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. Food and Beverage 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.

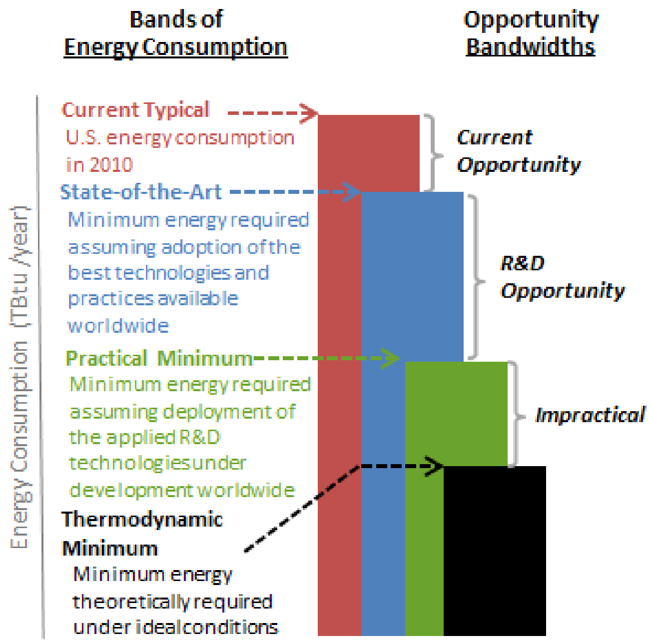

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Two on-site energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. The total opportunity is the sum of the R&D and the current opportunities. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy

[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 (when it was called the Office of Industrial Technologies). Most recently, revised and consistent versions of bandwidth studies for the *Chemicals, Petroleum Refining, Iron and Steel*, and *Pulp and Paper* sectors were published in 2015.

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.

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.

Acknowledgments

Joseph Cresko of DOE/AMO led the conceptual development and publication of the bandwidth study series with support from Dr. Alberta Carpenter of the National Renewable Energy Laboratory. AMO recognizes the efforts of Caroline Dollinger, Nicholas Ward, Dr. Benjamin Levie, Amit Talapatra, and Sabine Brueske of Energetics Incorporated for conducting the research and analysis and writing this study. AMO wishes to acknowledge the contributions made by Dr. Swamy Anantheswaran of Pennsylvania State University and Mr. Fabio Monforti of the European Commission for their work reviewing this study.

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List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
bbl	barrel
Btu	British thermal unit
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
G	Gibbs free energy
H	Enthalpy
kWh	Kilowatt hour
lb.	Pound
MECS	Manufacturing Energy Consumption Survey
MMBtu	Million British thermal units
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
PM	Practical minimum energy consumption or energy intensity
R&D	Research and development
SOA	State of the art energy consumption or energy intensity
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
USDA	U.S. Department of Agriculture
yr	year

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Executive Summary

This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. food and beverage product manufacturing (North American Industry Classification System (NAICS) codes 311 and 3121). Industrial, government, and academic data are used to estimate the energy consumed in processes of six of the most energy intensive manufacturing subsectors—grain and oilseed milling, sugar manufacturing, fruit and vegetable preserving and specialty foods, dairy products, animal slaughtering and processing, and beverages manufacturing. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing subsectors based on referenced energy intensities of current, state of the art, and R&D technologies. A fourth thermodynamic minimum energy consumption *band* is also estimated. The *bandwidth*—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The costs associated with realizing these energy savings was not in the scope of this study.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for food and beverage products manufacturing subsectors 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 present document is organized as described below. The organization reflects the study approach.

- Chapter 1 provides an overview of the methodology and boundaries.
- Chapter 2 provides a sector overview and identifies 2010 production volumes.
- Chapter 3 estimates current typical (CT) energy consumption for six select subsectors and sector-wide.
- Chapter 4 estimates the minimum energy consumption for these subsectors and sector-wide. In developing these estimates, the study assumes the state of the art (SOA), i.e., adoption of best technologies and practices available worldwide.
- Chapter 5 estimates the practical minimum (PM) energy consumption for these subsectors and sector-wide, assuming the deployment of the applied R&D technologies available worldwide.
- Chapter 6 estimates the thermodynamic minimum (TM), i.e., the minimum amount of energy theoretically required for these subsectors, assuming ideal conditions. In some cases, exothermic processes result in this estimate being less than zero.
- Chapter 7 provides the estimated energy savings opportunity *bandwidths*, i.e., 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 and sector-wide estimates of energy consumption for U.S. food and beverage product manufacturing; this data is referenced as subsector and sector-wide CT energy consumption. In this study, CT, SOA, PM, and TM energy consumption for *individual* subsectors is estimated from multiple referenced sources. To estimate SOA, PM, and TM energy consumption for the food and beverage subsectors, available sources were reviewed to estimate the energy consumption data of the most energy intensive processes in each subsector; data for the processes studied in the six subsectors was extrapolated 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. In 2010, these six subsectors corresponded to 80% of the food and beverage sector's total energy consumption; data available for the processes studied covered about 40% of the food and beverage sector's total energy consumption.

Study Results*:* Two energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are presented in Table ES-1 and Figure ES-1 for food and beverage products manufacturing.[2] The current

[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

opportunity is the difference between the 2010 CT energy consumption and SOA energy consumption; the R&D opportunity is the difference between SOA energy consumption and PM energy consumption. Potential energy savings opportunities are presented for the processes studied in the six subsectors and for the entire food and beverage manufacturing sector based on extrapolated data. Note that the energy savings opportunities presented reflect the estimated production of food and beverage products for selected application areas in baseline year 2010. Therefore, it is important to note that the total energy opportunities would scale with increasing or decreasing production levels.

Table ES-1. Potential On-site Energy Savings Opportunities in the U.S. Food and Beverage Products Manufacturing Sector[3]

Opportunity Bandwidths	Estimated On-site Energy Savings Opportunity for Processes Studied in Six Food and Beverage Subsectors (per year)	Estimated Energy Savings Opportunity for total U.S. Food and Beverage 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	130 TBtu[4] (27% energy savings)[5]	336 TBtu[4] (27% energy savings)[5]
R&D Opportunity – additional on-site energy savings if applied R&D technologies under development worldwide are successfully deployed	54 TBtu[6] (11% energy savings)[7]	137 TBtu[6] (11% energy savings)[7]

achieving energy savings are not considered in this study. All estimates are for on-site energy use (i.e., energy consumed within the plant boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

[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.

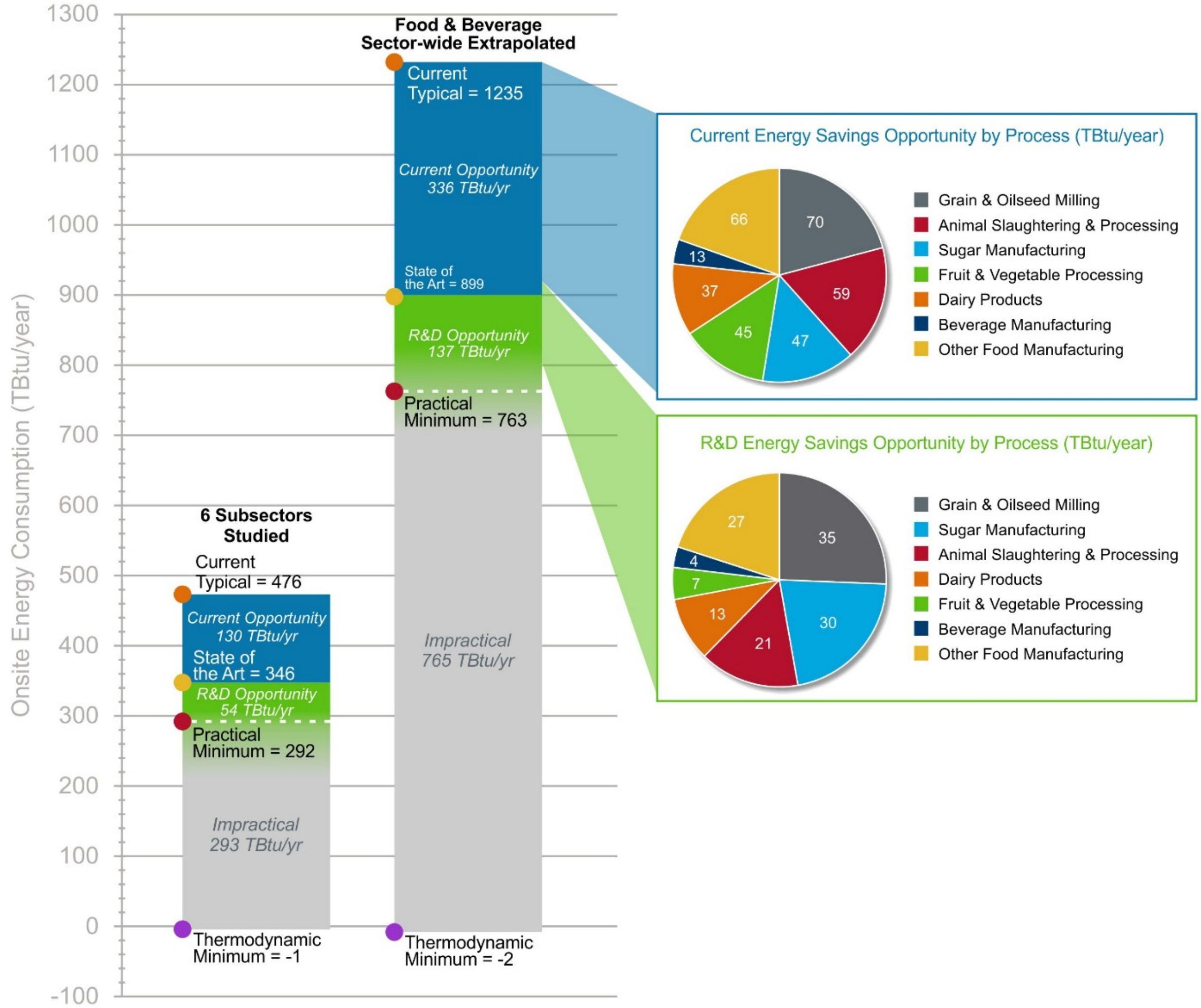

Figure ES-1. Current and R&D energy savings opportunities for the subsectors studied and for food and beverage products manufacturing sector-wide based on extrapolated data
Source: EERE

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.

Figure ES-1 shows 476 TBtu was consumed in 2010 to manufacture U.S. food and beverage products in the processes studied in the six subsectors; total sector-wide energy consumption in 2010 was 1,235 TBtu to manufacture all food and beverage products in the United States according to EIA MECS. Based on the results of this study, an estimated 130 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade the food and beverage manufacturing subsectors studied; an additional 54 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

The top three Current Energy Savings Opportunities for the processes are as follows:

- Soybean oil crushing and extraction– 24 TBtu (or 7% of the total sector current opportunity)
- Fluid milk processing – 23 TBtu (or 7% of the total sector current opportunity)
- Red meat products processing – 15 TBtu (or 4% of the total sector current opportunity).

The top three R&D Energy Saving Opportunities for the processes are as follows:

- Wet corn milling – 17 TBtu (or 13% of the total sector R&D opportunity)
- Beet sugar processing – 13 TBtu (or 9% of the total sector R&D opportunity)
- Fluid milk processing – 8 TBtu (or 6% of the total sector R&D opportunity).

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

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. food and beverage products 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 food and beverage products 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.

There are thousands of food and beverage products manufactured in the United States; six of the most energy-intensive subsectors were studied. Together, these subsectors accounted for 80% of energy consumption and over 500 trillion lb of products manufactured by the U.S. food and beverage products manufacturing 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.

History of DOE Advanced Manufacturing Office Energy Bandwidth Reports

Before 2013, the U.S. Department of Energy (DOE)'s Industrial Technologies Program (now known as the Advanced Manufacturing Office (AMO)) conducted industrial sector analyses (not necessarily conducted harmoniously) meant 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 United States, 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).

1.2. Comparison to Other Bandwidth Studies

This is the first DOE energy bandwidth study prepared specifically for the food and beverage products sector. 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 glass products, cement, and plastic and rubber products (DOE 2017).

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.

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.

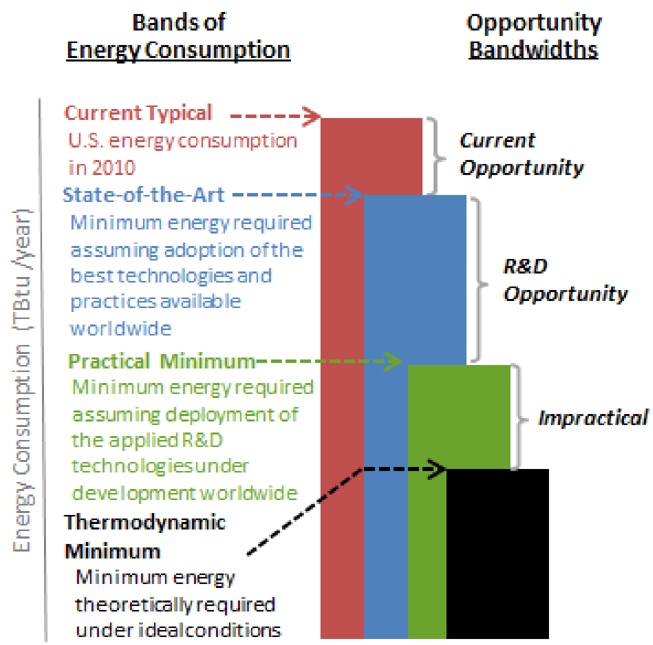

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

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.

