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

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Titanium

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DRAFT REPORT

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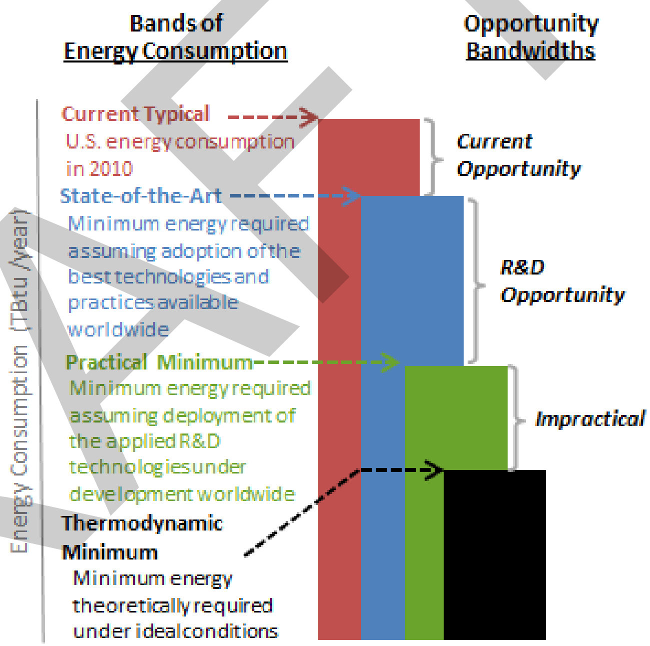
Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities. [1] The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the manufacturing of products that can be used for lightweighting applications, and provide hypothetical, technology-based estimates of potential energy savings opportunities in the manufacturing process. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale.

AMO is releasing this energy bandwidth study in draft form in order to solicit input from the public as part of the peer review process. 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, aluminum, magnesium, and titanium. Reviewer feedback will be used to update the bandwidth reports with the best available data and assumptions prior to final publication, and to generate input to support further analysis. In the next phase of work, data will be integrated and compared across all six materials, including a comparison of manufacturing energy intensity on a material performance (e.g., effective weight) basis for key applications.



Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure). **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be

[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.

possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or 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.

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

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

Acknowledgments

Joseph Cresko of DOE/AMO led the conceptual development and publication of the bandwidth study series with support from Dr. Alberta Carpenter of the National Renewable Energy Laboratory. AMO recognizes the efforts of Dr. Subodh Das, Caroline Kramer, Dr. Aaron Fisher, and Sabine Brueske of Energetics Incorporated for conducting the research and analysis and writing this study.

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 five 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 five select subareas. In addition, the minimum energy consumption for these processes was estimated assuming the adoption of best technologies and practices available worldwide (state of the art [SOA], Chapter 4) and assuming the deployment of the applied research and development (R&D) technologies available worldwide (practical minimum [PM], Chapter 5). The minimum amount of energy theoretically required for these processes assuming ideal conditions was also estimated (thermodynamic minimum [TM)], Chapter 6); in some cases, this is less than zero. The difference between the energy consumption *bands* (CT, SOA, PM, TM) are the estimated energy savings opportunity *bandwidths* (Chapter 7).

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

Study Results: Two energy savings opportunity *bandwidths* – current opportunity and R&D opportunity – are presented in Table ES-1 and Figure ES-1 for 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 3 of the report.)* Potential energy savings opportunities are presented as a total and broken

[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 onsite energy use (i.e., energy consumed within the facility boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

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 total U.S. titanium market. Titanium production has seen growth in the past several years, especially with increased application in areas such as the automotive sector. Therefore, it is important to note that the total energy opportunities would scale with increasing production.

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**[2]	0 TBtu (see notes)
R&D Opportunity **– additional energy savings if the applied R&D technologies under development worldwide are deployed**[3,4]	3 TBtu (85% energy savings, where TM is the baseline)

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

[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 savings calculation: 3 TBtu = 4 – 1 TBtu
[4] R&D opportunity energy savings percentage = [(SOA – PM)/(CT – TM)] x 100

