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. Magnesium Manufacturing

September 2017

(This page intentionally left blank)

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) 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.

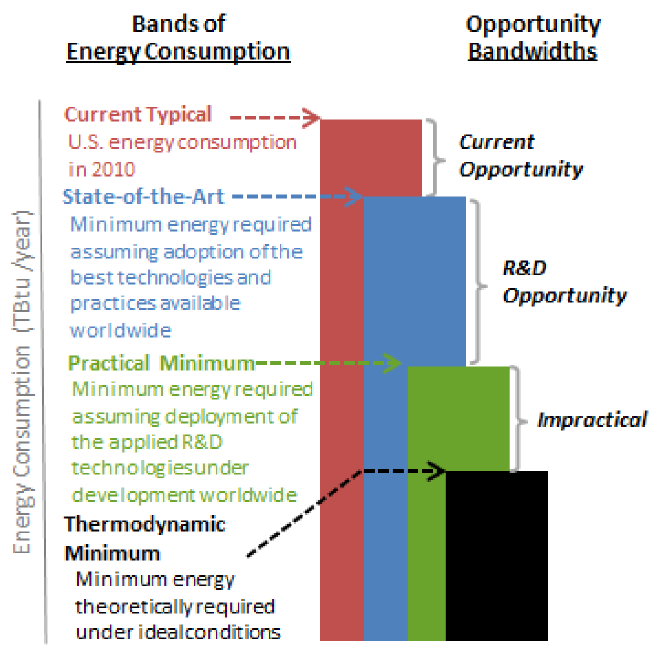

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

[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.

Acknowledgements

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 Neale Neelameggham of IND LLC for their work reviewing this study.

(This page intentionally left blank)

List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
BBtu	Billion British thermal units
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
Mg	Magnesium
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
TM	Thermodynamic minimum energy consumption or energy intensity

(This page intentionally left blank)

Executive Summary

Magnesium is an important manufacturing product in the United States. This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. magnesium manufacturing for lightweighting applications. Industrial, government, and academic data are used to estimate the energy consumed in four 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 magnesium 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 four 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 four *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. magnesium manufacturing subareas studied and as a total.

[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 facility boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

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

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Select Magnesium Manufacturing Subareas (per year)
Current Opportunity: energy savings if the best technologies and practices available are used to upgrade production	**23 BBtu** [3] (3% energy savings) [4]
R&D Opportunity: additional energy savings if the applied R&D technologies under development worldwide are deployed	**184 BBtu** [5] (22% energy savings) [6]

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

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” because 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 1,206 BBtu of energy was consumed in 2010 to manufacture magnesium in the United States for the structural applications considered in this study. Based on the results of this study, and estimated 23 BBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide were used to upgrade the magnesium manufacturing subareas studied; an additional 184 BBtu could be saved through the adoption of applied R&D technologies under development worldwide.

The two current energy savings opportunities for magnesium identified in this study are as follows:

- Secondary magnesium processing/production: 17 BBtu (or 74% of the current opportunity)
- Magnesium extrusion: 6 BBtu (or 26% of the current opportunity)

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

- Primary magnesium production, electrolysis: 103 BBtu (or 56% of the R&D opportunity)
- Raw material preparation: 59 BBtu (or 32% of the R&D opportunity)
- Secondary magnesium processing/production: 13 BBtu (or 7% of the R&D opportunity).

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

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

[4] Current opportunity (or SOA) percentage = $\left(\frac{CT - SOA}{CT - TM}\right) x\ 100$, as shown in Table 4-3.

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

[6] R&D opportunity percentage = $\left(\frac{SOA - PM}{CT - TM}\right) x\ 100$, as shown in Table 5-4.

