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. Glass Manufacturing

September 2017

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# Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities.[1] The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to 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.

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.

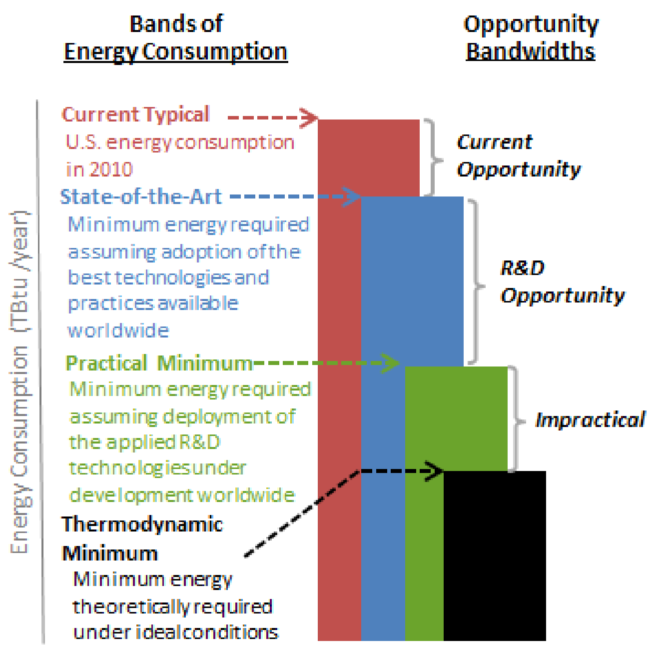


Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

In this study, the four energy bands are estimated for select individual sub-products or sub-processes and sector-wide. The estimation method compares diverse industry, governmental, and academic data to analyses of reported plant energy consumption data from the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA). MECS is a national sample survey of U.S. manufacturing establishments conducted every four years; information is collected and reported on U.S. manufacturing energy consumption and expenditures. Where published data were unavailable, best engineering judgment was used.

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

[1] The concept of an energy bandwidth and its use as an analysis tool for identifying potential energy savings opportunities originated in AMO in 2002 (then called the Office of Industrial Technologies). Revised and consistent versions of bandwidth studies for the Chemicals, Petroleum Refining, Iron and Steel, and Pulp and Paper sectors were published in 2015.

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.

# Acknowledgments

Joseph Cresko of DOE-AMO led the conceptual development of the bandwidth study series, with support from Dr. Alberta Carpenter at the National Renewable Energy Laboratory. AMO recognizes the efforts of Mauricio Justiniano, Dr. Benjamin Levie, Keith Jamison, Dr. Heather Liddell, Brad Chadwell, and Sabine Brueske of Energetics Incorporated, who conducted the research and analysis and wrote this report. AMO wishes to acknowledge the contributions made by Dr. Diane Graziano of Argonne National Laboratory, Dr. Oscar Verheijen of CelSian Glass & Solar B.V., and David Rue of the Gas Technology Institute for their work reviewing this study. Appreciation is also extended to Aaron Huber of Johns Manville for providing input during the development of this study.

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# List of Acronyms and Abbreviations

| | |
|---|---|
| AMO | Advanced Manufacturing Office |
| Btu | British thermal unit |
| CHP | Combined heat and power |
| CT | Current typical energy consumption or energy intensity |
| DOE | U.S. Department of Energy |
| EERE | DOE Office of Energy Efficiency and Renewable Energy |
| EIA | U.S. Energy Information Administration |
| HVAC | Heating, ventilation and air conditioning |
| kg | Kilogram(s) |
| MECS | Manufacturing Energy Consumption Survey |
| MMBtu/ton | Million British thermal units per short ton |
| MJ | Megajoule(s) |
| NAICS | North American Industrial Classification System |
| PM | Practical minimum energy consumption or energy intensity |
| PSA | Pressure swing absorption |
| R&D | Research and development |
| SOA | State of the art energy consumption or energy intensity |
| TBtu | Trillion British thermal units |
| TM | Thermodynamic minimum energy consumption or energy intensity |
| VSA | Vacuum swing absorption |
| VSD | Variable speed drive (motor) |

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# Executive Summary

Glass is an ancient material that has been produced since as long ago as the year 2,000 BC in former Mesopotamia (CMOG 2016). Today, thanks to its versatility, glass can be commonly found in packaging, architectural, household, automotive, optical, lighting, electronics, and many other applications. Glass can be produced in many different forms, including flat glass for windows, fibers for fiberglass or glass wool insulation, containers, and molded shapes formed through pressing and blowing. It is commonly made from silica sand, soda ash, and/or limestone through a series of manufacturing processes, some of which can be highly energy-intensive.

This report investigates the manufacturing energy consumption and energy intensity associated with glass production. The study is limited to five glass sub-products, namely flat glass, container glass, glass fiber wool, glass fiber textiles, and pressed and blown glass. For each sub-product, energy use and energy saving opportunities are identified and quantified for each of the following four manufacturing sub-processes considered:

- *Batch Preparation:* preparing the glass batch, including measuring, grinding, and mixing the constituent materials (silica and additives)
- *Melting and Refining:* melting the glass mixture and refining the molten glass to remove impurities and air bubbles
- *Forming:* shaping the molten glass into its desired form
- *Finishing:* applying surface treatments and/or coatings to affect the glass product characteristics

The sub-products and sub-processes included in this study comprise about 79% of the total 2010 energy consumption of Glass and Glass Product Manufacturing (NAICS Code 3272) and Mineral Wool Manufacturing (NAICS Code 327993).

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for each glass manufacturing sub-product and sector-wide. 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:*** The following describes the approach to this study and how the findings are organized and presented in the current document:

- Chapter 1 provides an overview of the methodology and boundaries.
- Chapter 2 estimates the 2010 production volumes for glass products.
- Chapter 3 estimates current typical (CT) energy intensity and consumption for the four sub-processes and five glass sub-products and sector-wide.
- Chapter 4 estimates the state of the art (SOA) energy intensity and consumption for these processes, assuming the adoption of best technologies and practices available worldwide.
- Chapter 5 assesses the practical minimum (PM) energy intensity and consumption for these processes, assuming deployment of the applied research and development (R&D) technologies available worldwide.
- Chapter 6 estimates the thermodynamic minimum (TM) energy, that is, the minimum amount of energy theoretically required for these processes, assuming ideal conditions. In some cases, this is less than zero.
- Chapter 7 presents the estimated energy savings opportunity *bandwidths*, which are the differences between the energy consumption *bands* (CT, SOA, PM, TM).

The U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) provides subsector estimates of 2010 energy consumption for U.S. Glass and Glass Product Manufacturing (NAICS Code 3272) and Mineral Wool Manufacturing (NAICS Code 327993). The total of these two subsectors is references as glass sector-wide CT energy consumption. In 2010, the sub-products and sub-processes studied corresponded to 79% of the industry's energy consumption. In this study, CT, SOA, PM, and TM energy consumption for *individual* sub-products and sub-processes included in this study is estimated from multiple referenced sources; this data was then extrapolated based on the 79% coverage to estimate total subsector SOA, PM, and TM energy consumption. The subsector energy consumption values were summed to determine sector-wide SOA, PM, and TM energy consumption.

***Study Results:*** Two energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are shown in Table ES-1 and Figure ES-1 [data calculated using methods and sources identified in this document].[2] The current opportunity is the difference between the 2010 CT energy consumption and the SOA energy consumption; the R&D opportunity is the difference between the SOA energy consumption and the PM energy consumption. Potential energy savings opportunities are presented for the four sub-processes studied and for all of U.S. glass and glass products manufacturing sector, based on extrapolated data. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual processes based on the sector-wide extrapolated data. The energy savings opportunities presented reflect the estimated production of glass products in baseline year 2010. Therefore, it is important to note that total energy savings opportunities would scale with increasing or decreasing production levels.

**Table ES-1. Potential On-Site Energy Savings Opportunities in the U.S. Glass Products Manufacturing Sector[3]**

| Opportunity Bandwidths | Estimated On-site Energy Savings Opportunity for Glass Manufacturing Sub-Products/Sub-Processes Studied (per year) | Estimated Energy Savings Opportunity for All of the U.S. Glass and Glass Products Manufacturing Sector Based on Extrapolated Data (per year) |
|---|---|---|
| **Current Opportunity:** on-site energy savings if the best technologies and practices available are used to upgrade production | 48.2 TBtu [4] (33% energy savings)[5] | 61.2 TBtu [4] (33% energy savings)[5] |
| **R&D Opportunity**: additional on-site energy savings if applied R&D technologies under development worldwide are successfully deployed | 12.7 TBtu [6] (9% energy savings)[7] | 16.2 TBtu [6] (9% energy savings)[7] |

[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 (nonfuel inputs) to production is excluded.

[3] Calculated using estimated production values. Note that the thermodynamic minimum (TM) is used as the baseline (rather than zero) for energy savings percent calculations.

[4] Current opportunity = CT - SOA, as shown in Table 4-2 and Table 4-3.

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

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

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

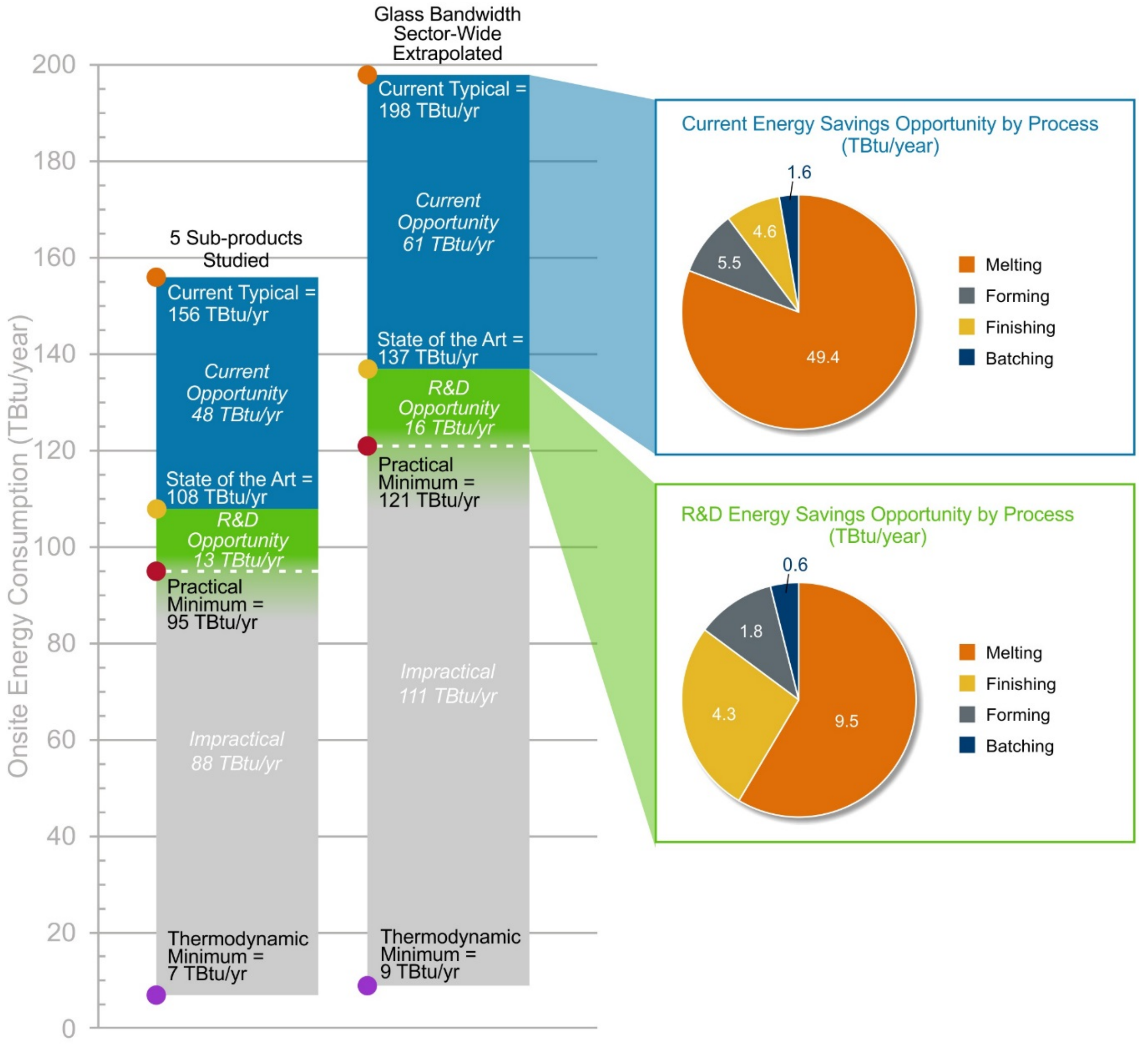


Figure ES-1. Current and R&D energy savings opportunities for the processes studied and for glass and glass products manufacturing (sector-wide), based on extrapolated data
Source: EERE

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume the successful deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” in Figure ES-1 because the PM energy consumption is based on today’s knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, it is shown as a dashed line with color fading because emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

The current energy savings opportunities for glass product manufacturing by process are as follows:

- Glass Melting/Refining, representing 80.7% of the current opportunity (39.0 TBtu/yr)
- Glass Forming, representing 9.0% of the current opportunity (4.3 TBtu/yr)
- Glass Finishing, representing 7.6% of the current opportunity (3.7 TBtu/yr)
- Glass Batching, representing 2.7% of the current opportunity (1.3 TBtu/yr)

R&D energy savings for glass product manufacturing by process are as follows:

- Glass Melting/Refining, representing 58.5% of the R&D opportunity (7.5 TBtu/yr)
- Glass Finishing, representing 26.6% of the R&D opportunity (3.4 TBtu/yr)
- Glass Forming, representing 10.9% of the R&D opportunity (1.4 TBtu/yr)
- Glass Batching, representing 3.9% of the R&D opportunity (0.5 TBtu/yr)

The results presented show that 48.2 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide were used to upgrade the four glass manufacturing sub-processes included in this study; an additional 12.7 TBtu could be saved through the adoption of applied R&D technologies under development worldwide. However, if the energy savings potential is estimated for the U.S. glass manufacturing industry as a whole, the current energy savings opportunity is 61.2 TBtu per year, and the R&D opportunity increases to 16.2 TBtu per year.

The savings opportunities by process are different for each glass sub-product, and the above estimates correspond to the total energy savings opportunities for all sub-products included in this study. Based on the bandwidth analysis, the greatest *current and R&D opportunities* for glass manufacturing involve more efficient glass melting/refining. On-site energy savings in glass melting/refining account for 81% of the *current opportunity* and 58% of the *R&D opportunity*. Because of its high energy intensity compared to other processes in glass manufacturing, most of the industry's energy-saving efforts have focused on improvements in the melting process.

Energy savings opportunities that do not involve glass melting/refining represent about 19% of the *current opportunity* and 42% of the *R&D opportunity*. Current opportunities include best practices, such as motor re-sizing, the use of variable speed drives, and the use of process controls. R&D opportunities include new technologies for grinding batch and cullet, forming glass in forehearths, drying glass fibers, finishing flat glass, and others. Appendix A4 includes a full list of technologies included or excluded from the analysis.

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

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# 1. Introduction

## 1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. glass manufacturing sector, as defined by classifications 311 and 3121 of the North American Industry Classification System (NAICS). The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for glass manufacturing subsectors and sector-wide. In this study, four different energy consumption *bands* (or measures) are estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

Numerous glass products are manufactured in the United States; five sub-products and four sub-processes were studied. Together, these accounted for 79% of energy consumption in the U.S. glass sector in 2010.