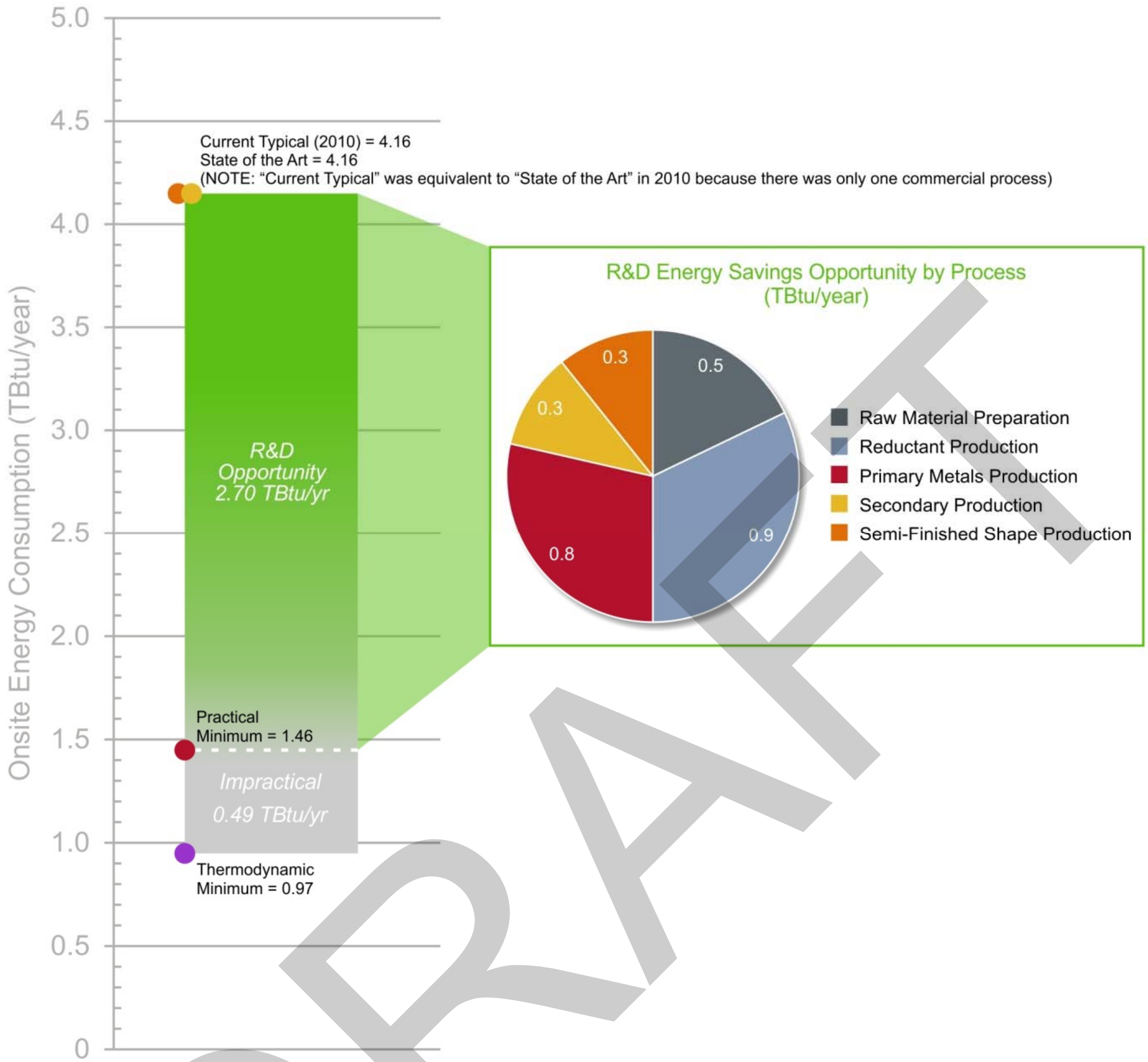


Figure ES-1. R&D Energy Savings Opportunities for the Titanium Manufacturing Subareas Studied (Considering Lightweighting Application Area Production Only)

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 conversation with experts in the field. The difference between PM and TM is labeled "impractical" in Figure ES-1 because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

An estimated 4.16 TBtu of energy was consumed in 2010 to manufacture titanium mill products in the U.S. for the structural applications considered in this study. Based on the results of this study, an estimated 2.70 TBtu of energy could be saved each year through the adoption of applied R&D technologies under development worldwide.

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
F	Fahrenheit
FFC	Farthing, Fray, Chen (process for reducing metal oxides to metals or alloys)
ITA	International Titanium Association
PM	Practical minimum energy consumption or energy intensity
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
USGS	United States Geological Survey

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1. Introduction

1.1. Overview

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

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

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

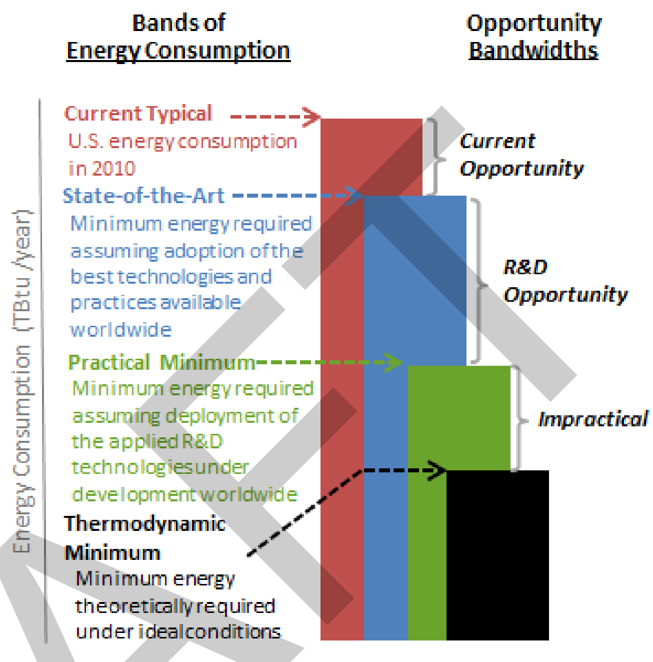
1.2. Definitions of Energy Consumption Bands and Opportunity Bandwidths

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.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare 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.

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 onsite energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. *(In the case of this titanium study, current opportunity was determined to be zero; this is explained in Chapter 3.)* These bandwidths are estimated for processes and products studied and for all manufacturing within a sector based on extrapolated data. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.



Energy Consumption Bands and Opportunity Bandwidths Estimated in 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 "onsite energy" or "primary energy" and defined as follows:

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

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

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 seven 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 onsite **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 onsite **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 onsite **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 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 titanium from relevant input materials. The focus of this bandwidth study is thus the *onsite* use of process energy (including purchased energy and onsite generated steam and electricity) that is directly applied to titanium manufacturing at a production facility.

This study does not consider life cycle energy consumed during raw material extraction, off-site treatment, transportation of materials, product use, or disposal. For consistency with previous bandwidth studies, feedstock energy and the energy associated with delivering feedstocks to the plant gate (e.g., producing, conditioning, and transporting feedstocks) are *excluded* from the energy consumption bands in this analysis.

Titanium is used in many diverse 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. 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); 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 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 75% of overall titanium mill production in the U.S., as shown in Figure 1-1. In the case of titanium, the full 75% of this use is assumed to be for aerospace applications (USGS 2011). Other application areas may include medical devices, marine equipment, military armor, specialty chemicals and power generation equipment, sporting goods, and other consumer goods.

