U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Titanium 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)'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 P-1). **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.

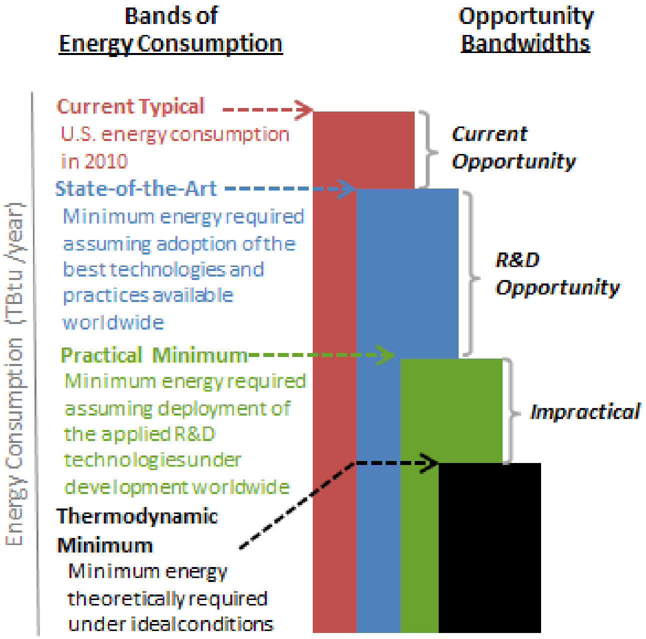

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

---

[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, government, and academic sources. Where published data were unavailable, best engineering judgment was used.

Acknowledgments

Joseph Cresko of the U.S. Department of Energy's Advanced Manufacturing Office (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 Dr. Yellapu Murty of MC Technologies LLC for his work reviewing this study.

(This page intentionally left blank)

List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
Btu	British thermal unit
C	Celsius
CT	current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
DRTS	direct reduction of titanium slag
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
F	Fahrenheit
FFC	Farthing, Fray, Chen (process for reducing metal oxides to metals or alloys)
G	Gibbs free energy
HST	hydrogen sintered titanium
ITA	International Titanium Association
kg	kilogram
kWh	kilowatt-hour
MJ	megajoule
NAICS	North American Industry Classification System
PM	practical minimum energy consumption or energy intensity
R&D	research and development
SOA	state of the art energy consumption or energy intensity
TBtu	trillion British thermal units
Ti	titanium
TM	thermodynamic minimum energy consumption or energy intensity
TRL	technology readiness level
USGS	United States Geological Survey

(This page intentionally left blank)

Executive Summary

Titanium has many useful properties that make it a valuable structural material. Titanium has a high strength-to-weight ratio, corrosion resistance, and thermal stability. Titanium is the fourth-most abundant metal in the earth's crust and the ninth-most common element on the entire planet. (Rand 2009) Titanium is however expensive to refine, process and fabricate. In this report, the manufacturing energy consumption associated with the production of titanium mill products is investigated. Industrial, government, and academic data are used to estimate the energy consumed in three 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 titanium 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 three 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 three *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 titanium.[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. *(In the case of this titanium study, current opportunity was determined to be zero; this is explained in Chapter 4 of the report.)* 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 titanium for selected application areas in baseline year 2010. This study is limited to four energy-critical structural application areas (automotive, wind energy, aerospace, and pressure vessels), which together comprise about 75% of the market for U.S. titanium metal production. Titanium production has seen growth in the past several years, especially with increased application in areas such as the aerospace and automotive sectors. 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 facility boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

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

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Select Titanium Manufacturing Subareas (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	**0 TBtu**[2] (see notes)
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	**1.15 TBtu**[3] (69% energy savings)[4]

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

The PM energy consumption estimates are speculative because they are based on unproven technologies. Additionally, there are very few publicly available sources for determining research savings potential; for this study, the savings rely largely on best engineering judgment based on review of available literature and conversations with experts in the field. 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, the demarcation 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 1.77 TBtu of energy was consumed in 2010 to manufacture titanium products in the United States for the structural applications considered in this study. Based on the results of this study, an estimated 1.15 TBtu of energy could be saved each year through the adoption of applied R&D technologies under development worldwide. DOE researchers will continue to evaluate the energy consumption and opportunity bandwidths in U.S. titanium manufacturing, along with bandwidth study results from other manufacturing sectors.

---

[2] Current Typical energy consumption is assumed equivalent to State of the Art; there was only one commercial titanium manufacturing process in 2010.

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

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

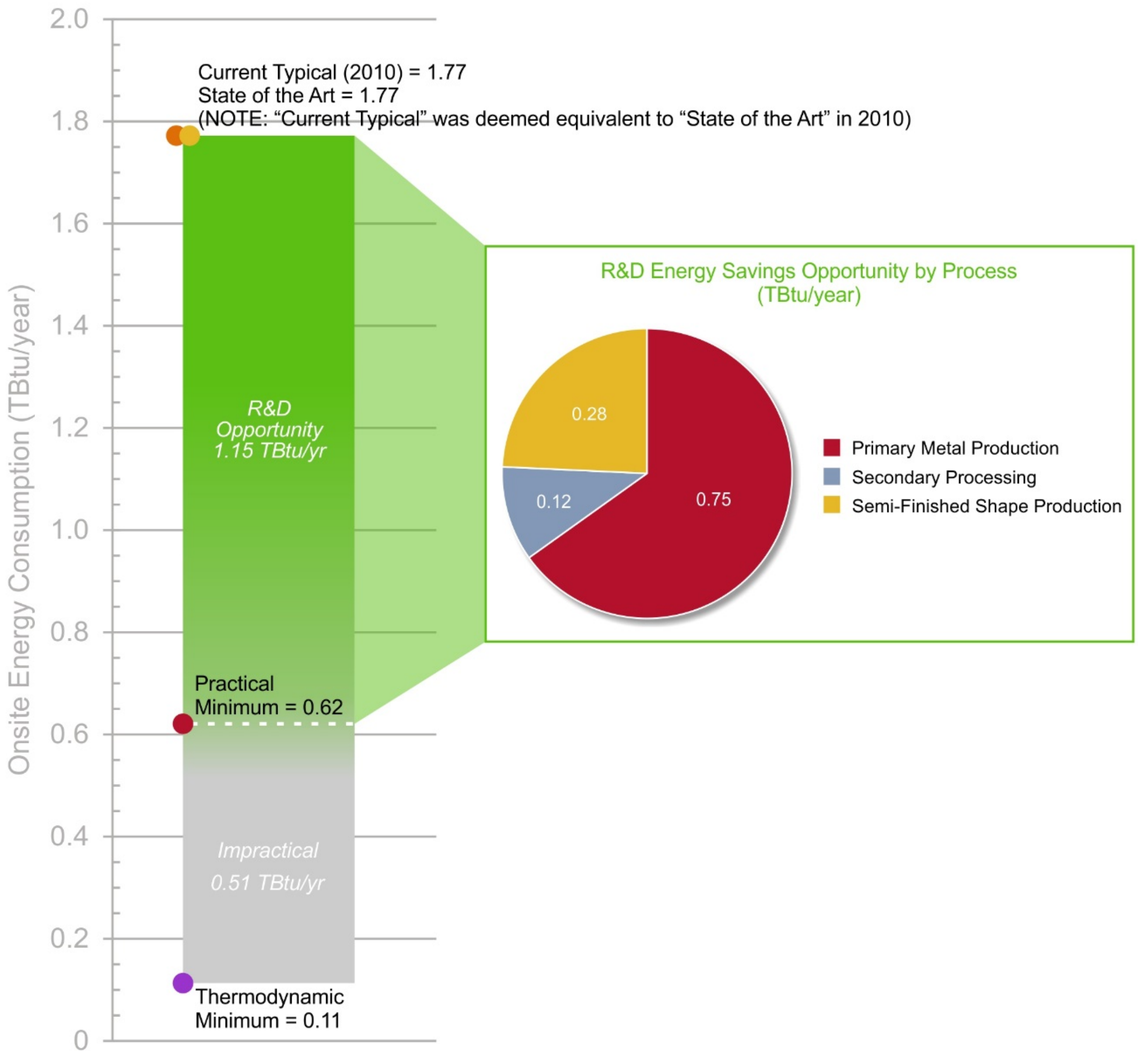

Figure ES-1. R&D energy savings opportunities for the titanium manufacturing subareas studied (considering selected lightweighting applications)
Source: EERE

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 manufacturing 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 processes in titanium (Ti) manufacturing that consume the most energy.