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

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 food and beverage 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" and defined as follows:

- **On-site energy** (sometimes referred to as site or end use energy) is the energy consumed within the manufacturing plant boundary (i.e., within the plant gates). Non-fuel feedstock energy is not included in the on-site energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both off-site and on-site during the manufacturing process. Off-site energy consumption includes generation and transmission losses associated with bringing electricity and steam to the plant boundary. Non-fuel feedstock energy is not included in the primary energy values. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

The four bands of energy consumption described above are quantified for processes and for the material total. To determine the total annual on-site CT, SOA, PM, and TM energy consumption (TBtu per year), energy intensity values per unit weight (Btu per pound (lb.) of material manufactured) are estimated and multiplied by the production amount (lb. per year of material manufactured). The year 2010 is used as a base year since it is the most recent year for which consistent energy consumption and production data are available for all materials and manufacturing sectors analyzed in this series of bandwidth studies. Unless otherwise noted, 2010 production data is used.

The estimates presented are for macro-scale consideration of energy use in food and beverage products manufacturing. The estimates reported herein are representative of average U.S. food and beverage products manufacturing; they do not represent energy use in any specific facility or any particular region in the United States or the world.

Significant investment in technology development and implementation would be needed to fully realize the potential energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.

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.

Chapter 2 presents the **U.S. production volumes** (million lb. per year) for 2010

Chapter 3 presents the calculated on-site **CT energy intensity** (Btu per lb.) and **CT energy consumption** (TBtu per year) for the products, processes, subsectors studied, totals, and sector-wide (along with sources).

Chapter 4 presents the estimated on-site **SOA energy intensity** (Btu per lb.) and **SOA energy consumption** (TBtu per year) for the products, processes, subsectors studied, totals, and sector-wide (along with sources). The SOA energy consumption for the process areas studied in the six subsectors is extrapolated to estimate the entire SOA energy consumption for each subsector (see inset). The extrapolated data for each subsector is summed to provide an estimate of sector-wide SOA energy consumption.

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per lb.) and **PM energy consumption** for the products, processes, subsectors studied, totals, and sector-wide (along with sources). The PM energy intensity for the process areas studied in the six subsectors is extrapolated to estimate the entire PM energy consumption for each subsector (see inset). The extrapolated data for each subsector is summed to provide an estimate of sector-wide PM energy consumption.

Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per lb.) and **TM energy consumption** for the products, processes, subsectors studied, totals, and sector-wide (along with sources).

Chapter 7 provides a summary **of current and R&D opportunity** analysis based on bandwidth summary results for the food and beverage subsectors and sector-wide.

Food and Beverage Subsector Analysis for SOA, PM, and TM Energy Consumption

To estimate SOA, PM, and TM energy consumption for the food and beverage subsectors, the energy consumption data for individual processes was aligned and grouped with its NAICS-defined subsector.

The SOA, PM, and TM energy consumption data for the processes grouped by subsector is extrapolated to estimate SOA, PM, and TM energy consumption for entire subsectors. A consistent extrapolation method is used. The subsector values are summed to provide sector-wide SOA, PM and TM energy consumption estimates.

1.5. Boundaries of the Study

The U.S. food and beverage products manufacturing sector is the physical boundary of this study. It is recognized that some of the major energy benefits (and costs) associated with the use of food and beverage products often occur *outside* of the products manufacturing sector (e.g., improvements made in the agriculture sector). While such impacts are recognized as important, they will not be quantified as this is not a life cycle assessment study. Instead, this report focuses exclusively on the energy use directly involved in the production of food and beverage products within the manufacturing sector. The focus of this bandwidth study is thus the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to food and beverage products manufacturing at a production facility.

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

2. U.S. Food and Beverage Manufacturing Sector Production

2.1. U.S. Food and Beverage Manufacturing Overview

The U.S. food and beverage manufacturing sector can be considered unique when compared to other traditional manufacturing industries as there are larger number of small facilities as opposed to mainly larger centralized facilities, which may produce one or many different products. In total the industry produces a large number of diverse products that are consumed both domestically and exported to international markets. Because of this, a variety of energy consuming steps are typically required to manufacture the final product. Overall, the main sources of energy consumption include on-site steam, general process heating, process cooling and refrigeration, and machine drive (DOE 2014).

According to the U.S. Census Bureau, in 2010 there were 24,773 establishments involved in food manufacturing and 4,527 establishments involved in beverage manufacturing (USCB 2012). These establishments employed nearly 1.5 million individuals and created over $312 billion in value added (USCB 2011a).

2.2. U.S. Food and Beverage Manufacturing Sector Description

The U.S. Food and Beverage sector produces a wide variety of products (one must only think of how many different items are available in a grocery store). There is no source that tracks the total amount of products that are produced annually, however production volumes were researched and estimated for individual products for the six subsectors. Table 2-1 shows the specific processes considered under the six subsectors studied (by NAICS code) based on available recent data. Most of the NAICS codes are identified at the four digit level, with a few exceptions:

- Wet corn milling (NAICS 311221) is considered as a subcategory under grain and oilseed milling subsector (NAICS 3112) as it is a large energy consumer
- Sugar manufacturing is identified under its five digit code (NAICS 31131) based on available energy consumption data

Table 2-1. Food and Beverage Products Manufacturing Subsectors and End-use Processes Considered in Bandwidth Analysis Based on Available Data

Subsector	NAICS* Code	End Use Processes
Grain and Oilseed Milling	3112	Soy Bean Crushing and Extraction
Wet Corn Milling	311221	Soy Bean Refining Unit Corn Receiving Steeping Steep Water Evaporation Germ Recovery Germ Dewatering and Drying Fiber Recovery Fiber Dewatering Protein (Gluten) Recovery Gluten Thickening and Drying Starch Washing Starch Dewatering and Drying Gluten Feed Dryer
Sugar Manufacturing	31131	Total Product

Table 2-1. Food and Beverage Products Manufacturing Subsectors and End-use Processes Considered in Bandwidth Analysis Based on Available Data

Subsector	NAICS* Code	End Use Processes
Fruit and Vegetable Preserving and Specialty Foods	3114	Washing Can Washing Pasteurization (Heat Treatment) Heat Sterilization (Retort) Can Sealing Vacuum Deaeration Packaging Blanching Cooking Can Exhausting Brine Heating Sorting/Screening, Grading Peeling Cutting/Slicing Frying (Potatoes Only) Freezing
Dairy Products	3115	Pasteurization Cooling Receiving and Storage Deodorization Final Storage Separation Packaging Motors, Pumps Make Vat Freezing Concentration Canning Spray Drying
Animal Slaughtering and Processing	3116	Edible Rendering Splitting Scalding Singeing Blood Processing Chilling/Refrigeration Dressing and Cutting Processing (Curing, Smoking, Cooking) Packaging Lairage (Holding Pen) Hanging, Scalding, Slaughtering, and Defeathering Evisceration and Cooling Liquid Effluent Treatment

Table 2-1. Food and Beverage Products Manufacturing Subsectors and End-use Processes Considered in Bandwidth Analysis Based on Available Data

Subsector	NAICS* Code	End Use Processes
Beverages	3121	Brewhouse Packaging Space Heating Utilities Refrigeration Lighting Compressed Air Boiler Other Grape Reception & Extraction Alcoholic Fermentation Pressing Stabilization Bottling, Storage, and Delivery Lighting Auxiliary Processes

* NAICS = North American Industry Classification System (2007 codes were used)

2.3. U.S. Food and Beverage Manufacturing Energy Consumption

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

Food and Beverage manufacturing accounted for 1,827 TBtu (9.5%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Additional detail on these CT energy consumption estimates can be found in Chapter 3. Additional detail on these CT energy consumption estimates can be found in Chapter 3.

Table 2-2. U.S. Plastics and Rubber Products Manufacturing Energy Consumption Sector-Wide, 2010

On-site Energy Consumption **(includes electricity, steam, and fuel energy used on site at the facility)**	1,235 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)**	1,827 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.

2.4. U.S. Food and Beverage Manufacturing Production Values

In this report, production data refers to the amount of food or beverage produced in the United States. Energy intensity values represent the energy that the end-use process requires to create a lb. of the food or bbl[8] of beverage product. Energy intensity values are multiplied by the production values in Table 2-3 in order to estimate total energy consumption by process.

The leading source for data on food production (grain and oilseed milling, dairy, animal slaughtering, and sugar) is the U.S. Department of Agriculture (USDA), which provides most of the values in Table 2-3 as domestic production by product type. The domestic production for fruits and vegetables preserving (NAICS 3114) were calculated based on USDA input values and adjusted for processing stage losses. For example, the USDA reported total vegetables input for canning as 30,766 million lb. in 2010 (USDA 2016h). The processing losses for canning vegetables in 2010 ranged between 5% and 73% for the vegetables considered, such as sweet corn, potatoes, broccoli and carrots (USDA 2016c). Therefore, the adjusted canned vegetable production used in this report is calculated as 14,768 million lb. in 2010. Applying the same methodology for frozen fruits (1,612 million lb. input and 6% average losses) yielded 1,520 million lb. of frozen fruit in 2010 (USDA 2016c, USDA 2016d). These values are organized into major product types, and insignificant production quantities where little or no energy intensity data is available were removed. The exception for the subsector is canned fruits production, where the data is directly reported by the USDA (USDA 2016d).

For beverage production, the leading source is the U.S. Department of the Treasury. The production values were determined primarily for alcoholic beverages, such as beer, still wine, and sparkling wine. The total amounts of beverage production was determined by calculating the cumulative 2010 production total in the U.S., which includes increases in production volumes after fermentation from processes such as sweetening and amelioration. The production data was calculated from the Department of the Treasury, Alcohol and Tobacco Tax and Trade Bureau Statistical Report for beer, still wine and sparkling wine (DOT 2011a, DOT 2011b, DOT 2013).

Table 2-3. U.S. Food and Beverage Products 2010 Production for each Subsector Studied

Subsector	Product	2010 Total Production (million lb)
Grain and Oilseed Milling	Soybean oil	19,331
	Soybean meal[1]	75,981
Wet Corn Milling	Corn oil	2,479
	Corn grind[2]	61,383
Sugar Manufacturing	Cane sugar	7,327
	Beet sugar	9,517
Fruit and Vegetable Preserving and Specialty Foods	Fruit juice	9,813
	Canned fruits and vegetables	17,658
	Canned vegetables	14,768
	Canned fruits	2,890
	Frozen vegetables	20,639
	Frozen potatoes	15,650
	Other frozen vegetables	4,989
	Frozen fruit	1,520
Dairy Products	Fluid milk	192,877

[8] 1 U.S. bbl = 31 gallons for beverages

Table 2-3. U.S. Food and Beverage Products 2010 Production for each Subsector Studied

Subsector	Product	2010 Total Production (million lb)
	American and other cheese	10,443
	Ice cream and frozen desserts	5,990
	Condensed/evaporated milk	2,488
	Creamery butter	1,564
Animal Slaughtering and Processing	Lard, tallow, and fat	2,996
	Red meat products	49,039
	Pork	22,437
	Beef	26,304
	Lamb	164
	Poultry	50,134
		2010 Total Production (million bbls[3])
Beverages	Beer	194.6
	Still wine	12.5

[1] In soybean processing, soybean meal is considered to be a byproduct while soybean oil is the main product; energy intensities are provided in terms of energy per unit of soybean oil produced, which are inclusive of the amount of soybean meal produced.

[2]Because of the way energy intensity data is provided, the amount of corn that is processed in wet corn milling facilities (or "corn grind") was used to calculated energy consumption, instead of the amount of corn oil produced.

[3] 1 U.S. bbl = 31 gallons for beverages

3. Current Typical Energy Intensity and Energy Consumption for U.S. Food and Beverage Product Manufacturing

This chapter presents energy intensities and energy consumption data for food and beverage manufacturing subsectors and sector-wide. Energy intensities were identified for each food and beverage product and/or process and applied to the production values reported in the previous chapter to determine U.S. energy consumption. The estimates reported are representative of U.S. consumption. In some cases, non-U.S. energy intensity values are used to fill in data gaps, if it was determined that the data would be representative of U.S. manufacturing, and high-quality U.S. data were unavailable.

3.1. Sources for Current Typical Energy Intensity

Appendix A1 presents the CT energy intensities and energy consumption for the subsectors studied. Table 3-1 presents a summary of the main references consulted to identify CT energy intensity by process. Appendix A2 provides the references used for each process.