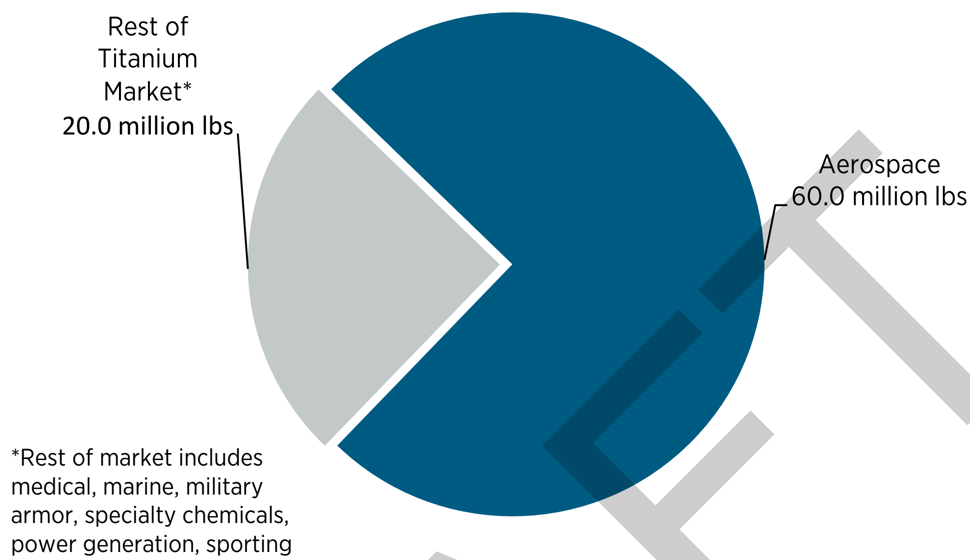


Figure 1-1. Estimated Makeup of the Titanium Market in 2010 (USGS 2011)

2. Titanium Production

2.1. Manufacturing Overview

In 2010, the United States produced 62,000 tons (124 million lbs) of titanium ingot and 40,000 tons (80 million lbs) of titanium mill products (USGS 2010).United States 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 lbs) in 2010 (USGS 2011). Three manufacturers produce the majority of titanium metal in the U.S. – Titanium Metals Corporation (TIMET), Allegheny Technologies Inc. (ATI), and RTI International Metals. The primary production process used by all of these manufacturers is the Kroll process.

This study focuses on energy consumption in five energy intensive process subareas in titanium manufacturing. Figure 2-1 shows the titanium manufacturing process flow diagram addressing the subareas that were considered in this bandwidth analysis. The basic Kroll process steps are pictured for primary metals production. For raw material preparation there are two main subareas in converting rutile or ilmenite in to titanium oxide: wet treatment and separation. Reductant production involves the production and later recovery of magnesium (in the Kroll process diagramed). Primary metal production is a multi-step process involving chlorination, separation, purification, reduction, distillation, and energy-intensive vacuum arc melting to produce first titanium sponge and then titanium ingot as either a cylinder or rectangular slab. Secondary production involves the production of titanium from titanium scrap. 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. Note that further steps, such as the production of titanium parts (such as those for automobiles) 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

	Process Area	Including Subareas Such As:
1	Raw Material Preparation	Wet treatment, separation
2	Reductant Production	
3	Primary Metal Production	Chlorination, separation, purification, reduction, distillation, melting
4	Secondary Production	
5	Semi-Finished Shape Production	Forging, rolling, pressing

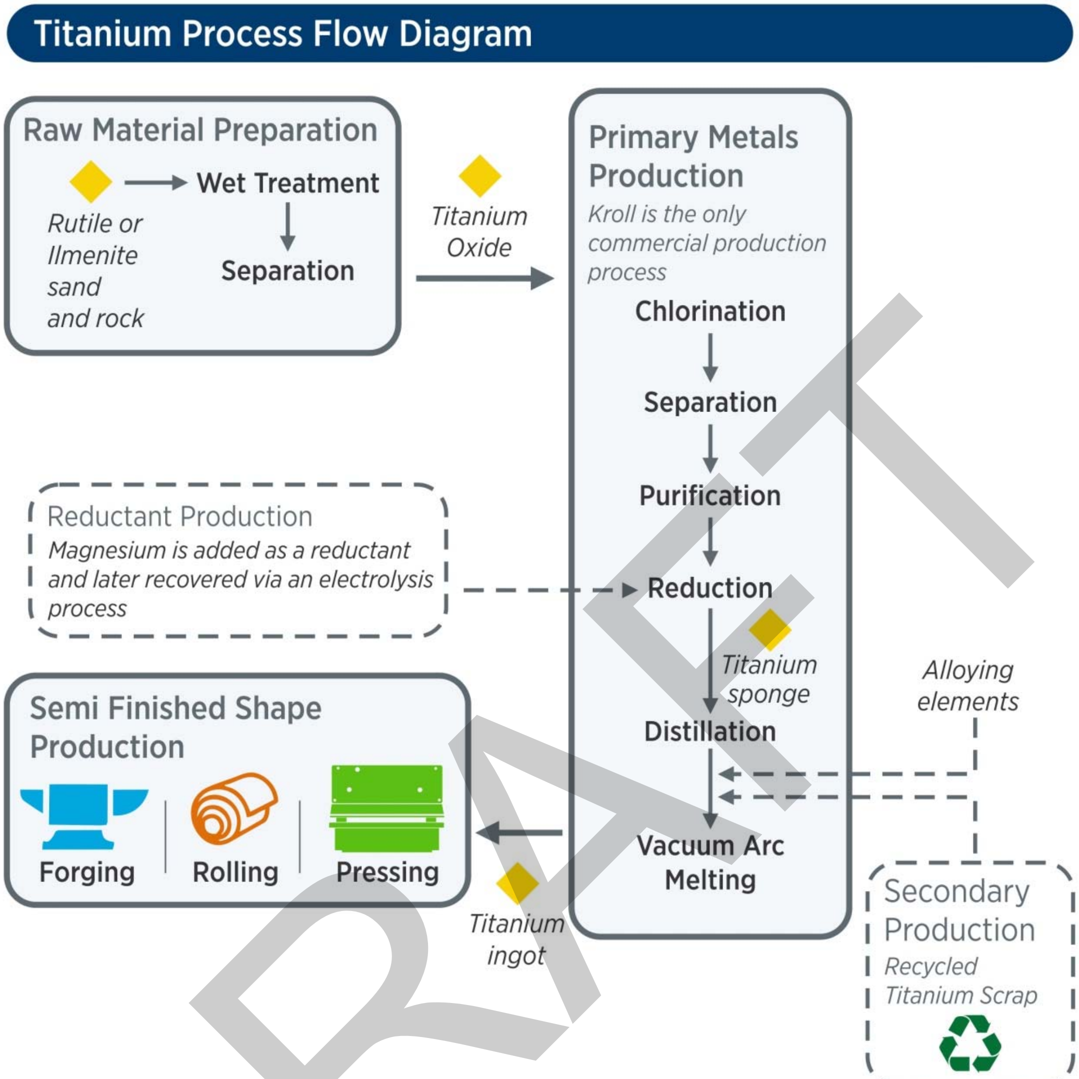


Figure 2-1. Titanium Manufacturing Process Flow Diagram

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 for Key Titanium Manufacturing Process Areas, 2010