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

Similar energy bandwidth studies have also been prepared for four U.S. manufacturing sectors: petroleum refining (Energetics 2015a), chemicals (Energetics 2015b), iron and steel (Energetics 2015c), and pulp and paper (Energetics 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 for evaluating and comparing energy savings potentials within and across manufacturing sectors at the macro-scale.

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 (see Figure 1-1). **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.

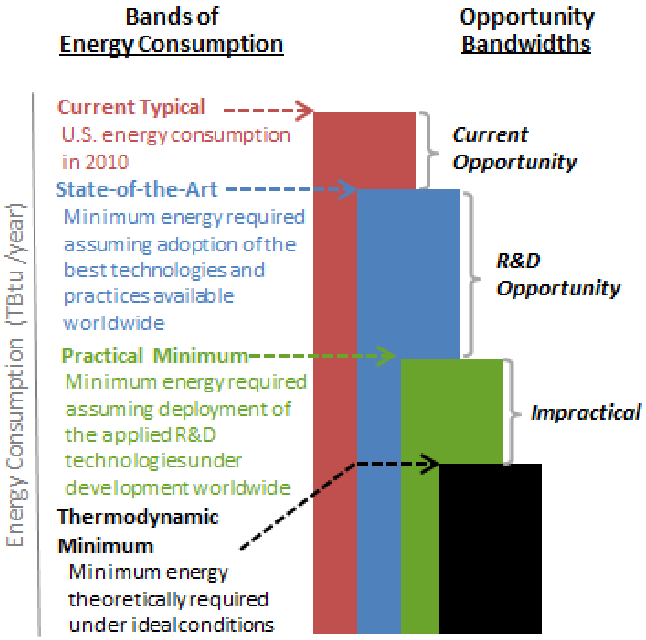

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

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. *(In the case of this titanium study, current opportunity was determined to be zero; this is* *explained in Chapter 4.)* 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 Chapter 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 Chapter 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. To determine the total annual 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 per year). 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.

- Chapter 2 presents the U.S. **production** (million pounds per year) in 2010, including an overview of major applications areas. Four structural application areas for titanium 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 estimated **CT energy intensity** (Btu per pound) and **CT energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).
- 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 and assumptions).
- Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per pound) and **PM energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).
- Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per pound) and **TM energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources and assumptions).
- Chapter 7 provides a summary **of current and R&D opportunity** analysis based on bandwidth summary results.

1.4. Boundaries of the Titanium 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. Economic impacts are also important: an advanced lightweight aerospace component may be more expensive than the conventional choice. While such impacts matter, they are not quantified as part of this report.

This study also does not consider life cycle energy consumed during raw material extraction and preparation, 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.

As distinct from a life cycle assessment, this report focuses exclusively on the energy use directly involved in the production of titanium from relevant input materials. This bandwidth study focuses on the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to titanium manufacturing at a production facility.

Titanium is used in many applications that differ substantially in product use, performance requirements, and relevance to energy use. Titanium materials have strong lightweighting potential 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 valuable applications, however, are less relevant to the DOE; for example, medical devices or military armor applications. 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); and
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 2014a). The last application area (aerospace) is an additional high value-add market for lightweight structural materials. Together, these four application areas account for approximately 75% of overall titanium metal production in the United States, as shown in Figure 1-2. In the case of titanium, the full 75% of this use is assumed to be for aerospace applications (USGS 2011b). Other application areas may include medical devices, marine equipment, military armor, specialty chemicals and power generation equipment, sporting goods, and other consumer goods.

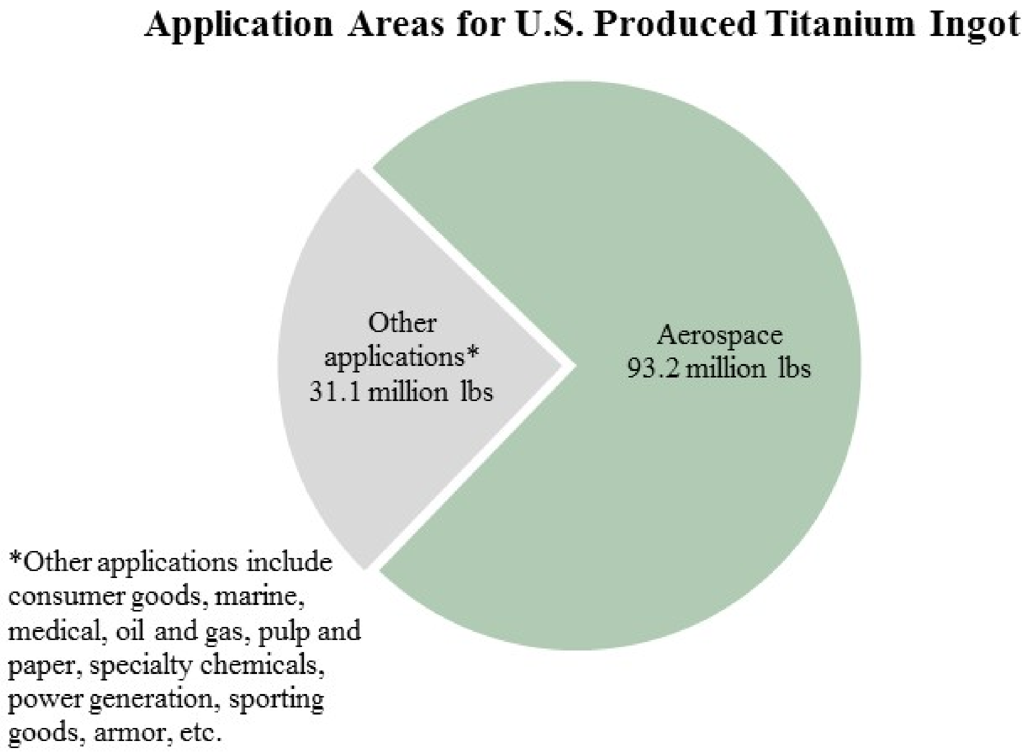

Figure 1-2. Estimated makeup of the titanium market in 2010
Source: USGS 2011b

2. Titanium Production

2.1. Manufacturing Overview

In 2010, the United States produced 62,000 tons (124 million lb) of titanium ingot and 40,000 tons (80 million lb) of titanium mill products (USGS 2012). U.S. titanium sponge production capacity was about 10% of world capacity in 2010. U.S. capacity has declined to 8.6% of world capacity in 2014 due to over 40% increase in capacity in China, and over 20% increase in capacity in Russia. New scrap metal recycled by the titanium industry totaled about 29,000 tons (58 million lb) in 2010 (USGS 2011b). Three manufacturers produce the majority of titanium metal in the United States: Titanium Metals Corporation (TIMET), Allegheny Technologies Inc. (ATI), and RTI International Metals. In the manufacture of titanium from raw materials, the primary production process used is the Kroll process.