The four bands of energy consumption estimated in this report include: the on-site energy consumption associated with manufacturing processes in six subsectors in 2010; two hypothetical energy consumption levels with progressively more advanced technologies and practices (state of the art and practical minimum); and one energy consumption level based on the minimum amount of energy needed to theoretically complete a manufacturing process (thermodynamic minimum). The bands of energy consumption are used to calculate *current* and *R&D opportunity* bandwidths for energy savings.

## 1.2. Comparison to Other Bandwidth Studies

Similar energy bandwidth studies (see inset) were prepared in 2015 for four other U.S. manufacturing sectors: chemicals, iron and steel, petroleum refining, and pulp and paper. Additional bandwidth studies were subsequently prepared to characterize energy use in manufacturing six lightweight structural materials in the United States: aluminum, magnesium, titanium, advanced high strength steel, carbon fiber reinforced polymer composites, and glass fiber reinforced composites. This report is one of a more recently commissioned set of bandwidth studies that also includes cement, food and beverage products, and plastic and rubber products (DOE 2017).

In 2007, DOE published a glass bandwidth study (Rue 2007) prior to development of the now standard bandwidth methodology. The energy bandwidth studies completed in 2015 and later all follow the same analysis methodology and presentation format. Collectively, these studies explore the potential energy savings opportunities in manufacturing that are available through existing technology and investment in research and development (R&D) technologies.

### History of DOE Advanced Manufacturing Office Energy Bandwidth Reports

Before 2013, the U.S. Department of Energy (DOE)'s Industrial Technologies Program (now the Advanced Manufacturing Office or AMO) conducted industrial sector analyses (methods not necessarily harmonized) to quantify savings opportunities.

- 2013: Developed and refined a consistent methodology for bandwidth studies such that comparisons could be made across the manufacturing sectors.
- 2015: Published revised reports for four U.S. manufacturing sectors: chemicals, iron and steel, petroleum refining, and pulp and paper.
- 2016: Published six additional bandwidth studies on the energy use in manufacturing lightweight structural materials (aluminum alloys, magnesium alloys, titanium alloys, advanced high strength steel alloys, carbon fiber reinforced polymer composites, and glass fiber reinforced composites) in the U.S., following the same analysis methodology and presentation format.
- 2017: Prepared bandwidth studies (including this report) for four additional U.S. manufacturing sectors: cement, food and beverage products, glass, and plastics and rubber products.

All of these reports are available on the AMO website (DOE 2017) at energy.gov/amo/energy-analysis-sector

## 1.3. 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. There are four energy consumption bands referenced throughout this report: current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy consumption. These bands describe different levels of energy consumption to manufacture products.

As shown in Figure 1-1, the bands progress from higher to lower levels of energy consumption, reflecting the use of increasingly more efficient manufacturing technologies and practices. The upper bound is set by a mix of new and older technologies and practices in current use (the current typical level of energy consumption). The lower bound is defined by the theoretical minimum energy requirement assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption).

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If manufacturers use the most efficient technologies and practices available in the world, energy consumption could decrease from the current typical to the level defined by the state of the art. Since these state of the art technologies already exist, the difference between the current typical and the state of the art energy consumption levels defines the *current opportunity* to decrease energy consumption. Given that this is an evaluation of technical potential, fully realizing the current opportunity would require investments in capital that may not be economically viable for any given facility. Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

Definitions of the four energy bands are provided in the inset (box at right). Definitions of the two opportunity bandwidths are provided below:

The *current opportunity* is the energy savings that is potentially attainable through capital investments in the best technologies and practices available worldwide. It is the difference between CT and SOA energy consumption.

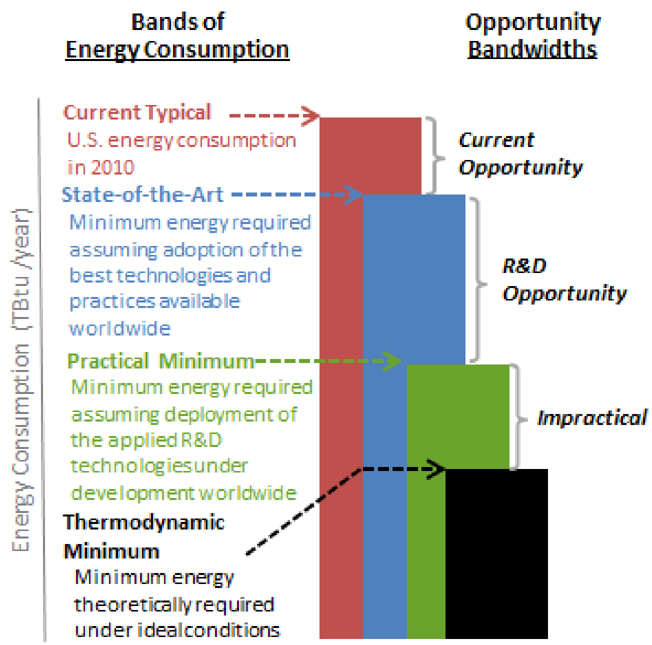


Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

### Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption to manufacture a specific product industry-wide:

**Current Typical (CT) energy consumption:**
U.S. energy consumption in 2010.

**State of the Art (SOA) energy consumption:**
The minimum amount of energy required assuming the adoption of the best technologies and practices available worldwide.

**Practical Minimum (PM) energy consumption:**
The minimum amount of energy required assuming the deployment of the best applied R&D technologies under development worldwide. This measure is expressed as a range to reflect the speculative nature of the energy impacts of the unproven technologies considered.

**Thermodynamic Minimum (TM) energy consumption:**
The minimum amount of energy theoretically required assuming ideal conditions typically unachievable in real-world applications.

The *R&D opportunity* is the energy savings that is potentially attainable through the applied R&D technologies under development. It is the difference between SOA and PM energy consumption. To attain this energy savings, manufacturers would need to produce glass products in new ways with technologies that are not commercially available.

The difference between PM 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. 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.

## 1.4. Bandwidth Analysis Method

This section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "on-site energy" or "primary energy," 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). Nonfuel feedstock energy is not included in the on-site energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) is energy in its original form, before transformation to secondary or tertiary forms of energy (i.e., electricity). Primary energy calculations include 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. Nonfuel feedstock energy is not included in the primary energy values. In some cases, references do not differentiate steam from fuel as an energy source, and without a better estimate, it is difficult to determine what portion of steam losses should be accounted for in primary energy. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

The four bands of energy consumption described above were quantified for sub-processes and for the material total. The bands of energy consumption and the opportunity bandwidths presented herein consider only on-site energy consumption and exclude feedstocks.[8] To determine the total annual CT, SOA, PM, and TM energy consumption (TBtu per year), energy intensity values per unit weight (Btu per ton of material manufactured) were estimated and multiplied by the annual production total (tons of material manufactured per year). The year 2010 was used as a base year. Unless otherwise noted, 2010 production data were used.

The calculated energy consumption values in this report are based on an examination of referenced data and extrapolation to sector-wide energy savings opportunities. The references, methodology, and assumptions employed are presented with the data in each chapter and were peer reviewed.

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

Findings are presented as follows:

Chapter 2 presents **U.S. production** (million tons per year) for the glass sub-products included within the scope of this bandwidth report for 2010.

Chapter 3 presents the estimated on-site **CT energy intensity** (Btu per ton) and **CT energy consumption** (TBtu per year) for the sub-processes studied and material total (along with sources and assumptions).

Chapter 4 presents the estimated on-site **SOA energy intensity** (Btu per ton) and **SOA energy consumption** (TBtu per year) for the sub-processes studied and material total (along with sources and assumptions). The sector-wide SOA energy consumption is estimated based on an extrapolation of the SOA energy consumption for the four sub-processes studied.

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per ton) and **PM energy consumption** (TBtu per year) for the sub-processes studied and material total (along with sources and assumptions). The sector-wide PM energy consumption is estimated based on an extrapolation of the PM energy consumption for the four sub-processes studied.

Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per ton) and **TM energy consumption** (TBtu per year) for the sub-processes studied and material total (along with sources and assumptions).

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

## 1.5. Boundaries of the Study

The U.S. glass manufacturing sector is the physical boundary of this bandwidth study. The study focuses exclusively on the energy use directly involved in the production of glass, i.e., the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to glass manufacturing at a production facility.

This is not a life-cycle assessment study. This study does not consider life-cycle energy consumed during raw material extraction, off-site treatment, transportation of materials, product use, or disposal. Similarly, the study does not quantify the major energy benefits from the use of glass products that occur *outside* of the manufacturing sector—for example, the energy savings achieved in buildings that use glass wool insulation.

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.

This study focuses on the production of five glass sub-products:

1) Flat glass: used in the production of window panes, automotive glass, and glass for photovoltaics
2) Container glass: bottles, jars, and glass packaging
3) Glass wool: thermal insulation
4) Glass fibers: textile fiber for material reinforcement and optical fibers
5) Other pressed and blown glass (specialty glass): tableware, stemware, ovenware, blanks for electric light bulbs, scientific and medical glass, and others

For each of these glass sub-products, the analysis focuses on the energy intensity of the following four processes steps: batch preparation and mixing, melting and refining, forming, and finishing. These processes are described in further detail in Section 2.

Glass Product Manufacturing Made of Purchased Glass (NAICS Code 327215) is not included in the analysis. This sub-product includes items made from intermediate glass products, such as furniture tops, aquariums, doors, lenses, ornaments, watch crystals, and other products made from purchased glass. Glass wool manufacturing is categorized as part of NAICS Code 327993, Mineral Wool Manufacturing, which also includes the manufacture of mineral wool from rock and slag. Although the glass wool manufacturing energy profile is very different from the energy profile of other mineral wools, sources that report energy or production data for NAICS Code 327993 do not commonly separate out glass wool. The study focuses on glass wool manufacturing and excludes mineral wool made from rock and slag. The production of rock and slag wools involves the use of very different furnaces (cupola furnaces), which use coke as fuel rather than electricity or natural gas.

# 2. U.S. Glass Manufacturing Sector Overview

This chapter presents an overview of the U.S. glass manufacturing sector, including its impact on the economy and jobs, number of establishments, and types of energy consumed. The data and information in this chapter provide the basis for understanding the energy consumption estimates.

## 2.1. U.S. Glass Manufacturing Overview

In 2010, the U.S. glass industry, defined as all of NAICS codes 3272 and 327993, employed 90,506 people and produced $24.9 billion in product shipments (ASM 2010a). Figure 2-1 shows a breakdown of the 2010 value of shipments by glass sub-product.[9] The value added of the glass industry accounted for 0.6% of the total value added of the U.S. manufacturing sector (ASM 2010a).

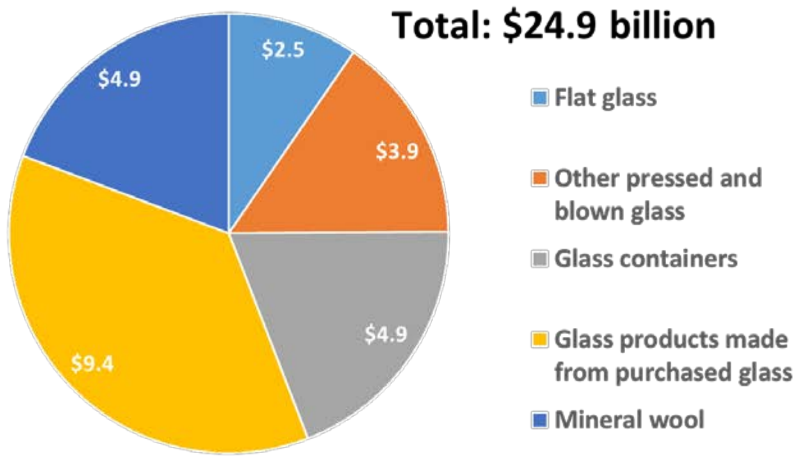


Figure 2-1. Value of product shipments by glass sub-product
Source: ASM 2010a

## 2.2. U.S. Glass Manufacturing Sector Description

In 2010, there were 1,821 establishments involved in Glass and Glass Product Manufacturing, NAICS Code 3272, and 283 establishments involved in Mineral Wool Manufacturing, NAICS Code 327993 (SUSB 2010).[10] Historically, both the U.S. production and consumption of glass products have concentrated near population centers because of the high shipping costs of raw materials and glass products, as well as the large concentrations of end-use customers (Pellegrino 2002). The bulk of glass plants are located in the Northeast, Midwest, and California. Figure 2-2 shows the 2010 distribution of manufacturing establishments by state for Glass and Glass Product Manufacturing, NAICS Code 3272. Figure 2-2 does not include manufacturing establishments for Mineral Wool Manufacturing, NAICS Code 327993, as data were available at the four-digit level of the NAICS code only.

[9] The breakdown shown corresponds to the data breakdown of *NAICS Code 3272, to the six-digit level, and NAICS Code 327993*. Note that in this breakdown, textile fiber manufacturing is included in Other Pressed and Blown Glass (*NAICS Code 32721*), and wool glass is included in Mineral Wool (*NAICS Code 327993*). However, *NAICS Code 327993* includes mineral wool made from rock and slag, which is excluded from the energy analysis of this study. Glass products made from purchased glass *(NAICS Code 327215)* are also excluded from the energy analysis of this study.
[10] Includes manufacturing establishments that process materials and establishments that contract with other establishments to process their materials for them. Establishments involved in mineral wool manufacturing include facilities that process non-glass mineral wool (made from rock or slag).

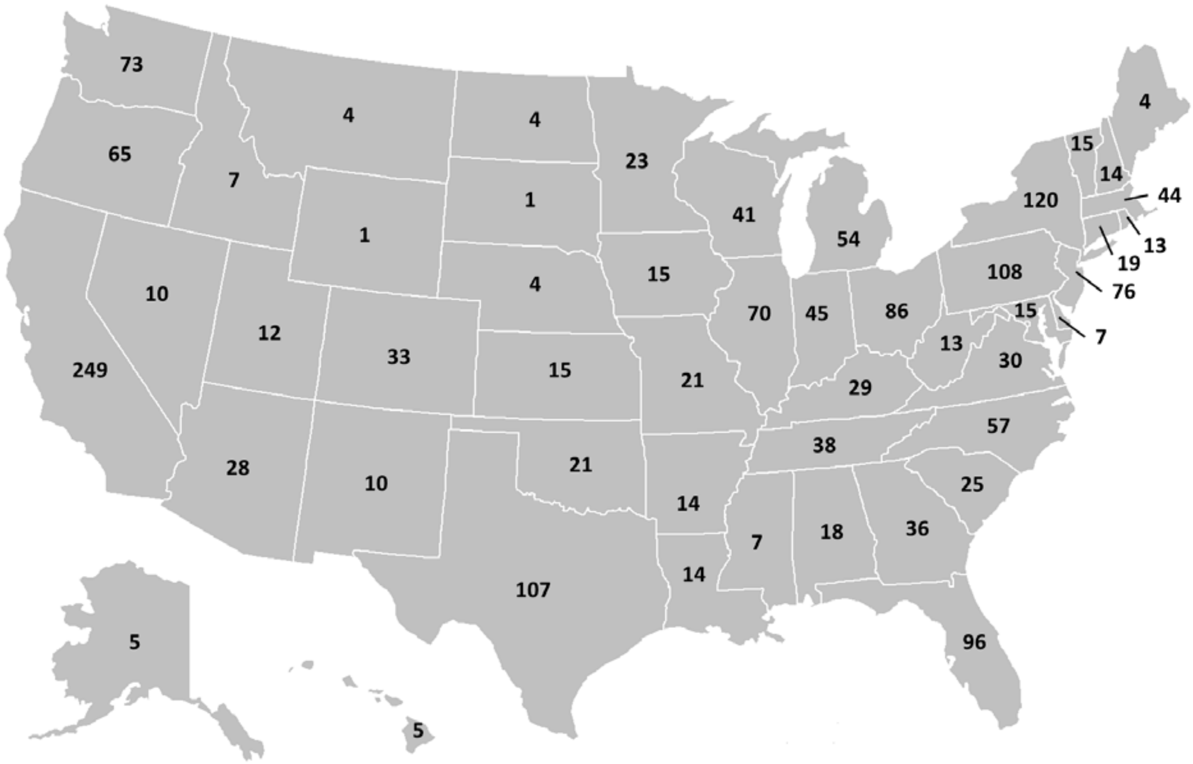


Figure 2-2. Geographic distribution of U.S. manufacturing establishments in 2010 for glass and glass product manufacturing, NAICS Code 3272. (Does not include manufacturing establishments for *Mineral Wool Manufacturing, NAICS Code 327993.)*

Source: SBA 2010

Figure 2-3 shows the glass manufacturing process schematically. The manufacturing process can be divided into four main process steps:

1) *Batch Preparation and Mixing:* Raw materials are blended, ground, and mixed before they enter the melting furnace. Raw materials can include silica, limestone, soda ash, borosilicate, additives, recycled glass (cullet), and others.
2) *Melting, Refining, and Conditioning:* Raw materials are melted in glass melting furnaces, which exist in varying sizes and designs. The melted glass is then refined—freed of bubbles and homogenized—and heat-conditioned.
3) *Forming:* Melted glass can be formed in a variety of processes, depending on the desired final shape. Forming processes include fiberization, blow forming, casting, and others.
4) *Finishing:* Formed glass may go through finishing processes, depending on the final desired characteristics and the type of glass. Finishing processes include the drying of glass wool fibers; surface treatments, such as laminating, annealing, tempering, and sizing; and others.