The food and beverage sector incorporates a wide range of products that can vary significantly in energy consumption depending on the specifics of the product and process used. The energy intensity values selected are determined to be the best approximation of the on-site energy consumption. The best criteria for selection include data that specify the process, food and beverage type, and are based on U.S. facilities. In cases where this level of detail is not available, data gaps are filled in using the next best available source, with a priority on sources that accurately represent typical energy intensities for the type of process (e.g., pasteurization, extraction, fermentation, etc.).

It should be noted that for the food and beverage manufacturing sector, there is a lack of data for energy intensity of some subsectors that led to lower overall "percent coverage" for the total sector. While certain industries, such as the dairy processing industry, have a wider range of data, other industries, such as sugar manufacturing, there was a lack of energy intensity breakdown for process steps and an overall product energy intensity was referenced instead. Also, in certain subsectors such as beverage processing, there was a lack of energy intensity and production data for products such as sodas; without production data (or energy intensity data to calculate total energy consumption), opportunities for savings into this type of product manufacturing were not able to be researched. This may suggest that it is harder to generalize energy intensity for food and beverage processing, as noted earlier, due to the fact that facilities can vary in size, efficiency, output, and overall energy consumption.

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

Source Abbreviation	Description
Grain and Oilseed Milling	
Omni Tech International 2010	This report provided the CT values for crushing and extracting soybean oil. The source reports energy values in terms of material, electricity, natural gas and steam inputs for every soybean oil output unit.
LBNL 2003	This report provided CT energy values for corn wet milling operations. The electricity, fuel, and steam energy inputs for producing corn oil and corn grind were based on a 100,000 bushel/day facility.
Sugar Processing	
Wang 2008	This reference provided the total product production energy requirements for cane sugar. Limited literature cited process-specific values for cane sugar manufacturing, so the energy requirements for the entire process were used.
IPPC 2006; UNEP 2008	The IPPC (2006) reference provided the total product production energy requirements for beet sugar. These values were subsequently cited in the UNEP (2008) report. The high value from these reports was used as a conservative estimate for CT. Limited literature cited process-specific values for beet sugar manufacturing, so the energy requirements for the entire process were used.
Fruit and Vegetable Processing	
LBNL 2008	This report provided the CT energy intensity values for process specific energy inputs for the following fruit and vegetable products: fruit juice, canned fruits and vegetables, frozen fruits, frozen vegetables (frozen potatoes). The high values for each energy-intensive process was used as a conservative estimate for CT.
Dairy Products	
LBNL 2011	This report provided the CT energy intensity values for process specific energy inputs for the following fruit and vegetable products: fluid milk, canned evaporated milk, powdered dry milk, butter, cheese, ice cream and frozen desserts. The high values for each energy-intensive process was used as a conservative estimate for CT.
Animal Slaughtering and Processing	
Brown 1996	This reference provided the CT energy values for meat rendering (edible and inedible), curing, smoking, cooking, chilling, packaging, scalding and dehairing. These values were calculated based on the energy input from steam, electricity and fuel per unit product output.
IPPC 2006	This report provided energy values for slaughterhouses, particularly pig slaughterhouses. The energy values were reported in the literature as energy per unit carcass output.
Meat and Livestock Australia Ltd 2002	This report provided the breakdown of energy usage at a typical cattle processing plant.
Goldthorpe 2002	This report provided the average electricity, and fuel usage for red meat processing (cattle/sheep/pigs).
Harding et al. 2016	This report provided the CT energy requirements for typical poultry broiler processing plant.
Beverage Manufacturing	
Brewers Association 2014	This report provided the typical energy usage for beer manufacturing. These energy usage values were broken down by process type, and reported in terms of energy per barrel of beer produced.
UPM 2013	This report provided the typical energy usage for wine manufacturing. These energy usage values were broken down by process type, and reported in terms of energy per barrel of wine produced.

3.2. Current Typical Energy Intensity and Energy Consumption

Table 3-2 presents the energy intensities and calculated on-site and primary CT energy consumption for the food and beverage product manufacturing subsectors studied and sector-wide. Energy consumption values were calculated by multiplying energy intensity (Btu/lb or Btu/bbl) by 2010 production (million lb./year or bbl/year). Feedstock energy is excluded from the consumption values.

While multiple process types may be included at a food or beverage products manufacturing facility, the energy intensity data collected is selected based on the primary process at the facility, and is matched to the process identified for end-use food and beverage consumption (See Production Values in the previous chapter). For example, fruit juice manufacturing requires process steps in washing, pasteurization, heat sterilization, can sealing, vacuum deaeration, and packaging steps. Note that not all processes or steps were included in the analysis, as the data for the full process was often not available in references; instead energy intensity or saving information was provided on the most energy intensive steps. To calculate on-site CT energy consumption, energy intensity for each step (presented initially in Appendix A1) is multiplied by the 2010 production data.

Food and Beverage manufacturing accounted for 1,827 TBtu (9.5%) 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 food and beverage products manufacturing totaled 592 TBtu in 2010; on-site energy consumed within the boundaries of U.S. food and beverage products manufacturing plants totaled 1,235 TBtu.

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Food and Beverage Products Manufacturing in Six Subsectors Studied and Sector-wide in 2010, with Percent of Sector Coverage

Subsector/Product	On-site CT Energy Intensity for Processes Studied (Btu/lb) (Btu/bbl for Beverages)	Production (Million lb/year) (million bbl*/year for beverages)	On-site CT Energy Consumption (TBtu/year)	Off-site Losses (TBtu/year)	Primary CT Energy Consumption (TBtu/year)	Percent Coverage (On-site CT as a % of Sub-sector and Sector-wide Total)
Grain and Oil Seed Milling						
Soybean Oil	3,688	19,311	72	24	96	
Wet Corn Milling Corn Oil	1,665†	61,383†	102	25	128	
Subtotal			**174**	**49**	**224**	**50%**
Sugar Manufacturing						
Cane Sugar	2,526	7,327	19	2	20	
Beet Sugar	3,682	9,517	35	3	38	
Subtotal			**54**	**5**	**58**	**50%**
Fruit and Vegetable Processing						
Fruit Juice	741	9,813	7	3	11	
Canned Fruits and Vegetables	942	17,658	20	9	29	
Frozen Vegetables	1,293	20,639	25	11	36	
Frozen Fruit	776	1,520	1	0.5	2	
Subtotal			**54**	**24**	**78**	**38%**

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Food and Beverage Products Manufacturing in Six Subsectors Studied and Sector-wide in 2010, with Percent of Sector Coverage

Subsector/Product	On-site CT Energy Intensity for Processes Studied (Btu/lb) (Btu/bbl for Beverages)	Production (Million lb/year) (million bbl*/year for beverages)	On-site CT Energy Consumption (TBtu/year)	Off-site Losses (TBtu/year)	Primary CT Energy Consumption (TBtu/year)	Percent Coverage (On-site CT as a % of Sub-sector and Sector-wide Total)
Dairy Products						
Fluid Milk	283	192,877	55	35	90	
Cheese	1,183	10,443	12	8	20	
Ice Cream	715	5,990	4	3	7	
Butter	534	1,564	1	0.5	1	
Canned Evaporated Milk/Powdered Dry Milk	407	2,488	1	0.5	1	
Subtotal			**73**	**47**	**120**	**69%**
Animal Slaughtering and Processing						
Lard, Tallow, Fat	4,573	2,996	14	9	23	
Pork	348**	22,437	8	5	13	
Red Meat Products (Beef, Pork, Lamb)	1,141**	49,039	56	37	93	
Poultry	91***	50,134	5	3	8	
Subtotal			**82**	**55**	**137**	**39%**
Beverage Manufacturing						
Beer	198,000 ****	194.6††	39	26	64	
Wine	93,000****	12.5††	1	1	2	
Subtotal			**40**	**26**	**66**	**52%**
Total for Processes in Subsectors Studied†††		**N/A**	**476**	**207**	**682**	**48%**
Total for Food and Beverage Sector-wide†††		**N/A**	**1,235**	**592**	**1,827**	**39%**

Current Typical (CT)
† Energy intensity for corn oil is in terms of per lb corn processed or "corn grind" and production value provided is in corresponding units (lb corn grind)
†† Production values for beverages are provided in terms of bbl
††† Totals may not sum due to independent rounding.
* 1 U.S. bbl = 31 gal for beverages
** Values are in Btu/lb of products
*** Values are in Btu/lb slaughtered
**** Values are in Btu/bbl

4. State of the Art Energy Intensity and Energy Consumption for U.S. Food and Beverage Product Manufacturing

This chapter estimates energy savings possible in food and beverage products manufacturing plants to achieve state of the art (SOA) energy consumption levels. State of the art energy consumption represents savings possible when applying best practices and technologies that are currently commercially available. Plants can vary widely in size, age, efficiency, energy consumption, and production. To develop an estimate representative of U.S. industries, this analysis uses typical energy savings found from measures applicable to major processes including pasteurization, refrigeration, freezing, and blanching, as well as measures more widely applicable to food and beverage processing facilities.

4.1. Sources for State of the Art Energy Intensity

Appendix A1 presents the on-site SOA energy intensity and consumption for the processes considered in this bandwidth study. The on-site SOA energy consumption values are the net energy consumed in the process using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a lb. of product. The on-site SOA energy consumption estimates exclude feedstock energy.

Table 4-1 presents the main published sources referenced to identify the SOA energy intensities.

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

Source Abbreviation	Description
Grain and Oilseed Milling	
DOE 2004	This report provided values for energy savings for steam system improvements.
DOE 2011	This report provided multiple energy efficiency measures for wet corn milling.
Sugar Processing	
IAC 2016	This reference provides energy efficiency measures from real plants as a result of energy auditing. The energy savings values for cane sugar were reported from a cane sugar plant assessment from 2007.
IPPC 2006; UNEP 2008	The IPPC (2006) reference provided the total product production energy requirements for beet sugar. These values were subsequently cited in the UNEP (2008) report. The low value from this report was used as the SOA. Limited literature sited process-specific values for beet sugar manufacturing, so the energy requirements for the entire process was used.
Fruit and Vegetable Processing	
LBNL 2008	Energy savings for heat and hold blancher for canned vegetables, as well as induction heating of liquids for pasteurization were reported from this reference.
UNEP 2008	This report determined energy savings for can washing, and vegetable steam peeling.
DOE 2004	This report provided values for energy savings for steam system improvements.
DOE 2011	Multiple energy efficiency measures for canned fruits and vegetables, and frozen fruits and vegetables

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

Source Abbreviation	Description
IPPC 2006	Low value reported for sorting/screening, grading, dehulling, destemming/destalking, and trimming; average value reported for freezing.
Dairy Products	
LBNL 2011	Low values reported for pasteurization; energy savings for induction heating of liquids in pasteurization, monitoring system in refrigeration.
DOE 2011	This report determined multiple energy efficiency measures for cheese, fluid milk and butter.
DOE 2004	This report provided values for energy savings for steam system improvements.
Liu et al. 2014	This report provided primary energy savings for utilizing carbon dioxide (CO_2) heat pump in heating and cooling processes.
Animal Slaughtering and Processing	
IPPC 2006	The low value reported for pig slaughter (particularly scalding) were reported from this reference.
Meat and Livestock Australia Ltd 2002	Energy savings by heat recovery from cooking vapors in rendering processes were reported from this reference.
DOE 2004	This report provided values for energy savings for steam system improvements.
DOE 2011	Multiple energy efficiency measures in animal slaughtering.
AMIC 2013	Energy efficiency improvements in meat refrigeration units were determined in this reference.
Fritzson & Berntsson 2006	This report provided energy (particularly electricity) savings in refrigeration units during meat processing.
Beverage Manufacturing	
IAC 2016	Cumulative electricity and fuel savings for beer manufacturers for energy efficiency improvements were determined from real facility energy audits reported from this reference.
LBNL 2003a	Energy savings from reducing space heating demand, refrigeration load and cooling system modifications, lighting motor sensors, boiler and steam distribution maintenance, and engine driven chiller systems were reported from this reference.
UPM 2013	For wine manufacturing, the reported energy savings included geoexchange pumps, heat and cold recovery, electronic ballasts, and pipe thermal insulation.

4.2. State of the Art Energy Intensity and Energy Consumption

Table 4-2 presents the on-site SOA energy intensity and consumption for the food and beverage manufacturing products for the processes studied. The SOA energy intensities are averages based on the processes studied for the products in each subsector; full details on process energy intensities used can be found in Appendix A1.

In Table 4-3, data from Table 4-2 is extrapolated to estimate the total SOA subsector and sector-wide opportunity. SOA subsector energy savings, which is the *current opportunity*, is also expressed as a percent in Table 4-3. It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is cane sugar retrofitting at 64% energy savings.