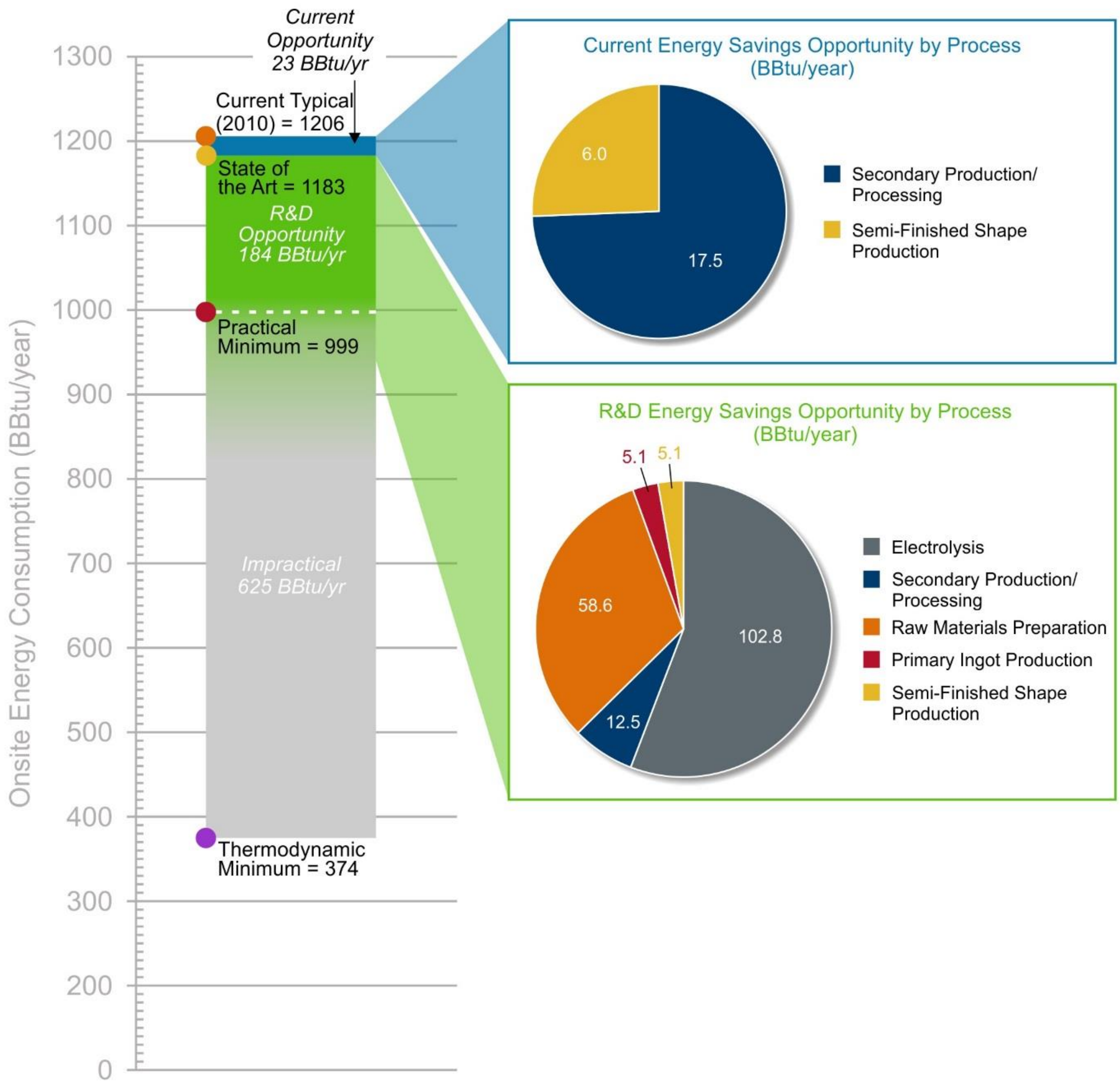

Figure ES-1. Current and R&D energy savings opportunities for the magnesium manufacturing subareas studied (considering selected lightweighting applications)
Source: EERE

(This page intentionally left blank)

Table of Contents

List of Figures

List of Tables

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 the processes and products that consume the most energy, 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 magnesium (Mg).

This study is one in a series of seven bandwidth studies characterizing energy use in manufacturing lightweight structural materials in the United States. The other materials, studied in parallel, include: magnesium alloys, titanium alloys, advanced high strength steel alloys, carbon fiber composites, and glass fiber 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 six 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 Figure 1-1, 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.

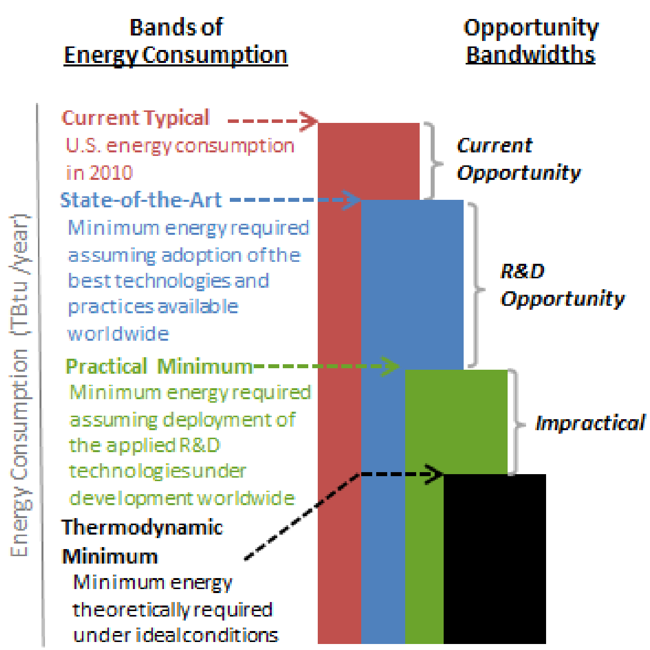

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

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. These bandwidths are estimated for processes and products studied and for all manufacturing within a sector based on extrapolated data. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because 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 (BBtu per year), energy intensity values per unit weight (Btu per pound of material manufactured) were estimated and multiplied by the production volumes (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 sector-wide energy consumption data were available. 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 **production volumes** (million lb 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 consumption** (BBtu per year) for the process subareas studied and material total (along with sources).
- Chapter 4 presents the estimated on-site **SOA energy consumption** (BBtu per year) for the process subareas studied and material total (along with sources).

[7] Feedstock energy is the nonfuel use of combustible energy. Feedstocks are converted to magnesium 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 consumption** for the process subareas studied and material total (along with sources).
- Chapter 6 presents the estimated on-site **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 Magnesium 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 magnesium 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 magnesium manufacturing at a production facility.

This study does not consider life cycle energy consumed during raw material extraction, off-site treatment, transport 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.

Magnesium is used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. Magnesium 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 construction/ 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 32% of overall magnesium production in the United States, as shown in Figure 1-2 (see Section 2.2 for more detail). Castings and wrought products would be used in the transportation sector, which falls within the boundary application areas for this study.

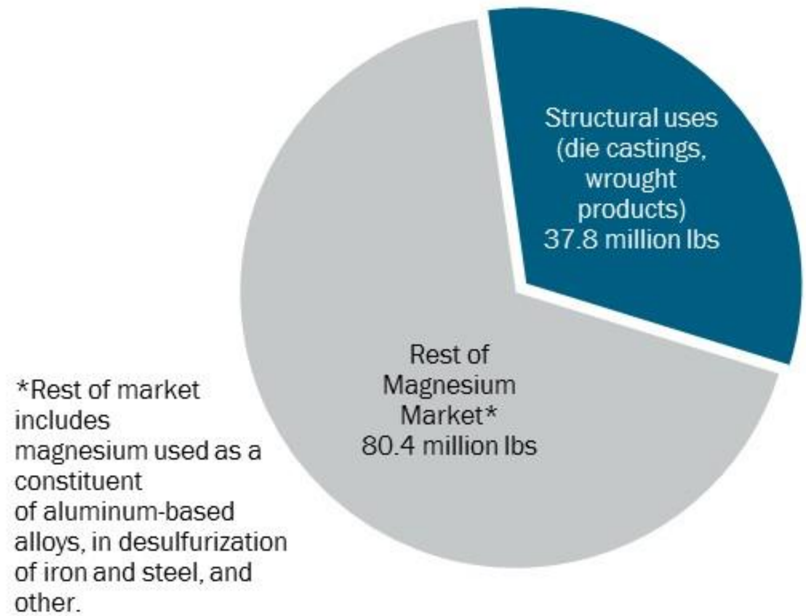

Figure 1-2. Estimated makeup of the magnesium market in 2010.
Data source: USGS 2011b