This study focuses on energy consumption in three energy-intensive process subareas in titanium manufacturing. Figure 2-1 shows the titanium manufacturing process flow subareas considered in this bandwidth analysis (primary metal production, secondary processing, and semi-finished shape production), along with other raw material preparation steps. After mining, rutile or ilmenite undergoes treatment and separation; and ilmenite is beneficiated to synthetic rutile (through the Becher process). The majority of these mineral concentrates are imported. The Kroll process for primary metal production is a multi-step process involving chlorination, separation, purification, reduction, and distillation to produce titanium sponge. Magnesium and chlorine used in the process are recovered for re-use. Subsequently, vacuum arc melting is used to refine crushed titanium sponge into titanium ingot as either a cylinder or rectangular slab. Secondary processing involves the production of titanium ingot from titanium scrap using melting furnaces. In both cases, alloys can be added during melting operations. And finally, semi-finished shape production involves primary fabrication processes such as rolling and forging. Titanium mill products take the form of billet, bar, plate, sheet, tube, and wire. Approximately half of titanium mill products were in the form of forging and extrusion billet in 2010 (ITA 2013).

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 Chapters 3 through 6 of this report. These subareas and sub-processes fall within North American Industry Classification System (NAICS) codes 331419, primary smelting and refining of nonferrous metal (except copper and aluminum), and 33149, nonferrous metal (except copper and aluminum) rolling, drawing, extruding, and alloying (USCB 2016). Note that pre-processing steps, such as raw materials preparation including titanium ores mining and/or beneficiating and concentrates beneficiating fall under NAICS 212299 (All Other Metal Ore Mining), which is outside of the manufacturing sector and further steps, such as the production of titanium parts and castings (such as those for automobiles) and the production of ferrotitanium (used in the steel industry) fall outside of the scope of this analysis and outside of the study area.

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

Subarea		Including Sub-processes Such As:
1	Primary Metal Production	Chlorination, separation, purification, reduction, reductant recovery, distillation, melting
2	Secondary Processing	Melting
3	Semi-Finished Shape Production	Forging, rolling, pressing

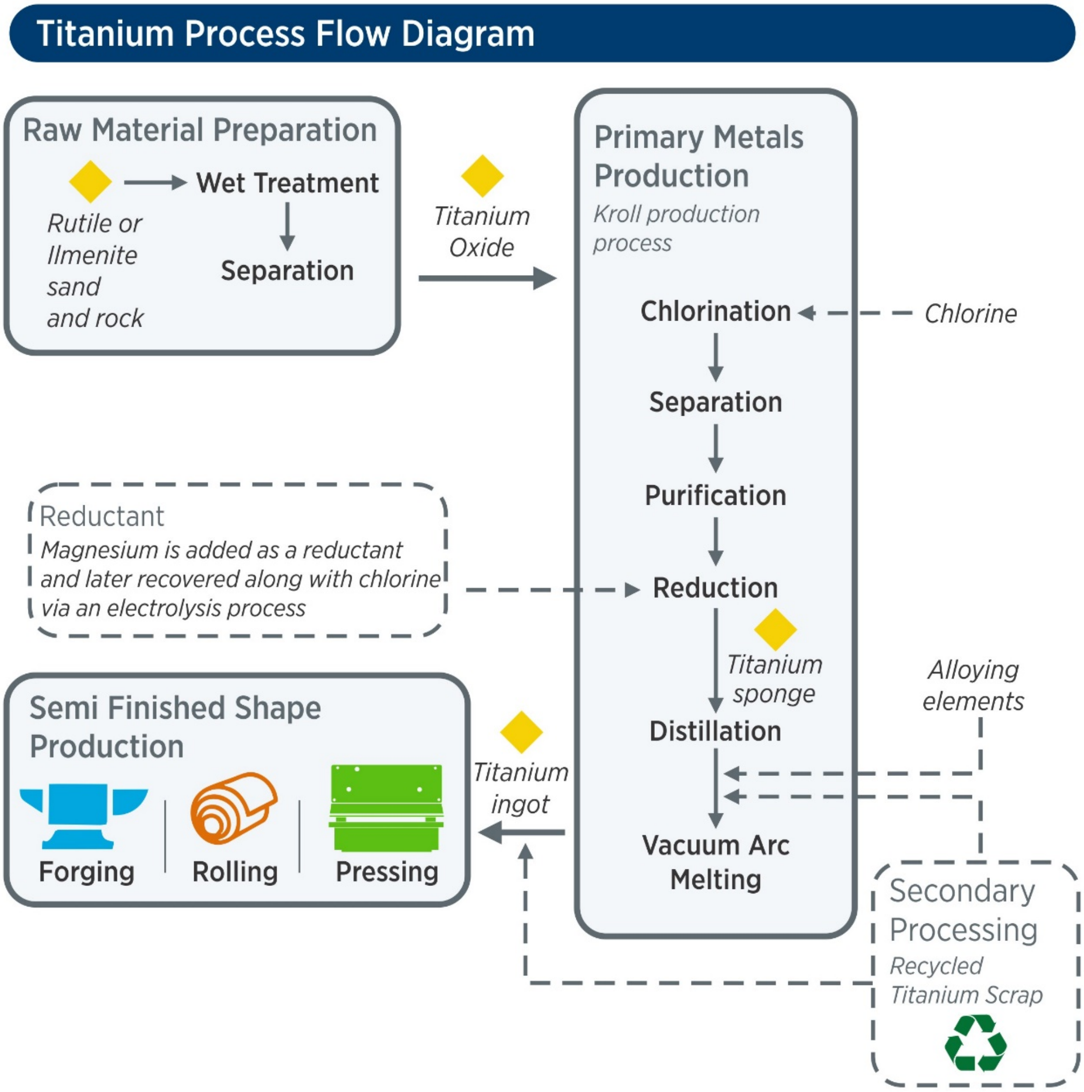

Figure 2-1. Titanium production process flow
Source: EERE

2.2. Production Values

Production data were gathered in order to calculate the annual energy consumption by process and sector-wide for titanium manufacturing. The International Titanium Association and the U.S. Geological Survey are the leading sources for information on titanium production in North America. Production data for 2010 is summarized in Table 2-2 and reference sources are summarized in Table 2-3.

Table 2-2. U.S. Production Values Titanium Manufacturing Process Areas, 2010

Subarea	Product	2010 Total Titanium Sector Production (million lb)	2010 Estimated Production for Boundary Applications* (million lb)
Primary Metal Production	Sponge**	21.8	16.4
	Ingots***	124.3	93.2
Secondary Processing			
Semi-Finished Shape Production	Mill Products (billet, bar, plate, etc.)	80.0	53.6
Total Production for Study Application Area* (ingots)			**93.2**

* Production for boundary applications reflects study application areas only. Domestic aerospace application is estimated to total 75% of titanium metal production (USGS 2011), and 67% of mill products (USGS 2012).

** Total sponge consumption was estimated at 76.9 million lb (USGS 2012 and USGS 2011a); 21.8 million lb was produced domestically with the remainder coming from imported sources and inventories.

*** Ingots are produced in both primary and secondary processing, which is why the production value is shown in both rows.