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Food and Beverage Products Manufacturing Processes in Six Subsectors Studied

Subsector/Product	**On-site SOA Energy Intensity for Processes Studied** (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	**Production** (Million lb/year) (million bbl/year for beverages)	**On-site SOA Energy Consumption, Calculated** (TBtu/year)
Grain and Oil Seed Milling			
Soybean Oil	2,425	19,311	47
Wet Corn Milling Corn Oil	1,507†	61,383†	93
Subtotal			**139**
Sugar Manufacturing			
Cane Sugar	946	7,327	7
Beet Sugar	2,405	9,517	23
Subtotal			**30**
Fruit and Vegetable Processing			
Fruit Juice	591	9,813	6
Canned Fruits and Vegetables	823	17,658	15
Frozen Vegetables	847	20,639	16
Frozen Fruit	324	1,520	0.7
Subtotal			**37**
Dairy Products			
Fluid Milk	23	192,877	31
Cheese	257	10,443	11
Ice Cream	233	5,990	4
Butter	121	1,564	0.4
Canned Evaporated Milk/Powdered Dry Milk	127	2,488	0.6
Subtotal			**47**

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Food and Beverage Products Manufacturing Processes in Six Subsectors Studied

Subsector/Product	On-site SOA Energy Intensity for Processes Studied (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	Production (Million lb/year) (million bbl/year for beverages)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Animal Slaughtering and Processing			
Lard, Tallow, Fat	2,973	2,996	9
Pork	69*	22,437	5
Red Meat Products (Beef, Pork, Lamb)	169*	49,039	41
Poultry	15**	50,134	4
Subtotal			**59**
Beverage Manufacturing			
Beer	18,472***	194.6	32
Wine	10,208***	12.5	0.9
Subtotal	N/A		33
Total for Processes in Subsectors Studied******	N/A	N/A	**346**

Current Typical (CT), State of the Art (SOA)
† Energy intensity for corn oil is in terms of per lb corn processed or "corn grind" and production value provided is in corresponding units (lb corn grind)
* Values are in Btu/lb of products
** Values are in Btu/lb slaughtered
*** Values are in Btu/bbl
**** Totals may not sum due to independent rounding.

To calculate the extrapolated data presented in Table 4-3, the SOA energy consumption of each individual process studied within a subsector is summed, and the sum is divided by the CT percent coverage for the entire subsector. The percent coverage of processes studied compared to the total CT energy consumption of the subsector is shown in Table 3-2. The extrapolated number is the estimated SOA energy consumption for the entire subsector. For the "all other food manufacturing" subsector, which comprises the remainder of the food and beverage product manufacturing sector, the SOA energy savings percent is assumed to be the average taken across all the subsectors studied (27%) and this is applied to the CT energy consumption in order to calculate an extrapolated sector-wide SOA energy consumption.

If U.S food and beverage products manufacturing were able to attain on-site SOA energy intensities, it is estimated that 270 TBtu per year of energy could be saved from the processes studied alone, corresponding to a 27% energy savings overall (see equation below). This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings; it should not be inferred that all existing plants could achieve these SOA values or that the improvements would prove to be cost effective in all cases.

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Food and Beverage Products Manufacturing in Six Subsectors Studied and Sector-wide

Subsector	On-site CT Energy Consumption, MECS (TBtu/year)	On-site SOA Energy Consumption for Total Subsector (extrapolated)* (TBtu/year)	SOA Energy Savings For Total Subsector (extrapolated)* (CT-SOA) (TBtu/year)	SOA Energy Savings Percent** (CT-SOA)/(CT-TM)
Grain and Oil Seed Milling	350	280	70	20%
Sugar Manufacturing	107	60	47	45%
Fruit and Vegetable Processing	143	98	45	31%
Dairy Products	105	68	37	35%
Animal Slaughtering and Processing	212	153	59	28%
Beverage Manufacturing	77	65	13	16%
Total for Subsectors Studied* **	**994**	**724**	**270**	**27%**
All other food manufacturing	241	175	66	27%
Total for Food and Beverage Sector-wide* **	**1,235**	**899**	**336**	**27%**

Current Typical (CT), State of the art (SOA), Thermodynamic Minimum (TM)
* Estimates for the entire subsector were extrapolated by dividing the total on-site SOA energy consumption for all the processes studied within the subsector by the subsector % coverage, found in Chapter 3.
** 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: (CT- SOA)/(CT- TM).
*** Totals may not sum due to independent rounding.

The SOA energy savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in Chapter 6, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site SOA energy savings percent is:

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

5. Practical Minimum Energy Intensity and Energy Consumption for U.S. Food and Beverage Product Manufacturing

For the food and beverage products industry, the majority of the practical energy savings potential comes from state-of-the-art technologies that are already commercially available. The remaining energy savings potential comes in the form of R&D technologies. Innovation in these technologies can further improve efficiency and drive U.S. economic growth. This chapter determines the R&D opportunity for the food and beverage products industry as defined by the practical minimum (PM): the minimum amount of energy required assuming the deployment of applied R&D technologies currently under development worldwide.

5.1. Sources for Practical Minimum Energy Intensity

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific food or beverage product manufacturing process assuming that the most advanced technologies under research or development around the globe are deployed.

R&D progress is difficult to predict and potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a search of R&D activities in the food and beverage products industry was conducted. The focus of this study's 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. Basic research, involving experimentation and modeling to expand understanding of fundamental mechanisms and principles without a direct link to commercial objectives, was not considered. Many of the technologies identified were disqualified from consideration due a lack of data from which to draw energy savings conclusions. Further, applied R&D technologies without a clear connection to manufacturing energy consumption were not considered in this study. Appendix A3 provides an example of the range of technologies considered for evaluation.

Table 5-1 presents some key sources consulted to identify PM energy intensities in food and beverage products manufacturing.

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

Source Abbreviation	Description
Grain and Oilseed Milling	
Wang 2008	This report identifies energy efficiency measures and savings estimates applicable to a range of food manufacturing processes. It provides energy savings from membrane separation and desalination techniques applicable to water removal processes in wet corn milling.
Tuncel et al. 2010	This study analyzes the effects of infrared and hot air drying on corn. It provides energy savings estimates for corn drying using infrared (IR) heating.
Sugar Manufacturing	
Wang 2008	Provides energy savings estimates applicable to dewatering, evaporation, and crystallization in sugar manufacturing.
Fruit and Vegetable Processing	
Wang 2008	Provides energy savings estimates applicable to distillation, evaporation, sterilization, and heating in fruit and vegetable processing.
CORDIS 2016	This report estimates energy savings from Ohmic heating which can be applied to cooking or blanching in fruit and vegetable processing.
Liato et al. 2006	This study estimates the energy savings potential of electro-activated brine solutions and low heat treatment for sterilization of canned peas and corn.
Heinz et al. 2003	This study estimates the energy savings potential of pasteurization by pulsed electric fields as compared to traditional pasteurization processes.
Dairy Processing	
Lung, Masanet & McKane 2006	This report provides energy savings estimates for the use of evaporator fan controls for refrigerated storage.
Heinz et al. 2003	This study estimates the energy savings potential of pasteurization by pulsed electric fields as compared to traditional pasteurization processes.
DOE 2016	This report provides an energy savings estimate for no-heat spray drying technology as applicable to the production of powdered dry milk.
Animal Slaughtering and Processing	
AMIC 2013	This report estimates energy savings measures for refrigeration as applicable to meat processing.
CORDIS 2015b	This report estimates energy savings from By-Product Value; where animal byproducts are converted into fuel for biogas generation through anaerobic digestion. These savings can be applied to rendering processes in meat processing.
Beverage Manufacturing	
Lung, Masanet & McKane 2006	This report provides energy savings estimates for the use of evaporator fan controls for refrigerated storage.
Brewers Association 2014	Provides an energy savings estimate for the use of tankless water heaters for on-demand water heating in beverage processing.
CORDIS 2015a	Identifies a leak-proof double seat control valve for the brewery and dairy industries which can provide energy savings in compressed air use.
CORDIS 2017	Provides an energy savings estimate for low-frequency high-power (LFHP) ultrasound equipment designed for optimizing the extraction of phenolic compounds in wine production.

5.2. Practical Minimum Energy Intensity and Energy Consumption

Table 5-2 presents the on-site PM energy consumption for the food and beverage products manufacturing processes studied. The PM energy intensities are averages based on the processes studied for the products in each subsector; full details on process energy intensities used can be found in Appendix A1.

Table 5-2. On-site Practical Minimum Energy Intensities and Consumption for Food and Beverage Products Manufacturing Processes in Six Subsectors Studied

Subsector/Product	**On-site PM Energy Intensity for Processes Studied** (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	**Production** (Million lb/year) (million bbl/year for beverages)	**On-site PM Energy Consumption, Calculated** (TBtu/year)
Grain and Oil Seed Milling			
Soybean Oil	1,645	19,311	47
Wet Corn Milling (Corn Oil)	87†	61,383†	75
Subtotal			**122**
Sugar Manufacturing			
Cane Sugar	671	7,327	5
Beet Sugar	1,063	9,517	10
Subtotal			**15**
Fruit and Vegetable Processing			
Fruit Juice	74	9,813	5
Canned Fruits and Vegetables	82	17,658	13
Frozen Vegetables	98	20,639	16
Frozen Fruit	215	1,520	0.7
Subtotal			**34**
Dairy Products			
Fluid Milk	17	192,877	23
Cheese	250	10,443	10
Ice Cream	205	5,990	4
Butter	50	1,564	0.2
Canned Evaporated Milk/Powdered Dry Milk	110	2,488	0.6
Subtotal			**38**
Animal Slaughtering and Processing			
Lard, Tallow, Fat	1,784	2,996	5
Pork	69*	22,437	5
Red Meat Products (Beef, Pork, Lamb)	153*	49,039	37
Poultry	13**	50,134	4

Table 5-2. On-site Practical Minimum Energy Intensities and Consumption for Food and Beverage Products Manufacturing Processes in Six Subsectors Studied

Subsector/Product	On-site PM Energy Intensity for Processes Studied (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	Production (Million lb/year) (million bbl/year for beverages)	On-site PM Energy Consumption, Calculated (TBtu/year)
Subtotal			**51**
Beverage Manufacturing			
Beer	17,237***	194.6	30
Wine	9,678***	12.5	0.8
Subtotal	N/A		**31**
Total for Processes in Subsectors Studied******	N/A		**292**

Current Typical (CT), Practical Minimum (PM)
† Energy intensity for corn oil is in terms of per lb corn processed or "corn grind" and production value provided is in corresponding units (lb corn grind)
* Values are in Btu/lb of products
** Values are in Btu/lb slaughtered
*** Values are in Btu/bbl
**** Totals may not sum due to independent rounding.

In Table 5-3, data from Table 5-2 is extrapolated to estimate the total PM subsector and sector-wide savings. Table 5-3 presents the PM subsector energy savings, which is the sum of *current* and *R&D opportunity*, and the PM energy savings percent. PM subsector energy savings is also expressed as a percent inTable 4-3.

Table 5-4 calculates the R&D opportunity for the processes studied and sector-wide. To calculate the extrapolated data presented in Table 5-3, the PM energy consumption of each individual process studied within a subsector is summed, and the sum is divided by the CT percent coverage for the entire subsector. The percent coverage of processes studied compared to the total CT energy consumption of the subsector is shown in Table 3-2. The extrapolated number is the estimated PM energy consumption for the entire subsector. For the "all other food manufacturing" subsector, which comprises the remainder of the food and beverage product manufacturing sector, the PM energy savings percent is assumed to be the average taken across all the subsectors studied (39%) and this is applied to the CT energy consumption in order to calculate an extrapolated sector-wide PM energy consumption.

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Food and Beverage Products Manufacturing in Subsectors Studied and Sector-Wide

Subsector	On-site CT Energy Consumption, MECS (TBtu/year)	On-site PM Energy Consumption for Total Subsector (extrapolated)* (TBtu/year)	PM Energy Savings for Total Subsector (extrapolated)† (CT-PM) (TBtu/year)	PM Energy Savings Percent** (CT-PM)/ (CT-TM)
Grain and Oil Seed Milling	350	245	105	30%
Sugar Manufacturing	107	30	77	73%
Fruit and Vegetable Processing	143	92	51	35%
Dairy Products	105	55	50	47%
Animal Slaughtering and Processing	212	133	79	37%
Beverage Manufacturing	77	60	17	22%
Total for Subsectors Studied* **	**994**	**615**	**379**	**38%**
All other food manufacturing	241	148	93	39%
Total for Food and Beverage Sector-wide* **	**1,235**	**763**	**472**	**38%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
† PM energy savings is the *Current Opportunity* plus the *R&D Opportunity*.
* Estimates for the entire subsector were extrapolated by dividing the total on-site PM energy consumption for all the processes studied within the subsector by the subsector % coverage, found in Chapter 3.
** 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: (CT- PM)/(CT- TM).
*** Totals may not sum due to independent rounding.

It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. Among the processes studied the greatest *current* plus *R&D opportunity* in terms of percent energy savings is in sugar manufacturing at 73% energy savings; the greatest *current* plus *R&D opportunity* in terms of TBtu savings is grain and oilseed milling at 105 TBtu per year savings.

If U.S food and beverage products manufacturing (for the 2010 production level) were able to attain on-site PM energy intensities, it is estimated that 379 TBtu per year of energy could be saved from the processes studied alone, corresponding to a 38% energy savings overall. This energy savings estimate is based on adopting available PM technologies and practices. This is a simple estimate for potential savings; it is not inferred that all existing plants could achieve these PM energy intensity values or that the improvements would prove to be cost effective in all cases.