Subarea	Product	2010 Total Titanium Sector Production (million lb)	2010 Estimated Production for Boundary Applications* (million lb)
Raw Material Preparation	Concentrated Rutile	81.0	60.8
	Titanium Tetrachloride	129.6	97.2
Reductant Production	Carbon	14.2	10.7
	Chlorine	10.1	7.6
	Magnesium	0.5	0.4
Primary Metal Production	Sponge	32.4	24.3
Secondary Processing	Pre and Post Consumer Scrap	89.1	66.8
Semi-Finished Shape Production	Mill Products (billet, bar, plate, etc.)	80.0	60.0
Total Production for Study Application Area*			**60.0**

* Production for Boundary Applications reflects study application areas) only. Aerospace application are estimated to total 75% of total titanium production (USGS-2011).

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 2010	United States Geological Survey, Titanium Minerals Yearbook, 2010 provides statistics on U.S. Titanium Mill Products by year, in addition to a number of other U.S. production statistics
Norgate 2004	Production volumes for raw material preparation (rutile, and $TiCl_4$) are available in this reference paper, in addition to production volumes of reductants (Cl_2, Mg, and C).
Das 2014	Primary and secondary metals production volumes are estimated in this conference paper

* Production for Boundary Applications reflects study application areas) only. Aerospace application are estimated to total 75% of total titanium production (USGS-2011).

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 U.S. 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 manufacturing intensity. There are a limited number of titanium manufacturing facilities in the U.S. 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.

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

Source Abbreviation	Description
ARPA-E 2013	Financial Assistance Funding Opportunity Announcement, March 2013. This reference provided information on titanium processing energy, it was determined that this source data is life cycle analysis intensity, also referred to as embodied energy or "cumulate amount of primary energy consumed in all stages of a metals production life cycle". Values from this source were adjusted to reflect total onsite manufacturing energy intensity.
Norgate 2007	This journal article is the source cited in determining the processing energy in ARPA-E 2013, titled the Gross Energy Requirement.
Fang 2013	This journal article was used as the source for determining magnesium reductant production energy intensity. This source also provides an estimate of slag production intensity which is subtracted from the ARPA-E processing energy to determine total primary manufacturing intensity.
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. Primary metals production intensity is also estimated in these slides and found to be within 2% of the value estimated in this study. (unpublished)
Das 2015	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). Best engineering judgment was used in determining raw material preparation intensity and secondary production intensity. Best engineering judgment was used in determining primary metals production intensity to be the remaining balance when other subareas were subtracted from total manufacturing intensity. These estimates are summarized below, and in Appendix A1.
Das Sources 2015	Many additional references were consulted in support of best engineering judgment

Total titanium manufacturing energy use was determined by subtracting slag production intensity (Fang 2013) from the total titanium manufacturing intensity. Removing this mining portion of the life cycle estimate provided in the ARPA-E 2013 and Norgate 2007 references leaves an approximate primary total manufacturing estimate. Subarea energy intensity is sourced for reductant production (Fang 2013) and for semi-finished shape production (DOE IMI). The remaining subareas—raw material preparation, primary metals production, and secondary production—were determined largely based on best engineering judgment. A number of reference sources were consulted (Das Sources 2015), and conversations with titanium experts guided this judgment. Raw materials preparation was determined to be approximately 11% of total manufacturing intensity. Secondary production was determined to be approximately 10% of total production. Primary metals production was determined as the remainder of total manufacturing intensity, or approximately 51%. The primary metals production intensity derived in this manner was found to be within 3% of the "energy to make raw titanium" in the unpublished reference DOE IMI. The energy values described here all represent primary energy. These CT calculations are outlined in Appendix A1.

Energy intensities for all sub-processes are presented in Table 3-2 in terms of Btu per pound (Btu/lb) of titanium mill products. The subarea intensity data for titanium was determined in terms of total mill product, not the intermediate manufacturing products. In other words, primary metals production intensity is presented in terms of Btu per pound of titanium mill product (not per pound of titanium sponge). Due to limited data availability, determining intensity in terms of total mill products was the most uniform approach for determining energy consumption.

Titanium manufacturing intensity data was available primarily from life cycle analyses, representing embodied or primary energy. CT intensity from referenced sources is primary CT intensity. Whereas in other bandwidth studies onsite energy is converted to primary energy through the accounting of offsite electricity and steam generation and distribution losses, in this study onsite energy is determined through the omission of offsite losses (see notes in Table 3-2). The estimation of offsite losses is derived from the Aluminum Lightweight Materials Bandwidth Study; energy use by energy type (fuel, electricity, steam) is more readily available for NAICS 3313 (alumina and aluminum). From the aluminum study we are able to estimate the proportion of fuel, electricity and steam by subarea (raw material prep, reductant production, primary metal production, etc.) and apply the same % offsite loss to titanium. Offsite generation and transmission losses are calculated for electricity and steam to convert between primary energy and onsite energy. See footnote in Table **3-2** for details on the conversion from primary to onsite energy.

3.2. Current Typical Energy Consumption

In Table 3-2 the CT primary energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 total mill product production (lbs). See Appendix A1 for explanation of the calculations involved in the values presented here. As described in the previous sections, total mill product production was used in calculating subarea and total energy consumption, and primary energy consumptions were converted to onsite energy consumptions referencing aluminum process-specific energy mix data. Electricity losses were calculated by subtracting the onsite energy consumption from the primary energy consumption. Primary energy includes offsite energy generation and transmission losses. In other bandwidth studies onsite energy is converted to primary energy, adding offsite losses. In this study, since source data is determined to represent primary energy, primary energy is converted to onsite energy by subtracting losses.