Table 2-3. Sources Referenced in Identifying Production Values for Manufacturing Titanium

Source Abbreviation	Description
ITA 2013	International Titanium Association (ITA) Statistical Review 2009–2013 provides statistics on U.S. Titanium Mill Products by year, in addition to a number of other production statistics, by country.
USGS 2011a	United States Geological Survey, Titanium Minerals Yearbook, 2009
USGS 2011b	United States Geological Survey, Titanium and Titanium Dioxide Mineral Commodity Summary, 2011.
USGS 2012	United States Geological Survey, 2010 Titanium Minerals Yearbook provides statistics on U.S. Titanium Mill Products by year, in addition to a number of other U.S. production statistics
Das 2014	Primary and secondary metals processing volumes are estimated in this conference paper

3. Current Typical Energy Intensity and Energy Consumption

This chapter presents energy intensity and consumption data for titanium manufacturing processes, based on 2010 production data for the boundary application areas. It is noted that energy consumption in a manufacturing process can vary widely for diverse reasons, including differences in equipment and processing techniques employed. The energy intensity estimates reported herein are considered representative of typical processes used to produce titanium in the United States today; they do not represent energy consumption in any specific facility or any particular region in the United States.

3.1. Sources for Current Typical Energy Intensity

Appendix A2 presents 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 A3 provides the references used for each subarea.

A range of data sources were considered to determine the titanium current typical energy intensity. In some cases, multiple references were considered and conversations with experts in the field substantiated best engineering judgment. Table 3-1 summarizes the key sources referenced in determining titanium current typical manufacturing intensity. There are a limited number of titanium manufacturing facilities in the United States and as a result production information is highly proprietary. The values for energy intensity provided should be regarded as estimates based on best available information. Further discussion regarding determination of CT values is included in Appendix A1.

Table 3-1. Sources Referenced in Identifying Current Intensity by Process Area and Material Total

Source Abbreviation	Description
Norgate 2004	This journal article provides a cradle-to-gate lifecycle energy estimate for primary titanium production; with detailed material and energy estimates by process step.
Boeing 2012	This project technical report provided an estimate for semi-finished shape production energy consumption, along with another estimate for total cradle-to-gate energy required for primary metal production.
DOE IMI	This DOE Innovative Manufacturing Initiative (IMI) slide presentation on the topic of Hydrogen Sintered Titanium (HST) provides estimation of semi-finished shape production intensity, with reference to titanium forging energy intensity. (unpublished, based on a 2011 DOE internal report prepared by T. Muth and J. Williams of the Oak Ridge National Laboratory)
Fang 2015	This project technical report provided an estimate for forging and annealing energy consumption.
Das 2015 and Das Sources	Best engineering judgment based upon conversation with global Ti experts at TMS Annual Meeting March 2015 and review of multiple technical papers (Das Sources 2015).
Rankin 2011	This source provides another estimate for total cradle-to-gate energy required for primary metal production.

3.2. Current Typical Energy Consumption

Table 3-2 presents the energy intensities and calculated on-site and primary CT energy consumption for the titanium production subareas studied. Feedstock energy is excluded from the consumption values. The energy intensities are presented in terms of Btu per lb titanium produced. The CT energy consumption for these subareas is estimated to account for 1.77 TBtu of on-site energy and 4.26 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 2014b). 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. Titanium Manufacturing: Application Areas Studied (2010)

Process Subarea And Sub-process	Production (million lb Titanium)	On-site CT Energy Intensity * (Btu/lb)	On-site CT Energy Consumption, Calculated (TBtu/year)	Off-site Losses, Calculated** (TBtu/year)	Primary CT Energy Consumption, Calculated (TBtu/year)
Primary Metal Production***		56,920	1.16	1.97	3.13
$TiCl_4$ process	16.35	9,962	0.16	0.03	0.19
Kroll process (Sponge production)		40,767	0.67	1.26	1.93
Melting (produced and purchased sponge)	52.70	6,191	0.33	0.68	1.01
Secondary Processing (ingot)	40.53	4,643	0.19	0.39	0.58
Semi-Finished Shape Production	53.60	8,036	0.43	0.12	0.55
Total for Process Subareas Studied		**N/A**	**1.77**	**2.48**	**4.26**

Current typical (CT)

* Total production is adjusted to reflect the study application areas (see Section 1.4 for boundary applications), not the entire titanium 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 (EIA 2017).

*** Production values provided for titanium output, melting value includes sponge from imported sources and inventories.

4. State of the Art Energy Intensity and Energy Consumption

This Chapter estimates the energy savings possible if U.S. titanium 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. State of the Art Energy Intensity

Currently there is only one commercial titanium manufacturing process used in the United States for the production of primary titanium for aerospace applications, the Kroll process. The Kroll process replaced the Hunter process for the most part in the 1940s.[5] Many emerging titanium manufacturing processes have been proven to surpass the Kroll process in efficiency and cost; these are discussed in Chapter 5. Practical Minimum. For this section of the report SOA intensity is deemed to be equivalent to CT intensity. There are no calculations in this section, CT energy intensity is considered equal to SOA energy intensity based on best engineering judgment (Brueske 2015, Das 2015).

4.2. State of the Art Energy Consumption

Table 4-1 presents the on-site SOA energy intensities and energy consumption for the titanium manufacturing subareas studied. The SOA energy intensities are presented as Btu per lb titanium and the on-site SOA energy consumption is presented as TBtu per year. The on-site SOA energy consumption is equivalent to on-site CT energy consumption in Table 3-2.

Table 4-1. Calculated SOA Energy Consumption for Titanium Manufacturing: Application Areas Studied

Process Subarea	On-site SOA Energy Intensity (Btu/lb)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Primary Metal Production	56,920	1.16
Secondary Processing	4,643	0.19
Semi-Finished Shape Production	8,036	0.43
Total for Process Subareas Studied	N/A	**1.77**

It can be useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. In the case of titanium manufacturing CT is equal to SOA and SOA energy savings is found to be 0%. The difference between the CT and SOA energy consumption values is presented as the SOA energy savings (or *current opportunity*).

---

[5] Honeywell's small-scale titanium sponge plant in Utah uses the Hunter process in the production of electronic-grade titanium; but falls outside the scope of this report.

Table 4-2. Calculated SOA Energy Consumption for Titanium Manufacturing: Application Areas Studied

Process 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)***
Primary Metal Production	1.16	1.16	0	0%
Secondary Processing	0.19	0.19	0	0%
Semi-Finished Shape Production	0.43	0.43	0	0%
Total for Process Subareas Studied	**1.77**	**1.77**	**0**	**0%**

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 titanium sector.
** SOA energy savings is also called *Current Opportunity.*
*** SOA energy savings percent is the SOA energy savings opportunity from transforming titanium 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)

5. Practical Minimum Energy Intensity and Energy Consumption

In this chapter, the energy savings possible through R&D advancements in titanium manufacturing are estimated. Practical minimum (PM) is the minimum amount of energy required assuming the successful 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 titanium 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 titanium 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.

Table 5-1 presents some key sources consulted to identify PM energy intensities in titanium manufacturing. Numerous reports, articles and presentation were consulted in addition to conversations with Ti experts in the field.