The R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. The PM energy savings percent is the percent of energy saved with PM energy consumption compared to CT energy consumption and references the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed in the following section, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (e.g., from a chemical reaction or permanent crystalline change), TM is not necessarily equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equations for calculating on-site R&D opportunity and PM energy savings percent are:

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

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

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

Table 5-4. On-site Practical Minimum Energy Consumption, R&D Energy Savings, and R&D Energy Savings Percent for Food and Beverage Products Manufacturing in Subsectors Studied and Sector-Wide

Sub-Product/Sub-Process	On-site SOA Energy Consumption, Calculated (TBtu/year)	On-site PM Energy Consumption, Calculated (TBtu/year)	R&D Energy Savings (SOA–PM) (TBtu/year)	R&D Energy Savings Percentage* (SOA-PM)/ (CT-TM)
Total for Processes Studied	346	292	54	11%
Total for Food and Beverage Sector-wide	899**	763**	137	11%

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).
** Estimates for the entire subsector were extrapolated by dividing the total on-site PM energy consumption for all the processes studied within the subsector by the subsector % coverage, found in Chapter 3.

6. Thermodynamic Minimum Energy Intensity and Energy Consumption for U.S. Food and Beverage Product Manufacturing

Real world food and beverage products production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture a food or beverage product 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 to manufacture the food and beverage products studied.

6.1. Thermodynamic Minimum Energy Intensity

TM energy consumption, which is based on Gibbs free energy (ΔG) calculations, assumes ideal conditions that are unachievable in real-world applications. TM energy consumption assumes that all energy is used productively, that there are no energy losses, and that energy is ultimately perfectly conserved by the system (i.e., when cooling a material to room temperature or applying work to a process, the heat or work energy is fully recovered – perfect efficiency). It is not anticipated that any manufacturing process would ever attain this value in practice. A reasonable long-term goal for energy efficiency would be the practical minimum (see Chapter 5).

For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., a chemical reaction or permanent crystalline change due to deformation), TM is not necessary equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0).

6.2. Calculated Thermodynamic Minimum Energy Intensity for Individual Food and Beverage Products

The thermodynamic minimum energy intensity was calculated for each food and beverage product by determining the Gibbs free energy (G) associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[9] Table 6-1 provides the TM energy intensity and the calculated TM energy consumption for the food and beverage processes studied. Energy consumption values were calculated by multiplying energy intensity by the 2010 production volume.

The TM energy intensity calculation is path independent (state function), but is directly related to the relative energy levels of the substrates and the products. The reported value depends only on the starting material and the end product, and would not change if the process had greater or fewer process steps. Note that for processes that involve no net chemical changes or reactions, the TM energy intensity is *zero* because all energy expended is assumed to be perfectly recovered. The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[10] 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.

Most food and beverage products have a zero TM energy intensity because there are no significant chemical reactions involved. There were four products/processes of this sector that did involve chemical reactions: freezing (which applied to frozen fruit and vegetables and ice cream), sugar production, cheese production, and beer and wine production. The TMs for these processes/products were calculated based on the net Gibbs free

[9] Unless otherwise noted, "ideal conditions" means a pressure of one atmosphere and a temperature of 77°F.
[10] Exergonic (reaction is favorable) and endergonic (reaction is not favorable) are thermodynamic terms for total change in Gibbs free energy (delta G). This differs from exothermic (reaction is favorable) and endothermic (reaction is not favorable) terminology used in describing change in enthalpy (delta H).

energy change and can be found below in Table 6-1. Complete details on the calculations can be found in Appendix A4.

Table 6-1. On-site Thermodynamic Minimum Energy Intensities and Energy Consumption for Food and Beverage Products Manufacturing in Subsectors Studied and Sector-Wide

Subsector/Product	On-site TM Energy Intensity for Processes Studied (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	Production (Million lb/year) (million bbl/year for beverages)	On-site TM Energy Consumption, Calculated (TBtu/year)
Grain and Oil Seed Milling			
Soybean Oil	0	19,311	0
Wet Corn Milling (Corn Oil)	0	61,383†	0
Subtotal			**0**
Sugar Manufacturing			
Cane Sugar	41	7,327	0.3
Beet Sugar	41	9,517	0.4
Subtotal			**0.7**
Fruit and Vegetable Processing			
Fruit Juice	0	9,813	0
Canned Fruits and Vegetables	0	17,658	0
Frozen Vegetables	-53.5 to -48.6*	20,639	-1.0
Frozen Fruit	-55	1,520	-0.1
Subtotal			**-1.1**
Dairy Products			
Fluid Milk	0	192,877	0
Cheese	-1	10,443	-0.01
Ice Cream	-53	5,990	-0.3
Butter	0	1,564	0
Canned Evaporated Milk/Powdered Dry Milk	0	2,488	0
Subtotal			**-0.3**
Animal Slaughtering and Processing			
Lard, Tallow, Fat	0	2,996	0
Pork	0	22,437	0
Red Meat Products (Beef, Pork, Lamb)	0	49,039	0
Poultry	0	50,134	0
Subtotal			**0**
Beverage Manufacturing			

Table 6-1. On-site Thermodynamic Minimum Energy Intensities and Energy Consumption for Food and Beverage Products Manufacturing in Subsectors Studied and Sector-Wide

Subsector/Product	**On-site TM Energy Intensity for Processes Studied** (Btu/lb) (Btu/bbl for Beverages) (TBtu/year)	**Production** (Million lb/year) (million bbl/year for beverages)	**On-site TM Energy Consumption, Calculated** (TBtu/year)
Beer	-8.8**	194.6	<0
Wine	-26.2**	12.5	<0
Subtotal			**<0**
Total for Processes in Subsectors Studied******	N/A	N/A	**-0.75**

Thermodynamic Minimum (TM)
† Energy intensity for corn oil is in terms of per lb corn processed or "corn grind" and production value provided is in corresponding units (lb corn grind)
* Lower value (more negative) for general vegetables, higher value (less negative) for potatoes
** Values are in Btu/bbl
**** Totals may not sum due to independent rounding.

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., sugar), this percent energy savings approach results more realistic and comparable energy savings estimates. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

6.3. Thermodynamic Minimum Energy Consumption by Subsector and Sector-wide

The minimum baseline of energy consumption for a food and beverage products manufacturing process is its TM energy consumption. If all the 2010 level of food and beverage products manufacturing occurred at TM energy intensity, there would be 100% savings. The percentage of energy savings is determined by calculating the decrease in energy consumption and dividing it by the total possible savings (CT energy consumption-TM energy consumption).

Table 6-2 provides the TM energy consumption for the subsectors studied and sector-wide. It is important to keep in mind that ideal conditions are unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities. As mentioned, the TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero). The total TM energy consumption sector-wide for the processes studied is negative (although very small) because many of the products studied have a zero TM energy intensity (i.e., no chemical transformation), while some (e.g., frozen products) have negative TM energy intensity.

Table 6-2. On-site Thermodynamic Minimum Energy Consumption for Food and Beverage Products Manufacturing in Subsectors Studied and Sector-Wide

Subsector	**On-site TM Energy Consumption for Processes Studied** (TBtu/year)	**On-site TM Energy Consumption for Total Subsector (extrapolated)*** (TBtu/year)
Grain and Oil Seed Milling	0	0
Sugar Manufacturing	0.7	1.4
Fruit and Vegetable Processing	-1.1	-3.0
Dairy Products	-0.3	-0.5
Animal Slaughtering and Processing	0	0
Beverage Manufacturing	<0	<0
Total for Processes Studied**	**-0.8**	**-2.1**
All other food manufacturing	N/A	~0
Total for Food and Beverage Sector-wide**	N/A	**-2.1**

Thermodynamic Minimum (TM)
* Estimates for the entire subsector were extrapolated by dividing the total on-site PM energy consumption for all the processes studied within the subsector by the subsector % coverage, found in Chapter 3.
** Totals may not sum due to independent rounding.

7. U.S. Food and Beverage Product Manufacturing Current and R&D Opportunity Analysis/Bandwidth Summary

This chapter presents the energy savings bandwidths for the food and beverage manufacturing subsectors studied and sector-wide based on the analysis and data presented in the previous Chapters and the following Appendices. Data is presented for the six subsectors studied and extrapolated to estimate the energy savings potential for all of U.S. food and beverage manufacturing.

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings for the products studied for products manufacturing as well as the total subsector. A majority of these energy savings opportunities are due to energy efficiency improvements which would fall under current opportunity energy savings. For example, energy efficiency improvements for sugar plants include processes such as insulating steam lines, upgrading compressor controls, steam trap repairs or replacements, etc. These energy efficiency measures indicate that further current opportunity energy savings are possible for the food and beverage industry. Each row in Table 7-1 shows the opportunity bandwidth for a specific food and beverage subsector and as a sector-wide total. As previously noted, the energy savings opportunities presented reflect the estimated production of food and beverage products for selected subsectors and sector-wide in baseline year 2010.

Table 7-1. Current and R&D Opportunities for Food and Beverage Products Manufacturing

Sub-Product/Sub-process	Current Opportunity for Processes Studied (CT-SOA) (TBtu/year)	Current Opportunity for Total Subsector (extrapolated) (CT-SOA) (TBtu/year)	R&D Opportunity for Processes Studied (SOA-PM) (TBtu/year)	R&D Opportunity for Total Subsector (extrapolated) (SOA-PM) (TBtu/year)
Grain and Oil Seed Milling	35	70	17	35
Sugar Manufacturing	24	47	15	30
Fruit and Vegetable Processing	17	45	2	7
Dairy Products	25	37	9	13
Animal Slaughtering and Processing	23	59	8	21
Beverage Manufacturing	6	13	2	4
Total for Processes Studied*	**130**	**270**	**54**	**109**
All Other Food Manufacturing	N/A	66	N/A	27
Total for Food and Beverage Sector-wide*	N/A	**336**	N/A	**137**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Totals may not sum due to independent rounding.

As shown in Figure 7-1, four hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). For the process areas in the six subsectors studied, the analysis shows the following:

- *Current Opportunity* – 130 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 54 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

For sector-wide U.S. food and beverage manufacturing (based on extrapolated data), the analysis shows the following:

- *Current Opportunity* – 336 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 137 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 7-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual food and beverage products manufacturing subsectors as well as sector-wide. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are based on today's knowledge of research tested between laboratory and demonstration scale; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

From the processes studied, the greatest *current* energy savings opportunity for food and beverage products manufacturing comes from upgrading soybean oil milling processes. In addition, the greatest *R&D* energy savings opportunity for food and beverage products manufacturing comes from upgrading wet corn milling processes—this is largely due to the fact that a significant amount of energy consumed in the sector occurs in these processes.

The *impractical* bandwidth, or the difference between PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in food and beverage products manufacturing. The term *impractical* is used because the PM energy consumption is based on current knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

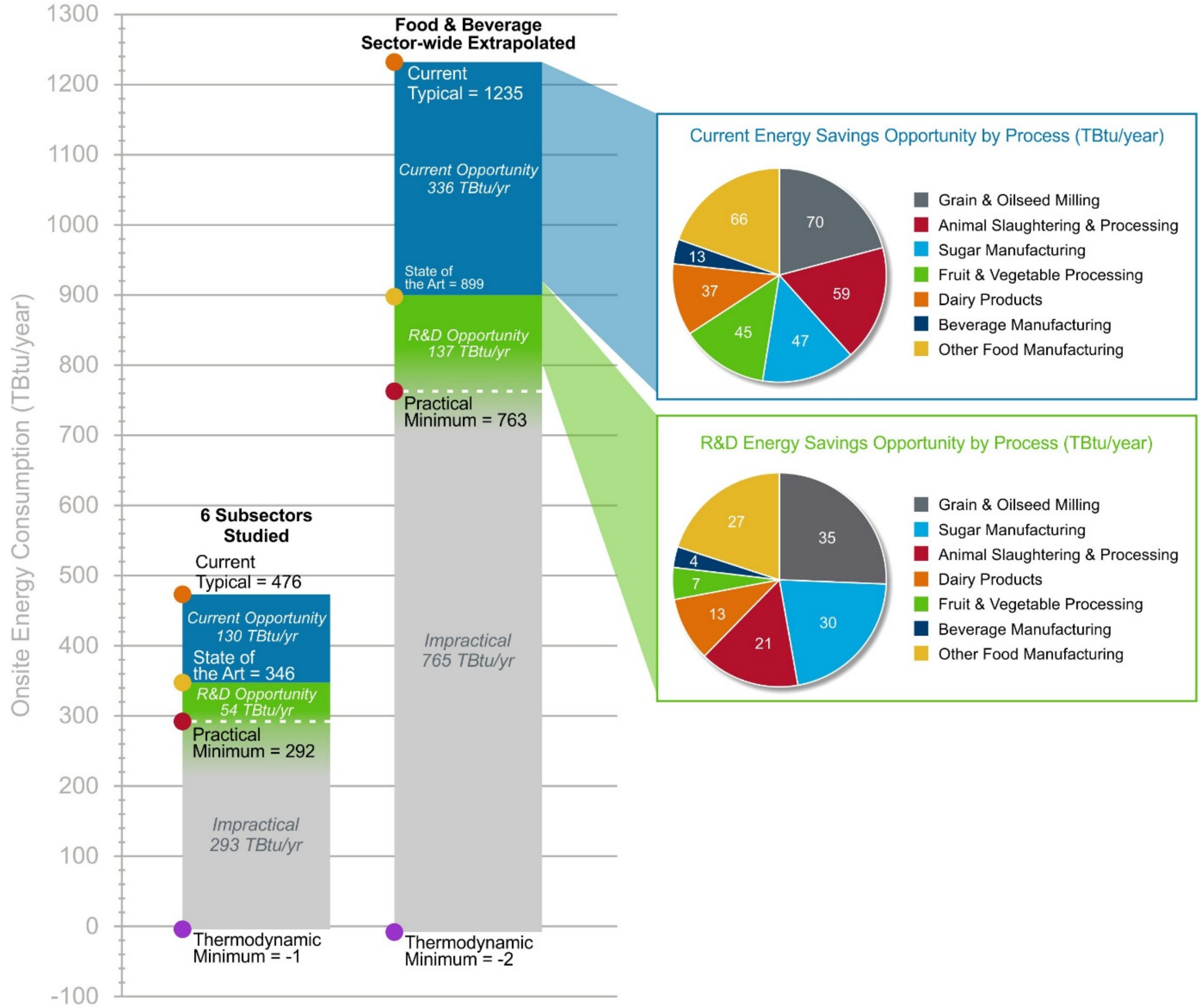

Figure 7-1. Current and R&D energy savings opportunities for the subsectors studied and for food and beverage products manufacturing sector-wide based on extrapolated data
Source: EERE