Total production, energy intensity and consumption, and energy savings opportunities for these steps are quantified in the remainder of this study. To ascertain the total energy consumption for a given glass product, it is necessary to first determine the energy consumption for all glass production steps, then add those subtotals. Energy intensity and consumption are evaluated by process area and sub-process for CT, SOA, PM, and TM in Chapters 3 through 6 of this report. Appendix A1 provides a summary of all data.

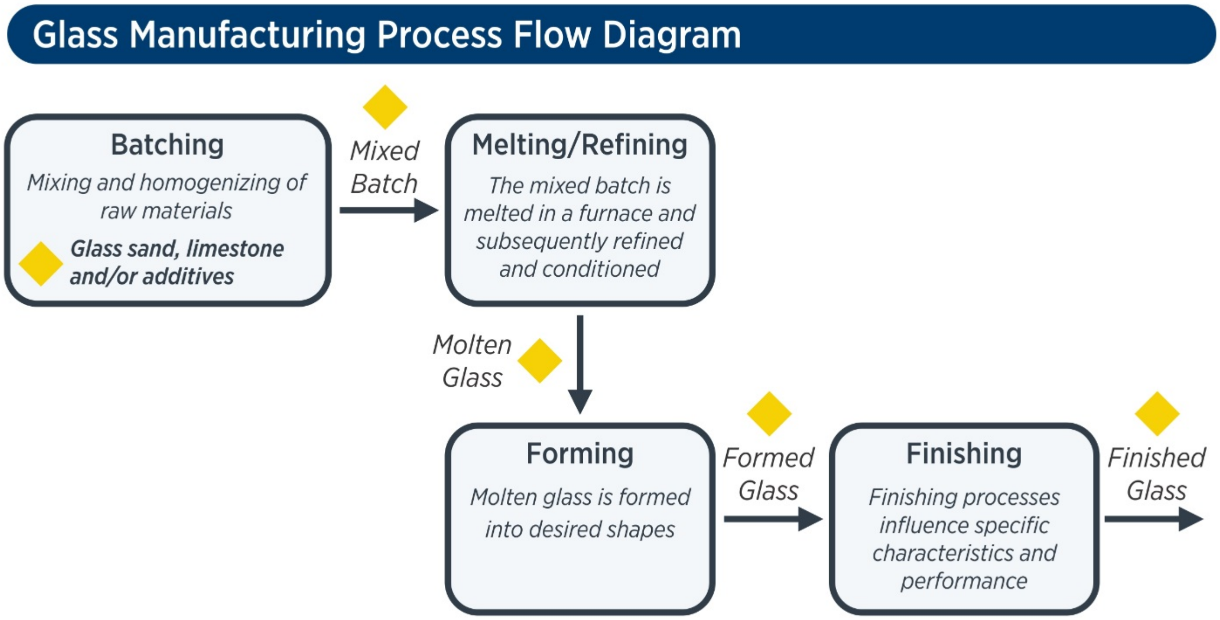


Figure 2-3. Process flow diagram for glass manufacturing
Source: EERE

## 2.3. U.S. Glass Manufacturing Energy Consumption

On-site energy and primary energy for the U.S. glass manufacturing sector are provided in Table 2-1. DOE's Manufacturing Energy Consumption Survey (MECS) provides on-site energy consumption data by end use, including on-site fuel and electricity consumption. Primary energy includes assumptions for off-site losses (DOE 2014).

Glass manufacturing accounted for 299 TBtu (1.6%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Off-site electricity and steam generation and transmission losses in glass manufacturing totaled 101 TBtu in 2010; on-site energy consumed within the boundaries of U.S. glass manufacturing plants totaled 198 TBtu. Additional detail on these CT energy consumption estimates can be found in Chapter 3.

Table 2-1. U.S. Glass Manufacturing Energy Consumption Sector-Wide, 2010

| | |
|---|---|
| **On-site Energy Consumption (includes electricity, steam, and fuel energy used on site at the facility)** | 198 TBtu |
| **Primary Energy Consumption* (includes on-site energy consumption, and off-site energy losses associated with generating electricity and steam off site and delivering to the facility)** | 299 TBtu |

Source: DOE 2014

* Primary energy accounts for off-site electricity generation and transmission losses. Off-site electrical losses are based on published grid efficiency. The Energy Information Administration (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. See Appendix A2 for energy mix assumptions.

## 2.4. U.S. Glass Manufacturing Production Values

In 2010, U.S. manufacturers produced an estimated total of 16.5 million tons of glass. Container glass accounted for almost half of the total U.S. glass production, and flat glass represented about another quarter of the total production. Estimated U.S. glass production data for 2010, by sub-product, are summarized in Table 2-2. Because no comprehensive industry or government production data are available, these estimates have been calculated using production data from years other than 2010 and adjusted to 2010 production levels using purchased fuels and electricity data from the U.S. Census Bureau, industrial production indices from the Federal Reserve Board, energy consumption data from the EIA, energy intensity by glass product from the Gas Technology Institute's 2007 Glass Bandwidth study, or a combination of these sources. Because of the uncertainties introduced using this approach, these estimates should be considered approximations. However, these approximations can provide a sense of the general production levels of each of the five glass sub-products and are also used throughout the document to estimate the energy consumption of each sub-product. More information about the approach used to estimate 2010 glass production by sub-product is available in Appendix A5.

**Table 2-2. 2010 Production of Glass by Sub-Product**

| Glass Sub-Product | 2010 Estimated U.S. Glass Production (million tons/yr)* | Estimated Percentage Share of 2010 Estimated U.S. Glass Production |
|---|---|---|
| Flat Glass | 4.4 | 26% |
| Container Glass | 8.0 | 48% |
| Glass Wool | 1.6 | 9% |
| Glass Fiber Textiles | 1.0 | 6% |
| Other Pressed and Blown Glass | 1.5 | 9% |
| **TOTAL*** | **16.5** | **100%** |

Production estimates calculated using combination of data from the following sources: AER 2012, ASM 2010, FRB 2015, Freedonia 2009, Freedonia 2013, and Rue 2007
* Totals may not add up due to rounding

# 3. Current Typical Energy Intensity and Energy Consumption for U.S. Glass Manufacturing

This chapter presents energy intensity and consumption data for the glass manufacturing processes and sector-wide, based on 2010 production data. 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 glass 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

Table 3-1 presents the key sources consulted to identify the current typical energy intensities of the sub-products and sub-processes included in this study. Each glass facility is unique, and glass is produced in different scales and by different processes; thus, it is difficult to ascertain an exact amount of energy necessary to produce a certain volume of a product. Higher efficiency is often easier to achieve in larger plants. Consequently, the values for energy intensity provided should be regarded as estimates based on the best available information.

**Table 3-1. Published Sources Reviewed to Identify Current Typical Energy Intensities for Processes Studied**

| Source Abbreviation | Description |
|---|---|
| Rue 2007 | The Glass Bandwidth Study, prepared by the Gas Technology Institute, provides a detailed breakdown of the energy use and energy intensity of the major glass sub-products and sub-processes included in this study. The authors derived a baseline from available sources and employed a Delphi approach to gather additional information to develop an energy benchmark of the glass industry. |
| Worrell 2008 | This Lawrence Berkeley National Laboratory report discusses energy efficiency practices and energy-efficient technologies that can be implemented in the glass industry. |

## 3.2. Current Typical Energy Intensity and Energy Consumption

Table 3-2 presents the estimated CT energy intensities for flat glass, container glass, glass wool, glass fibers, and other pressed and blown glass. Energy intensities for all sub-processes are presented in terms of million Btu per ton (MMBtu/ton) of finished glass. Data were drawn from a 2007 report from the Gas Technology Institute, *Industrial Glass Bandwidth Analysis* (Rue 2007), which quantified the average energy intensity of major glassmaking process steps for the five different glass industry segments. On-site CT energy intensity data were converted to primary energy data using process-specific energy mix assumptions, taking into account the relative use of electricity and fuel in each sub-process. Primary energy includes off-site energy generation and transmission losses. These assumptions are described in Appendix A2. CT energy intensity estimates for the melting of all glass sub-products were adjusted to include the energy intensity of oxygen generation. The assumptions and calculations used to make these adjustments are described in Appendix A3.

**Table 3-2. Current Typical Energy Intensities for Glass Manufacturing Sub-products and Sub-processes Studied**

| Glass Sub-Product | On-site CT Energy Intensity (MMBtu/ton) | Primary* CT Energy Intensity (MMBtu/ton) |
|---|---|---|
| **Flat Glass** | | |
| Batching | 0.68 | 2.10 |
| Melting/Refining** | 6.19 | 6.83 |
| Forming | 1.50 | 4.64 |
| Finishing | 2.20 | 3.45 |
| **Total Energy Intensity for Flat Glass*** ** | **10.57** | **17.02** |
| **Container Glass** | | |
| Batching | 0.68 | 2.10 |
| Melting/Refining ** | 5.55 | 6.85 |
| Forming | 0.12 | 0.37 |
| Finishing | 0.56 | 0.71 |
| **Total Energy Intensity for Container Glass*** ** | **6.91** | **10.04** |
| **Glass Wool** | | |
| Batching | 0.68 | 2.10 |
| Melting/Refining ** | 4.18 | 9.17 |
| Forming | 4.50 | 6.95 |
| Finishing | 2.00 | 2.21 |
| **Total Energy Intensity for Glass Fiber Wool*** ** | **11.36** | **20.43** |

**Table 3-2. Current Typical Energy Intensities for Glass Manufacturing Sub-products and Sub-processes Studied**

| Glass Sub-Product | On-site CT Energy Intensity (MMBtu/ton) | Primary* CT Energy Intensity (MMBtu/ton) |
|---|---|---|
| **Glass Fiber Textiles** | | |
| Batching | 0.68 | 2.10 |
| Melting/Refining ** | 6.39 | 7.21 |
| Forming | 1.50 | 2.32 |
| Finishing | 1.50 | 1.66 |
| **Total Energy Intensity for Flat Glass*** ** | **10.07** | **13.28** |
| **Other Pressed and Blown (Specialty) Glass** | | |
| Batching | | |
| Melting/Refining ** | 0.68 | 2.10 |
| Forming | 8.10 | 9.76 |
| Finishing | 5.30 | 16.39 |
| **Total Energy Intensity for Other Pressed and** | 3.00 | 4.18 |
| **Blown (Specialty) Glass*** ** | **17.08** | **32.44** |

*Current Typical (CT)*
* Primary energy accounts for off-site electricity 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. See Appendix A2 for energy mix assumptions.
** Adjusted to include the energy intensity of oxygen production, based on calculated energy intensities for oxygen generation and furnace type share from Rue 2007, Table 11. Assumes oxygen is produced using vacuum swing adsorption.
*** Totals may not add owing to independent rounding.

Table 3-3 presents the calculated on-site and primary CT energy consumption for the glass sub-products and the sub-processes studied. Energy consumption values were calculated by multiplying energy intensity (MMBtu/ton) by 2010 production (tons). As explained in the previous section, on-site energy intensities were converted to primary (and vice versa) using the process-specific energy mix data described in Appendix A2. Some data sources provided primary values, and others provided on-site values; off-site losses attributed to electricity generation and transmission are accounted for in the conversion between the on-site and primary.

For calculating the offsite losses when converting from primary to onsite energy, an energy mix of electricity and fuel was used based on the Manufacturing Energy Consumption Survey's (MECS) Glass Manufacturing Energy and Carbon Footprint (DOE 2014). Percent coverage is calculated by dividing the on-site CT energy consumption for the processes studied by sector-wide on-site CT energy consumption. The CT energy consumption for the four sub-processes and five sub-products studied, is estimated to account for 156 TBtu of on-site energy, or 79% of the 198 TBtu of sector-wide on-site energy use in 2010.

Glass manufacturing accounted for 299 TBtu (1.6%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Off-site electricity and steam generation and transmission losses in glass manufacturing totaled 101 TBtu in 2010; on-site energy consumed within the boundaries of U.S. glass manufacturing plants totaled 198 TBtu.