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

Source Abbreviation	Description
Das 2015	Best engineering judgment based upon conversations with experts at TMS Annual Meeting March 2015, and review of multiple technical papers (Das Sources 2015). See Appendix A4 for a listing of some of the R&D technologies considered and a summary of the calculation.
DEER 2007	In this paper presented at the 13th Diesel Engine Efficiency & Emissions Research Conference (DEER), ORNL, AMETEK, and International Titanium Powder discuss solid state processing of low cost titanium powders, the Armstrong Process
Fang 2013	In this journal article the author describes the benefits of direct reduction of Ti-slag (DRTS) with MgH_2 manufacturing process. In the Supporting Information document the author provides an energy consumption comparison of DRTS, Farthing, Fray, Chen (FFC) Cambridge, and Armstrong processes to the conventional Kroll process.
DOE IMI	In this paper presented as part of an Innovative Manufacturing Initiative effort a proposed hydrogen sintered titanium (HST) production pathway is described (unpublished)
Infinium 2008	In this paper solid oxide membrane (SOM) electrolysis is presented as a cost effective and environmentally friendly method for production of titanium from its oxides.
SRI 2015	Description of SRI International's multi-arc fluidized bed reactor (MAFBR) is available on the SRI's website. The process is based on the simultaneous reduction of metal chlorides to produce Ti alloy granules in a single step.
Das Sources 2015	Many additional references were consulted in support of best engineering judgment but not specifically referenced

5.2. Practical Minimum Energy Consumption

Many sources were consulted to guide approximately of R&D savings potential for manufacturing titanium. Best engineering judgment was used to determine total overall R&D savings potential (DAS 2015). The calculation for determining PM intensity and consumption from best engineering judgment can be found in Appendix A4. PM was estimated to be 35% of CT titanium manufacturing intensity. This same savings estimate was applied to all subareas of manufacturing energy consumption studied, outlined in Table 5-3, as new processes may replace existing process routes.

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

Process Subarea	On-site PM Energy Intensity, Calculated* (Btu/lb)	On-site PM Energy Consumption, Calculated* (TBtu/year)
Primary Metal Production	19,922	0.40
Secondary Processing	1,625	0.07
Semi-Finished Shape Production	2,813	0.15
Total for Process Subareas Studied	**N/A**	**0.62**

Practical Minimum (PM)
* See Appendix A4 for explanation of calculating PM intensity and consumption. Calculated using the production values for the applications studied (see Section 1.4), and not the entire titanium 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, which is the sum of the *Current Opportunity* plus the *R&D Opportunity*) and PM energy savings percent. Table 5-4 calculates the R&D opportunity for the subareas studied, which for titanium is the same as the PM energy savings because the CT energy consumption and SOA energy consumption are equivalent.

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

Process 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)
Primary Metal Production***	1.16	0.40	0.75	N/A
Secondary Processing	0.19	0.07	0.12	N/A
Semi-Finished Shape Production	0.43	0.15	0.28	N/A
Total for Process Subareas Studied	**1.77**	**0.62**	**1.15**	**69%**

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 titanium 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 titanium production processes. Energy savings percent is calculated using TM energy consumption shown in Table 6-2 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT - PM)/(CT - TM). Savings percent is not provided for subareas – this information would be misleading given that the equivalent savings estimate is applied uniformly to all subareas.

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 technology readiness level (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 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.

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

Process Subarea	On-site SOA Energy Consumption, Calculated* (TBtu/year)	On-site PM Energy Consumption, Calculated* (TBtu/year)	R&D Opportunity (SOA-PM) (TBtu/year)	R&D Opportunity Savings Percent** (SOA - PM) / (CT - TM)
Total for Process Subareas Studied	1.77	0.62	1.15	69%

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire titanium sector.
** 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 titanium production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture titanium 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 primary titanium production by determining the Gibbs free energy associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[6] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[7] 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.[8]

While the TM energy intensity is process independent (state function), it is directly related to the relative energy levels of the substrate reactants and the products. It is only dependent on the starting material and the end product, and would not change if the process had greater or fewer process steps or if a catalyst was involved. All reactions were assumed to proceed in stoichiometric ratios at the indicated temperature, and at one atmosphere of pressure.

For primary titanium production, the TM energy intensity was calculated based upon the titanium decomposition reaction, such that would occur in electrowinning (e.g., the novel FFC Cambridge process). The TM values are predicated on beginning and ending with materials at 77 °F (25°C), with energy requirements based upon the material's heat capacity between the starting and ending temperatures (NIST 2011). The reaction below results in a thermodynamic minimum energy intensity of 6,537 Btu/lb Ti (4.2 kWh/kilogram (kg) Ti).

$1\ TiO_2 \rightarrow 1\ Ti + 1\ O_2$ 950°C

An alternative approach to calculating the TM energy intensity is for the most commonly used current synthesis pathway (as is presented for the CT and SOA energy intensity): the reaction sequence for the Kroll process using magnesium as a reductant and recovery of the magnesium through electrolysis. Again, the TM values are predicated on beginning and ending with materials at 77 °F (25°C), with energy requirements based upon the material's heat capacity between the starting and ending temperatures (NIST 2011).

Chlorination:	$1\ TiO_2 + 2\ Cl_2 + 1\ C$	→	$1\ TiCl_4 + 1\ CO_2$	800°C
Reduction:	$1\ TiCl_4 + 2\ Mg$	→	$1\ Ti + 1\ MgCl_2$	1000°C
Reductant recovery:	$1\ MgCl_2$	→	$1\ Mg + 1\ Cl_2$	750°C

---

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

[7] 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 used in describing change in enthalpy (delta H).

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

The first two steps (chlorination, where the titanium [IV] chloride is produced, and reduction) are both exothermic reactions, with a thermodynamic minimum energy intensity of -3,612 Btu/lb Ti (-2.3 kWh/kg Ti). Because reductant recovery is included on site, the thermodynamic minimum energy intensity of magnesium electrolysis is added, resulting in an overall TM energy intensity of 7,313 Btu/lb Ti (4.7 kWh/kg Ti) for the primary production step for titanium via the Kroll process. The TM energy intensity may vary slightly, depending upon the specific process temperature and reductant used (in this case magnesium).

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 titanium production), 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 Consumption for Individual Subareas and Material Total

The minimum baseline of energy consumption for each titanium production subarea is its TM energy consumption. If all the 2010 level of titanium 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 minus 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).

TM energy is calculated based on thermodynamic properties of chemical reactions occurring. CT/SOA and by extension PM are determined through published intensities and production values and applied best engineering judgment. The intersection of these two approaches is likely a point of consideration.

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

Process Subarea	TM Energy Intensity (Btu/lb)	TM Energy Consumption, Calculated* (TBtu/year)
Primary Metal Production**	7,313	0.11
Secondary Processing	0	0
Semi-Finished Shape Production	0	0
Total for Process Subareas Studied		**0.11**

Thermodynamic minimum (TM)
* Calculated using the production values for the applications studied (see Section 1.4), and not the entire titanium sector.
** Includes energy for reductant (magnesium) recovery.

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

Table 7-1 summarizes the *current opportunity* and *R&D opportunity* energy savings for the subareas studied, based on titanium production in 2010 for the boundary application area identified. Titanium manufacturing is broken down into three subareas.

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

Process Subarea	Current Opportunity* (CT - SOA) (TBtu/year)	R&D Opportunity (SOA - PM) (TBtu/year)
Primary Metal Production	0	0.75
Secondary Processing	0	0.12
Semi-Finished Shape Production	0	0.28
Total for Process Subareas Studied	**0**	**1.15**

*** The current opportunity is 0 TBtu/year because CT energy consumption is assumed equivalent to SOA energy consumption.**
**** Calculated using the production values for the applications studied (see Section 1.4), and not the entire magnesium sector.**

In this study, two hypothetical opportunity bandwidths for energy savings were estimated (as defined in Chapter 1). The analysis shows the following:

- *Current Opportunity:* not applicable in the case of titanium given that SOA and CT are identical; and
- *R&D Opportunity:* 1.15 TBtu per year of energy savings could be attained in the future if applied R&D technologies under development worldwide are successfully deployed (i.e., reaching the practical minimum).