2. Magnesium Production

2.1. Manufacturing Overview

In 2010, the United States produced 94.4 million lb of primary magnesium (USGS 2011a). Additionally, it is estimated that the United States recovered 207.3 million lb of magnesium scrap to be processed into secondary magnesium. During the year for this study (2010), there was only one primary magnesium production facility in the United States, located in Utah (USGS 2011a).

This study focuses on energy consumption in four energy intensive process subareas in magnesium manufacturing. Figure 2-1 shows the magnesium manufacturing process flow diagram addressing the subareas that were considered in this bandwidth analysis. For primary magnesium production there are two main subareas: raw material preparation and primary magnesium production (which encompasses the Western electrolytic process and the casting of primary ingots). Secondary production involves the production of magnesium ingot from recycled and processed magnesium scrap. Both primary and secondary cast magnesium ingots are then shipped to be further processed or used to produce rolled and extruded magnesium products in semi-finished shape production.

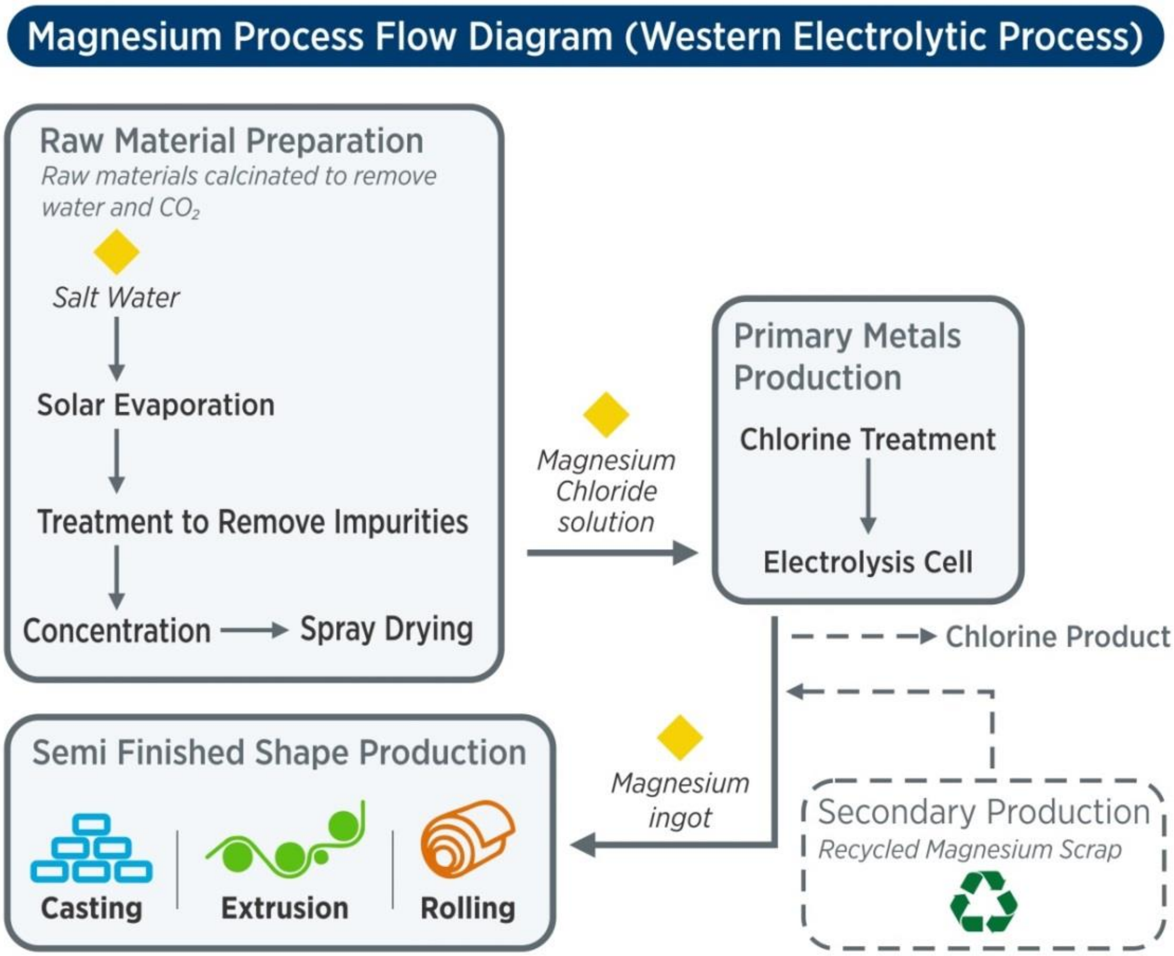

Figure 2-1. Magnesium manufacturing process flow diagram
Source: EERE

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 the following 2007 North American Industry Classification System (NAICS) codes (USCB 2012):

- 331419 (primary magnesium refining)
- 331491 (magnesium rolling, drawing, or extruding purchased metals or scrap), and
- 331492 (magnesium recovering from scrap and/or alloying purchased metals)

These NAICS sectors cover multiple additional types of metal manufacturing, such as titanium, tin, zinc, platinum, and others. Note that further steps, such as the production of magnesium parts (such as those for automobiles) and the die-casting of magnesium falls outside of the scope of this analysis and outside of NAICS 3314 (magnesium die-castings fall within a different industry, NAICS 331523).