Table 3-2. Calculated Current Energy Consumption for Titanium Manufacturing (2010)

(see Appendix A1 for explanation of calculations)

Process Subarea (product)	Primary CT Energy Intensity (Btu/lb)	Production* (million lbs)	Primary CT Energy Consumption, Calculated *** (TBtu/year)	Offsite Losses, Calculated ** (TBtu/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)
Raw Material Preparation	13,850		0.83	0.09	0.74
Reductant Production	26,892		1.61	0.29	1.32
Primary Metal Production	64,292		3.86	2.62	1.23
Secondary Processing	12,591		0.76	0.30	0.45
Semi-Finished Shape Production	8,286		0.50	0.09	0.41
Total for Process Subareas Studied		**60**	**7.56**	**3.40**	**4.16**

Current typical (CT)

* Total production is adjusted to reflect the study application areas (see Section 1.4 for boundary applications). Total mill production is used to calculate subarea energy consumption because energy intensity data is in terms of total mill product not intermediate product.

** Onsite and primary energy are defined in Section 1.3; offsite losses is the calculated difference. The percent offsite loss is obtained from the aluminum lightweight bandwidth study. Assuming a similar proportion of fuel/elec/steam by subarea for aluminum and titanium the offsite losses are approximately 11% of primary energy for raw material preparation, 18% for reductant production, 68% for primary metal production, 40% for secondary metal production, and 18% for extrusion. Refer to the aluminum lightweight bandwidth study, CT energy consumption section, for details on grid efficiency and steam generation and distribution loss.

*** Primary energy is calculated by multiplying energy intensity by production. Onsite energy is calculated by subtracting offsite losses from primary energy.

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, the Kroll process. The Kroll process replaced the Hunter process in the 1940s. 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

In Table 4-1 the SOA primary energy consumption values were calculated by multiplying energy intensity (Btu/lb) by 2010 total mill product production (lbs). The source data for primary energy intensity is based on production of total mill products. For this reason, although process area production is known, the total production number is used in calculating process subarea energy consumption. Primary energy was converted to onsite energy as explained in Section 3.2. The onsite SOA energy consumption is equivalent to onsite CT energy consumption in Table 3-2.

Table 4-1. Calculated SOA Energy Consumption for Titanium Manufacturing

Process Subarea	Primary SOA Energy Intensity (Btu/lb)	Production (million lbs)	Onsite SOA Energy Consumption, Calculated (TBtu/year)	Primary SOA Energy Consumption, Calculated * (TBtu/year)
Raw Material Preparation	13,850		0.74	0.83
Reductant Production	26,892		1.32	1.61
Primary Metal Production	64,292		1.23	3.86
Secondary Processing	12,591		0.45	0.76
Semi-Finished Shape Production	8,286		0.41	0.50
Total for Process Subareas Studied		**60**	**4.16**	**7.56**

State of the Art (SOA)
* Primary SOA energy is calculated by multiplying energy intensity by production. Total mill production is used to calculate subarea energy consumption because energy intensity data is in terms of total mill product not intermediate product. Primary and onsite energy consumption is found to be the same for SOA as it is for CT as there was only one commercial process in base year 2010.

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*).

Table 4-2. Calculated SOA Energy Consumption for Titanium Manufacturing

Process Subarea	Onsite CT Consumption, Calculated (TBtu/year)	Onsite SOA Consumption, Calculated (TBtu/year)	SOA Energy Savings* (CT-SOA) (TBtu/year)	SOA Energy Savings Percent (CT-SOA)/ (CT-TM)**
Raw Material Preparation	0.74	0.74	0	0%
Reductant Production	1.32	1.32	0	0%
Primary Metal Production	1.23	1.23	0	0%
Secondary Processing	0.45	0.45	0	0%
Semi-Finished Shape Production	0.41	0.41	0	0%
Total for Process Subareas Studied	**4.16**	**4.16**	**0**	**0%**

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* SOA energy savings is also called *Current Opportunity.*
** SOA energy savings percent is the SOA energy savings opportunity from transforming 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 with MgH2 (DRTS) manufacturing process. In the Supporting Information document the author provides an energy consumption comparison of DRTS, 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. Primary savings potential was estimated to be 35% of CT total primary manufacturing intensity and consumption, and this value was converted to primary intensity and consumption. This same savings estimate was applied to all five subareas of manufacturing energy consumption, outlined in Table 5-2.

Table 5-2. Calculated PM Energy Consumption for Titanium Manufacturing

Process Subarea	Onsite PM Energy Intensity, Calculated * (Btu/lb)	Onsite PM Energy Consumption, Calculated * (TBtu/year)
Raw Material Preparation	4,314	0.26
Reductant Production	7,718	0.46
Primary Metal Production	7,201	0.43
Secondary Processing	2,644	0.16
Semi-Finished Shape Production	2,378	0.14
Total for Process Subareas Studied		**1.46**

Practical Minimum (PM)
* See Appendix A4 for explanation of calculating PM intensity and consumption.

Table 5-3 presents a comparison of the onsite 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.

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 equation for calculating onsite PM energy savings percent is:

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

Table 5-3. Calculated PM Energy Consumption for Titanium Manufacturing

Process Subarea	Onsite CT Consumption, Calculated (TBtu/year)	Onsite PM Consumption, Calculated (TBtu/year)	PM Energy Savings* (CT-PM) (TBtu/year)	PM Energy Savings Percent** (CT-PM)/ (CT-TM)
Raw Material Preparation	0.74	0.26	0.48	NA
Reductant Production	1.32	0.46	0.86	NA
Primary Metal Production	1.23	0.43	0.80	NA
Secondary Processing	0.45	0.16	0.29	NA
Semi-Finished Shape Production	0.41	0.14	0.27	NA
Total for Process Subareas Studied	**4.16**	**1.46**	**2.70**	**85%**

Current Typical (CT), State of the art (SOA), Practical Minimum (PM)
* 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.

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 each sub-process by determining the Gibbs free energy associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[5] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[6] 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.[7]

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 at 500 °C (NIST 2011).

$$1\ TiO_2 + 2\ Cl_2 + 1\ C \rightarrow 1\ TiCl_4 + 1\ CO_2 \qquad 800\ °C$$

$$1\ TiCl_4 + 2\ Mg \rightarrow 1\ Ti + 1\ MgCl_2 \qquad 1000\ °C$$

[5] Unless otherwise noted, "ideal conditions" means a pressure of 1 atmosphere and a temperature of 77°F.
[6] 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).
[7] Note that the bond energy values are averages, not specific to the molecule in question.

TM energy intensity is process independent (state function), but 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 1 atmosphere of pressure.