Figure 7-1 depicts the opportunity bandwidths graphically. 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.

From this figure it is apparent that primary metals production offers the greatest opportunity for R&D savings. Caution should be taken in drawing conclusions from the comparative savings in the R&D energy savings pie chart; the savings from CT/SOA to PM are calculated with an equivalent savings estimate applied to all subareas. More savings are evident for primary metals production as this subarea consumes the most energy.

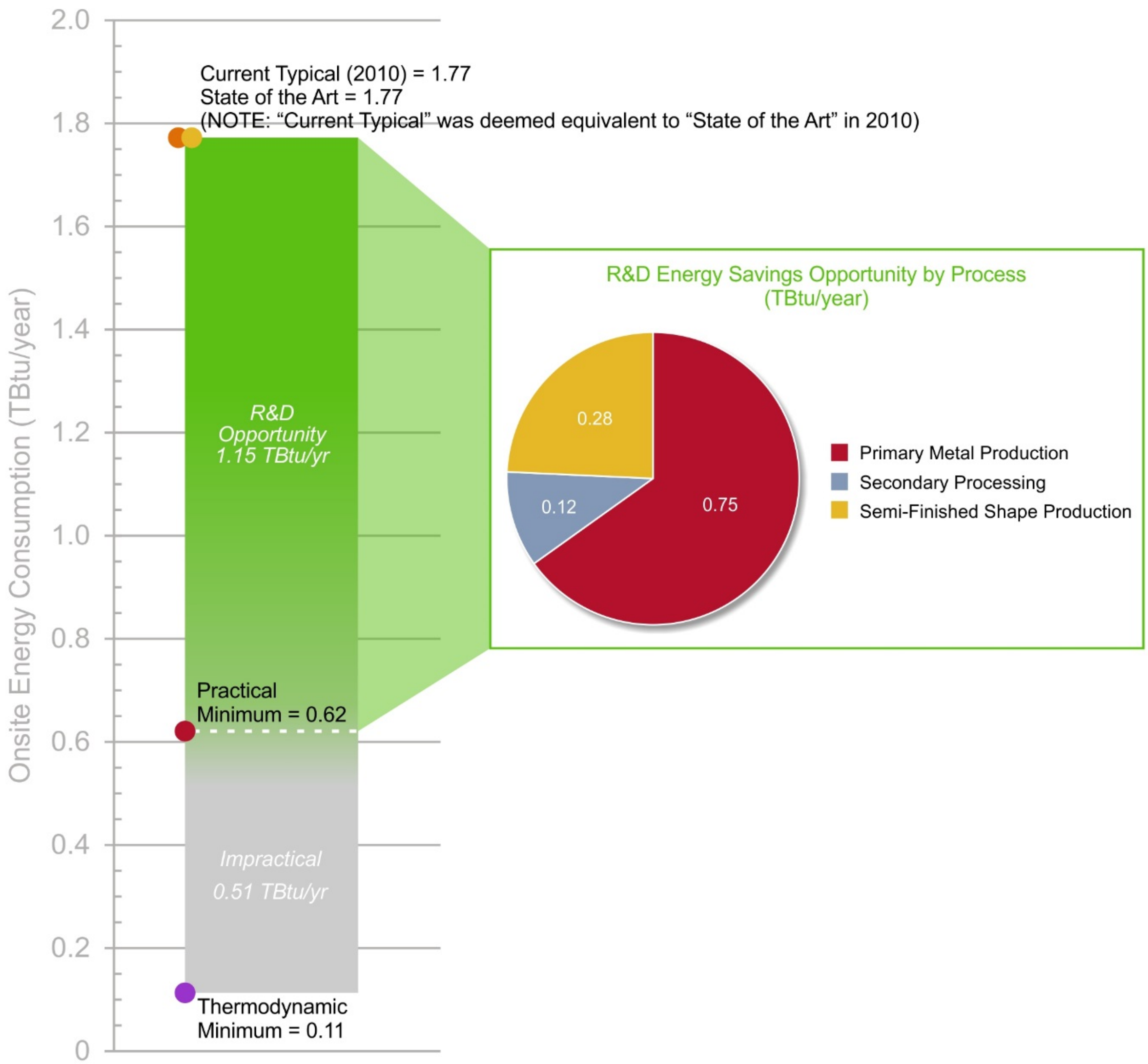

Figure 7-1. R&D energy savings opportunities for the titanium manufacturing subareas studied (considering selected lightweighting applications)
Source: EERE

8. References

ARPA-E 2013	"Modern Electro/Thermochemical Advances in Light-Metal Systems (METALS)," Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy. Funding Opportunity No. DE-FOA-0000882, May 2013. https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=35d7f503-803b-4a31-a713-d29d081608b5
Boeing 2012	The Boeing Company. Final Technical Report: *Near-Net Shape Fabrication Using Low-Cost Titanium Alloy Powders.* March 2012. www.osti.gov/scitech/servlets/purl/1040632
Brueske 2015	Sabine Brueske of Energetics Incorporated. Best engineering judgment based upon conversation with Titanium manufacturer and review of technical papers. August 2015.
Chemistry-reference.com n.d.	"Standard Thermodynamic Values at 25°C." Chemistry-reference.com, n.d. http://chemistry-reference.com/Standard%20Thermodynamic%20Values.pdf.
Das 2014	"Metal Flow, Recycling, Energy and Environment: Al, Cu, Mg and Ti," presented by Dr. Sabodh Das at the Annual TMS Meeting, February 18, 2014, in San Diego, CA.
Das 2015	Dr. Subodh Das. Best engineering judgment based upon conversations with experts at TMS Annual Meeting, March 2015, and review of multiple technical papers. April-June 2015
Das Sources 2015	Many additional sources (listed below) were consulted in developing best engineering judgment but not specifically referenced in this report. The author and title of the article/proceeding is provided here under the common reference of Das Sources: Akolkar, Rohan, "Novel Titanium Electrowinning Process Using Specialized Segmented Diaphragms," presented at TMS Annual Meeting on March 18, 2015, in Orlando, FL.Muth et.al. "Energy Analysis for Emerging Economical Titanium Production Technologies," ORNL Paper, 2011. Allnore, Antoine, "Electrolytic Extraction of Light Metals: The 21st Century Electrochemical Engineering Challenges," presented at the TMS Annual Meeting on March 18, 2015, in Orlando, FL. EHK Technologies, "Opportunities for Low-Cost Titanium in Reduced Fuel Consumption, Improved Emissions, and Enhanced Durability in Heavy-Duty Trucks," July 2002. Fang, et al. "A New, Energy-Efficient Chemical Pathway for Extracting Ti Metal from Ti Minerals," *Journal of the American Chemical Society*, November 2013 (including "Supporting Information"). Fang, Zak, "Novel Chemical Pathway for Titanium Production," presented at ARPA-E Annual Meeting on March 19, 2015, in Orlando, FL. Fang, Zak, "An Overview of Thermochemical Processes for Low-Cost Production of Ti: Challenges and Opportunities," presented at TMS Annual Meeting on March 16, 2015, in Orlando, FL. Fox, Stephen, "Electrochemical Cell for Advanced Titanium Production," presented at ARPA-E Annual Meeting on March 19, 2015, in Orlando, FL. Gilman, Steve, "Macro Economic Challenges of Titanium Production," presented at ARPA-E Annual Meeting on March 19, 2015, in Orlando, FL. Kirchain R. and Roth R. "The Role of Titanium in the Automobile," Cambridge, MA; Camanoe Associates, 2002 p. 43. Klausner, James, "The ARPA-E Light Metals Production Technology Programs," presented at TMS Annual Meeting on March 16, 2015, in Orlando, FL. McGregor, Kathie, "Emerging Titanium Production Processes," presented at TMS Annual Meeting on March 16, 2015, in Orlando, FL. Metson, James, "An Overview of Alternate Smelting Processes for Light Metals," presented at TMS Annual Meeting on March 16, 2015, in Orlando, FL.

