a]	0.4 [a]
Primary Metal Production						*25.45*	*19.43*	*13.17*	*9.88*
Electrolysis	1,065	23,388	18,109	12,248	9,271	24.92	19	13.05	9.9
Primary Casting	1,065	503	129	110	0	0.54	0.14	0.12	0.0
Secondary Metal Production						*4.11*	*1.97*	*1.41*	*0.0*
Secondary Processing	1,469	567	482	409	0	0.83	0.71	0.60	0.0
Secondary Melting and Casting	1,469	2,229	860	850	581	3.27	1.26	1.25	0.9
Semi-Finished Shape Production						*9.97*	*8.55*	*7.33*	*0.1*
Hot Rolling	2,753	1,814	1,572	1,572	28[c]	4.99	4.33	4.33	0.1[c]
Cold Rolling	1,544	1,511	1,284	1,092	n/a[d]	2.33	1.98	1.69	n/a[d]
Extrusion	895	2,948	2,506	1,474	0	2.64	2.24	1.32	0.0

[a] Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.
[b] Calculated by multiplying energy intensity by primary aluminum produced (1,065 million lb for the application areas studied).
[c] Value for both hot and cold rolling
[d] Included in TM value for hot rolling
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 Aluminum 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)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Raw Material Beneficiation	USGS 2011b	Aluminum Association 2013	IPPC 2014	Outotec 2015	DOE 2007
Reductant Production	USGS 2012, Aluminum Association 2013	Aluminum Association 2013	IPPC 2014	Calculated	DOE 2007
Primary Metal Production					
Electrolysis	USGS 2012	Aluminum Association 2013	Luo & Soria 2008	Bruggeman et al. 2003, DOE 2003	DOE 2007
Primary Casting	USGS 2012	Aluminum Association 2013	IPPC 2014	Calculated	Set to zero due to minimal chemical conversions
Secondary Metal Production					
Secondary Processing	USGS 2012, DOE 2007	Aluminum Association 2013	Das 2015	Calculated	Set to zero due to minimal chemical conversions
Secondary Melting and Casting	USGS 2012, DOE 2007	Aluminum Association 2013	IPPC 2014	Apogee Technology, Inc. 2010, DOE 2001	Internal Calculations
Semi-Finished Shape Production					
Hot Rolling	USGS 2012	Aluminum Association 2013	Das 2015	Johns Hopkins University 2012, DOE 2011	MatWeb 2015, Internal Calculations
Cold Rolling	USGS 2012, Aluminum Association 2014, DOE 2007	Aluminum Association 2013	Das 2015	Calculated	MatWeb 2015, Internal Calculations
Extrusion	USGS 2012	Aluminum Association 2013	Das 2015	European Commission n.d.	Set to zero due to minimal chemical conversions

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 Example Technologies Considered

To estimate PM energy consumption for this bandwidth analysis, a broad search of R&D activities in the aluminum 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 Aluminum Manufacturing: Application Areas Studied

Subarea	On-site PM Energy Intensity (Btu/lb Aluminum)	On-site PM Energy Consumption, Calculated* (TBtu/year)
Raw Material Beneficiation	2,334	2.49
Reductant Production	394	0.42
Primary Metal Production		
Electrolysis	12,248	13.05
Primary Casting	110	0.12
Secondary Metal Production		
Secondary Processing	409	0.60
Secondary Melting and Casting	850	1.25
Semi-Finished Shape Production		
Hot Rolling	1,572	4.33
Cold Rolling	1,092	1.69
Extrusion	1,474	1.32
Total for Process Subareas Studied		**25.26***

Practical Minimum (PM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire aluminum sector.

The PM energy intensity for aluminum 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 conservative compared to SOA energy intensity).