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

Subareas	Sub-Processes
Raw Material Preparation	
Primary Metal Production	Electrolysis Primary Ingot Production
Secondary Metal Processing/Production	
Semi-Finished Shape Production	Extrusion

2.2. Production Values

Production data was gathered to calculate the annual energy consumption by process and sector-wide for magnesium manufacturing. The U.S. Geological Survey (USGS) is the leading sources for information magnesium production in the United States and releases data on magnesium production annually. The USGS provides U.S. magnesium production (as well as import and export) data and data on amounts of magnesium recycled and was used as the primary production data source. 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 magnesium 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 other bandwidths and the most widely available current and production energy data. According to the U.S. Geological Survey (USGS), 32% of U.S. magnesium consumption was for structural uses, including castings and wrought products (USGS 2011b). While die-casting itself is not included in the processes studied in this bandwidth as they are considered a part of a different industry (foundries, or NAICS 3315), castings and wrought products would be used in the transportation sector, which falls within the boundary application areas for this study. A further breakdown within the 32% of consumption attributed to transportation versus other structural applications is unavailable.

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

Subarea	Product	2010 Total Magnesium Sector Production (million lb)	2010 Estimated Production for Boundary Applications (million lb)
Raw Material Preparation		N/A*	N/A*
Primary Metal Production	Primary magnesium	94.4	30.2
Secondary Metal Processing/Production	Secondary magnesium	207.3	66.3
Semi-Finished Shape Production	Semi-finished shapes	118.1	37.8

*Because the energy intensity values for these subareas are based upon and are presented as the energy required to produce a pound of magnesium (Btu/lb magnesium) rather than to produce a pound of raw material, the estimated production for this subarea for the boundary applications was not needed to be calculated.
Source: Calculated using values from USGS 2011a, USGS 2011b, USGS 2012

3. Current Typical Energy Intensity and Energy Consumption

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

3.1. Current Typical Energy Intensity

Appendix A1 presents the CT energy intensities and energy consumption for the subareas studied. Appendix A2 provides the references used for each subarea.

A range of data sources were considered to determine the magnesium current typical energy intensity. In most cases, multiple references were considered for each process. Magnesium manufacturing is unique and magnesium 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.

However, one main source was determined as the best source for current typical energy intensity: Johnson & Sullivan's *Lightweight Materials for Automotive Application: An Assessment of Material Production Data for Magnesium and Carbon Fiber*. This report provided data for an Australian plant that is considered to be very close the primary magnesium plant in the United States (for which public data is unavailable). While no energy intensity value was available for extrusion, a best engineering judgment was used.

3.2. Current Typical Energy Consumption

Table 3-1 presents the energy intensities and calculated on-site and primary CT energy consumption for the magnesium production subareas studied. Appendix A2 provides the references used for CT energy intensity for each subarea. Feedstock energy is excluded from the consumption values. The energy intensities are presented in terms of Btu per lb magnesium produced. The CT energy consumption for these subareas is estimated to account for 1,206 BBtu of on-site energy and 2,764 BBtu of primary energy in 2010.

Primary energy is calculated from on-site CT energy consumption data based on an analysis of the aluminum lightweight bandwidth data, which was considered to have similar processes for magnesium which lacked primary energy intensity 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 3-1 for details on the scaling method).

Table 3-1. On-site CT Energy Intensity and Calculated Energy Consumption and Calculated Primary CT Energy Consumption for U.S. Magnesium Manufacturing: Application Areas Studied (2010)

Subarea	On-site CT Energy Intensity (Btu/lb Magnesium)	On-site CT Energy Consumption, Calculated* (BBtu/year)	Off-site Losses, Calculated*,**,*** (BBtu/year)	Primary CT Energy Consumption, Calculated* (BBtu/year)
Raw Material Preparation	12,939	391	48	439
Primary Metal Production				
Electrolysis	21,200	640	1,360	2,000
Ingot Production	1,134	34	73	107
Secondary Metal Processing/Production	1,524	101	67	168
Semi-Finished Shape Production				
Extrusion	1,060	40	9	49
Total for Process Subareas Studied	**N/A**	**1,206**	**1,558**	**2,764**

Current typical (CT)

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

*** Based on calculations from CT primary energy for aluminum lightweight energy bandwidth due to lack of energy type breakdown and availability of primary energy intensity data, using the following assumptions: off-site losses assumed to be approximately 11% of primary energy for raw material preparation, 68% for primary metal production, 40% for secondary metal production, and 18% for extrusion.

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

This chapter estimates the energy savings possible if U.S. magnesium 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 Magnesium 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. Appendix A2 provides the references used for each subarea. 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
Das 2015	In certain cases, citable data was unavailable for magnesium 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 on discussions with experts, presentations at the Minerals, Metals, and Materials Society (TMS) 2015 annual meeting, and knowledge of the field.
Ehrenberger 2013	The *Life Cycle Assessment of Magnesium Components in Vehicle Construction* report produced for the International Magnesium Association provides some information on energy intensity for magnesium manufacturing, but mostly focuses on end use energy benefits.
Johnson & Sullivan 2014	The report *Lightweight Materials for Automotive Application: An Assessment of Material Production Data for Magnesium and Carbon Fiber* provides good current typical energy intensity values as well as information on state of the art technologies.

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 magnesium manufacturing subareas studied. Appendix A2 provides the references used for SOA energy intensity for each subarea. The SOA energy intensities are presented as Btu per lb magnesium and the on-site SOA energy consumption is presented as BBtu per year.