**Table 3-3. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Glass Sub-processes Studied and Sector-Wide in 2010, with Percent of Sector Coverage**

| Sub-Product/Sub-Process | On-site CT Energy Intensity (MMBtu/ton) | Production (million tons)* | On-site CT Energy Consumption (TBtu/yr) | Off-site Losses (TBtu/yr) | Primary CT Energy Consumption (TBtu/yr) | Percent Coverage (On-site CT as a % of Sector-wide Total)*** |
|---|---|---|---|---|---|---|
| **Flat Glass** | | | | | | |
| Batching | 0.68 | 4.4 | 2.97 | 6.21 | 9.18 | 1.5% |
| Melting/Ref. | 6.19 | 4.4 | 27.01 | 2.81 | 29.82 | 13.6% |
| Forming | 1.50 | 4.4 | 6.55 | 13.71 | 20.25 | 3.3% |
| Finishing | 2.20 | 4.4 | 9.60 | 5.44 | 15.05 | 4.9% |
| **Total** ** | **10.57** | **4.4** | **46.13** | **28.17** | **74.30** | **23.3%** |
| **Container Glass** | | | | | | |
| Batching | 0.68 | 8.0 | 5.43 | 11.36 | 16.79 | 2.7% |
| Melting/Ref. | 5.55 | 8.0 | 44.29 | 10.40 | 54.70 | 22.4% |
| Forming | 0.12 | 8.0 | 0.96 | 2.00 | 2.96 | 0.5% |
| Finishing | 0.56 | 8.0 | 4.47 | 1.22 | 5.69 | 2.3% |
| **Total** ** | **6.91** | **8.0** | **55.15** | **24.98** | **80.13** | **27.9%** |
| **Glass Wool** | | | | | | |
| Batching | 0.68 | 1.6 | 1.07 | 2.23 | 3.30 | 0.5% |
| Melting/Ref. | 4.18 | 1.6 | 6.56 | 7.82 | 14.37 | 3.3% |
| Forming | 4.50 | 1.6 | 7.05 | 3.84 | 10.89 | 3.6% |
| Finishing | 2.00 | 1.6 | 3.14 | 0.33 | 3.46 | 1.6% |
| **Total** ** | **11.36** | **1.6** | **17.81** | **14.21** | **32.03** | **9.0%** |
| **Glass Fiber Textiles** | | | | | | |
| Batching | 0.68 | 1.0 | 0.71 | 1.49 | 2.21 | 0.4% |
| Melting/Ref. | 6.39 | 1.0 | 6.70 | 0.86 | 7.56 | 3.4% |
| Forming | 1.50 | 1.0 | 1.57 | 0.86 | 2.43 | 0.8% |
| Finishing | 1.50 | 1.0 | 1.57 | 0.16 | 1.74 | 0.8% |
| **Total** ** | **10.07** | **1.0** | **10.56** | **3.37** | **13.93** | **5.3%** |
| **Other Pressed/ Blown (Specialty) Glass** | | | | | | |
| Batching | 0.68 | 1.5 | 1.05 | 2.20 | 3.26 | 0.5% |
| Melting/Ref. | 8.10 | 1.5 | 12.53 | 2.58 | 15.11 | 6.3% |
| Forming | 5.30 | 1.5 | 8.21 | 17.17 | 25.38 | 4.1% |
| Finishing | 3.00 | 1.5 | 4.64 | 1.83 | 6.47 | 2.3% |
| **Total** ** | **17.08** | **1.5** | **26.44** | **23.78** | **50.22** | **13.4%** |
| **Total for Sub-processes and Sub-products Studied**** | **N/A** | **16.5** | **156.09** | **94.51** | **250.61** | **78.8%** |
| All Other Sub-Processes and Sub-products | N/A | N/A | 41.91 | 6.48 | 48.39 | 21.2% |
| **Total for Glass and Glass Products Manufacturing, Sector-wide**** | **N/A** | **N/A** | **198** | **101** | **299** | **100%** |

*Current Typical (CT)*
** Analysis utilizes constant production estimates across sub-processes, neglecting intermediate product losses.*
*** Totals may not add due to independent rounding.*
**** Calculated by dividing the on-site CT energy consumption for the processes studied by sector-wide on-site CT energy consumption (198 TBtu).*

# 4. State of the Art Energy Intensity and Energy Consumption for U.S. Glass Manufacturing

This chapter estimates the energy savings possible if U.S. glass manufacturers were to adopt the best technologies and practices available worldwide. State of the art (SOA) energy intensity is considered the minimum amount of energy needed for a specific process, assuming use of best-available commercial technologies and practices.

## 4.1. Sources for State of the Art Energy Intensity

To estimate SOA energy consumption for this bandwidth analysis, a review of existing technologies used in glass manufacturing was conducted. The literature search focused on technologies or practices available today that can result in the lowest energy intensities in glassmaking as well as published SOA estimates of the glass sub-processes included in the boundaries of this analysis.

The SOA estimates for the glass melting/refining process of all glass sub-products were obtained from published studies and reports. Table 4-1 presents the published sources reviewed to identify the SOA energy intensities. For glass wool, glass fibers, and other pressed and blown glass, this study considered oxy-fuel-fired furnaces to be the SOA melting furnace type. The SOA specific energy intensity estimates, obtained from Rue 2007, were adjusted to include the energy intensity of oxygen generation. The energy intensity of cryogenic oxygen generation was used as the SOA oxygen-generation process, without consideration of its practicality for small-production furnaces. The calculations and assumptions used to estimate the energy intensity of cryogenic oxygen generation are included in Appendix A3.

For flat glass melting, the SOA furnace considered in the analysis is a regenerative furnace from a German plant, which uses exhaust gas heat recovery, no electric boosting, and 30% cullet. The SOA energy intensity estimate corresponds to the performance of the furnace at rebuild. The specific energy intensity of glass furnaces increases with age, and for furnaces with regenerative air preheating, energy intensity is estimated to increase by 2.7% per year (Gitzhofer 2007). Every 10% increase in cullet use results in an approximate 2.5% to 3% reduction in energy use in the glass melting sub-process (Scalet 2013). However, most of the recycled glass in the United States is used as cullet in the glass container sector to make bottles and jars (Van Rossum 2012). The constraints associated with cullet availability or costs were not taken into account in this analysis.

A few sources identify the SOA energy intensity for container glass melting at about 3.2–3.4 MJ/kg (2.7–2.9 MMBtu/ton). A European survey of 168 surveyed furnaces identified a container glass furnace using 50% cullet with a specific energy of 3.4 MJ/kg (2.9 MMBtu/ton) of primary energy (Beerkens 2011a), which this analysis estimates at 2.7 MMBtu/ton on an on-site energy basis.[11] A plant in Germany reported a container glass furnace with regenerative preheating achieving specific energy consumption of 2.7 MMBtu/ton at rebuild (Gitzhofer 2007). For glass containers, both oxy-fuel-fired furnaces and large regenerative furnaces with large capacities (above 331 short tons per day) can achieve the lowest energy intensities (Beerkens 2011b).

[11] A European survey of 168 surveyed furnaces identified a container glass furnace using 50% cullet with a specific energy of 3.4 MJ/kg (2.9 MMBtu/ton) of primary energy (Beerkens 2011a). The furnace type was not specified, but this study assumed it corresponds to a regenerative furnace. An assumed fuel mix of 96% fuel and 4% electricity was used to convert this data point to on-site energy intensity.

**Table 4-1. Published Sources Reviewed to Identify SOA Energy Intensities for Processes Studied**

| Source Abbreviation | Description |
|---|---|
| Beerkens 2011a | This presentation, titled "New Concepts for Energy & Emission Friendly Glass Melting: Evolution or Revolution in Glass Melting," was presented in Cairns, Australia, at the 9th International Conference on Advances in Fusion and Processing of Glass in July 2011. The paper presents an analysis of the current performance of glass furnaces used in container glass and also provides SOA estimates for furnaces in that sector. |
| Beerkens 2011b | This paper, titled "New Concepts for Energy & Emission Friendly Glass Melting: Evolution or Revolution in Glass Melting," was presented in Cairns, Australia, at the 9th International Conference on Advances in Fusion and Processing of Glass in July 2011. The paper presents an analysis of the current performance of glass furnaces used in container glass and also provides SOA estimates for furnaces in that sector. |
| Gitzhofer 2007 | This report is the German contribution to the Review of the Reference Document on Best Available Techniques in the Glass Manufacturing Industry. In preparation of this report, 16 glass melting plants in Germany, believed to be employing best available techniques in glass production, were examined. Plants specializing in the manufacture of container, flat, special glass, domestic glass, and glass fiber were examined. Energy intensities, emissions, and cost considerations at these plants are documented in the report. |
| Rue 2007 | The *Glass Bandwidth Study*, prepared by the Gas Technology Institute, provides a detailed breakdown of the energy use and energy intensity of the major glass sub-products and sub-processes included in this study. The authors derived a baseline from available sources and employed a Delphi approach to gather additional information to develop an energy benchmark of the glass industry. |
| Scalet 2013 | Produced by the European Integrated Pollution Prevention and Control Bureau, the report provides general information on the glass industry, as well as details about techniques that can be used to reduce the energy and environmental impact of glassmaking installations. |
| Worrell 2008 | This Lawrence Berkeley National Laboratory report discusses energy efficiency practices and energy-efficient technologies that can be implemented in the glass industry. |

The literature search did not unearth SOA energy intensity estimates for batching, forming, and finishing. Instead, SOA estimates were calculated by applying assumed energy savings percentages for applicable SOA technologies to the baseline CT energy intensities for each manufacturing sub-process. The SOA technologies included in this analysis and assumed energy savings were:

- **Motor re-sizing or variable speed drives (VSDs):** 12% savings in batching and forming processes
- **Process controls in forehearths (or temperature controls in tin bath, for float glass):** 3.5% savings in the forming process
- **Compressor controls for forming operations:** 10% savings in the forming process
- **Optimization of the annealing process:** 3%–38% savings in the finishing process

Appendix A4 provides a discussion of these energy savings estimates and sources, as well as details of additional technologies that were considered but not included in the final SOA calculations. For example, some technologies were excluded because they were considered incompatible with other SOA technologies included in the analysis. As noted earlier, SOA values were not estimated for glass melting/refining and were instead obtained from published studies. However, Appendix A4 lists technologies applicable to glass melting as well. In some cases, the energy savings estimates listed above are shown as ranges because opportunities may differ among the glass sub-products included in the analysis. Additional details about these opportunities are presented in Appendix A4.

## 4.2. State of the Art Energy Intensity and Energy Consumption

Table 4-2 presents the SOA energy intensities and calculated on-site SOA energy consumption for the glass sub-products studied. Energy intensities for all glass products and sub-processes are presented in terms of million Btu per ton (MMBtu/ton) of finished glass. Energy consumption values were calculated by multiplying energy intensity (MMBtu/ton) by 2010 production (tons).

Table 4-3 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each glass sub-product and sub-process, and as a total. In this table, the SOA energy consumptions for the processes studied are also summed and extrapolated to provide a sector-wide on-site SOA energy consumption. To extrapolate the data for all other processes that is shown in the table, the PM energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire sector (79%, see Table 3-3). The difference between the CT and SOA energy consumption values is presented as the SOA energy savings (or current opportunity).

**Table 4-2. State of the Art Energy Intensity and Calculated On-site Energy Consumption for Glass Manufacturing Sub-products and Sub-areas Studied**

| Glass Sub-Product | On-site SOA Energy Intensity (MMBtu/ton) | Production, 2010 (million tons)* | On-site SOA Energy Consumption, Calculated (TBtu/yr) |
|---|---|---|---|
| **Flat Glass** | | | |
| Batching | 0.60 | 4.4 | 2.63 |
| Melting/Ref. | 4.34 | 4.4 | 18.94 |
| Forming | 1.28 | 4.4 | 5.59 |
| Finishing | 2.15 | 4.4 | 9.36 |
| **Total**** | **8.37** | **4.4** | **36.52** |
| **Container Glass** | | | |
| Batching | 0.60 | 8.0 | 4.80 |
| Melting/Ref. | 2.70 | 8.0 | 21.57 |
| Forming | 0.09 | 8.0 | 0.74 |
| Finishing | 0.35 | 8.0 | 2.77 |
| **Total**** | **3.74** | **8.0** | **29.88** |
| **Glass Wool** | | | |
| Batching | 0.60 | 1.6 | 0.94 |
| Melting/Ref. | 2.99 | 1.6 | 4.68 |
| Forming | 3.84 | 1.6 | 6.02 |
| Finishing | 1.94 | 1.6 | 3.04 |
| **Total**** | **9.37** | **1.6** | **14.69** |
| **Glass Fiber Textiles** | | | |
| Batching | 0.60 | 1.0 | 0.63 |
| Melting/Ref. | 3.59 | 1.0 | 3.76 |
| Forming | 1.28 | 1.0 | 1.34 |
| Finishing | 1.46 | 1.0 | 1.53 |
| **Total**** | **6.93** | **1.0** | **7.27** |

**Table 4-2. State of the Art Energy Intensity and Calculated On-site Energy Consumption for Glass Manufacturing Sub-products and Sub-areas Studied**

| Glass Sub-Product | On-site SOA Energy Intensity (MMBtu/ton) | Production, 2010 (million tons)* | On-site SOA Energy Consumption, Calculated (TBtu/yr) |
|---|---|---|---|
| **Other Pressed and Blown (Specialty) Glass** | | | |
| Batching | 0.60 | 1.5 | 0.93 |
| Melting/Ref. | 5.94 | 1.5 | 9.19 |
| Forming | 4.07 | 1.5 | 6.31 |
| Finishing | 1.98 | 1.5 | 3.07 |
| **Total**** | **12.59** | **1.5** | **19.50** |
| **Total for Sub-processes and Sub-products Studied***** | | **16.5** | **107.86** |

*State of the Art (SOA)*
* Analysis Utilizes constant production estimates across sub-processes, neglecting intermediate product losses.
** Adjusted to include the energy intensity of oxygen generation.
*** Totals may not add owing to independent rounding.
Note: A European survey of 168 surveyed furnaces identified a container glass furnace using 50% cullet with a specific primary energy of 3.4 MJ/kg (2.9 MMBtu/ton) of primary energy (Beerkens 2011a). The furnace type was not specified, but this study assumes it corresponds to a regenerative furnace. An assumed fuel mix of 96% fuel and 4% electricity was used to convert this data point to on-site energy intensity.

**Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Glass Manufacturing in Sub-Processes Studied and Sector-Wide**

| Sub-Product/Sub-Process | On-site CT Energy Consumption, Calculated (TBtu/yr) | On-site SOA Energy Consumption, Calculated (TBtu/yr) | SOA Energy Savings* (CT - SOA) (TBtu/yr) | SOA Energy Savings Percent** (CT - SOA)/ (CT - TM) |
|---|---|---|---|---|
| **Flat Glass** | | | | |
| Batching | 2.97 | 2.63 | 0.34 | 11.5% |
| Melting/Ref. | 27.01 | 18.94 | 8.07 | 45.9% |
| Forming | 6.55 | 5.59 | 0.96 | 11.2% |
| Finishing | 9.60 | 9.36 | 0.24 | 1.6% |
| **Total ** ** | **46.13** | **36.52** | **9.61** | **21.8%** |
| **Container Glass** | | | | |
| Batching | 5.43 | 4.80 | 0.62 | 11.5% |
| Melting/Ref. | 44.29 | 21.57 | 22.72 | 85.3% |
| Forming | 0.96 | 0.74 | 0.22 | 4.6% |
| Finishing | 4.47 | 2.77 | 1.70 | 11.5% |
| **Total ** ** | **55.15** | **29.88** | **25.26** | **48.9%** |
| **Glass Wool** | | | | |
| Batching | 1.07 | 0.94 | 0.12 | 11.5% |
| Melting/Ref. | 6.56 | 4.68 | 1.87 | 54.8% |
| Forming | 7.05 | 6.02 | 1.03 | 13.1% |
| Finishing | 3.14 | 3.04 | 0.09 | 1.9% |
| **Total ** ** | **17.81** | **14.69** | **3.12** | **18.0%** |

**Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Glass Manufacturing in Sub-Processes Studied and Sector-Wide**

| Sub-Product/Sub-Process | On-site CT Energy Consumption, Calculated (TBtu/yr) | On-site SOA Energy Consumption, Calculated (TBtu/yr) | SOA Energy Savings* (CT - SOA) (TBtu/yr) | SOA Energy Savings Percent** (CT - SOA)/ (CT - TM) |
|---|---|---|---|---|
| **Glass Fiber Textiles** | | | | |
| Batching | 0.71 | 0.63 | 0.08 | 11.5% |
| Melting/Ref. | 6.70 | 3.76 | 2.94 | 66.2% |
| Forming | 1.57 | 1.34 | 0.23 | 12.0% |
| Finishing | 1.57 | 1.53 | 0.05 | 1.6% |
| **Total **** | **10.56** | **7.27** | **3.30** | **32.9%** |
| **Other Pressed/ Blown (Specialty) Glass** | | | | |
| Batching | 1.05 | 0.93 | 0.12 | 11.5% |
| Melting/Ref. | 12.53 | 9.19 | 3.34 | 36.1% |
| Forming | 8.21 | 6.31 | 1.90 | 21.5% |
| Finishing | 4.64 | 3.07 | 1.58 | 25.2% |
| **Total **** | **26.44** | **19.50** | **6.94** | **27.3%** |
| **Total for Sub-processes and Sub-products Studied** | **156.09** | **107.86** | **48.23** | **32.5%** |
| All Other Sub-Processes and Sub-products | 41.91 | 28.96 | 12.95 | 32.5% |
| **Total for Glass and Glass Products Manufacturing, Sector-wide** | **198** | **136.82** | **61.18** | **32.5%** |

*Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)*
* SOA energy savings is also called current opportunity.
** SOA energy savings percentage is the SOA energy savings opportunity from transforming glass production processes through the adoption of SOA equipment and practices. Energy savings percentage is calculated using the TM energy consumption shown in Table 6-1 as the minimum energy consumption. The energy savings percentage, with TM as the minimum, is calculated as follows: SOA Energy Savings Percentage = (CT - SOA)/(CT - TM).
*** SOA adjusted to include the energy intensity of oxygen generation.
**** Totals may not add owing to independent rounding.
***** The sector-wide SOA energy consumption was an extrapolated value, calculated by dividing the total on-site SOA energy consumption for the processes studied by the overall percent coverage from Table 3-3 (79%).