Table A3-2. Details of PM Technologies Considered

Technology Name	Description	Applicability	Energy savings Estimate	PM Energy Intensity (Btu/lb)	Included in PM model?	Reason for excluding (if applicable)	Reference
Alumina Calciners (outotec)	Multi-stage venturi preheating system is used to recover heat from the waste gas to preheat and dry the incoming $Al(OH)_3$. This process efficiently recovers heat to eliminate waste.	Raw material beneficiation	Efficient heat recovery scheme leads to an overall fuel energy consumption of less than 2.8 GJ/t of alumina for the calcination process	2,334 Btu/lb	Yes		Outotec 2015
Vertical Floatation Melter (VFM)	Use of a vertical floatation melter in place of a gas reverberatory furnace: the VFM is an innovative design which decoats, preheats and melts in one operation. Scrap falls as combustion products rise heating the scrap and increasing residence time in the melter until it becomes a more aerodynamic liquid droplet and falls.	Secondary aluminum production	Typical energy use is noted as 850 Btu/lb	850 Btu/lb	Yes		DOE 2000a, ERCo 2015a
IDEX Scrap Decoater and Dryer	Scrap is first fed into a sealed rotating kiln and scrap oil is then vaporized by a hot air stream with low oxygen content. The heat released from the oils provides all the energy needed to drive the process. The low oxygen content in the process prevents combustion and protects the metal.	Secondary aluminum production	Compared to conventional equipment, results in a 56% reduction in energy use	981 Btu/lb	No	Vertical floatation melter provides a lower baseline energy use.	ERCo 2015b

Technology Name	Description	Applicability	Energy savings Estimate	PM Energy Intensity (Btu/lb)	Included in PM model?	Reason for excluding (if applicable)	Reference
Isothermal Melting Process	The melting process is accomplished in a multi-bay flow system. Immersion heaters raise the temperature in the heating bay. Scrap is charged and mixed in the heating bay before being returned to the hearth. Because of the little change in melted aluminum throughout the process it is known as isothermal melting	Secondary aluminum production – melting and casting	50% lower than conventional melting	1,115 Btu/lb	No	Vertical floatation melter provides a lower baseline energy use.	Apogee Technology, Inc. 2010, DOE 2001
Ultrahigh Efficiency Cells (Multipolar Cells)	In this study, a systems approach was used to develop an ultra-high-efficiency aluminum production cell. The approach was to change the: • Electrolyte chemistry, thus allowing for a lower operating temperature; • Anode and cathode materials, since more material options are available with a lower operating temperature; and • Configuration to a vertical bipolar cell, since inert anodes enable new energy-efficient cell designs	Primary aluminum production – electrolysis	Total on-site cell and anode energy intensity is estimated to be 11.08 kWh/kg	17,149 Btu/lb	No	Wettable ceramic-based drained cathodes provide a lower baseline energy use.	ANL 2014

Technology Name	Description	Applicability	Energy savings Estimate	PM Energy Intensity (Btu/lb)	Included in PM model?	Reason for excluding (if applicable)	Reference
Wettable Ceramic-Based Drained Cathode Technology	Currently molten aluminum sits at the bottom of the electrolytic cell serving as the cathode. Because of its molten nature the surface undulates requiring greater separation between it and the anode to prevent shorting. Reducing this distance would reduce total energy demands. Having a solid wetted cathode with a sump where the molten aluminum pools would allow for shorter interelectrode distances. The research involves cathodes made up of ceramic based materials	Primary aluminum production – electrolysis	Energy savings are estimated at 7,200 kWh/ton	12,248 Btu/lb	Yes		Bruggeman et al. 2003, DOE 2003
Carbothermic Process	By reacting alumina at high temperatures (>2000 °C) the oxygen can be forced to react with carbon to make CO_2, similar to how iron is smelted.	Primary aluminum production – electrolysis	Energy consumption is estimated at 8.5 kWh/kg	13,160 Btu/lb	No	Wettable ceramic-based drained cathodes provide a lower baseline energy use.	Alcoa 2011, DOE 2000b, Bruno 2004
Lower electrolysis temperature (PBRTE)	Currently electrolysis is performed under an average temperature of 1220K which is far above the melting point of aluminum (933K), which implies a high heat loss. Several approaches for temperature reduction have been investigated and the promising results come from new additives for electrolyte.	Primary aluminum production – electrolysis	The reduction in temperature is estimated to reduce electricity use by 1.5 kWh/kg or 2,320 Btu/lb	21,068 Btu/lb	No	Wettable ceramic-based drained cathodes provide a lower baseline energy use.	Luo & Soria 2008