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

Subarea	On-site SOA Energy Intensity (Btu/lb magnesium)	On-site SOA Energy Consumption, Calculated* (BBtu/year)
Raw Material Preparation	12,939	391
Primary Metal Production		
Electrolysis	21,200	640
Ingot Production	1,134	34
Secondary Metal Processing/Production	1,261	84
Semi-Finished Shape Production		
Extrusion	901	34
Total for Process Subareas Studied	**N/A**	**1,183**

State of the Art (SOA)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire magnesium 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 BBtu 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 both percent energy savings and BBtu savings is secondary magnesium processing/production at 26% and 17 BBtu per year savings. Note that there is no improvement for raw material preparation or primary metal production. This was because there was only one plant operating in the United States in 2010 to produce primary magnesium, and it was assumed that the plant was operating at SOA energy intensity (the most efficient process) as no other additional data could be located.

If U.S magnesium manufacturing (for the 2010 production level of magnesium for application areas considered) were able to attain on-site SOA energy intensities, it is estimated that 23 BBtu per year of energy could be saved from the subareas alone, corresponding to a 3% 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 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 Magnesium Manufacturing: Application Areas Studied

Subarea	On-site CT Energy Consumption, Calculated* (BBtu/year)	On-site SOA Energy Consumption, Calculated* (BBtu/year)	SOA Energy Savings** (CT - SOA) (BBtu/year)	SOA Energy Savings Percent*** (CT - SOA) / (CT - TM)
Raw Material Preparation	391	391	0	0%
Primary Metal Production				
Electrolysis	640	640	0	0%
Ingot Production	34	34	0	0%
Secondary Metal Processing/Production	101	84	17	26%
Semi-Finished Shape Production				
Extrusion	40	34	6	15%
Total for Process Subareas Studied	**1,206**	**1,183**	**23**	**3%**

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 magnesium sector.
** SOA energy savings is also called *Current Opportunity.*
*** SOA energy savings percent is the SOA energy savings opportunity from transforming magnesium 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 magnesium in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. magnesium manufacturing. In this chapter, the R&D energy savings made possible through R&D advancements in magnesium 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 Magnesium Practical Minimum Energy Intensity

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific magnesium 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 magnesium manufacturing 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 some key sources consulted to identify PM energy intensities in magnesium manufacturing. Additionally, numerous fact sheets, case studies, reports, and award notifications were referenced.

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

Source Abbreviation	Description
ARPA-E 2013	Project information from the ARPA-E website on various research projects funded by ARPA-E in magnesium production
Das 2015	In certain cases, citable data was unavailable for magnesium 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.

5.2. Practical Minimum Energy Intensity and Energy Consumption

Table 5-2 presents the on-site PM energy intensities and energy consumption for the magnesium manufacturing subareas studied. Appendices A2 and A3 provide the references used for SOA energy intensity for each subarea. The PM energy intensities are presented as Btu per lb magnesium and the on-site PM energy consumption is presented as BBtu per year.

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

Subarea	On-site PM Energy Intensity (Btu/lb Magnesium)	On-site PM Energy Consumption, Calculated* (BBtu/year)
Raw Material Preparation	10,999	332
Primary Metal Production		
Electrolysis	17,796	537
Ingot Production	964	29
Secondary Metal Processing/Production	1,072	71
Semi-Finished Shape Production		
Extrusion	766	29
Total for Process Subareas Studied	**N/A**	**999**

Practical Minimum (PM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire magnesium 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. Table 5-4 calculates the R&D opportunity for the process subareas studied.

It is useful to consider both BBtu 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 secondary magnesium processing/production at 45% energy savings; the greatest *current* plus *R&D opportunity* in terms of BBtu savings is electrolysis at 103 BBtu per year savings.

If U.S magnesium manufacturing (for the 2010 production level of magnesium for application areas considered) were able to attain on-site PM energy intensities, it is estimated that 208 BBtu per year of energy could be saved from the subareas alone, corresponding to a 25% energy savings overall (see equation below). 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 Magnesium Manufacturing: Application Areas Studied

Subarea	On-site CT Energy Consumption, Calculated* (BBtu/year)	On-site PM Energy Consumption, Calculated* (BBtu/year)	PM Energy Savings** (CT-PM) (BBtu/year)	PM Energy Savings Percent*** (CT-PM)/ (CT-TM)
Raw Material Preparation	391	332	59	15%
Primary Metal Production				
Electrolysis	640	537	103	34%
Ingot Production	34	29	5	15%
Secondary Metal Processing/Production	101	71	30	45%
Semi-Finished Shape Production				
Extrusion	40	29	11	28%
Total for Process Subareas Studied	**1,206***	**999***	**208**	**25%**

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 magnesium 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 magnesium 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 R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. 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 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 Magnesium Manufacturing: Application Areas Studied

Subarea	On-site SOA Energy Consumption, Calculated (BBtu/year)	On-site PM Energy Consumption, Calculated (BBtu/year)	R&D Opportunity (SOA-PM) (BBtu/year)	R&D Opportunity Savings Percent* (SOA-PM)/(CT-TM)
Total for Process Subareas Studied	**1,183**	**999**	**184**	**22%**

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 magnesium production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture magnesium 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 Magnesium 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 of the thermodynamic minimum energy intensity for primary magnesium production was Wulandari et al. 2010 and internal calculations.

For the remaining subareas considered (primary magnesium casting, secondary magnesium 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 magnesium 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 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

---

[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.