	Norgate, T.E. et.al. "Assessing the environmental impact of metal production processes," Journal of Cleaner Production, 15 (2007). Pal, Uday, "Green Technology for Metal Production," presented at TMS Annual Meeting on March 16, 2015, in Orlando, FL. Perez, Jordi, "Low-Cost Production of Titanium Alloys (USA)," presented at ARPA-E Annual Meeting on March 19, 2015, in Orlando, FL. Pistorius, Chris, "Review of Oxycarbide Approach to Electrolytic Titanium Production," presented at TMS Annual Meeting on March 18, 2015, in Orlando, FL. Subramanyam, R.B., "Some Recent Innovations in the Kroll Process of Titanium Sponge Production," *Bull. Mater. Sci*., Vol.16, No.6, December 1993, pp 343-451. Tripathy, Prabhat, "New Approaches for the Production of Titanium Metal," presented at TMS Annual Meeting on March 18, 2015, in Orlando, FL. US DOE report, Summary of Emerging Titanium Cost Reduction Technologies, 2004.
DEER 2007	13th Diesel Engine-Efficiency & Emissions Research Conference (DEER) paper, "Solid State Processing of New Low-Cost Titanium Powders Enabling Affordable Automotive Components," ORNL, AMETEK, International Titanium Powder (ITP).
DOE 2014a	"Clean Energy Manufacturing Innovation Institute for Composite Materials and Structures Funding Opportunity Announcement (FOA) Number: DE-FOA-0000977," U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE). 2014. https://eere-exchange.energy.gov/Default.aspx?Search=Clean%20Energy%20Manufacturing%20Innovation%20Institute%20for%20Composite%20Materials%20and%20Structures&SearchType=
DOE 2014b	"Manufacturing Energy and Carbon Footprints." U.S. Department of Energy (DOE), Advanced Manufacturing Office (AMO) (formerly Industrial Technologies Program, or ITP). 2014. http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs
DOE IMI	(unpublished) Paper presented as part of DOE Innovative Manufacturing Initiative. The topic is a proposed hydrogen sintered titanium (HST) production pathway.
EERE	Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy 2017.
EIA 2017	"Table 2.4 Industrial Sector Energy Consumption," U.S. Energy Information Administration (EIA). Monthly Energy Review. 2017. www.eia.gov/totalenergy/data/monthly/pdf/sec2_9.pdf
Energetics 2015a	*Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. www.energy.gov/eere/amo/downloads/bandwidth-study-us-petroleum-refining
Energetics 2015b	Energetics Inc. for the U.S. DOE Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing*. www.energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing
Energetics 2015c	Energetics Inc. for the U.S. DOE Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing*. www.energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing
Energetics 2015d	Energetics Inc. for the U.S. DOE Advanced Manufacturing Office 2015. *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper*

Manufacturing. www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing

Fang 2013 “A New, Energy-Efficient Chemical Pathway for Extracting Ti Metal from Ti Minerals”, Fang et al, *Journal of the American Chemical Society*. 2013. Also referenced “Supporting Information” http://pubs.acs.org/doi/suppl/10.1021/ja408118x/suppl_file/ja408118x_si_001.pdf

Fang 2015 *Final Technical Report: A New Method for Low Cost Production of Titanium Alloys for Reducing Energy Consumption of Mechanical Systems*. The University of Utah. February 2015. www.osti.gov/scitech/servlets/purl/1250865

ITA 2013 International Titanium Association. *Statistical Review 2009-2013*. https://c.ymcdn.com/sites/titanium.site-ym.com/resource/resmgr/Docs/ITA_Stats_Book_2013.pdf

Infinium 2008 “Solid oxide membrane technology for environmentally sound production of titanium,” Sput et al, Mineral Processing and Extractive Metallurgy. 2008

NIH 2003 National Institutes of Health (NIH), Toxicology Data Network (TOXNET). “Magnesium Chloride,” 2003. https://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+657

NIST 2011 National Institute of Standards and Technology (NIST). “Rutile (TiO2),” 2011. http://webbook.nist.gov/cgi/cbook.cgi?ID=C1317802&Units=SI&Mask=2&Type=JANAFS&Table=on#JANAFS

Norgate 2004 “Titanium and Other Light Metals: Technology Pathways to Sustainable Development”, Green Processing Conference, 2nd International Conference on Sustainable Processing of Minerals. May 2004.

Norgate 2007 “Assessing the Environmental Impact of Metal Production Processes,” *Journal of Cleaner Production*, Vol, 15, 8, pp. 838-848. 2001. www.researchgate.net/publication/222402610_Assessing_the_environmental_Impact_of_metal_production_processes

ORNL 2011 Oak Ridge National Laboratory 2011. U.S. Department of Energy. Internal Report: “Energy Analysis for Emerging Economical Titanium Production Technologies,” (unpublished) T. Muth and J. Williams

Rao 1985 Rao, Y. K., *Stoichiometry and Thermodynamics of Metallurgical Processes.* Cambridge University Press: Cambridge. 1985.

Rand 2009 RAND Corporation. "Titanium Industrial Base, Price Trends, and Technology Initiatives," prepared for the United States Air Force, 2009.

Rankin 2011 W.J. Rankin. CSIRO. Minerals, Metals and Sustainability: Meeting Future Material Needs. September 2011.

SRI 2015 SRI International describes its multi-arc fluidized bed reactor (MAFBR) (website): www.sri.com/work/projects/low-cost-production-titanium-alloys

UC Davis 2017 University of California, Davis (UC Davis), “Chemistry of Titanium.” LibreTexts. 2017. https://chem.libretexts.org/Core/Inorganic_Chemistry/Descriptive_Chemistry/Elements_Org

	anized_by_Block/3_d-Block_Elements/Group_04%3A_Transition_Metals/Chemistry_of_Titanium
USCB 2016	U.S. Census Bureau. 2016. “North American Industry Classification System,” www.census.gov/cgi-bin/sssd/naics/naicsrch
USGS 2011a	U.S. Geological Survey (USGS). 2011. “2009 Minerals Yearbook [Advance Release].” https://minerals.usgs.gov/minerals/pubs/commodity/titanium/myb1-2009-titan.pdf
USGS 2011b	U.S. Geological Survey (USGS). 2011. “2011 Minerals Commodity Summary.” http://minerals.usgs.gov/minerals/pubs/commodity/titanium/mcs-2011-titan.pdf
USGS 2012	U.S. Geological Survey (USGS). 2012. “2010 Minerals Yearbook [Advance Release].” http://minerals.usgs.gov/minerals/pubs/commodity/titanium/myb1-2010-titan.pdf
USGS 2013	U.S. Geological Survey (USGS). 2013. “2011 Minerals Yearbook: Titanium [Advance Release].” http://minerals.usgs.gov/minerals/pubs/commodity/titanium/myb1-2011-titan.pdf

Appendix A1. Current Typical Energy Intensity Discussion

In this Appendix further discussion regarding the determination of current typical values in the table below are explained. This is the same information presented in Table 3-2.