The top three Current Energy Savings Opportunities for the processes are as follows:

- Soybean oil crushing and extraction – 24 TBtu/year (or 7% of the total sector current opportunity)
    - Due to a newer plant in operation with an improved oil extraction rate per pound of soybean and use of energy-saving technologies and reduced hexane loss (see Han et al. 2014, Pradhan et al. 2011).
- Fluid milk processing – 23 TBtu/year (or 7% of the total sector current opportunity)
    - Due to multiple energy efficiency measures, including steam system improvements (such as improving insulation, reducing demand by changing process steam requirement, improving boiler efficiency) or using a CO_2 heat pump (DOE 2004, DOE 2011, Goldthorpe 2002, Liu et al. 2014).
- Red meat products processing – 15 TBtu/year (or 4% of the total sector current opportunity)
    - Due mainly to improvements to the efficiency of refrigeration, as well as steam and compressed air system improvements (higher efficiency, better recovery rates, etc.) (AMIC

2013, DOE 2004, DOE 2011, IPPC 2005, Meat and Livestock Australia Ltd 2002).

The top three R&D Energy Saving Opportunities for the processes are as follows:

- Wet corn milling – 17 TBtu/year (or 13% of the total sector R&D opportunity)
    - Due to use of membrane separation for water removal and infrared heating in place of conventional heating (Tuncel et al. 2010, Wang 2008).
- Beet sugar processing – 13 TBtu/year (or 9% of the total sector R&D opportunity)
    - Utilizing mechanical dewatering for beet sugar production (Wang 2008).
- Fluid milk processing – 8 TBtu/year (or 6% of the total sector R&D opportunity)
    - Due to new technology for refrigeration (evaporator fan controls) as well as for pasteurization (utilizing pulsed electric fields treatment) (Heinz et al. 2003, Lung, Masanet, & McKane 2006).

For each of the six subsectors studied, the greatest opportunity is:

- Grain and Oil Seed Milling
    - The current opportunity for soybean oil production, accounting for an estimated 24.4 TBtu/year savings, through soybean crushing and extration, as noted above.
- Sugar Manufacturing
    - The R&D opportunity for beet sugar processing, accounting for an estimated 12.8 TBtu/year savings, through total process savings, as noted above.
- Fruit and Vegetable Processing
    - The current opportunity for frozen vegetables production, accounting for an estimated 9.1 TBtu/year savings. The most opportunity comes from savings in the freezing process, comparing current U.S. practices to SOA practices available internationally (IPPC 2006).
- Dairy Products
    - The current opportunity for fluid milk processing, accounting for an estimated 23.1 TBtu/year savings, as noted above. The most opportunity comes from savings in the pasteurization step, where 10.2 TBtu/year of current opportunity savings could be achieved alone, comparing current U.S. practices to SOA practices available internationally (Goldthorpe 2002).
- Animal Slaughtering and Processing
    - The current opportunity for the production of beef, pork, and lamb (red meat products), accounting for an estimated 14.6 TBtu/year of savings. As noted above, the energy savings are due to efficiency improvements; a significant amount of this savings (9.8 TBtu/year) comes from refrigeration improvements (AMIC 2013, Fritzson & Berntsson 2006).
- Beverage Manufacturing
    - The current opportunity for the production of beer, accounting for an estimated 6.2 TBtu/year of savings. The largest opportunity, 1.6 TBtu/year, is accumulated from savings in space heating, due to heat recovery opportunities (LBNL 2003a).

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Appendix A1. Master Food and Beverage Product Manufacturing Summary Table

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
Grain and Oilseed Milling (NAICS 3112) & Wet Corn Milling (NAICS 311221)	Soybean Oil	19,331								
	Soybean crushing and extraction		3,688	2,425	2,425	0	72.0	46.9	46.9	0
	Corn Oil*	61,683* (*for corn oil, energy intensities are per amount of corn processed, or “corn grind”)								
	Corn receiving		8	7	7	0	0.47	0.5	0.5	0
	Steeping		60	48	48	0	3.7	3.0	3.0	0
	Steepwater evaporation		358	286	29	0	22.0	17.6	1.8	0
	Germ recovery (1st grind)		12	12	12	0	0.8	0.7	0.7	0
	Germ recovery (2nd grind)		6	6	6	0	0.4	0.4	0.4	0
	Germ recovery (germ washing)		0	0	0	0	0.03	0.03	0.03	0
	Germ dewatering and drying		129	103	76	0	7.9	6.3	4.7	0
	Fiber recovery		39	37	37	0	2.4	2.3	2.3	0
	Fiber dewatering		7	6	6	0	0.4	0.4	0.4	0
	Protein (gluten) recovery		18	17	17	0	1.10	1.05	1.05	0
	Gluten thickening and drying		73	70	70	0	4.5	4.3	4.3	0
	Starch washing		9	8	8	0	0.53	0.5	0.5	0
	Starch dewatering and drying		530	507	507	0	32.5	31.1	31.1	0
	Gluten feed dryer		418	400	400	0	25.6	24.5	24.5	0
	Grain and Oilseed Milling SUBTOTAL, Processes Studied						*174.3*	*139.4*	*121.9*	*0*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*350*	*280.0*	*244.9*	*0*

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
Sugar Manufacturing (NAICS 31131)	Cane Sugar Total Product	7,327	2,526	946	671	41	18.5	6.9	4.9	0.3
	Beet Sugar Total Product	9,517	3,682	2,405	1,063	41	35.0	22.9	10.1	0.4
	Sugar Manufacturing SUBTOTAL, Processes Studied						*53.5*	*29.8*	*15.0*	*0.7*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*107*	*59.6*	*30*	*1.4*
Fruits and Vegetable Processing (NAICS 3114)	Fruit juice									
	Washing	9,813	224	198	198	0	2.2	1.9	1.9	0
	Can washing		217	191	191	0	2.1	1.9	1.9	0
	Pasteurization (heat treatment)		133	84	34	0	1.3	0.8	0.3	0
	Heat sterilization (retorting)		100	63	42	0	1.0	0.6	0.4	0
	Can sealing		41	33	33	0	0.4	0.3	0.3	0
	Vacuum deaeration		13	11	11	0	0.1	0.1	0.1	0
	Packaging		13	11	11	0	0.1	0.1	0.1	0
	Canned fruits and vegetables									0
	Washing	17,658	224	198	198	0	4.0	3.5	3.5	0
	Heat sterilization (retorting)		217	137	92	0	3.8	2.4	1.6	0
	Blanching *(canned vegetables only)*		200	110	94	0	3.5	1.9	1.7	0
	Cooking *(canned fruits only)*		200	160	136	0	3.5	2.8	2.4	0
	Can exhausting		100	80	80	0	1.8	1.4	1.4	0
	Brine heating		100	80	80	0	1.8	1.4	1.4	0
	Can washing		43	11	11	0	0.8	0.2	0.2	0
	Can sealing		43	34	34	0	0.8	0.6	0.6	0
	Packaging		15	13	13	0	0.3	0.2	0.2	0

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
	Frozen vegetables									
	Sorting/screening, grading	20,639	5	2	2	0	0.1	0.03	0.03	0
	Washing		179	143	143	0	3.7	3.0	3.0	0
	Peeling		6	5	5	0	0.1	0.1	0.1	0
	Cutting/slicing		17	10	10	0	0.4	0.2	0.2	0
	Blanching		160	88	75	0	3.3	1.8	1.5	0
	Frying *(frozen potatoes only)*		325	305	305	0	5.1	4.8	4.8	0
	Freezing		586	279	279	-53.5 to -48.6	12.1	5.8	5.8	-1.02
	Packaging		15	14	14	0	0.3	0.3	0.3	0
	Frozen fruit									
	Freezing	1,520	586	279	279	-55	0.9	0.4	0.4	-0.08
	Washing		190	152	152	0	0.3	0.2	0.2	0
	Fruits and Vegetable Processing SUBTOTAL, Processes Studied						*53.7*	*36.9*	*34.5*	*-1.1*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*143*	*98.4*	*91.8*	*-3.0*
Dairy Products (NAICS 3115)	Fluid Milk									
	Pasteurization	192,877	92	39	16	0	17.7	7.5	3.0	0
	Cooling		85	41	23	0	16.4	8.0	4.4	0
	Receiving and Storage		30	23	23	0	5.8	4.5	4.5	0
	Deodorization		25	20	20	0	4.8	3.9	3.9	0
	Final Storage		18	14	14	0	3.5	2.7	2.7	0
	Separation		18	14	14	0	3.5	2.7	2.7	0
	Packaging		15	12	12	0	2.9	2.3	2.3	0
	Cheese									
	Motors, pumps	10,443	841	766	766	0	8.8	8.0	8.0	0
	Make Vat		178	142	142	-0.9	1.9	1.5	1.5	-0.01
	Cooking, Pasteurization (1)		92	74	74	0	1.0	0.8	0.8	0

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
	Pasteurization (2)		72	45	18	0	0.8	0.5	0.2	0
	Ice Cream									
	Freezing	5,990	538	538	538	-53	3.2	3.2	3.2	-0.32
	Pasteurization		92	76	31	0	0.6	0.5	0.2	0
	Cooling		85	85	47	0	0.5	0.5	0.3	0
	Butter									
	Pasteurization	1,564	359	226	90	0	0.6	0.6	0.1	0
	Refrigeration		175	16	9	0	0.3	0.02	0.01	0
	Canned Evaporated Milk/Powdered Dry Milk									
	Concentration	2,488	172	138	138	0	0.4	0.3	0.3	0
	Canning	672	120	120	120	0	0.1	0.1	0.1	0
	Spray Drying	1,816	115	115	69	0	0.2	0.2	0.1	0
	Dairy Products SUBTOTAL, Processes Studied						*72.8*	*47.4*	*38.2*	*-0.33*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*105*	*68.4*	*55.2*	*-0.5*
Animal Slaughtering and Processing (NAICS 3116)	Lard, Tallow, Fat	2,996								
	Edible rendering		4,573	2,973	1,784	0	13.7	8.9	5.3	0
	Pork	22,437								
	Splitting		117	101	101	0	2.6	2.3	2.3	0
	Scalding		149	36	36	0	3.3	0.8	0.8	0
	Singeing		82	70	70	0	1.8	1.6	1.6	0
	Red Meat Products (Beef, Pork, Lamb)	49,039								
	Blood processing		80	64	64	0	3.9	3.1	3.1	0
	Chilling/refrigeration		468	268	187	0	22.9	13.1	9.2	0
	Dressing and cutting		181	156	156	0	8.9	7.6	7.6	0
	Processing (curing, smoking, cooking)		320	276	276	0	15.7	13.6	13.6	0
	Packaging		93	80	80	0	4.5	3.9	3.9	0