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 magnesium 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 a magnesium production subarea is its TM energy consumption. If the 2010 level of magnesium 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 Magnesium Manufacturing: Application Areas Studied

Subarea	TM Energy Intensity (Btu/lb Magnesium)	TM Energy Consumption, Calculated* (BBtu/year)
Raw Material Preparation	0	0
Primary Metal Production		
Electrolysis	11,213	339
Ingot Production	0	0
Secondary Metal Processing/Production	530	35
Semi-Finished Shape Production		
Extrusion	0	0
Total for Process Subareas Studied	**N/A**	**374***

Thermodynamic minimum (TM)

* Calculated using the production values for the applications studied (see Section 1.4), and *not* the entire magnesium 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 magnesium production for the application area boundary considered for this study. Each row in Table 7-1 shows the opportunity bandwidth for a specific magnesium 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:* 23 BBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity:* 184 BBtu 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 magnesium 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 Magnesium Manufacturing: Application Areas Studied

Subarea	**Current Opportunity*** (CT - SOA) (BBtu/year)	**R&D Opportunity*** (SOA - PM) (BBtu/year)
Raw Material Preparation	0	59
Primary Metal Production		
Electrolysis	0	103
Ingot Production	0	5
Secondary Metal Processing/Production	17	13
Semi-Finished Shape Production		
Extrusion	6	5
Total for Process Subareas Studied	**23**	**184**

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 magnesium sector.

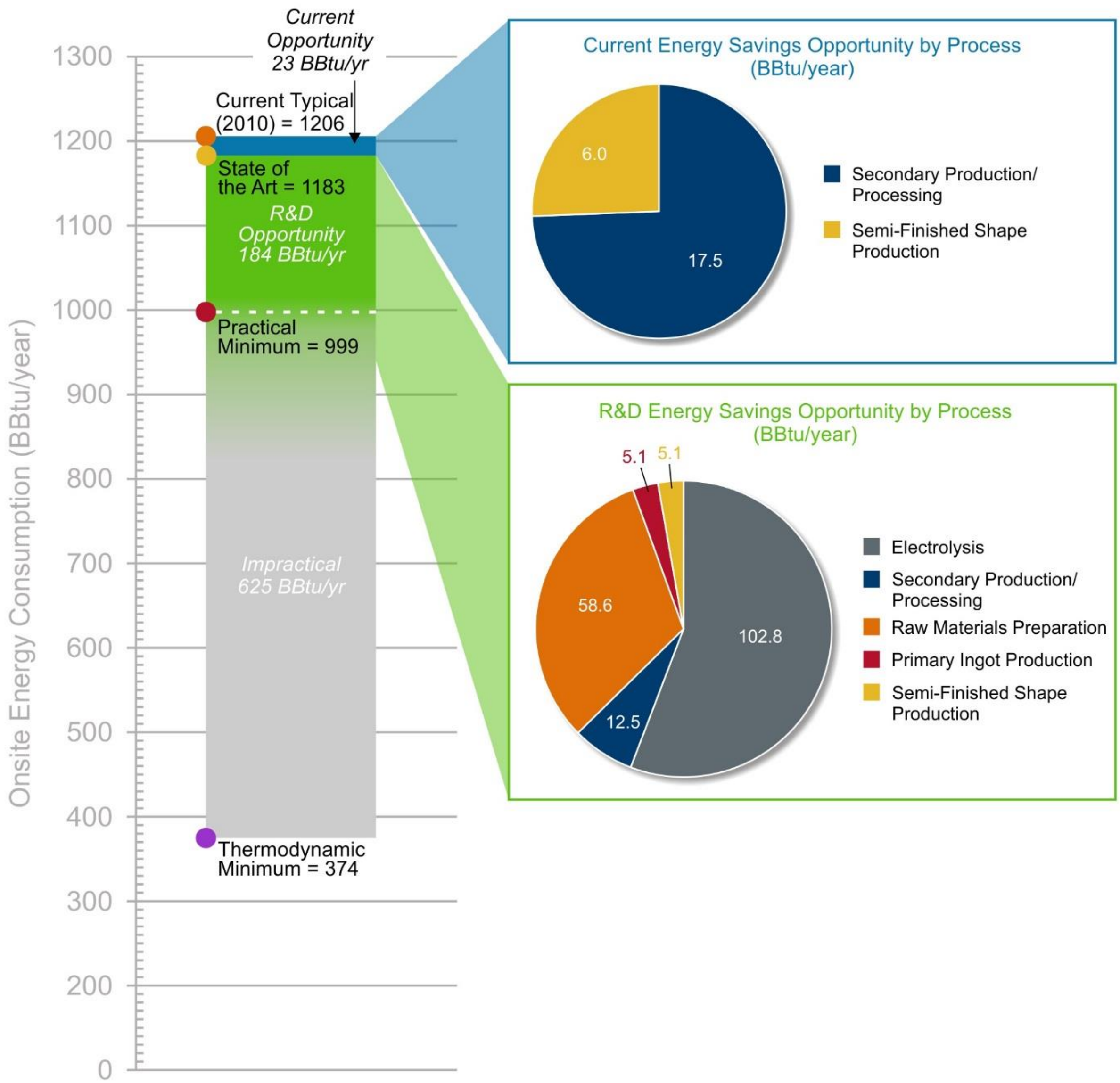

Figure 7-1. Current and R&D energy savings opportunities in U.S. magnesium manufacturing for the subareas and application areas studied
Source: EERE

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

8. References

AIChE 2014 American Institute of Chemical Engineers (AIChE) 2014. *Zero-Emissions Magnesium Process Debuts.* www.aiche.org/sites/default/files/cep/20140316.pdf

ARPA-E 2013a Advanced Research Projects Agency–Energy (ARPA-E), U.S. Department of Energy 2013. *Modern Electro/Thermochemical Advanced in Light-Metal Systems (METALS).* Funding Opportunity No. DE-FOA-0000882. May 2013. https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=35d7f503-803b-4a31-a713-d29d081608b5

ARPA-E 2013b Advanced Research Projects Agency–Energy (ARPA-E), U.S. Department of Energy 2013. "Pacific Northwest National Laboratory (PNNL) Catalyzed Organo-Metathetical (COMET) Process for Magnesium Production from Seawater." http://arpa-e.energy.gov/?q=slick-sheet-project/extracting-magnesium-seawater