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 SOA and PM are as follows:

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

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

For processes requiring an energy intensive transformation (e.g., 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).

The TM energy intensity and consumption for primary metal production is found to be higher than the PM intensity and consumption. There is no certain explanation for this anomaly. In the bandwidth methodology TM is typically the lowest value band of consumption, representing the minimum. 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

Process Subarea	TM Energy Intensity * (Btu/lb)	TM Energy Consumption, Calculated* (TBtu/year)
Raw Material Preparation	0	0
Reductant Production		Estimated to be 0
Chlorine	3,086	
Magnesium	10,834	
Carbon	-803	
Primary Metal Production	16,152	0.97
Secondary Processing	0	0
Semi-Finished Shape Production	0	0
Total for Process Subareas Studied		**0.97**

Thermodynamic minimum (TM)

* TM intensity is determined by considering Gibbs free energy associated with chemical transformations involved, under ideal conditions

** TM consumption calculated by multiplying energy intensity by production (subarea production used for reductant production (chlorine, magnesium, and carbon); total mill production used for other subareas).

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 in to five subareas.

Table 7-1. Current and R&D Opportunity for Titanium Manufacturing

Process Subarea	Current Opportunity (CT-SOA) (TBtu/year)	R&D Opportunity (SOA-PM) (TBtu/year)
Raw Material Preparation	0	0.48
Reductant Production	0	0.86
Primary Metal Production	0	0.80
Secondary Processing	0	0.29
Semi-Finished Shape Production	0	0.27
Total for Process Subareas Studied	**0**	**2.70**

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 there is only one commercial process; and
- *R&D Opportunity* – 2.70 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 speculative and based on unproven technologies.

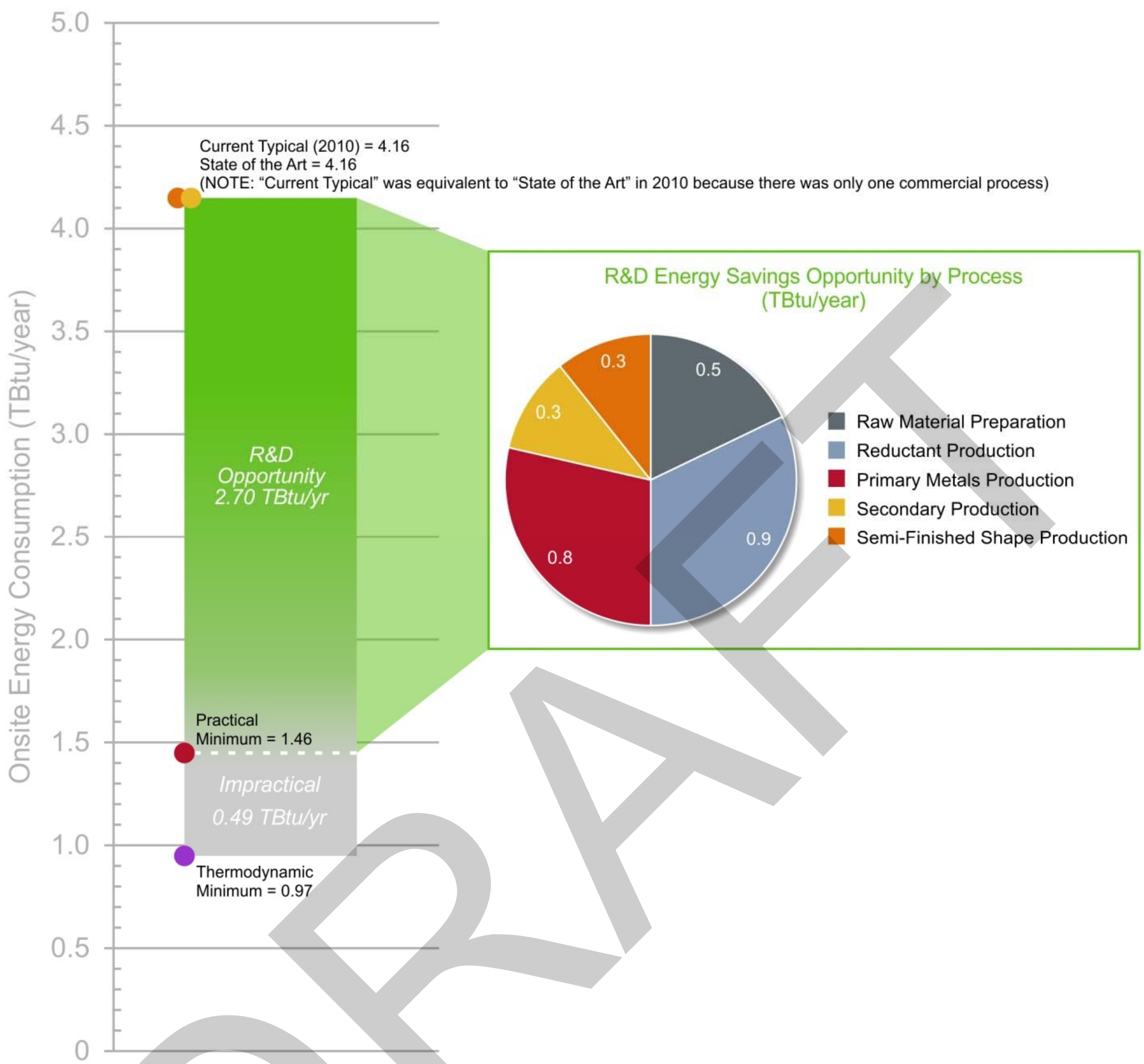


Figure 7-1. R&D Energy Savings Opportunities for Titanium Manufacturing by Process, Based on 2010 Titanium Production for Structural Applications

From this figure it is apparent than reductant production and primary metals production offer 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 reductant production and primary metals production as these are the subareas with the greatest energy consumption.