The SOA energy savings percent in Table 4-3 is the percent of energy saved with SOA energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in Chapter 6, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating the energy savings percentage provides the most accurate measure of absolute savings potential. The equation for calculating the on-site SOA energy savings percentage is:

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

It is useful to consider both TBtu energy savings and energy savings percentage when comparing energy savings opportunities. Both are good measures of opportunity; however, the conclusions are not always the same. A small percentage energy reduction in a process that consumes a large amount of energy may result in a larger total savings than a large percentage reduction in a process that consumes a relatively smaller amount of energy. Glass melting/refining represents the greatest *current opportunity,* in terms of the percentage of energy savings, which ranges from 36% to 85%, depending on the glass sub-product. The greatest *current opportunity*, in terms of TBtu savings, is container glass melting/refining at 22.7 TBtu per year savings.

If all U.S. glass producers (based on the 2010 production level) were able to attain SOA energy intensities, this analysis estimates that a total of 48.2 TBtu of on-site energy could be saved annually, corresponding to a 32.5% energy savings overall. This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings; not all existing plants could necessarily achieve these SOA values. No assessment was made in this study regarding whether the improvements would prove to be cost-effective in all cases.

# 5. Practical Minimum Energy Intensity and Energy Consumption for U.S. Glass Manufacturing

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway to make glass in new ways, improving energy efficiency as well as performance. Commercialization of these improvements will drive the competitiveness of U.S. glass manufacturing. In this chapter, the energy savings possible through R&D advancements and emerging technologies in glass 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

R&D progress is difficult to predict, and the realization of potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a review of R&D activities in glass manufacturing was conducted. The focus of this search was applied research and emerging technologies, defined as the investigation and development of new technologies with the intent of accomplishing a particular commercial objective. The study did not consider basic science research, which involves experimentation and modeling to expand understanding of fundamental mechanisms and principles without a direct link to commercial objectives. Further, applied R&D technologies without a clear connection to manufacturing energy consumption were also not considered.

The PM energy intensity data for melting/refining flat glass, container glass, glass wool, and glass fibers were derived from published studies. Table 5-1 presents the key sources consulted to identify PM energy intensities in glass manufacturing. Additionally, numerous other papers, articles, and websites were reviewed. A more detailed listing of references is provided in Appendix A4.

For flat glass, glass wool, glass fibers, and other pressed and blown glass, oxy-fuel-fired furnaces were identified as the PM melting furnace type, but the estimates identified in the literature did not include the energy intensity of oxygen generation. The SOA specific energy intensity estimates derived from Rue 2007, were adjusted to include the energy intensity of oxygen generation. The energy intensity of cryogenic oxygen generation was used as the SOA oxygen-generation process, without consideration of its practicality for small-production furnaces. The calculations and assumptions used to estimate the energy intensity of cryogenic oxygen generation are included in Appendix A3.

For flat glass, PM melting intensities could be achieved with oxygen-fired furnaces with improvements in refining and continued evolution in controls (Rue 2007). In container glass melting, PM energy intensity levels could be approached using batch preheating and high-cullet levels on the most efficient furnaces, oxy-fuel-fired furnaces and large-capacity regenerative furnaces (Beerkens 2011b). PM in glass wool and glass fiber melting would require the use of extensive batch preheating (Beerkens 2011b). The PM energy intensity for other pressed and blown glass was not found in the literature search and was calculated by applying assumed energy savings percentages to the SOA estimate for other pressed and blown glass, identified in Table 4-2. The PM technologies included in that estimate, and assumed energy savings, were:

- **Increased cullet rate:** 10% savings in the melting/refining process
- **Batch and cullet preheating:** 15% savings in the melting/refining process

In theory, batch and cullet preheating systems could be used on any glass melting furnace using at least 50% cullet in the batch mix. Preheating of batch mix without cullet use is not considered proven technology, and preheating of a batch and cullet mixture is more complicated than the preheating of cullet only. Because of these limitations, batch and cullet preheating is performed almost exclusively in the container glass sector (Scalet 2013).

**Table 5-1. Published Sources Reviewed to Identify PM Energy Intensities for Processes Studied**

| Source Abbreviation | Description |
|---|---|
| Beerkens 2011a | This presentation, titled "New Concepts for Energy & Emission Friendly Glass Melting: Evolution or Revolution in Glass Melting," was presented in Cairns, Australia, at the 9th International Conference on Advances in Fusion and Processing of Glass in July 2011. The paper presents an analysis of the current performance of glass furnaces used in container glass and also provides SOA estimates for furnaces in that sector. |
| Beerkens 2011b | This paper, titled "New Concepts for Energy & Emission Friendly Glass Melting: Evolution or Revolution in Glass Melting," was presented in Cairns, Australia, at the 9th International Conference on Advances in Fusion and Processing of Glass in July 2011. The paper presents an analysis of the current performance of glass furnaces used in container glass and also provides SOA estimates for furnaces in that sector. |
| Gitzhofer 2007 | This report is the German contribution to the Review of the Reference Document on Best Available Techniques in the Glass Manufacturing Industry. In preparation of this report, 16 glass melting plants in Germany, believed to be employing best available techniques in glass production, were examined. Plants specializing in the manufacture of container, flat, special glass, domestic glass, and glass fiber were examined. Energy intensities, emissions, and cost considerations at these plants are documented in the report. |
| Rue 2007 | The Glass Bandwidth Study, prepared by the Gas Technology Institute, provides a detailed breakdown of the energy use and energy intensity of the major glass sub-products and sub-processes included in this study. The authors derived a baseline from available sources and employed a Delphi approach to gather additional information to develop an energy benchmark of the glass industry. |
| Scalet 2013 | Produced by the European Integrated Pollution Prevention and Control Bureau, the report provides general information on the glass industry, as well as details about techniques that can be used to reduce the energy and environmental impact of glassmaking installations. |
| Worrell 2008 | This Lawrence Berkeley National Laboratory report discusses energy efficiency practices and energy-efficient technologies that can be implemented in the glass industry. |

The literature search did not unearth PM energy intensity estimates for batching, forming, and finishing. Instead, PM energy intensity was estimated for glass by applying assumed energy savings percentages for applicable PM technologies to the baseline CT energy intensities for each manufacturing sub-process. The PM technologies included in this analysis and assumed energy savings were:

- **Motor re-sizing or VSDs:** 12% savings in batching and forming processes
- **New grinding technologies:** 6% savings in the batching process
- **Process controls in forehearths (or temperature controls in tin bath, for float glass):** 3.5% savings in the forming process
- **Compressor controls for forming operations:** 10% savings in the forming process
- **More efficient forehearths or oxy-fuel-fired forehearths:** 4%–12% savings in the forming process
- **Optimization of the annealing process**: 3%–38% savings in the finishing process
- **Improved fiber drying systems:** 30% savings in the finishing process

- **Radio frequency laminating in autoclaves:** 5%–30% savings in the finishing process
- **New tempering technology with more efficient quenching:** 19% savings in the finishing process

In some cases, the energy savings estimates listed above are shown as ranges because opportunities may differ among the glass sub-products included in the analysis. Note that because the baseline of the PM analysis corresponds to CT energy intensities, some of the technologies used to estimate PM energy intensities were also used to calculate SOA energy intensities. Therefore, in some cases, achieving PM may be attainable by using a combination of SOA and PM technologies. However, in other cases, the PM technology replaces or is not compatible with the SOA technology, and the PM estimate is based solely on PM technology. Appendix A4 provides a discussion of the PM energy savings estimates and sources, as well as details of additional technologies that were considered but not included in the final PM calculations.

## 5.2. Practical Minimum Energy Intensity and Energy Consumption

Table 5-2 presents the estimated PM energy intensities and calculated on-site PM energy consumption for the glass sub-products and sub-processes studied. Energy consumption values were calculated by multiplying energy intensity (MMBtu/ton) by 2010 production (tons).

Table 5-3 presents a comparison of the on-site CT energy consumption and PM energy consumption for each sub-product and sub-process, and as a total. The difference between the CT and PM energy consumption values is presented as the PM energy savings (or the sum of the *current opportunity* plus the *R&D opportunity*). In Table 5-3, data is extrapolated to estimate the total PM opportunity. To extrapolate the data for all other processes that is shown in the table, the PM energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire sector (79%, see Table 3-3). Table 5-4calculates the R&D opportunity for the processes studied and sector-wide opportunity.

The R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. The PM energy savings percentage in Table 5-3 is the percentage 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). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating the energy savings percentage provides the most accurate measure of absolute savings potential. The equations for calculating the on-site R&D opportunity and PM energy savings percentage are:

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

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

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

**Table 5-2. Practical Minimum Energy Intensities and Calculated On-site Energy Consumption for Glass Manufacturing Sub-Products and Sub-processes Studied**

| Sub-Product/Sub-Process | On-site PM Energy Intensity (MMBtu/ton) | Production, 2010 (million tons)* | On-site PM Energy Consumption, Calculated (TBtu/yr) |
|---|---|---|---|
| **Flat Glass** | | | |
| Batching | 0.57 | 4.4 | 2.50 |
| Melting/Ref. | 3.84 | 4.4 | 16.76 |
| Forming | 1.23 | 4.4 | 5.37 |
| Finishing | 1.66 | 4.4 | 7.24 |
| **Total**** | **7.30** | **4.4** | **31.86** |
| **Container Glass** | | | |
| Batching | 0.57 | 8.0 | 4.56 |
| Melting/Ref. | 2.46 | 8.0 | 19.67 |
| Forming | 0.09 | 8.0 | 0.71 |
| Finishing | 0.35 | 8.0 | 2.77 |
| **Total**** | **3.47** | **8.0** | **27.71** |
| **Glass Wool** | | | |
| Batching | 0.57 | 1.6 | 0.90 |
| Melting/Ref. | 2.49 | 1.6 | 3.90 |
| Forming | 3.38 | 1.6 | 5.30 |
| Finishing | 1.40 | 1.6 | 2.19 |
| **Total**** | **7.84** | **1.6** | **12.29** |
| **Glass Fiber Textiles** | | | |
| Batching | 0.57 | 1.0 | 0.60 |
| Melting/Ref. | 3.19 | 1.0 | 3.34 |
| Forming | 1.13 | 1.0 | 1.18 |
| Finishing | 1.05 | 1.0 | 1.10 |
| **Total**** | **5.94** | **1.0** | **6.23** |
| **Other Pressed and Blown (Specialty) Glass** | | | |
| Batching | 0.57 | 1.5 | 0.89 |
| Melting/Ref. | 4.54 | 1.5 | 7.03 |
| Forming | 3.91 | 1.5 | 6.05 |
| Finishing | 1.98 | 1.5 | 3.07 |
| **Total**** | **11.00** | **1.5** | **17.04** |
| **Total for Sub-processes and Sub-products Studied***** | | **16.5** | **95.13** |

*Practical Minimum (PM)*
*Analysis utilizes constant production estimates across sub-processes, neglecting intermediate product losses.
** Totals may not add owing to independent rounding.
*** Adjusted to include the energy intensity of oxygen generation.
Note: A European survey of 168 surveyed furnaces identified that the specific energy of 3.1 MJ/kg (2.7 MMBtu/ton) of primary energy could be achieved in the most efficient container glass furnaces using batch and cullet preheating and a high cullet rate (Beerkens 2011a). The furnace type was not specified, but this study assumed it corresponds to a regenerative furnace. An assumed fuel mix of 96% fuel and 4% electricity was used to convert this data point to on-site energy intensity.

**Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Glass Manufacturing in Processes Studied and Sector-Wide**

| Sub-Product/Sub-Process | On-site CT Energy Consumption, Calculated (TBtu/yr) | On-site PM Energy Consumption, Calculated (TBtu/yr) | PM Energy Savings* (CT - PM) (TBtu/yr) | PM Energy Savings Percent** (CT - PM)/ (CT - TM) |
|---|---|---|---|---|
| **Flat Glass** | | | | |
| Batching | 2.97 | 2.50 | 0.47 | 15.9% |
| Melting/Ref. | 27.01 | 16.76 | 10.26 | 58.3% |
| Forming | 6.55 | 5.37 | 1.18 | 13.8% |
| Finishing | 9.60 | 7.24 | 2.36 | 15.7% |
| **Total **** | **46.13** | **31.86** | **14.27** | **32.3%** |
| **Container Glass** | | | | |
| Batching | 5.43 | 4.56 | 0.86 | 15.9% |
| Melting/Ref. | 44.29 | 19.67 | 24.62 | 92.5% |
| Forming | 0.96 | 0.71 | 0.25 | 5.2% |
| Finishing | 4.47 | 2.77 | 1.70 | 11.5% |
| **Total **** | **55.15** | **27.71** | **27.44** | **53.1%** |
| **Glass Wool** | | | | |
| Batching | 1.07 | 0.90 | 0.17 | 15.9% |
| Melting/Ref. | 6.56 | 3.90 | 2.66 | 77.8% |
| Forming | 7.05 | 5.30 | 1.75 | 22.2% |
| Finishing | 3.14 | 2.19 | 0.94 | 19.0% |
| **Total **** | **17.81** | **12.29** | **5.52** | **31.9%** |
| **Glass Fiber Textiles** | | | | |
| Batching | 0.71 | 0.60 | 0.11 | 15.9% |
| Melting/Ref. | 6.70 | 3.34 | 3.36 | 75.7% |
| Forming | 1.57 | 1.18 | 0.39 | 20.3% |
| Finishing | 1.57 | 1.10 | 0.47 | 15.9% |
| **Total **** | **10.56** | **6.23** | **4.34** | **43.2%** |
| **Other Pressed/ Blown (Specialty) Glass** | | | | |
| Batching | 1.05 | 0.89 | 0.17 | 15.9% |
| Melting/Ref. | 12.53 | 7.03 | 5.50 | 59.5% |
| Forming | 8.21 | 6.05 | 2.15 | 24.4% |
| Finishing | 4.64 | 3.07 | 1.58 | 25.2% |
| **Total **** | **26.44** | **17.04** | **9.40** | **37.0%** |
| **Total for Sub-processes and Sub-products Studied** | **156.09** | **95.13** | **60.96** | **41.0%** |
| All Other Sub-Processes and Sub-products | 41.91 | **25.54** | **16.37** | **41.0%** |
| **Total for Glass and Glass Products Manufacturing, Sector-wide** | **198** | **120.67** | **77.33** | **41.0%** |

*Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)*

* PM energy savings is the current opportunity plus the R&D opportunity.