ARPA-E 2013c Advanced Research Projects Agency–Energy (ARPA-E), U.S. Department of Energy 2013. "Valparaiso University. Solar Thermal Electrolytic Production of Mg from MgO." http://arpa-e.energy.gov/?q=slick-sheet-project/solarelectrolytic-production-magnesium-ore

ARPA-E 2013d Advanced Research Projects Agency–Energy (ARPA-E), U.S. Department of Energy 2013. "University of Colorado Boulder (CU-Boulder) Carbothermal Reduction Process for Producing Magnesium Metal using a Hybrid Solar/Electric Reactor." http://arpa-e.energy.gov/?q=slick-sheet-project/solarelectric-powered-magnesium-production

Das 2015 Engineering estimates from S. Das. 2015.

DOE 2015a U.S. Department of Energy (DOE), Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing.* Prepared by Energetics Incorporated. http://energy.gov/sites/prod/files/2015/08/f26/chemical_bandwidth_report.pdf

DOE 2015b U.S. Department of Energy (DOE), Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing.* Prepared by Energetics Incorporated. http://energy.gov/sites/prod/files/2015/08/f26/iron_and_steel_bandwidth_report_0.pdf

DOE 2015c U.S. Department of Energy (DOE), Advanced Manufacturing Office 2015.*Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining.* Prepared by Energetics Incorporated. http://energy.gov/sites/prod/files/2015/08/f26/petroleum_refining_bandwidth_report.pdf

DOE 2015d U.S. Department of Energy, Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing.* Prepared by Energetics Incorporated. http://energy.gov/sites/prod/files/2015/08/f26/pulp_and_paper_bandwidth_report.pdf

EERE Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy

Ehrenberger 2013 S. Ehrenberger for the International Magnesium Association (IMA) 2013. *Life Cycle Assessment of Magnesium Components in Vehicle Construction*, May 2013. http://c.ymcdn.com/sites/intlmag.site-ym.com/resource/resmgr/docs/lca/2013IMA_LCA_Report_Public.pdf

IMA 2014	International Magnesium Association (IMA) 2014. “Overview.” Accessed November 6, 2014. www.intlmag.org/
Johnson & Sullivan 2014	Johnson, M.C., & J.L. Sullivan 2014. *Lightweight Materials for Automotive Application: An Assessment of Material Production Data for Magnesium and Carbon Fiber.* Argonne National Laboratory. September 2014. https://greet.es.anl.gov/files/lightweight-automotive
Palumbo et al. n.d.	Palumbo, R., Beyers, E., Diver, R., Duncan, S., Fosheim, J., Kissinger, P., Nudehi, S., Ogland-Hand, J., Saks, L., Schoer, J., Schrader, A., & Venstrom, L. n.d. “Environmentally and Economically Conscious Magnesium Production: Solar Thermal Electrolytic Production of Mg from MgO.” http://scholar.valpo.edu/cgi/viewcontent.cgi?filename=0&article=1286&context=cus&type=additional
PNNL 2013	Pacific Northwest National Laboratory (PNNL) 2013. “Fuel-efficient cars & planes cheaper with magnesium drawn from ocean.” www.pnnl.gov/news/release.aspx?id=1009
Powell 2012	Powell, A.C. 2012. *Efficient One-Step Electrolytic Recycling of Low-Grade and Post-Consumer Magnesium Scrap.* www.osti.gov/scitech/servlets/purl/1046980
Powell, Earlam, and Barriga 2014	*Pure Oxygen Anodes™ for Low- or Zero-Carbon Energy Efficiency Metal Oxide Reduction.* Powell, Adam, Earlam, Matthew, and Barriga, Salvador. Presented at Energy Technology 2014: Carbon Dioxide Management and Other Technologies. 2014.
USCB 2012	United States Census Bureau (USCB). 2012. “North American Industry Classification System.” www.census.gov/eos/www/naics/index.html
USGS 2011a	U.S. Geological Survey (USGS) 2011. *2010 Minerals Yearbook: Magnesium, September 2011. [Advance Release].* http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/myb1-2010-mgmet.pdf
USGS 2011b	U.S. Geological Survey (USGS) 2011. *Magnesium Metal.* Mineral Commodity Summaries, January 2011. https://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2011-mgmet.pdf
USGS 2012	U.S. Geological Survey (USGS) 2012. *2011 Minerals Yearbook: Magnesium [Advance Release]*, November 2012. http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/myb1-2011-mgmet.pdf
Wulandari et al. 2010	Wulandari, Winny, Brooks, Geoffrey A., Rhamdhani, Muhammad A., & Monaghan, Brian J. 2010. *Magnesium. Current and Alternative Production Routes.* Presented at Chemeca: Austalasian Conference on Chemical Engineering.

Appendix A1. Master Magnesium Summary Table

Table A1-1. U.S. Production Volume of Magnesium 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 Magnesium)				Calculated On-site Energy Consumption* (BBtu/year)			
		CT	SOA	PM	TM**	CT*	SOA*	PM*	TM*
Raw Material Preparation	N/A	12,939	12,939	10,999	0	391**	391**	332**	0**
Primary Metal Production	30.2								
Electrolysis	30.2	21,200	21,200	17,796	11,213	640	640	537	339
Ingot Production	30.2	1,134	1,134	964	0	34	34	29	0
Secondary Metal Processing/Production	66.3	1,524	1,261	1,072	530	101	84	71	35
Semi-Finished Shape Production	37.8								
Extrusion	37.8	1,060	901	766	0	40	34	29	0

* Calculated using the production values for the applications studied (see Section 1.4), and not the entire magnesium sector.
** Calculated by multiplying energy intensity by primary magnesium produced (30.2 million lb for the application areas studied).