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
	Poultry									
	Lairage (holding pen)	50,134	0.3	0.3	0.3	0	0.01	0.01	0.01	0
	Hanging, scalding, slaughtering, and defeathering		15	15	15	0	0.8	0.7	0.7	0
	Evisceration and cooling		9	9	9	0	0.5	0.5	0.5	0
	Liquid effluent treatment		23	22	22	0	1.1	1.1	1.1	0
	Refrigeration		36	34	24	0	1.8	1.7	1.2	0
	Packaging		7	7	7	0	0.4	0.3	0.3	0
	Animal Slaughtering and Processing SUBTOTAL, Processes Studied						*82.0*	*59.3*	*51.3*	*0*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*212*	*153.2*	*132.5*	*0*
Beverages (NAICS 3121)	Beer (million bbls, and Btu/bbl)									
	Brewhouse	195	67,045	63,571	63,571	-8.8	13.1	12.4	12.4	-0.002
	Packaging		49,493	43,174	43,174	0	9.6	8.4	8.4	0
	Space Heating		13,997	5,997	4,497	0	2.7	1.2	0.9	0
	Utilities		27,993	27,096	27,096	0	5.5	5.3	5.3	0
	Refrigeration		20,302	15,986	8,792	0	4.0	3.1	1.7	0
	Lighting		3,480	2,152	2,152	0	0.7	0.4	0.4	0
	Compressed Air		5,801	3,722	1,303	0	1.1	0.7	0.3	0
	Boiler		2,900	1,572	1,572	0	0.6	0.3	0.3	0
	Other		6,961	2,977	2,977	0	1.4	0.6	0.6	0
	Wine (million bbls, and Btu/bbl)									
	Grape reception & extraction	13	4,262	3,836	128	0	0.05	0.05	0.002	0
	Alcoholic fermentation		38,749	30,999	30,999	-26.2	0.5	0.4	0.4	<0
	Pressing		5,812	4,941	4,941	0	0.07	0.06	0.06	0
	Stabilization		6,975	5,580	5,580	0	0.09	0.07	0.07	0

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

Subsector	Product/Process	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption (TBtu/year)			
			CT	SOA	PM	TM	CT	SOA	PM	TM
	Bottling, storage and delivery		18,987	12,187	12,187	0	0.2	0.2	0.2	0
	Lighting		5,812	5,231	5,231	0	0.07	0.07	0.07	0
	Auxiliary processes		12,400	8,680	8,680	0	0.2	0.1	0.1	0
	Beverages SUBTOTAL, Processes Studied						*39.7*	*33.2*	*31.0*	*<0*
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						*77*	*64.5*	*60.2*	*<0*
	Total for all Subsectors Studied, Processes Studied						**476.0**	**346.1**	**292.0**	**-0.75**
	Total for Sector-Wide, CT from MECS, Extrapolated for SOA, PM, TM						**1,235**	**899.5**	**762.6**	**-2.0**

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

Appendix A2. References for Production, CT, SOA, PM, and TM

Table A2-1. U.S. Production Volume of Food and Beverage Products Manufacturing Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Subsector	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Grain and Oil Seed Milling					
Soybean crushing and extraction (soybean oil)	USCB 2011b	Omni Tech International 2010	Han et al. 2014, Pradhan et al. 2011	DOE 2004	Set to zero due to minimal chemical conversions Set to zero due to minimal chemical conversions
Wet Corn Milling					
Corn receiving	USCB 2011b	LBNL 2003b	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Steeping			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Steepwater evaporation				Wang 2008	Set to zero due to minimal chemical conversions
Germ recovery (1st grind)			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Germ recovery (2nd grind)					Set to zero due to minimal chemical conversions
Germ recovery (germ washing)					Set to zero due to minimal chemical conversions
Germ dewatering and drying			DOE 2004	Tuncel et al. 2010	Set to zero due to minimal chemical conversions
Fiber recovery			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Fiber dewatering					Set to zero due to minimal chemical conversions
Protein (gluten) recovery					Set to zero due to minimal chemical conversions

Gluten thickening and drying					Set to zero due to minimal chemical conversions
Starch washing					Set to zero due to minimal chemical conversions
Starch dewatering and drying					Set to zero due to minimal chemical conversions
Gluten feed dryer					Set to zero due to minimal chemical conversions
Sugar Manufacturing					
Cane Sugar Total Product	USDA 2016g	Wang 2008	IAC 2016	Wang 2008	Internal calculations
Beet Sugar Total Product		IPPC 2006	IPPC 2006		Internal calculations
Fruit and Vegetable Processing					
Fruit Juice					
Washing	USDA 2016d, Charrondiere, Haytowitz, & Stadlymayr 2012	LBNL 2008	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Can washing			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Pasteurization (heat treatment)			LBNL 2008, DOE 2004	Heinz et al 2003	Set to zero due to minimal chemical conversions
Heat sterilization (retort)			LBNL 2008, DOE 2004	Liato et al 2016	Set to zero due to minimal chemical conversions
Can sealing			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Vacuum deaeration			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Packaging			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Canned Fruits and Vegetables					
Washing	USDA 2016c, USDA 2016d, USDA 2016h	LBNL 2008	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Heat sterilization (retorting)			LBNL 2008, DOE 2004	Liato et al 2016	Set to zero due to minimal chemical conversions
Blanching *(canned vegetables only)*			LBNL 2008, DOE 2004	CORDIS 2016d	Set to zero due to minimal chemical conversions
Cooking *(canned fruits only)*			DOE 2004	CORDIS 2016d	Set to zero due to minimal chemical conversions
Can exhausting				DOE 2004	Set to zero due to minimal chemical conversions

Brine heating				DOE 2004	Set to zero due to minimal chemical conversions
Can washing			UNEP 2008	UNEP 2008	Set to zero due to minimal chemical conversions
Can sealing			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Packaging			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Frozen Vegetables					
Sorting/screening, grading	USDA 2016h	LBNL 2008	IPPC 2006	IPPC 2006	Set to zero due to minimal chemical conversions
Washing			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Peeling			UNEP 2008	UNEP 2008	Set to zero due to minimal chemical conversions
Cutting/slicing			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Blanching			LBNL 2008, DOE 2004	CORDIS 2016d	Set to zero due to minimal chemical conversions
Frying *(frozen potatoes only)*			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Freezing			IPPC 2006	IPPC 2006	Internal calculations
Packaging			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Frozen Fruit					
Freezing	USDA 2016c, USDA 2016d	LBNL 2008	IPPC 2006	IPPC 2006	Internal calculations
Washing			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Dairy Products					
Fluid Milk					
Pasteurization	USDA 2016b	LBNL 2011	Goldthorpe 2002	Heinz et al 2003	Set to zero due to minimal chemical conversions
Cooling			Liu et al. 2014	Lung, Masanet, & McKane 2006	Set to zero due to minimal chemical conversions
Receiving and Storage			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Deodorization			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Final Storage			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions

Separation					Set to zero due to minimal chemical conversions
Packaging					Set to zero due to minimal chemical conversions
Cheese					
Motors, pumps	USDA 2016a	LBNL 2011	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Make Vat			DOE 2004	DOE 2004	Internal calculations
Cooking, Pasteurization			DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Pasteurization			LBNL 2011, DOE 2004	Heinz et al 2003	Set to zero due to minimal chemical conversions
Ice Cream					
Freezing	USDA 2016a	LBNL 2011	LBNL 2011	LBNL 2011	Internal calculations
Pasteurization				Heinz et al 2003	Set to zero due to minimal chemical conversions
Cooling				Lung, Masanet, & McKane 2006	Set to zero due to minimal chemical conversions
Butter					
Pasteurization	USDA 2016a	LBNL 2011	LBNL 2011, DOE 2004	Heinz et al 2003	Set to zero due to minimal chemical conversions
Refrigeration			LBNL 2011	Lung, Masanet, & McKane 2006	Set to zero due to minimal chemical conversions
Canned evaporated milk/powdered dry milk					
Concentration	USDA 2016a	LBNL 2011	DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Canning			LBNL 2011	LBNL 2011	Set to zero due to minimal chemical conversions
Spray Drying				DOE 2016	Set to zero due to minimal chemical conversions
Animal Slaughtering and Processing					
Lard, tallow, fat					
Edible rendering	USDA 2016f	Brown 1996	Meat and Livestock Australia Ltd 2002, DOE 2004	CORDIS 2015b	Set to zero due to minimal chemical conversions
Pork					
Splitting	USDA 2016e	IPPC 2005	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions

Scalding			IPPC 2005	IPPC 2005	Set to zero due to minimal chemical conversions
Singeing			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Red meat products (beef, pork, lamb)					
Blood processing	USDA 2016e	Meat and Livestock Australia Ltd 2002	DOE 2004	DOE 2004	Set to zero due to minimal chemical conversions
Chilling		Brown 1996	AMIC 2013, Fritzson & Berntsson 2006	AMIC 2013	Set to zero due to minimal chemical conversions
Dressing and cutting			DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Processing (curing, smoking, cooking)					Set to zero due to minimal chemical conversions
Packaging					Set to zero due to minimal chemical conversions
Poultry					
Lairage (holding pen)	USDA 2016e	Harding et al 2006	DOE 2011	DOE 2011	Set to zero due to minimal chemical conversions
Hanging, scalding, slaughtering, and defeathering					Set to zero due to minimal chemical conversions
Evisceration and cooling					Set to zero due to minimal chemical conversions
Liquid Effluent Treatment					Set to zero due to minimal chemical conversions
Refrigeration				AMIC 2013	Set to zero due to minimal chemical conversions
Packaging				DOE 2011	Set to zero due to minimal chemical conversions
Beverage Manufacturing					
Beer					
Brewhouse	DOT 2011a	Brewers Association 2014	IAC 2016	IAC 2016	Internal calculations
Packaging			IAC 2016	IAC 2016	Set to zero due to minimal chemical conversions
Space Heating			LBNL 2003a	Brewers Association 2014	Set to zero due to minimal chemical conversions
Utilities			IAC 2016	IAC 2016	Set to zero due to minimal chemical conversions
Refrigeration			LBNL 2003a	Lung, Masanet, & McKane 2006	Set to zero due to minimal chemical conversions

Lighting			LBNL 2003a	LBNL 2003a	Set to zero due to minimal chemical conversions
Compressed Air			IAC 2016	CORDIS 2015a	Set to zero due to minimal chemical conversions
Boiler			LBNL 2003a	LBNL 2003a	Set to zero due to minimal chemical conversions
Other			LBNL 2003a	LBNL 2003a	Set to zero due to minimal chemical conversions
Wine					
Grape reception & extraction	DOT 2011b	UPM 2013	UPM 2013	CORDIS 2017	Set to zero due to minimal chemical conversions
Alcoholic fermentation				UPM 2013	Internal calculations
Pressing					Set to zero due to minimal chemical conversions
Stabilization					Set to zero due to minimal chemical conversions
Bottling, storage and delivery					Set to zero due to minimal chemical conversions
Lighting					Set to zero due to minimal chemical conversions
Auxiliary processes					Set to zero due to minimal chemical conversions

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

Appendix A3. Practical Minimum (R&D) Technologies Considered

Table A3-1. Details of Food and Beverage Products Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
Grain & Oilseed Milling							
Membrane separation	Use of membranes and desalination techniques (particularly reverse osmosis) to remove water in wet corn milling	Wet corn milling	Reported energy savings of 90% were observed by replacing evaporation with membrane filtration.	90%	No	Yes	Wang 2008
Infrared (IR) heating for corn drying	The transfer of thermal energy in the form of electromagnetic waves to replace conventional process heating.	Corn Drying	"We observed that IR radiation did not cause any negative impact on crude protein, total carotenoid, color characteristics and phenolic acid content of corn in noted conditions. Besides, IR and IR-HA drying methods dramatically reduced the drying time. Evaporation of unit water took 12 and 40% less energy in IR drying of corn samples with the moisture content of 24 and 16%, respectively, as compared to HA drying alone. Thus, IR drying is considered to be a promising alternative for drying of corn with the initial moisture content above 16%."	26%	No	Yes	Tuncel et al 2010
Sugar Manufacturing							
Mechanical dewatering	water removed by mechanical screw press from beet	Dewater and drying	Using mechanical dewatering, therefore, saved 55.8% in primary energy use	56%	No	Yes	Wang 2008

Table A3-1. Details of Food and Beverage Products Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
Change to five-effect evaporators	a simple, series arrangement of several evaporators, which use steam to remove product moisture by evaporation	Evaporation	It was found that changing from four-effect evaporators to five-effect evaporators could save 20% energy.	20%	No	No	Wang 2008
Retrofit design of energy systems	a new approach for the retrofit design of energy systems in sugar processing facilities	Crystallization	Urbaniec et al. (2000) introduced a new approach for the retrofit design of energy systems in sugar processing facilities. The energy saving was estimated at 29% and the payback period was four years.	29%	No	Yes	Wang 2008
Fruit and Vegetable Preserving and Specialty Foods							
Advanced Ohmic Heating for resource efficient Thermal Treatment to produce high quality food products	Ohmic heating is an alternative fast heating method for food products; results in less thermal damage than conventional heating. In Ohmic heating, foods are made part of an electric circuit and heat is generated within the foods due to their electrical resistance. The process offers advantages such as rapid uniform heating, reduced surface fouling, high energy efficiency and high quality food products.	Cooking, blanching	Noted that food processing companies will have a 15% reduction in energy use	15%	No	Yes	CORDIS 2016d
Electro-activated brine solution and low heat treatment for sterilization	Electro-activated brine solutions can lower the temperature required for sterilization and/or	Heat sterilization (retort)	"In a previous work, it was found that by utilizing EABS instead of the conventional brine solution, we could either lower the temperature	33%	No	Yes	Liato et al. 2016