** PM energy savings percentage is the PM energy savings opportunity from transforming glass production processes through the adoption of SOA equipment and practices. Energy savings percentage is calculated using the 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: PM Energy Savings Percent = (Current - PM)/(Current - TM).

*** PM values adjusted to include the energy intensity of oxygen generation.

**** Totals may not add owing to independent rounding.

***** The sector-wide PM energy consumption was an extrapolated value, calculated by dividing the total on-site PM energy consumption for the processes studied by the overall percent coverage from Table 3-3 (79%).

**Table 5-4. On-site Practical Minimum Energy Consumption, R&D Energy Savings, and R&D Energy Savings Percent for Glass Manufacturing in Processes Studied and Sector-Wide**

| Sub-Product/Sub-Process | On-site SOA Energy Consumption, Calculated (TBtu/yr) | On-site PM Energy Consumption, Calculated (TBtu/yr) | R&D Energy Savings (SOA - PM) (TBtu/yr) | R&D Energy Savings Percent* (SOA - PM)/ (CT - TM) |
|---|---|---|---|---|
| Total for Sub-processes and Sub-products Studied | 107.86 | 95.13 | 12.73 | 8.6% |
| Total for Glass and Glass Products Manufacturing, Sector-wide | 136.82 | 120.67 | 16.15 | 8.6% |

*Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)*
* Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (SOA - PM)/(CT - TM).
** The sector-wide PM energy consumption was an extrapolated value, calculated by dividing the total on-site PM energy consumption for the processes studied by the overall percent coverage from Table 3-3 (79%).

Among the processes studied, the greatest *current opportunity* plus *R&D opportunity* in terms of the percentage of energy savings is glass melting/refining at 58% to 93% energy savings, depending on the glass sub-product. The greatest *current opportunity* plus *R&D opportunity* in terms of TBtu savings is container glass melting/refining at 24.6 TBtu per year savings.

If all U.S. glass producers (based on the 2010 production levels) were able to attain PM energy intensities, it is estimated that a total of 61 TBtu of on-site energy could be saved annually, corresponding to a 41% energy savings overall, over the CT baseline. This energy savings estimate assumes the adoption of the PM technologies and practices described in this report. This is a simple estimate for potential savings, as the PM technologies considered are unproven, and not all existing plants could necessarily deploy all of the practices considered. No assessment was made in this study regarding whether the improvements would prove to be cost-effective in all cases, nor whether satisfactory glass product performance could be achieved via the PM processes.

# 6. Thermodynamic Minimum Energy Intensity and Energy Consumption for U.S. Glass Manufacturing

Real-world manufacturing does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture glass 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 sub-processes studied.

TM energy consumption, which is based on Gibbs free energy 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 that involve 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).

## 6.1. Thermodynamic Minimum Energy Intensity

The TM 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.[12] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[13] Changes in surface energy were not considered in the TM analysis.

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

For glass manufacturing, only the batching processes were considered to have zero TM energy intensity. The TM energy for these processes was estimated on the basis of a constant heat capacity.

The sub-process steps have TM values that are driven mostly by the composition of the material and the starting and ending temperatures of the process. For example, the melting and refining step is assumed to start with standard conditions (25°C) and end at the temperature of the refining step (1500°C). The forming step ends at a temperature between 1000°C and 1100°C, depending on the exact product formed. In the forming and finishing steps, enthalpy is recovered as the products return to lower temperatures and back to standard conditions, respectively. The net change in energy from all the process steps is the heat of reaction for the reactions that have occurred to make the final product and the change in entropy of the products versus the reactants (Gibbs free energy). This is dependent on the type of glass produced, which influences the raw materials used and the final composition of the product.

[12] Unless otherwise noted, "ideal conditions" means a pressure of 1 atmosphere and a temperature of 77°F.
[13] Exergonic (reaction is favorable) and endergonic (reaction is not favorable) are thermodynamic terms describing the 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).

## 6.2. Thermodynamic Minimum Energy Intensity and Energy Consumption

Table 6-1 provides the TM energy intensity and the calculated TM energy consumption for the glass sub-products and sub-processes studied. Energy consumption values were calculated by multiplying energy intensity (MMBtu/ton) by the 2010 production volume (tons). The table also presents the extrapolated TM energy consumption for the entire sector. The extrapolation for sector-wide TM energy consumption is done with the same methodology as for SOA energy consumption and PM energy consumption. Estimates for the entire sector were extrapolated by dividing the on-site TM energy consumption for the processes studied by the overall percent coverage of 79% (see Table 3-3).

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 food and beverage products requiring an energy intensive transformation (e.g., melting/refining), 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.

**Table 6-1. Thermodynamic Minimum Energy Intensities and On-site Energy Consumption for Glass Manufacturing by Process and Sector-Wide for the Sub-products and Sub-Processes Studied**

| Glass Sub-Product | TM Energy Intensity^ (MMBtu/ton) | Production, 2010 (million tons)* | TM Energy Consumption, Calculated (TBtu/yr) |
|---|---|---|---|
| **Flat Glass** | | | |
| Batching | 0.00 | 4.4 | 0.00 |
| Melting/Ref. | 2.16 | 4.4 | 9.42 |
| Forming | -0.46 | 4.4 | -2.02 |
| Finishing | -1.25 | 4.4 | -5.44 |
| **Total**** | **0.45** | **4.4** | **1.95** |
| **Container Glass** | | | |
| Batching | 0.00 | 8.0 | 0.00 |
| Melting/Ref. | 2.21 | 8.0 | 17.66 |
| Forming | -0.48 | 8.0 | -3.85 |
| Finishing | -1.30 | 8.0 | -10.35 |
| **Total**** | **0.43** | **8.0** | **3.46** |
| **Glass Wool** | | | |
| Batching | 0.00 | 1.6 | 0.00 |
| Melting/Ref. | 2.00 | 1.6 | 3.14 |
| Forming | -0.53 | 1.6 | -0.83 |
| Finishing | -1.16 | 1.6 | -1.82 |
| **Total**** | **0.31** | **1.6** | **0.49** |
| **Glass Fiber Textiles** | | | |
| Batching | 0.00 | 1.0 | 0.00 |
| Melting/Ref. | 2.16 | 1.0 | 2.26 |
| Forming | -0.33 | 1.0 | -0.35 |
| Finishing | -1.32 | 1.0 | -1.39 |
| **Total**** | **0.50** | **1.0** | **0.53** |
| **Other Pressed and Blown (Specialty) Glass** | | | |
| Batching | 0.00 | 1.5 | 0.00 |
| Melting/Ref. | 2.12 | 1.5 | 3.29 |
| Forming | -0.39 | 1.5 | -0.61 |
| Finishing | -1.06 | 1.5 | -1.63 |
| **Total**** | **0.68** | **1.5** | **1.05** |
| **Total for Sub-processes and Sub-products Studied***** | **N/A** | **16.5** | **7.47** |

*Thermodynamic Minimum (TM)*
^ See preceding discussion in text for description of methodology.
* Analysis utilizes constant production estimates across sub-processes, neglecting intermediate product losses.
** Totals may not add owing to independent rounding.
*** Estimates for the entire sector were extrapolated by dividing the on-site TM energy consumption for the processes studied by the overall percent coverage of 79% (see from Table 3-3).

# 7. U.S. Glass Manufacturing Current and R&D Opportunity Analysis/Bandwidth Summary

This chapter presents the energy savings bandwidths for the glass manufacturing sub-products and sub-processes studied and sector-wide based on the analysis and data presented in the previous Chapters and the following Appendices. Data is presented for the five sub-products studied and extrapolated to estimate the energy savings potential for all of U.S. glass manufacturing.

Table 7-1 summarizes the *current opportunity* and *R&D opportunity* energy savings (on site) for the glass sub-products and sub-processes studied, based on 2010 glass production. The savings are also and extrapolated to estimate the sector total and the process totals are summed to provide a sector-wide estimate. Glass production is broken down into its four sub-processes (batching, melting/refining, forming, and finishing).

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

- *Current Opportunity*. 48.2 TBtu per year of energy savings could be realized if SOA technologies and practices are deployed.
- *R&D Opportunity*. 12.7 TBtu per year of additional 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).

To complete all of the U.S. glass and glass products sector processes (based on extrapolated data), the analysis shows the following:

- *Current Opportunity*. 61.2 TBtu per year of energy savings could be realized if SOA technologies and practices are deployed.
- *R&D Opportunity*. 16.2 TBtu per year of additional 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 these two on-site 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. The *impractical* bandwidth, or the difference between the PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in glass manufacturing. The term *impractical* is used because the PM energy consumption is based on current knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. The TM energy consumption is based on ideal conditions that are unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

**Table 7-1. Current and R&D Opportunities for Energy Savings in the Sub-Products and Sub-Processes Studied, and Extrapolated to Sector-Wide Total (On site)**

| Sub-Product/Sub-process | Current Opportunity (CT-SOA) (TBtu/yr) | R&D Opportunity (SOA-PM) (TBtu/yr) |
|---|---|---|
| **Flat Glass** | | |
| Batching | 0.34 | 0.13 |
| Melting/Ref. | 8.07 | 2.18 |
| Forming | 0.96 | 0.22 |
| Finishing | 0.24 | 2.12 |
| **Total *** | **9.61** | **4.66** |
| **Container Glass** | | |
| Batching | 0.62 | 0.24 |
| Melting/Ref. | 22.72 | 1.90 |
| Forming | 0.22 | 0.03 |
| Finishing | 1.70 | 0.00 |
| **Total *** | **25.26** | **2.17** |
| **Glass Wool** | | |
| Batching | 0.12 | 0.05 |
| Melting/Ref. | 1.87 | 0.78 |
| Forming | 1.03 | 0.72 |
| Finishing | 0.09 | 0.85 |
| **Total *** | **3.12** | **2.40** |
| **Glass Fiber Textiles** | | |
| Batching | 0.08 | 0.03 |
| Melting/Ref. | 2.94 | 0.42 |
| Forming | 0.23 | 0.16 |
| Finishing | 0.05 | 0.42 |
| **Total *** | **3.30** | **1.04** |
| **Other Pressed and Blown (Specialty) Glass** | | |
| Batching | 0.12 | 0.05 |
| Melting/Ref. | 3.34 | 2.16 |
| Forming | 1.90 | 0.25 |
| Finishing | 1.58 | 0.00 |
| **Total *** | **6.94** | **2.46** |
| **Total for Sub-processes and Sub-products Studied*** | **48.23** | **12.73** |
| All Other Sub-processes and Sub-products | 12.95 | 3.42 |
| **Total for Glass and Glass Products Manufacturing, Sector-wide (extrapolated)**** | **61.18** | **16.15** |

*Current typical (CT), state of the art (SOA), practical minimum (PM)*
* Totals may not add owing to independent rounding.
** The sector-wide energy SOA and PM values are extrapolated values, calculated by dividing the total on-site SOA and PM energy consumptions for the processes studied by the overall percent coverage from Table 3-3 (79%).

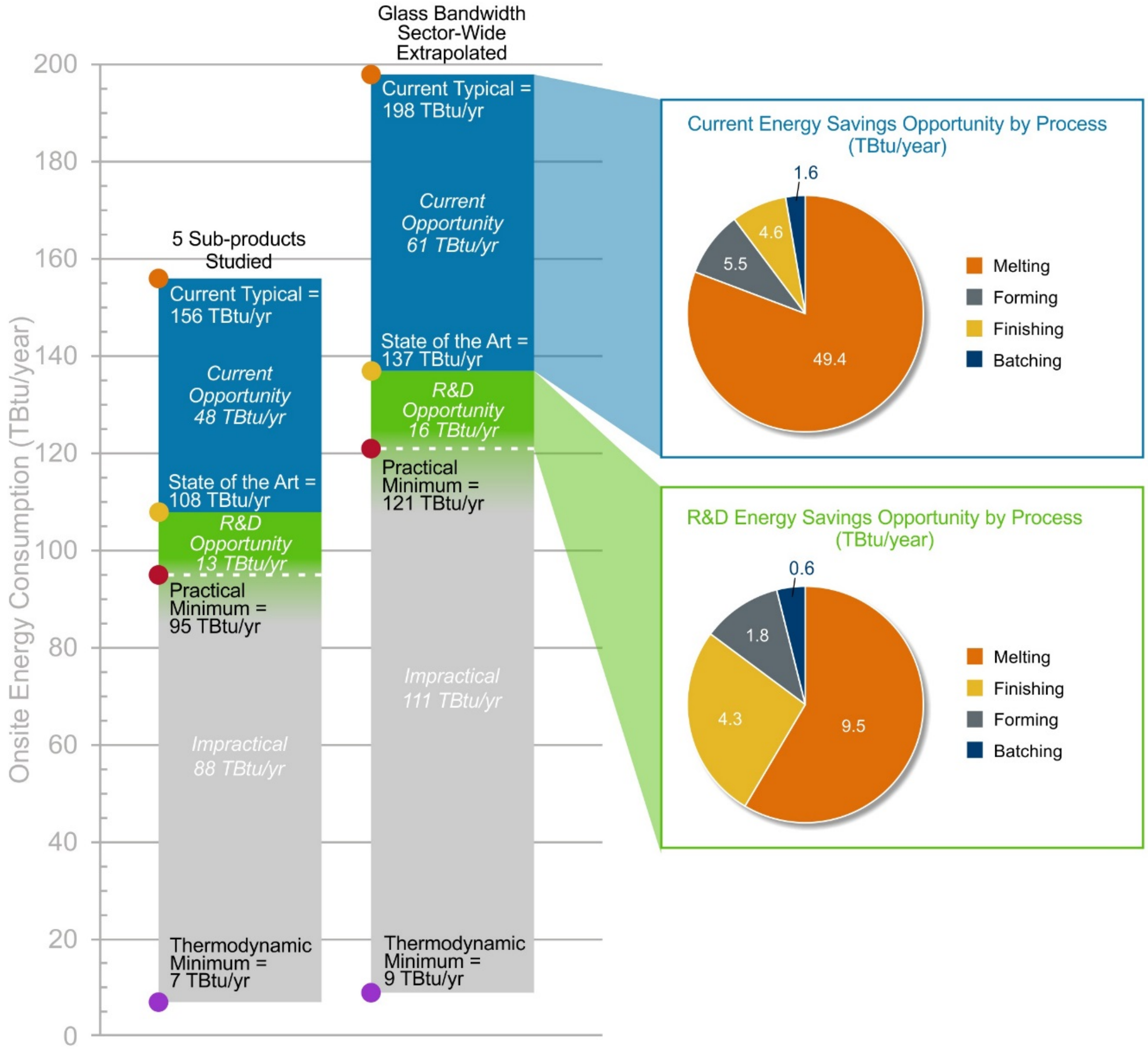


Figure 7-1. Current and R&D energy savings opportunities for the processes studied and for glass and glass products manufacturing (sector-wide), based on extrapolated data

Source: EERE

The results presented show that 48.2 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade the four glass manufacturing sub-processes included in this study; an additional 12.7 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

However, if the energy savings potential is estimated for the U.S. glass manufacturing industry as a whole, the current energy savings opportunity is 61.2 TBtu per year and the R&D opportunity increases to 16.2 TBtu per year.

The savings opportunities by process are different for each glass sub-product, and the above estimates correspond to the total energy savings opportunities for all sub-products included in this study. Based on the bandwidth analysis, the greatest *current and R&D opportunities* for glass manufacturing involve more efficient glass melting/refining. On-site energy savings in glass melting/refining account for 81% of the *current opportunity* and 58% of the *R&D opportunity*. Because of its high energy intensity compared to other processes in glass manufacturing, most of the industry's energy-saving efforts have focused on improvements in the melting process.