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 Magnesium 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)
Raw Material Preparation	N/A	Johnson & Sullivan 2014	Johnson & Sullivan 2014	Best engineering judgment
Primary Metal Production				
Electrolysis	USGS 2012, USGS 2011b	Johnson & Sullivan 2014	Johnson & Sullivan 2014	Wulandari et al. 2010
Ingot Production	USGS 2012, USGS 2011b	Johnson & Sullivan 2014	Johnson & Sullivan 2014	Best engineering judgment
Secondary Metal Processing/Production	USGS 2012, USGS 2011b	Johnson & Sullivan 2014	Ehrenberger 2013	Best engineering judgment
Semi-Finished Shape Production				
Extrusion	USGS 2012, Das 2015, USGS 2011b	Best engineering judgment	Das 2015, Best engineering judgment	Best engineering judgment

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 magnesium 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 Magnesium Manufacturing: Application Areas Studied

Subarea	On-site PM Energy Intensity (Btu/lb Magnesium)	On-site PM Energy Consumption, Calculated* (BBtu/year)
Raw Material Preparation	10,999	332
Primary Metal Production		
Electrolysis	17,796	537
Ingot Production	964	29
Secondary Metal Processing/Production	1,072	71
Semi-Finished Shape Production		
Extrusion	766	29
Total for Process Subareas Studied	**N/A**	**999**

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

The PM energy intensity for magnesium 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 PM energy intensity is estimated, along with a brief explanation. Some technologies in Table A3-2 were considered but not included in the final PM model.

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
Catalyzed Organo-Metathetical (COMET) Process for Magnesium Production from Seawater	A radically new process to produce magnesium from seawater (replaces brine spray drying with a low-temperature, low-energy dehydration process). That step is combined with a new catalyst-assisted process to generate an organometallic reactant directly from magnesium chloride. The organometallic is decomposed to magnesium metal via a proprietary process at temperatures less than 300°C, thus eliminating electrolysis of magnesium chloride salt. The overall process could be significantly less expensive and more efficient than any conventional magnesium extraction method available today and uses seawater as an abundant, free resource.	Primary production - electrolysis	Efficiencies in magnesium extraction technologies could offer a 50% reduction in energy consumption	10,600 Btu/lb	No	Energy savings estimate results in an energy intensity lower than the TM	ARPA-E 2013b, PNNL 2013
Solar Thermal Electrolytic Production of Magnesium from MgO	A solar electro-thermal reactor that produces magnesium from magnesium oxide - the reactor would extract magnesium using concentrated solar power to supply its thermal energy, minimizing the need for electricity. The reactor would be surrounded by mirrors that track the sun and capture heat for high-temperature magnesium electrolysis.	Primary production - electrolysis	This process requires approximately 8.3 - 11.5 kWh/kg Mg of energy	17,796 Btu/lb	Yes		ARPA-E 2013c, Palumbo et al. n.d.

Technology Name	Description	Applicability	Energy savings Estimate	PM Energy Intensity (Btu/lb)	Included in PM model?	Reason for excluding (if applicable)	Reference
Carbothermal Reduction Process for Producing Magnesium Metal using a Hybrid Solar/Electric Reactor	A new solar-powered magnesium production reactor with dramatically improved energy efficiency compared to conventional technologies. The reactor can be heated using either concentrated solar power during the day or by electricity at night. In addition, the reactor can produce syngas, a synthetic gasoline precursor, which could be used to power cars and trucks.	Primary production	None available	N/A	No	No energy savings estimate available	ARPA-E 2013d
Efficient One-Step Electrolytic Recycling of Low-Grade and Post-Consumer Magnesium Scrap (MagReGen™)	A new low-cost process for recycling post-consumer co-mingled and heavily-oxidized magnesium scrap and a new chemical mechanism for magnesium separations in the process. The new process, designated MagReGen™, is very effective in laboratory experiments, and on scale-up promises to be the lowest-cost lowest-energy lowest-impact method for separating magnesium metal from aluminum while recovering oxidized magnesium.	Secondary production	Uses at little as 1/8th as much energy as today's methods for recycling magnesium from scrap. 3.3-3.4 kWh/kg Mg	5,108 Btu/lb	No		Powell 2012

In some cases, a limited amount of information was available on technologies for specific subareas (raw material preparation, primary ingot production, and semi-finished shape production), requiring best engineering judgment to be used in determining the PM energy intensity. For these subareas, 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.

PM Energy Intensity Calculation:

On-site PM energy intensity is calculated to be 15% lower than the SOA energy intensity values from Table 4-2 for raw material preparation, primary ingot production, and semi-finished shape production. An example calculation is provided here:

$$Onsite\ PM\ Energy\ Intensity\ (raw\ material\ prep) = onsite\ SOA\ energy\ intensity * 0.85 = 12{,}939\frac{Btu}{lb} * 0.85 = 10{,}999\frac{Btu}{lb}$$

PM Technologies Considered:

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

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

Subarea	Technology Name
Magnesium Production	Metal Oxygen Separation Technologies, Inc. (MoxST) Magnesium Production Process
Magnesium Production	Catalyzed Organo-Metathetical (COMET) Process for Magnesium Production from Seawater
Magnesium Production	Solar Thermal Electrolytic Production of Magnesium from MgO
Magnesium Production	Carbothermal Reduction Process for Producing Magnesium Metal using a Hybrid Solar/Electric Reactor
Secondary Magnesium	Efficient One-Step Electrolytic Recycling of Low-Grade and Post-Consumer Magnesium Scrap (MagReGen™)
Magnesium Production	MagGen (Infinium, Inc. modular approach to magnesium production)
Magnesium Production	Solid Oxide Membrane (SOM) electrolysis

U.S. DEPARTMENT OF ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

For more information, visit: energy.gov/eere/amo

DOE/EE-1665 • September 2017