Technology Name	Description	Applicability	Energy savings Estimate	PM Energy Intensity (Btu/lb)	Included in PM model?	Reason for excluding (if applicable)	Reference
Hot Rolling Scrap Reduction through Edge Cracking and Surface Defects Control	Integrated computer models and process optimization tools to reduce scrap and improve energy efficiency in hot rolling; integrate microstructure characterization, computational modeling of microstructures and fracture nucleation, 3D rolling modeling and process optimization approaches.	Semi-finished shape production – hot rolling	Estimated to improve hot rolling recovery by 10%; based on source estimates, results in 242 Btu/lb of energy savings	1,572 Btu/lb	Yes		Johns Hopkins University 2012, DOE 2011
MAGNHEAT-LIFE - Induction oven with rotating permanent magnets for energy efficient aluminum heating	An industrial-scale prototype of a direct current induction heating system using rotating permanent magnets. Expected to deliver significant reductions in the time needed for metal extrusion and a particularly high degree of control of temperature distribution in the process.	Semi-finished shape production – extrusion	Energy savings of 50%	1,474 Btu/lb	Yes		European Commission n.d.

In some cases, there was a limited amount of information available on technologies for specific subareas (reductant production, primary aluminum casting, secondary aluminum processing, and cold rolling), requiring best engineering judgment to be used in determining the PM energy intensity. For primary aluminum casting, secondary aluminum processing, and cold rolling, the PM energy intensity and consumption values are calculated to be 15% lower than the SOA energy intensity and consumption values based on best engineering judgment (Das 2015). Example calculations are provided below. For reductant production, since the SOA energy intensity is only 6% higher than the TM energy intensity, a more conservative estimate of 3% energy savings was assumed.

<u>PM Energy Intensity Calculation:</u>

On-site PM energy intensity is calculated to be 15% lower than the SOA energy intensity values from Table 4-2 for primary aluminum casting, secondary aluminum processing, and cold rolling. An example calculation is provided here:

$$Onsite\ PM\ Energy\ Intensity\ (primary\ Al\ casting) = onsite\ SOA\ energy\ intensity * 0.85 = 129\frac{Btu}{lb} * 0.85 = 110\frac{Btu}{lb}$$

PM Technologies Considered:

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

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

Subarea	Technology Name
Aluminum – Anode preparation	Automatic Stub Repair
Aluminum	Pure Oxygen Anodes™
Aluminum – Bayer Process (alumina)	Alumina Calciners
Aluminum – Bayer Process (alumina)	Bauxite Bacteria
Aluminum – Calcining Plant	Boffins (emissions reduction)
Aluminum – Melting	Furnace Modeling
Aluminum – Post Processing	Friction Stir Processing
Aluminum – Post Processing	Fractional Crystallization
Aluminum – Primary	Energy Transformers
Aluminum – Processing	Novel heating method
Aluminum – Secondary Production	Vertical Floatation Melter (VFM)
Aluminum – Secondary Production	IDEX Scrap Decoater and Dryer
Aluminum – Secondary Production	Laser Induced Breakdown Spectroscopy
Aluminum – Secondary Production	Isothermal Melting Process
Aluminum – Secondary Production	Distillation
Aluminum – Secondary Production	Unidirectional Solidification
Aluminum – Electrolysis	Ultrahigh Efficiency Cells (Multipolar Cells)
Aluminum – Electrolysis	Wettable Ceramic-Based Drained Cathode Technology for Aluminum Electrolysis
Aluminum – Electrolysis	Inert anodes
Aluminum – Electrolysis	Prebake Inert anode (PBANOD)
Aluminum – Electrolysis	Carbothermic Process
Aluminum – Electrolysis	Dual Electrolyte and Electrolytic Membrane Extraction for Aluminum Production
Aluminum – Electrolysis	Ionic Liquid Electrolytes
Aluminum – Electrolysis	Kaolinite Process
Aluminum – Electrolysis	Low Temperature Heat Recovery
Aluminum	Energy Efficient, High Productivity Aluminum Electrolytic Cell with Integrated Power Modulation and Heat Recovery
Aluminum	Development of an Integrated Minimill for the Aluminum Industry: Scrap to Product in One Step
Aluminum – Electrolysis	Lower the electrolysis temperature (e.g., Prebake Reduced Temperature Electrode [PBRTE])
Aluminum – Electrolysis	Drained-cell technology (wettable cathode)
Aluminum – secondary production	Membrane Purification Cell for Aluminum Recycling (electrorefining)
Aluminum – secondary production	Improved materials and operation of recuperators for aluminum melting furnaces
Aluminum – hot rolling	Hot Rolling Scrap Reduction through Edge Cracking and Surface Defects Control
Aluminum – extrusion	MAGNHEAT-LIFE - Induction oven with rotating permanent MAGNets for energy efficient aluminum HEATing

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