Energy savings opportunities that do not involve glass melting/refining represent about 19% of the *current opportunity* and 42% of the *R&D opportunity*. Current opportunities include best practices, such as motor re-sizing, the use of variable speed drives, and the use of process controls. R&D opportunities include new technologies for grinding batch and cullet, forming glass in forehearths, drying glass fibers, finishing flat glass, and others. Appendix A4 includes a full list of technologies included or excluded from the analysis.

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# Appendix A1. Master Glass Manufacturing Summary Tables

**Table A1-1. On-site Energy Intensity and Energy Consumption Estimates for Glass Manufacturing, Based on 2010 Production Estimates**

| Sub-Product/Sub-Process | 2010 Production (million tons) | Estimated On-site Energy Intensity (MMBtu/ton) | | | | Calculated On-site Energy Consumption (TBtu/yr) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CT | SOA | PM | TM | CT | SOA | PM | TM |
| **Flat Glass** | | | | | | | | | |
| Batching | 4.4 | 0.68 | 0.60 | 0.57 | 0.00 | 2.97 | 2.63 | 2.50 | 0.00 |
| Melting/Refining | | 6.19 | 4.34 | 3.84 | 2.16 | 27.01 | 18.94 | 16.76 | 9.42 |
| Forming | | 1.50 | 1.28 | 1.23 | -0.46 | 6.55 | 5.59 | 5.37 | -2.02 |
| Finishing | | 2.20 | 2.15 | 1.66 | -1.25 | 9.60 | 9.36 | 7.24 | -5.44 |
| Total Flat Glass Production* | | 10.57 | 8.37 | 7.30 | 0.45 | 46.13 | 36.52 | 31.86 | 1.95 |
| **Container Glass** | | | | | | | | | |
| Batching | 8.0 | 0.68 | 0.60 | 0.57 | 0.00 | 5.43 | 4.80 | 4.56 | 0.00 |
| Melting/Refining | | 5.55 | 2.70 | 2.46 | 2.21 | 44.29 | 21.57 | 19.67 | 17.66 |
| Forming | | 0.12 | 0.09 | 0.09 | -0.48 | 0.96 | 0.74 | 0.71 | -3.85 |
| Finishing | | 0.56 | 0.35 | 0.35 | -1.30 | 4.47 | 2.77 | 2.77 | -10.35 |
| Total Container Glass Production* | | 6.91 | 3.74 | 3.47 | 0.43 | 55.15 | 29.88 | 27.71 | 3.46 |
| **Glass Wool** | | | | | | | | | |
| Batching | 1.6 | 0.68 | 0.60 | 0.57 | 0.00 | 1.07 | 0.94 | 0.90 | 0.00 |
| Melting/Refining | | 4.18 | 2.99 | 2.49 | 2.00 | 6.56 | 4.68 | 3.90 | 3.14 |
| Forming | | 4.50 | 3.84 | 3.38 | -0.53 | 7.05 | 6.02 | 5.30 | -0.83 |
| Finishing | | 2.00 | 1.94 | 1.40 | -1.16 | 3.14 | 3.04 | 2.19 | -1.82 |
| Total Glass Wool Production* | | 11.36 | 9.37 | 7.84 | 0.31 | 17.81 | 14.69 | 12.29 | 0.49 |
| **Glass Fiber Textiles** | | | | | | | | | |
| Batching | 1.0 | 0.68 | 0.60 | 0.57 | 0.00 | 0.71 | 0.63 | 0.60 | 0.00 |
| Melting/Refining | | 6.39 | 3.59 | 3.19 | 2.16 | 6.70 | 3.76 | 3.34 | 2.26 |
| Forming | | 1.50 | 1.28 | 1.13 | -0.33 | 1.57 | 1.34 | 1.18 | -0.35 |
| Finishing | | 1.50 | 1.46 | 1.05 | -1.32 | 1.57 | 1.53 | 1.10 | -1.39 |
| Total Glass Fiber Textiles Production* | | 10.07 | 6.93 | 5.94 | 0.50 | 10.56 | 7.27 | 6.23 | 0.53 |
| **Other Pressed and Blown Glass** | | | | | | | | | |
| Batching | 1.5 | 0.68 | 0.60 | 0.57 | 0.00 | 1.05 | 0.93 | 0.89 | 0.00 |
| Melting | | 8.10 | 5.94 | 4.54 | 2.12 | 12.53 | 9.19 | 7.03 | 3.29 |
| Forming | | 5.30 | 4.07 | 3.91 | -0.39 | 8.21 | 6.31 | 6.05 | -0.61 |
| Finishing | | 3.00 | 1.98 | 1.98 | -1.06 | 4.64 | 3.07 | 3.07 | -1.63 |

### Table A1-1. On-site Energy Intensity and Energy Consumption Estimates for Glass Manufacturing, Based on 2010 Production Estimates

| Sub-Product/Sub-Process | 2010 Production (million tons) | Estimated On-site Energy Intensity (MMBtu/ton) | | | | Calculated On-site Energy Consumption (TBtu/yr) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CT | SOA | PM | TM | CT | SOA | PM | TM |
| Total Other Pressed and blown Glass Production* | | 17.08 | 12.59 | 11.00 | 0.68 | 26.44 | 19.50 | 17.04 | 1.05 |
| **Total for Sub-processes and Sub-products Studied*** | **16.5** | | | | | **156.09** | **107.86** | **95.13** | **7.47** |
| All Other Processes | | | | | | 41.91 | 28.96 | 25.54 | 2.00 |
| **Total for Glass and Glass Products Manufacturing, Sector-wide**** | | | | | | **198.00** | **136.82** | **120.67** | **9.47** |

* Totals may not add owing to independent rounding.
**Estimates for the entire sector were extrapolated by dividing the on-site TM energy consumption for the processes studied by the overall percent coverage of 79% (see Table 3-3).

# Appendix A2. Energy Mix Assumptions

The fuel and electricity requirements for manufacturing processes depend strongly on the specifics of the process: motor-driven processes such as conveyer belts and mixers typically use mostly electric energy, whereas thermal processes generally use mostly fuel energy. In this study, energy mixes were assumed for each sub-process to maximize the accuracy of conversions between on-site and primary energy intensity and consumption (Table A2-1). These energy mixes were generally drawn from the same sources that were used for baseline energy intensity data. Normally the steam generation and transmission losses would be accounted for when converting from on-site to primary energy consumption, but the sources used in this report did not provide that level of detail for the fuel energy data provided. Consequently, the primary energy intensities may be considered conservative, as they contain only off-site electricity generation and transmission losses.

An electricity generation efficiency of 32.3% was used to calculate off-site electricity generation losses. The formula used to convert between on-site and primary consumption is as follows:

$$E_{primary} = E_{onsite}\left(f_{fuel} + \frac{f_{elec}}{\varepsilon}\right)$$

where $E_{primary}$ and $E_{on\text{-}site}$ are the primary and on-site energy consumption values (or energy intensities), respectively; $f_{fuel}$ and $f_{elec}$ are the fractions of fuel and electricity usage for the process, respectively; and $\varepsilon$ is the electricity generation efficiency.

**Table A2-1. Energy Mix Assumptions for Glass Manufacturing Processes**

| Sub-Product/Sub-Process | Current Typical | | Data Sources |
|---|---|---|---|
| | Fuel % | Electric % | |
| **Flat Glass Production** | | | |
| Batching | 0.0% | 100.0% | Rue 2007 |
| Melting/Refining | 95.0% | 5.0% | Rue 2007* |
| Forming | 0.0% | 100.0% | Rue 2007 |
| Finishing | 72.9% | 27.1% | Worrell 2008 |
| **Container Glass Production** | | | |
| Batching | 0.0% | 100.0% | Rue 2007 |
| Melting/Refining | 88.8% | 11.2% | Worrell 2008* |
| Forming | 0% | 100.0% | Rue 2007 |
| Finishing | 87.0% | 13.0% | Rue 2007 |
| **Glass Wool Production** | | | |
| Batching | 0.0% | 100.0% | Rue 2007 |
| Melting/Refining | 43.0% | 57.0% | Worrell 2008* |
| Forming | 74.0% | 26.0% | Rue 2007 |
| Finishing | 95.0% | 5.0% | Rue 2007 |
| **Glass Fiber Textiles Production** | | | |
| Batching | 0.0% | 100.0% | Rue 2007 |
| Melting/Refining | 93.9% | 6.1% | Worrell 2008* |
| Forming | 74% | 26% | Rue 2007 |

**Table A2-1. Energy Mix Assumptions for Glass Manufacturing Processes**

| Sub-Product/Sub-Process | Current Typical | | Data Sources |
|---|---|---|---|
| | Fuel % | Electric % | |
| Finishing | 95.0% | 5.0% | Rue 2007 |
| **Other Pressed and Blown Glass** | | | |
| Batching | 0.0% | 100.0% | Rue 2007 |
| Melting | 90.2% | 9.8% | Worrell 2008* |
| Forming | 0.0% | 100.0% | Worrell 2008 |
| Finishing | 81.2% | 18.8% | Rue 2007 |

*Adjusted to include estimated fuel mix of oxygen production, based on calculated energy intensities for oxygen generation and furnace type share from Rue 2007, Table 11. Assumes oxygen is produced using vacuum swing adsorption.

# Appendix A3. Calculated Energy Intensity of Oxygen Production

Some of the current average, state of the art, and practical minimum estimates for glass melting used in this study involve the use of oxygen-gas burners instead of conventional air-gas burners. In cases where the published data sources used in the analysis did not include the energy used to make oxygen, energy intensity estimates for glass melting were adjusted to include the energy intensity of oxygen generation.

There are three main processes currently used to produce oxygen, namely vacuum swing absorption (VSA), cryogenic air separation, and pressure swing absorption (PSA). The energy intensity of these processes differs considerably, and the preferred process used by each plant depends on its size and volume of production. The cryogenic oxygen production process has the lowest energy intensity of the three approaches, but is mainly used for large production volumes. Smaller production volumes commonly use the VSA or PSA methods (Rue 2007). VSA is the second least energy-intensive oxygen production process, and PSA is the most energy-intensive. Because the cryogenic process has the highest efficiency of the three processes, adjustments made in this study to the state of the art and practical minimum melting/refining energy intensities assume that oxygen is produced on site using the cryogenic process, without taking into consideration its practicality for small glass-production volumes. Adjustments made in this study to the current average melting/refining energy intensities assume that oxygen is produced on site using either the VSA process or the cryogenic process.

Table A3-1 shows the data used to estimate the on-site energy intensity of oxygen production using the VSA and PSA processes, by glass product area. The estimated energy required to make oxygen is multiplied by the tons of oxygen used per ton of glass product to estimate the required energy, per ton of glass, needed to produce oxygen. On average, this analysis estimates the energy intensity of oxygen generation using the VSA and PSA processes at 0.8 MMBtu/ton of glass and 0.9 MMBtu/ton of glass respectively, with variations depending on the glass sub-product.

Similarly, Table A3-2 shows the data used to estimate the on-site energy intensity of oxygen production using the cryogenic process, by glass sub-product. The analysis assumes that SOA cryogenic oxygen generation requires 0.75 MMBtu of electricity per ton of oxygen (NETL 2007). On average, this analysis estimates the energy intensity of oxygen generation using the cryogenic process at 0.3 Btu/ton of glass.

**Table A3-1. Calculated On-site Energy Intensity of VSA and PSA Oxygen Production**

| **Sub-Product** | **Tons of oxygen per ton of glass*** | | **Furnace capacity** (tons per day)* | **Electricity Consumption VSA Process** (MMBtu/ton of oxygen)** | **Electricity Consumption PSA Process** (MMBtu/ton of oxygen)** | **Calculated Energy Intensity of VSA Oxygen Generation** (MMBtu/ton of glass) | **Calculated Energy Intensity of PSA Oxygen Generation** (MMBtu/ton of glass) |
|---|---|---|---|---|---|---|---|
| | **Min** | **Max** | | | | | |
| Specialty | 0.4 | 0.5 | 20-180 | 2.1 | 2.6 | 1.1 | 1.4 |
| Fiberglass | 0.2 | 0.3 | 40-120 | 2.1 | 2.6 | 0.6 | 0.8 |
| Container | 0.25 | 0.35 | 100-350 | 2.1 | 2.6 | 0.7 | 0.9 |
| Float | 0.4 | 0.5 | 400-600 | 2.1 | 2.6 | 1.1 | 1.4 |
| **Average** | **0.3** | **0.4** | | **2.1** | **2.6** | **0.8** | **0.9** |

* Source: ACS 1993

**Source: Rue 2007

### Table A3-2. Calculated On-site Energy Intensity of Cryogenic Oxygen Production

| Sub-Product | Tons of oxygen per ton of glass* | | Furnace capacity (tons per day)* | Electricity Consumption Cryogenic Process (MMBtu/ton of oxygen)** | Calculated Energy Intensity of Cryogenic Oxygen Generation (MMBtu/ton of glass) |
|---|---|---|---|---|---|
| | Min | Max | | | |
| Specialty | 0.4 | 0.5 | 20-180 | 0.75 | 0.3 |
| Fiberglass | 0.2 | 0.3 | 40-120 | 0.75 | 0.2 |
| Container | 0.25 | 0.35 | 100-350 | 0.75 | 0.3 |
| Float | 0.4 | 0.5 | 400-600 | 0.75 | 0.4 |
| **Average** | **0.3** | **0.4** | | **0.75** | **0.3** |

* Source: ACS 1993

**Source: NETL 2007. Electricity consumption of 220 kWh/ton of oxygen (at 99% oxygen purity) converted to Btu/ton of oxygen using an energy conversion factor of 3.412 Btu per kWh.

# Appendix A4. State of the Art and Practical Minimum (R&D) Technologies Considered

The state of the art (SOA) and practical minimum (PM) energy intensity for glass manufacturing was determined based on the technologies outlined in Table A4-1. The applicability column indicates the sub-process to which the technology is considered for application. The percentage savings over the PM baseline is estimated, along with a brief explanation (note that the PM baseline energy intensity is considered equal to the SOA energy intensity in this study). Some technologies in Table A4-1 were considered but not included in the final SOA and/or PM calculations. In some cases, the excluded technologies were considered incompatible with other technologies already included in the calculations. In some cases, SOA and or PM values were obtained from published reports, and new values were not calculated; for example, SOA and PM values for the melting/refining process for flat glass, container glass, glass wool, and glass fibers were obtained from published reports. In cases in which SOA or PM glass melting/refining involved oxy-fuel furnaces, the values from the published reports were recalculated to include the energy needed for oxygen generation.

In cases where more than one technology was considered for a given sub-product or sub-process, the following calculation was used:

$$PM = PMBaseline * [(1 - P_1) * (1 - P_2) * \dots * (1 - P_n)]$$

where *PM* is the practical minimum energy intensity, *PMBaseline* is the baseline energy intensity (i.e., the SOA energy intensity), and $P_1$, $P_2$, … $P_n$ are the percent savings for each of the *n* PM technologies included in the model. Energy savings from different technologies were not considered additive; rather, this formula considers technologies as compounding when more than one is applicable to a certain sub-process.