Table A3-1. Details of Food and Beverage Products Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
	reduce processing times to save energy.		of sterilisation or shorten the time of processing."				
Pasteurization by pulsed electric fields treatment	"In the pulsed electric field process, liquids are exposed to high voltage pulses of electricity to inactivate harmful micro-organisms"	Pasteurization (heat treatment)	"The energy savings associated with pulsed electric field processing arise from the fact that the process operates at lower temperatures than conventional heat-based pasteurization methods and thus the pasteurized fluid requires less cooling energy (Lung, Masanet & McKane 2006)."	60%	No	Yes	Heinz et al. 2003, Description of the technology from: Lung, Masanet & McKane 2006
Dairy Products							
Evaporator Fan Controls for Refrigerated Storage	controllers that regulate the speed of the fan motors to better match the energy demand of the refrigeration cycle	Refrigeration	significantly reduced energy consumption for the evaporator and the compressor; capital costs for retrofitting refrigeration cycle	45%	No	Yes	Lung, Masanet & McKane 2006
Pasteurization by pulsed electric fields treatment	"In the pulsed electric field process, liquids are exposed to high voltage pulses of electricity to inactivate harmful micro-organisms"	Pasteurization (heat treatment)	Associated energy savings arise from the fact that the process operates at lower temperatures than conventional heat-based pasteurization methods and thus the pasteurized fluid requires less cooling energy (Lung, Masanet & McKane 2006).	60%	No	Yes	Heinz et al. 2003, Description of the technology from: Lung, Masanet & McKane 2006
No Heat Spray Drying Technology	"The innovative DriZoom™ technology atomizes liquids to powders at ambient temperature, saving energy and water	Spray Drying	Cons: "Spray drying of liquids into powders at ambient temperatures has not yet been demonstrated at commercial scale because of the significant challenges	40%	No	Yes	DOE 2016

Table A3-1. Details of Food and Beverage Products Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
	while preserving key attributes of the liquid."		compared to heated spray drying —which provides up to two orders of magnitude greater drying force." Pros: "Reduces energy use by 40% or more • Consumes about half as much water • Improves product yield and shelf life • Reduces capital system costs • Produces powdered products with properties closer to those of the original liquid, such as flavor, color, and potency."				
Animal Slaughtering and Processing							
Total expected energy savings for refrigeration in the red meat processing industry	Combination of the other refrigeration technologies listed by this source.	Refrigeration	"Total energy savings of 15-45% can be expected depending upon the type of initiative undertaken (NSW OEH 2011)."	30%	No	Yes	AMIC 2013
BPV (By-Product Value)	a customizable rendering process to valorise slaughterhouse waste in such a way that animal byproducts (ABP) are converted into fuel for biogas generation through anaerobic digestion	Rendering	Reduces the number of steps of the waste processing and save energy (by 40%), is more efficient for biogas production than classic waste (28%), easy to implement and can be made serially at industrial premises	40%	No	Yes	CORDIS 2016b
Beverages							
Tankless water heater	tankless water heater incorporates technology that will only heat water that is	Space heating	"Energy savings in that can range from 10% to 40% over traditional hot water heaters"	25%	No	Yes	Brewers Association 2014

Table A3-1. Details of Food and Beverage Products Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
	required for a given application (on demand water heating)						
HYDRACTVAL (Low-energy leak-proof double seat control valve based on a water hydraulic actuator system)	a leak-proof double seat control valve for the brewery and dairy industries	Compressed air	"Energy efficiency and reduced CO2 emission: Reducing electricity consumption and carbon emissions by more than 65%"	65%	No	Yes	CORDIS 2016a
ULTRAWINE	A low frequency high power (LFHP) ultrasound equipment designed for optimizing the extraction of phenolic compounds from grape skins during the first stages of winemaking	Extraction	completing the grape maceration process in 6 hours while current systems take approximately 4 days, with 30 times less energy and the ability to process triple amount of grape	97%	No	Yes	CORDIS 2016e
Evaporator Fan Controls for Refrigerated Storage	Controllers that regulate the speed of the fan motors to better match the energy demand of the refrigeration cycle	Refrigeration	significantly reduced energy consumption for the evaporator and the compressor; capital costs for retrofitting refrigeration cycle	45%	No	Yes	Lung, Masanet & McKane 2006

Appendix A4. Thermodynamic Minimum Calculation Details

This Appendix provides details on how the thermodynamic minimum energy intensities for freezing (fruits, vegetables, and frozen desserts), cheese production, sugar production, and beer and wine production were calculated and assumptions and reference values used.

Freezing Thermodynamic Minimum Energy Intensity

The thermodynamic minimum energy intensity of freezing depends upon the moisture content fraction of the input materials. Freezing was calculated for frozen desserts, general frozen vegetables, frozen potatoes, and frozen fruits.

$$c_{p,fresh} = 3.35a + 0.48\ \frac{kJ}{kg}\ °C$$

$$c_{p,frozen} = 1.26a + 0.84\ \frac{kJ}{kg}\ °C$$

Where $c_{p,\ fresh}$ is the specific heat of the food before freezing, $c_{p,\ frozen}$ is the specific heat after freezing, and a is the moisture content. The specific heats are needed to calculate the Gibb's free energy for the TM energy intensity, which is typically expressed as:

$$\Delta G = \Delta H - T\Delta S$$

Where G is the Gibb's free energy, H is enthalpy, T is temperature, and S in entropy. In this case, there is no Gibb's free energy change for the phase change. The room temperature is 25ºC, the freezing occurs at -1ºC, and the freezer is at -18°C. Taking the specific heats and temperature changes into account, the formula becomes:

$$\Delta G = T_F c_{p,frozen} - \Delta T_R c_{p,fresh}$$

$$= -17(1.26a + 0.84) - 26(3.35a + 0.48)$$

Where ΔT_F denotes the temperature difference between freezer and freezing temperature (-18 °C - (-1 °C) = -17 °C) and ΔT_R denotes the temperature difference between freezing and room temperature (25 °C – (-1 °C) = 26 °C). The values in the above formulas are calculated in Table A4-1, giving the TM energy intensities for freezing of frozen desserts, vegetables, and fruits. The values for TM energy intensity are negative, as the process of freezing is exothermic, or where energy is produced; in this case, the moisture in the materials being frozen is released, thus netting a negative energy.

Table A4-1. Calculated TM Energy Intensity for Freezing

Input Material	Moisture content fraction, a*	$C_{p,\ fresh}$** (kJ/(kg°C))	$C_{p,\ frozen}$** (kJ/(kg°C))	Gibbs free energy (ΔG) = TM energy intensity (kJ/kg) [Btu/lb]
Milk (to produce frozen desserts)	0.894	3.47	1.97	-123.8 [-53.2]
General vegetables (to produce frozen vegetables)	0.9	3.50	1.97	-124.4 [-53.5]
Potatoes (to produce frozen potatoes)	0.791	3.13	1.84	-112.6 [-48.4]
Fruits (to produce frozen fruits)	0.94	3.63	2.02	-128.8 [-55.4]

* Reference: Schmidt & Fontana 2008
** Reference: Siebel's formula from Chapter 17 of Cengel & Ghajar 2015

Cheese Production Thermodynamic Minimum Energy Intensity

For cheese production, there is a thermodynamic minimum energy intensity due to the addition of casein protein, which causes protein denaturing (unfolding and hydrogen bonding). The mean molecular weight of the casein protein is 23,000 grams/mol. According to Steinberg & Scheraga 1963, the entropy change (ΔS) for the protein reaction is 16.4. Again, the change in Gibb's free energy is calculated using the equation:

$$\Delta G = \Delta H - T\Delta S$$

Where the temperature is assumed to be room temperature, 25 °C or 298 K. Thus the Gibb's free energy, also the TM energy intensity, is calculated as:

$$\Delta G = -6700 \cdot 4.18 - 298 \cdot 68.6 = 48{,}449\ J/mol$$

When converted to BTU/lb (by multiplying by the molecular weight, noted above, and conversion factors for BTU/kJ and kg/lb the value for TM energy intensity for cheese production is -0.9 Btu/lb.

Sugar Production Thermodynamic Minimum Energy Intensity

For sugar production, the thermodynamic minimum energy intensity is the same for cane and beet sugar and was calculated through multiple steps. The input materials are water, and then the steps involve transforming the mixture from 15º brix to 65º brix through a multi-effect evaporator, then 65º brix to dry sugar through a drum or spray dryer (involving crystallization). Brix can also be defined as the concentration of sucrose in the water solution by weight (0.15 or 0.65). For the 15º brix solution, the mean molecular weight is 18 g/mol and for the 65º brix solution, the mean molecular weight is 342.2 g/mol.

For the evaporator, the overall equation from Crapiste & Lozano 1988 below was used to help calculate the TM energy intensity:

$$T - T_w = T_{rise} = R \cdot T_w^2 \cdot \frac{1 - x_w}{\Delta H_v}$$

Where T_r is the rise in boiling point of the solution, T_w is the boiling point of pure water, R is the gas constant 8.3144 J/(K·mol), x_w is the mole fraction of water, and ΔH_v is the change in enthalpy. The mole fraction (using the molecular weights of the brix solutions and the concentration) and change in enthalpy can be calculated as follows:

$$x_w = 1 - \frac{\frac{0.65}{342.2g/mol}}{\frac{0.65}{342.2g/mol} + \frac{1-0.65}{18g/mol}} = 0.911$$

The change in enthalpy, ΔH_v, is calculated based on the specific heat, c_p, and the molecular weight of the solution as below:

$$\Delta H_v = m \cdot c_p \Delta T = 1030 \frac{Btu}{lb} \cdot 18 \frac{g}{mol} \cdot 2.33 \frac{\frac{J}{mol}}{\frac{Btu}{lb}} = 43{,}200\ J/mol$$

Assuming the T_w is 43ºC or 316 K at 73 millibar, going back to the first equation, the rise in boiling point can be calculated as:

$$T_{rise} = 8.3144 \frac{J}{Kmol} \cdot (316K)^2 \cdot \frac{1-0.911}{43{,}200 \frac{J}{mol}} = 1.7\ K$$

As assessed from Mistry & Lienhard 2013, the change in Gibb's free energy (ΔG) can be calculated as:

$$\frac{\Delta G}{\Delta n_w} = -RT \ln a_w$$

Where n_w is the mols of water and a_w is the water activity. The natural logarithm of a_w is calculated using the following equation from Crapiste & Lozano 1988:

$$\ln a_w = \frac{\Delta H_v}{R}\left(\frac{1}{T} - \frac{1}{T_w}\right)$$

$$\ln a_w = \frac{43{,}200\ J/mol}{\frac{8.3144J}{Kmol}}\left(\frac{1}{316K} - \frac{1}{316K - 1.7K}\right) = -0.0895$$

The $\Delta G / \Delta n_w$ can then be calculated as:

$$\frac{\Delta G}{\Delta n_w} = -\frac{8.3144J}{Kmol} \cdot 316K \cdot (-0.895) = 235 \frac{J}{mol} = 0.235 \frac{kJ}{mol}$$

For the spray drying step, the value of 7.0 kJ/mol is cited from Largo-Avila, Rodríguez, & Ciro-Velasquez 2014.

The total Gibb's free energy, also the thermodynamic minimum energy intensity, is calculated based on the concentration of sucrose at the evaporator step (15º brix), the mean molecular weights, and the Gibb's free energies for the two steps:

$$\Delta G = TM = 430 \frac{Btu \cdot g}{kJ \cdot lb} \cdot \left(\frac{0.235 \frac{kJ}{mol}}{18 \frac{g}{mol}} \cdot \frac{0.85}{0.15} + \frac{7.0 \frac{kJ}{mol}}{342.2 \frac{g}{mol}} \right) = 40.6 \frac{Btu}{lb}$$

Therefore the total TM energy intensity for sugar production is 40.6 Btu/lb.

Beer and Wine Production Thermodynamic Minimum Energy Intensity

For beer and wine production, there is a thermodynamic minimum energy intensity associated with alcoholic fermentation, where sugar ($C_6H_{12}O_6$) is added and broken down into ethanol (C_2H_5OH) and carbon dioxide (CO_2) in the following reaction:

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Where the mean molecular weights of sugar, ethanol, and carbon dioxide are 180, 46, and 44 g/mol respectively. In order to calculate the Gibb's free energy (ΔG), the standard enthalpy of formation (H) was calculated for ethanol using Green & Perry 2007, determining a value of -227.92 kJ/mol. The ΔG could then be calculated as H divided by two times the molecular weight of ethanol (see the balanced reaction above), resulting in:

$$\Delta G = \frac{-227.92}{2 \cdot 46} = -2.48\frac{kJ}{kg} = -1.1\ Btu/lb$$

Because beer is typically 4% ethanol by volume and wine 12% ethanol by volume, this -1.1 Btu/lb value is multiplied by these values to determine the TM energy intensities of -0.03 Btu/lb and -0.10 Btu/lb for beer and wine respectively. Because the production volumes are in terms of bbl, these values are converted to Btu/bbl using the densities of beer and wine from Charrondiere, Haytowitz, & Stadlymayr (2012) of 1.00 gram/milliliter and 0.99 gram/milliliter respectively. After conversion, the TM energy intensity values are -8.8 Btu/bbl for beer and -26.2 Btu/bbl for wine.

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DOE/EE-1571 • September 2017