8. References

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Brueske 2015	Best engineering judgment based upon conversation with Titanium manufacturer, and review of technical papers. Sabine Brueske August 2015
Das 2014	"Metal Flow, Recycling, Energy and Environment - Al, Cu, Mg and Ti" Presented by Das, S. at Annual TMS Meeting, February 18 , 2014, San Diego, CA.
Das 2015	Best engineering judgment based upon conversations with experts at TMS Annual Meeting March 2015, and review of multiple technical papers. Subodh Das, April-June 2015
Das Sources 2015	Many additional sources (listed below italicized) were consulted in developing best engineering judgment. These sources were not specifically referenced in this report, so the author and name of the article/proceeding is provided here under the common reference of Das Sources:

Listing of additional Das Sources 2015, not specifically referenced in study, but consulted in forming Best Engineering Judgment:

Muth et.al. - " Energy Analysis for Emerging Economical Titanium Production Technologies", ORNL Paper, 2011

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DOE IMI	(unpublished) Paper presented as part of DOE Innovative Manufacturing Initiative. The topic is a proposed hydrogen sintered titanium (HST) production pathway.
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. http://www.energy.gov/eere/amo/downloads/bandwidth-study-us-petroleum-refining
Energetics 2015b	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing
Energetics 2015c	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-us-iron-and-steel-manufacturing
Energetics 2015d	Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing. Prepared by Energetics Inc. for the U.S. DOE Advanced Manufacturing Office. 2015. http://www.energy.gov/eere/amo/downloads/bandwidth-study-us-pulp-and-paper-manufacturing

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Appendix A1. Current Typical Energy Intensity Calculations

In this Appendix the calculations involved in determining the values in the table below are explained. This is the same information presented in Table 3-2. A validation step is also noted that provides a second point of reference for the Primary Metal Production estimate.

Table A1-1. Calculated Current Energy Consumption for Titanium Manufacturing (2010)

Process Subarea (product)	Primary CT Energy Intensity (Btu/lb)	Production (million lbs)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated ** (TBtu/year)	Primary CT Energy Consumption, Calculated * (TBtu/year)
Raw Material Preparation	13,850		0.74	0.09	0.83
Reductant Production	26,892		1.32	0.29	1.61
Primary Metal Production	64,292		1.23	2.62	3.86
Secondary Processing	12,591		0.45	0.30	0.76
Semi-Finished Shape Production	8,286		0.41	0.09	0.50
Total for Process Subareas Studied		**60**	**4.16**	**3.40**	**7.56**

Current typical (CT)
* Calculated using the total production value for the applications studied (see Section 1.4).
** 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: offsite losses assumed to be approximately 11% of primary energy for raw material preparation, 68% for primary metal production, 40% for secondary metal production, and18% for extrusion.

Process level energy intensity data was not readily available for titanium manufacturing. As a result process level CT energy intensity was determined as an estimated percentage of total titanium manufacturing energy use for the production of titanium mill products.

Total for Process Subareas Studied: Total life cycle energy intensity for the Kroll process estimated in ARPA-E 2013 and Norgate 2007 were determined to be the best reference for total tinanium manufacturing energy intensity. Investigation of these sources identified that the referenced “Processing Energy”/ARPA-E and “Gross Energy Requirement”/Norgate 2007 (same value in both reports, 100kWh/kg or 361 MJ/kg or 154,772 Btu/lb) is defined as “…energy use included in LCAs is the Gross Energy Requirement (GER), also referred to as embodied energy or cumulative energy demand, which is the cumulative amount of primary energy consumed in all stages of a metal’s production life cycle". To align with the boundaries of this study, the energy intensity of mining production was subtracted from the total. Fang 2013 provides an estimate for slag production intensity of 60,900 MJ/Ton (28,861 Btu/lb). This value is subtracted from the ARPA-E intensity to determine approximate total primary manufacturing energy intensity.

Calculation:

154,772 Btu/lb – 28,861 Btu/lb = 125,991 Btu/lb

Raw Material Preparation: This value is determined based on best engineering judgment of Subodh Das (Das 2015, Das Sources 2015). Raw Material Production is estimated to be 11% of total manufacturing energy intensity.

Calculation:

125,991 x 0.11 = 13,850 Btu/lb

Reductant Production: Reductant production intensity is estimated in Fang 2013 from the direct reduction of Ti-slag (DRTS) process area breakdown; energy to recover and regenerate Mg reductant can be back calculated from these calculations.

Energy intensity from mining to slag production for DRTS = 60,900 MJ/ton Ti

Energy intensity from slag to powder for DRTS = 20,054 MJ/ton Ti

Total energy consumption for DRTS = 137,700 MJ/ton Ti

Calculation:

Energy to recover and regenerate Mg through electrolysis can be calculated as the remaining portion of total (137,700 – 60,900 – 20,054 = 56,746 MJ/ton Ti = 26,892 Btu/lb)

Primary Metals Production: Best engineering judgment was used in determining that Primary Metals Production intensity should be the remainder of total manufacturing energy intensity after all other subareas are subtracted. Referencing the other values calculated in this Appendix the Primary Metals Production is calculated as follows:

Calculation:

Total manufacturing energy intensity – raw material preparation intensity - reductant production intensity – secondary production intensity – semi-finished shape production intensity = primary metals production intensity

125,911 – 13,850 – 26,892 – 12,591 – 8,286 = 64,292 Btu/lb

Secondary Production: This value is determined based on best engineering judgment of Subodh Das (Das 2015, Das Sources 2015). Raw Material Production is estimated to be 10% of total manufacturing energy intensity.

Calculation:

125,991 x 0.10 = 12,591 Btu/lb

Semi-Finished Shape Production: Semi-finished shape production intensity can be estimated from calculations presented in DOE IMI, *this source is not publicly available*. The proposed hydrogen sintered titanium pathway avoids energy-intensive vacuum arc remelting (VAR), forge, and anneal steps. The energy for the forging and annealing steps can be gleaned from this analysis. Typical Kroll VAR and Forge Energy Estimate is provided as 7,816 kWh/tonne. From this we can subtract the energy attributed to pressing and welding electrode and VAR energy. The calculation is as follows.

Calculation:

7,816 – 372 (press electrode) – 1,000 (weld electrode) – three VAR steps (55+980+55) = 5,354 kWh/tonne = 8,286 Btu/lb

Validation of Primary Metal Production: The calculations presented in DOE IMI (not publicly available) provide a possible method for estimating primary metal production. Since this is not a publicly available source, this was not directly referenced for determining primary metal production intensity. However, it does serve as a potential point of validation. The hydrogen sintered titanium calculations provide estimated energy consumed (kWh/tonne) "for mill form" to "make raw Ti", which includes distillation, electrolysis, reactor, crushing sponge, etc. The energy intensity determined in this analysis is 40,246 kWh/ton = 62,288 Btu/lb. This value is within 3% of the value estimated through best engineering judgment.