## Table A4-1. Details of State of the Art and Practical Minimum Technologies Considered

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Motor re-sizing or VSDs | Motors and pumps that are improperly sized cause energy losses that could be avoided with an appropriately sized motor or a variable speed drive motor. | Batching/ Forming | Worrell et al. state typical energy savings of 8%–15% from VSDs for conveyer belt systems used in glass batching. The range was averaged to come up with an overall savings of 11.5% for batching, which is an all-electric process. This savings estimate was also used to calculate savings in forming processes. | 11.5% | Yes | Yes | Worrell 2008; Worrell 2010 |
| New Grinding Technology (such as fine grinding of glass with centrifugal ball mill) | Use of more efficient grinding technology, such as centrifugal ball mills with vertical axis and continuous operation (RM mills) | Batching | Sommariva *et al.* reported 15% lower specific energy consumption for RM mills, compared to continuous and horizontal axis ball mills.<br>This analysis assumes that grinding technology is used for cullet, assumes cullet use of 50%, and assumes grinding and milling accounts for 80% of cullet batch preparation energy intensity. Therefore, a 15% reduction in grinding and milling energy equates to 15%*40%*80% = a 5% of total batching energy use reduction. | 5% | No | Yes | Sommariva 2015 |
| Increased cullet rate | Use of cullet can reduce melting energy requirements | Melting | It is estimated that a 2.5% reduction in melting energy use results from every 10% increase in cullet. The analysis assumed a 10% savings. Note that the benefits of this technology occur in the melting stage, although it is implemented during batching. | 10% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting PM energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Yes for other pressed and blown glass PM glass melting energy intensity. | Worrell 2008; Scalet 2013 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Reduced batch wetting | A small quantity of water is added to the glass batch to reduce dust and prevent separation and non-homogeneity in the batch during transport, but this water increases energy use because it must be evaporated in the furnace. Reducing water content saves energy. | Melting | Worrell et al. indicated that a 1% reduction in the moisture content can provide fuel savings of 0.5% in the glass melting furnace. | 1% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br><br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |
| Batch and cullet preheating and other waste heat recovery | In batch and cullet preheating, waste heat from the furnace is used to preheat the incoming cullet batch, reducing energy losses.<br><br>Waste heat can also be used to preheat combustion air, for thermo-chemical recuperation, or to generate steam or power. | Melting | Worrell et al. estimated energy savings of 12% for batch and cullet preheating, when installed in an oxy-fuel glass melting furnace. | 12% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated | Glass melting PM energy intensity estimates for flat glass, container glass, glass wool, and glass fibers were obtained from the literature and were not calculated. However, literature estimates obtained for flat glass, glass wool, and glass fiber textiles mention that PM could be achieved with batch and cullet preheating.<br><br>Yes for other pressed and blown glass PM glass melting energy intensity. | Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Minimization of excess air in furnace | Non-optimal air/fuel ratios reduce furnace efficiencies. Reduction of excess air in the furnace reduces energy consumption. | Melting | Worrell et al. reported that the glass manufacturer Lax & Shaw (U.K.) demonstrated an energy savings of 12% from improved sealing and insulation. | 12% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |
| Low-NOx burner | Low-NOx burners can provide increased heat transfer rates and reduced flame temperatures, increasing furnace efficiency. | Melting | Worrell et al. reported that Air Liquide (France) had demonstrated a 5% savings from this technology compared to conventional oxy-fuel burners. | 5% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Improved heat transfer/ containment | Energy losses could be minimized through improved furnace technologies, including better insulation, sealing, and pressure control. | Melting | Worrell et al. reported typical savings of 5%–10% from cleaning heat transfer surfaces, 4%–12% from ceramic-coated furnace tubes, 2%–5% from better insulation, 5%–10% from controlling furnace pressure, and 0%–5% from maintaining door and tube seals. SOA glass melting ovens are assumed to be carefully pressure-controlled already, owing to process requirements. Summation of the remaining savings opportunities gives a range of 11%–29% savings. This was averaged to come up with an energy savings of 20%. | 20% | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2010 |
| Microwave melting | Microwave energy is used to selectively heat and melt the glass. | Melting | Actual energy savings of this emerging technology are unclear. | Unspecified | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Process heating control systems | Advanced sensors and control systems enable continuous monitoring and optimization of heat inputs for fuel savings. | Melting/ glass wool and glass fiber finishing (drying) | Worrell et al. reported energy savings of 2%–3% for glass melting furnaces. A 3% savings was assumed for glass melting and glass fiber drying. | 3% | Yes for glass wool and glass fiber finishing (drying).<br><br>No. Glass melting SOA energy intensity estimates for all other glass sub-products were obtained from the literature and were not calculated. | Yes for glass wool and glass fiber finishing (drying).<br><br>Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br><br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |
| Segmented glass melter | In the segmented melter, the batch is melted in an electric melter, after which the cullet is added in a separate oxy-fuel-fired melter. This results in lower emissions and increased thermal efficiency. | Melting | Demonstrated 4.0 MMBtu/ton (4.66 MJ/kg) for flat glass. Energy use reported explicitly (4.66 MJ/kg). Note: the reported energy use for this emerging technology is actually higher than the reported SOA energy use. | N/A | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Energy use reported explicitly (4.66 MJ/kg). Note: the reported energy use for this emerging technology is actually higher than the reported SOA energy use. | Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Submerged combustion melting | In submerged combustion melting, fuels are fired directly into and under the surface of the batch material being melted. Placing the burners in the bottom of the glass furnace results in improved heat transfer and vigorous convective stirring of the melt. The reduction in energy intensity is mainly achieved by a reduction in residence time in the furnace, as the system allows for a segmented melting approach" | Melting | Worrell et al. reported that the savings are estimated at 5%–7.5% when compared to an SOA oxy-fuel furnace and depend on the utilization of heat losses from the furnace wall. | Averaged range of 5%–7.5% to arrive at 6.3% savings | No. Glass melting SOA energy intensity estimates for all glass sub-products were obtained from the literature and were not calculated. | Glass melting energy intensity estimates for flat glass, container glass, glass wool and glass fibers were obtained from the literature and were not calculated.<br>Not used to calculate the energy intensity of other pressed and blown glass. | Worrell 2008 |
| Process controls in forehearths | Process controls in forehearths, such as gob weight in container glass, tin bath temperature in float glass, and quality controls reduce the number of rejects while increasing productivity and saving energy. | Forming | Estimated savings, depending on the process control technology and the project, have been documented at 2%-5%. Worrell et al. reported that the Rexam container glass plant in Dongen (the Netherlands) installed one of the first of these systems and was able to reduce fuel consumption of the plant by 5%.<br>Averages of 2% and 5% have been reported. This analysis assumes an average of 3.5% intensity savings. | 3.5% | Yes | Yes | Worrell 2008 |
| Compressor controls for forming operations | Modulating or throttling controls allows the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied to centrifugal and rotary screw compressors. Control loop positioning is also important. | Forming | Worrell et al. states that energy savings for sophisticated compressor controls have been reported at around 12% annually. | 10% | Yes for container and other pressed and blown glass. | Yes for container and other pressed and blown glass. | Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| More efficient forehearths or oxy-fuel-fired forehearths | The replacement of existing forehearths for more energy-efficient units can result in energy savings during the process. | Forming | There are several energy savings estimates; some as high as 70%. This analysis assumes energy savings of 40% (a more conservative estimate). It also assumes that forehearths account for 30% of all forming energy use for glass fibers and 10% for flat, container, and pressed and blown glass. Therefore savings are estimated as 40% x 30% = 12% for glass fibers and 40% x 10% = 4% for flat, container, and pressed and blown glass. | 12% for glass fibers; 4% for flat, container, and pressed and blown glass. | No | Yes | Worrell 2008; Linde 2016;<br><br>Praxair 2012 |
| Improved fiber drying and curing | After quenching molten glass during fiberization, water must be removed in a time-consuming drying process. Advanced drying technology can significantly reduce drying time and energy consumption of the process. | Finishing (glass wool and glass fiber) | Worrell et al. reported that the Viox Corporation was able to reduce drying time from 58–72 hours to 11 hours per batch. Adasen Machinery claims 50% energy savings in drying glass fibers with microwave ovens. Stalam claims that radio frequency dryers for glass fibers can “dry down to a residual moisture content below 0.1% in a time range of approx. 2 to 4 hours (depending on the winding density and the fiber count) instead of the 20–30 hours usually required by conventional hot air circulation ovens.”<br><br>Worrell et al. mentions that microwave heating can result in savings of 30%–50%. PNNL 1986, pg. 3.32, states that fiberglass post-forming, including drying and curing, account for 10% of total energy used for textile fibers and 12% for wool fibers. This analysis assumes 30% energy savings in wool and glass fiber finishing using advanced drying technologies that are less energy-intensive or that require less drying time. | 30%* | No | Yes for glass wool and glass fiber drying (on-site only). | Stalam 2016;<br><br>Adasen Machinery 2016; Worrell 2008 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| Radio frequency laminating in autoclaves | Radio frequency lamination can reduce the energy intensity of conventional autoclave lamination by reducing the processing time and energy needs of the process. | Finishing (flat glass) | According to Allan et al. 2011, RF technology has been used to laminate single-pane glass laminates in less than one minute and multilayer transparent armor panels (up to 3 inches thick) in just five minutes. This compares to process times of 1–6 hours using autoclaves and provides an energy savings of over 90%.<br>This analysis assumes savings of 90% in autoclaves for flat glass finishing. Rue 2007, pg. 12, states that autoclaves consume 5% of finishing energy use in flat glass. Therefore, the estimated savings are 90% x 5% = 4.5% of flat glass finishing operations. Note that Rue 2007, pg. 12, shows that 80% of all autoclave energy is from fuel. It is unclear whether switching to radio frequency laminating (a technology based on electricity use) would be beneficial on a primary energy basis. | 4.5% | No | Yes for flat glass (on-site). | Allan et al. 2011 |
| Optimization of annealing process | Energy savings could be achieved by changing the technological annealing process, investing in adjustments of the annealing lehr, conveyors, receivers, burners, control systems, product loaders, insulation, etc. | | Voldřich F. 2007 states that the combined energy savings achieved through adjustments of the annealing lehr, conveyors, receivers, burners, control systems, product loaders, insulation, etc. are estimated at 50% for annealing processes. This analysis assumes annealing accounts for 75% of container glass finishing energy use (Rue 2007, pg. 14), 68% of specialty glass finishing energy use (Rue 2007, pg. 15), and 5% of flat glass finishing energy use (Worrell 2008, pg. 22). Therefore, energy intensity reductions are estimated as 50% x 5%=2.5% for flat glass; 50% x 75%=38% for container glass, 50% x 68%=34% for specialty glass. | 2.5% for flat glass; 38% for container glass; 34% for specialty glass | Yes for flat glass, container glass, and other pressed and blown glass. | Yes for flat glass, container glass, and other pressed and blown glass. | Voldřich 2007 |

| Technology Name | Description | Applicability | Explanation of Energy Savings Assumptions | Percent Savings Estimate | Included in SOA Calculations | Included in PM Calculations | Reference |
|---|---|---|---|---|---|---|---|
| New tempering technology with more efficient quenching | Emerging glass tempering technology design with higher convective heat transfer coefficient for a given amount of air pressure can enables glass tempering with less air pressure and power. | Finishing (flat glass) | According to (GlasstechWorld 2013) new high-efficiency quench technology reduces the required quench power on 3.1mm glass by 50%.<br>According to Worrell (2008), Table 9, tempering accounts for 75% of all flat glass finishing energy use. And, according to Kuusela K. 2015, the quench accounts for almost the same amount of energy as heating in thinner glasses. Therefore, this analysis assumes that the new technology reduces quenching energy consumption by 50%, quenching accounts for 50% of all tempering energy, and tempering accounts for 75% of flat glass finishing. Therefore, energy intensity savings can be estimated at: 0.5 x 0.5 x 0.75 = 19% of all flat glass finishing. | 19% | No | Yes for flat glass. | Glasstech World 2013; Kuusela K. 2015 |

# Appendix A5. Estimated Glass Production

2010 production estimates for the glass sub-product areas included in this study were not available from a comprehensive industry or government source. Instead, production estimates for the year 2010 were calculated by adjusting production or demand data available for other years, using calculated adjustment factors. These adjustments were made using purchased fuels and electricity data from the U.S. Census Bureau, industrial production indices from the Federal Reserve Board, energy consumption data from the U.S. Department of Energy's Energy Information Administration, energy intensity by glass product from the Gas Technology Institute's 2007 Glass Bandwidth study, or a combination of these sources. Because this approach introduces uncertainties, these estimates should be considered approximations. However, these approximations can provide a sense of the general production levels of each of the five glass sub-products and are also used throughout the document to estimate the energy consumption of each sub-product. The calculations used to estimate the 2010 U.S. glass production by sub-product is summarized in Table A5-1.

**Table A5-1. Estimated Glass Production**

| Glass Sub-Product | Base Data | Base Data Source | Conversion to 2010, Description | Base Year Parameters | 2010 Parameters | Percentage Change | Estimated Production in 2010 (million tons/year) |
|---|---|---|---|---|---|---|---|
| Flat Glass (Production) | 2006 U.S. flat glass production (million pounds/year): 11,684 | Freedonia 2013 | A 2006 flat glass production data point from a 2013 Freedonia report was multiplied by the calculated percent change in total energy use (ASM) between 2006 and 2010, to estimate the 2010 production. | Total energy use in 2006: 63.82 TBtu | Total energy use in 2010: 47.65 TBtu | -25.4% | 4.4 |
| Container Glass (Production) | 2007 U.S. container glass production (million pounds/year): 18,012 | GPI 2010 | A 2007 container glass production data point from the Glass Packaging Institute was adjusted using the percent change in Industrial Production Indices (Federal Reserve Data) between 2007 and 2010, to estimate the 2010 production. | Industrial Production Index in 2007: 114.23 | Industrial Production Index in 2010: 101.14 | -11.5% | 8.0 |

| Glass Sub-Product | Base Data | Base Data Source | Conversion to 2010, Description | Base Year Parameters | 2010 Parameters | Percentage Change | Estimated Production in 2010 (million tons/year) |
|---|---|---|---|---|---|---|---|
| Glass Wool (Demand) | 2008 U.S. glass wool demand (million pounds/year): 8,113 | Freedonia 2009; ASM 2010a | A 2008 data point from a 2009 Freedonia report was multiplied by the percent change in electricity purchases for mineral wool manufacturing between 2008 and 2010, to estimate the 2010 production. | Electricity purchases in 2008: 3,846,138 thousand kWh | Electricity purchases in 2010: 3,273,972 Thousand kWh | -14.9% | 1.6 |
| Glass Fiber Textiles (Demand) | 2008 U.S. glass fiber textile demand (million pounds/year): 5,412 | Freedonia 2009; ASM 2010a | A 2008 data point from a 2009 Freedonia report was multiplied by the percent change in electricity purchases for pressed and blown glass products between 2008 and 2010, to estimate the 2010 production. | Electricity purchases in 2008: 3,162,244 thousand kWh | Electricity purchases in 2010: 2,699,974 Thousand kWh | -14.6 | 1.0 |
| Other Pressed and Blown Glass (Specialty Glass) | 1) 2010 calculated energy intensity of other pressed and blown glass: 17.08 MMBtu/ton<br>2) Energy consumption of pressed and blown glass sector: 37 TBtu/yr<br>3) Calculated energy consumption of glass fiber textiles: 10.56 TBtu/yr | 1) Calculated, see Table A1-1<br>2) MECS 2010<br>3) Calculated, see Table A1-1 | The calculated energy consumption for glass fiber textiles was subtracted from the on-site energy consumption for pressed and blown glass from MECS (2010), to estimate the energy consumption for other pressed and blown glass. The average energy intensity from Rue 2007 (adjusted for oxygen generation) was then used to estimate the production volume of the sector. | N/A | N/A | N/A | 1.5 |

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