Table A1-1. Calculated Current Energy Consumption for Titanium Manufacturing (2010): Application Areas Studied

Process Subarea And Sub-process	On-site CT Energy Intensity (Btu/lb)	Production (million lb)	On-site CT Energy Consumption, Calculated* (TBtu/year)	Off-site Losses, Calculated ** (TBtu/year)	Primary CT Energy Consumption, Calculated* (TBtu/year)
Primary Metal Production***	56,920	N/A	1.16	1.97	3.13
$TiCl_4$ process	9,962	16.35	0.16	0.03	0.19
Kroll process (Sponge production)	40,767		0.67	1.26	1.93
Melting (Produced and purchased sponge)	6,191	52.70	0.33	0.68	1.01
Secondary Processing (ingot)	4,643	40.53	0.19	0.39	0.58
Semi-Finished Shape Production	8,036	53.60	0.43	0.12	0.55
Total for Process Subareas Studied		**N/A**	**1.77**	**2.48**	**4.26**

Current typical (CT)

* Calculated using the production values for the applications studied (see Section 1.4), and not the entire titanium 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/kilowatt-hour (kWh) (EIA 2017)

***Production values provided for titanium output, melting value includes sponge from imported sources and inventories

Energy Intensity for Primary Production: Total cradle-to-gate life cycle energy intensity for the Kroll process was estimated by Norgate in 2004 (Norgate 2004), with details on individual process steps. This value, 361 megajoule (MJ)/kg (equivalent to 155,175 Btu/lb), was later referenced in a 2007 Norgate source, and subsequently utilized by ARPA-E in their 2013 Funding Opportunity Assessment. In 2011, Rankin (Rankin 2011) separately provided an estimate for life cycle energy intensity, indicating 381 MJ/kg (163,772 Btu/lb), though did not provide any supporting information, assumptions, or boundaries other than to reference an unpublished CSIRO (Commonwealth Scientific and Industrial Research Organisation, located in Australia) internal report. The Boeing Company (Boeing 2012) has indicated a 355 million Btu/ton (177,500 Btu/lb) value, but did not provide supporting information, assumptions, or boundaries. Given the depth of the Norgate 2004 reference, those values were used as the best estimate for individual process steps. For comparison, using the specific assumptions regarding electricity losses in this report along with the Norgate 2004 reference, a primary energy value of approximately 165,900 Btu/lb is implied.

To align with the boundaries of this study, energy requirements for mining production and raw material preparation (before manufacturing), estimated at approximately 14,000 Btu (on-site basis) per pound of primary titanium production, were not included in the analysis.

It is assumed that Norgate included energy used to recover magnesium and chlorine in the 2004 paper. Energy required to produce supplemental make-up magnesium and chlorine is not incorporated in this analysis.

Sponge is treated equivalently once produced, independent of whether manufactured domestically or obtained from imported sources or inventory stocks (which were drawn down considerably in 2010). This is reflected in the production value for melting associated with primary metal production.

Secondary Processing: This value, utilizing vacuum arc melting, is determined based on best engineering judgment of Subodh Das (Das 2015, Das Sources 2015); including information presented in Norgate 2004 and Fang 2015.

Semi-Finished Shape Production: Semi-finished shape production intensity will vary based on the mill product manufactured. Limited information is available on energy requirements for these processes, and product yield is also a consideration. Boeing 2012 provided estimates for rolling and heat treatment (equivalent to a total of 7,785 Btu/lb, assumed to be on-site basis). Unpublished DOE work (DOE IMI, based on internal Oak Ridge analysis, ORNL 2011) provided information from which an estimate could be determined for forging and annealing (equivalent to 8,286 Btu/lb, on-site basis). Absent further information, the average of these values (8,036 Btu/lb) was used as the best available estimate. Electricity share was derived from information presented by Fang (Fang 2015).

Appendix A2. Master Titanium Summary Table

Table A2-1. U.S. Production Volume of Titanium Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption: Application Areas Studied (Excludes Feedstock Energy)

Process Subarea and Sub-process	2010 Application Area Production (million lb)	On-site Energy Intensity (Btu/lb Titanium)				Calculated On-site Energy Consumption (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Primary Metal Production	N/A	56,920	56,920	19,922	6,537	1.16	1.16	0.40	0.11
$TiCl_4$ process	16.35	9,962	9,962	3,487		0.16	0.16	0.06	
Kroll process (Sponge production)		40,767	40,767	14,268		0.67	0.67	0.23	
Melting (produced and purchased sponge)	52.70	6,191	6,191	2,167		0.33	0.33	0.11	
Secondary Processing	40.53	4,463	4,463	1,625	0	0.19	0.19	0.07	0
Semi-Finished Shape Production	53.60	8,036	8,036	2,813	0	0.43	0.43	0.15	0
Total for Process Subareas Studied		N/A	N/A	N/A	N/A	**1.77**	**1.77**	**0.62**	**0.11**

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

Appendix A3. References for Production, CT, SOA, and TM

Table A3-1. U.S. Production Volume of Titanium 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)
Primary Metal Production	USGS 2011a, USGS 2012, USGS 2011b, ITA 2013	Norgate 2004, Rankin 2011, Boeing 2012	Equivalent to CT	Thermodynamic minimum calculation (Chemistry-reference.com n.d., NIH 2003, NIST 2011, Rao 1985, Rankin 2011, UC Davis 2017)
Secondary Processing	USGS 2012	Norgate 2004, Fang 2015, Das 2015, Das Sources 2015	Equivalent to CT	Thermodynamic minimum calculation (found to be zero)
Semi-Finished Shape (Mill) Production	ITA 2013, USGS 2012	DOE IMI, Boeing 2012, Fang 2015	Equivalent to CT	Thermodynamic minimum calculation (found to be zero)

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

Appendix A4. Practical Minimum Energy Intensity and Consumption Calculation, and PM Technologies Considered

In this appendix some of the technologies considered in studying R&D technology opportunities for titanium manufacturing are listed. Given the limited amount of information available on these technologies and scope of this analysis, best engineering judgment was ultimately used in determining the PM energy intensity.

On-site PM energy intensity and consumption values shown in Table 5-2 and Table A4-1 are calculated to be 35% of CT energy intensity based on best engineering judgement (Das 2015). This PM energy intensity is applied for each manufacturing process subarea, as new processes may replace existing process routes.

Table A4-1. Calculated PM Energy Consumption for Titanium Manufacturing: Application Areas Studied

Process Subarea	On-site PM Energy Intensity (Btu/lb)	On-site PM Energy Consumption, Calculated (TBtu/year)
Primary Metal Production	19,922	0.40
Secondary Processing	1,625	0.07
Semi-Finished Shape Production	2,813	0.15
Total for Process Subareas Studied	**N/A**	**0.62**

PM Technologies Considered:

Many technologies were considered in arriving at the best engineering judgment estimation; examples of these technologies are briefly outlined in Table A4-2.

Table A4-2. Example Titanium R&D Technologies Considered for PM Energy Intensity Analysis

Technology Name	Brief Description	Developer
Armstrong Process	Solid state processing of low cost titanium powders	ORNL, AMETEK, International Titanium Powder (ITP)
DRTS	Direct reduction of Ti-slag with MgH_2	University of Utah
Farthing, Fray, Chen (FFC) Cambridge Process	Direct electrochemical deoxygenation of titanium dioxide	Metalysis
SOM	Solid oxide membrane electrolysis	Infinium
MAFBR	Multi-arc fluidized bed reactor	SRI International
Hydrogen sintered titanium	Sintering of titanium powder to produce fully dense powder metallurgy titanium alloy	University of Utah

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

ADVANCED MANUFACTURING OFFICE

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

DOE/EE-1663 • September 2017