Production: The source data for primary energy intensity is based on production of total mill products. For this reason, although process area production is known, the total production number is used in calculating energy consumption.

Primary CT Energy Consumption: This value is calculated by multiplying the Primary CT Energy Intensity to the total production.

Onsite CT Energy Consumption: This value is calculated by subtracting the offsite energy losses from the primary CT energy consumption values.

Offsite Losses: Given the limited source data for titanium production energy consumption there was no information to determine the energy mix for the five process subareas. The assumption was made that the energy mix would be relatively equivalent to aluminum production. From Energy Information Administration, Manufacturing Energy Consumption data for NAICS 3313 (Alumina and Aluminum) that energy supplied to the facility boundary is: 45% fuel, 53% electricity, and 2% steam. From the aluminum bandwidth report prepared in parallel with this study we know that using this fuel mix, offsite losses are calculated to be 11% of primary energy for raw material preparation, 68% of primary metal production, 40% for secondary metal production, and 18% for extrusion. These same offsite loss estimates are applied to Titanium primary consumption to determine offsite loss.

Appendix A2. Master Titanium Summary Table

Table A2-1. U.S. Production Volume of Titanium Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption (Excludes Feedstock Energy)

Subarea	2010 Application Area Production (million lb)	Primary Energy Intensity (Btu/lb Titanium mill product)				Calculated Onsite Energy Consumption (TBtu/year)[8]			
		CT	SOA	PM	TM (TM is considered onsite intensity)	CT	SOA	PM	TM
Raw Material Preparation		13,850	13,850	4,848	0	0.74	0.74	0.26	0
Reductant Production		26,892	26,892	9,412	0	1.32	1.32	0.46	0
Primary Metal Production[9]		64,292	64,292	22,502	16,152	1.23	1.23	0.43	0.97
Secondary Metal Processing		12,591	12,591	4,407	0	0.45	0.45	0.16	0
Semi-Finished Shape Production		8,286	8,286	2,900	0	0.41	0.41	0.14	0
Mill Production Total	**60**					**4.16**	**4.16**	**1.46**	**0.97**

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

[8] The titanium energy intensity estimates in this report are determined to represent Primary intensity. Primary energy is converted to onsite energy by subtracting estimated offsite losses (referencing aluminum bandwidth as a guide) before onsite energy consumption is calculated. See report for details. The primary intensity listed here cannot be simply multiplied by production to determine onsite consumption.

[9] TM consumption is found to be higher than PM consumption for Primary Metal Production which does not agree with bandwidth methodology. This anomaly is currently unexplained.

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 Onsite 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	Norgate 2004	Das 2015, Das Sources 2015	Equivalent to CT	Thermodynamic minimum calculation – found to be zero
Reductant Production	Norgate 2004	Fang 2013	Equivalent to CT	Thermodynamic minimum calculation
Primary Metal Production	Das 2014, ITA 2013, USGS 2011	Das 2015, Das Sources 2015, DOE IMI	Equivalent to CT	Thermodynamic minimum calculation
Secondary Metal Processing	Das 2014, ITA 2013, USGS 2011	Das 2015, Das Sources 2015	Equivalent to CT	Thermodynamic minimum calculation – found to be zero
Semi-Finished Shape Production	ITA 2013, USGS 2011	DOE IMI	Equivalent to CT	Thermodynamic minimum calculation
Mill Production Total	USGS 2011	ARPA-E 2013, Norgate 2007, Fang 2013	Equivalent to CT	Sum of subareas

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.

Onsite PM energy intensity and consumption values shown in Table 5-2 are calculated to be 35% of CT primary intensity based on best engineering judgement (Das 2015), and converted to onsite intensity and consumption for comparison to other energy bands in this and other bandwidth reports.

Table 5-2 is included here again for reference and example calculations are provided for intensity and consumption.

Table A4-1. Calculated PM Energy Consumption for Titanium Manufacturing

Process Subarea	Onsite PM Energy Intensity (Btu/lb)	Onsite PM Energy Consumption, Calculated (TBtu/year)
Raw Material Preparation	4,314	0.26
Reductant Production	7,718	0.46
Primary Metal Production	7,201	0.43
Secondary Processing	2,644	0.16
Semi-Finished Shape Production	2,378	0.14
Total for Process Subareas Studied		**1.46**

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

PM Energy Intensity is calculated to be 35% of the CT Energy Intensity values from Table 3-2, based on best engineering judgement. The primary PM intensity is then converted to onsite PM intensity subtracting offsite losses; the conversion from primary to onsite energy is explained in Section 3.2 of this report. An example of the two-step calculation is provided here:

Primary PM Energy Intensity (Reductant Production) = CT Intensity (Reductant Production) x 0.35 = 26,892 Btu/lb x 0.35 = 9412 Btu/lb

Onsite PM Energy Intensity (Reductant Production) = Primary PM Intensity - offsite losses for reductant production (18% of primary energy – from aluminum bandwidth study) = 9412 Btu/lb – (9412 x 0.18) = 7,718 Btu/lb

PM Energy Consumption Calculation:

Onsite PM Energy Consumption is calculated to be 35% of the CT Energy Consumption values from Table 3-2[10]. An example calculation is provided here:

Onsite PM Energy Consumption (Secondary Processing) = CT Consumption (Secondary Processing) x 0.35 = 0.45 TBtu/year x 0.35 = 0.16 TBtu/year

PM Technologies Considered:

These technologies were considered in arriving at the best engineering judgment estimation.

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	
SOM	Solid oxide membrane electrolysis	Infinium
MAFBR	Multi-arc fluidized bed reactor	SRI International
Hydrogen sintered titanium		

[10] The same result is achieved when Onsite PM Energy Intensity is multiplied by total mill production [for the Secondary Processing example the equation would be: CT primary intensity Btu/lb x 0.35 – (CT primary intensity x 0.35 x 0.40 offsite losses) x 60 million lbs/year = (12,591 x 0.35 – (12,591 x 0.35 x 0.40)) x 60,000,000 = 0.16 TBtu/year]

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