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ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Plastics and Rubber Manufacturing

September 2017

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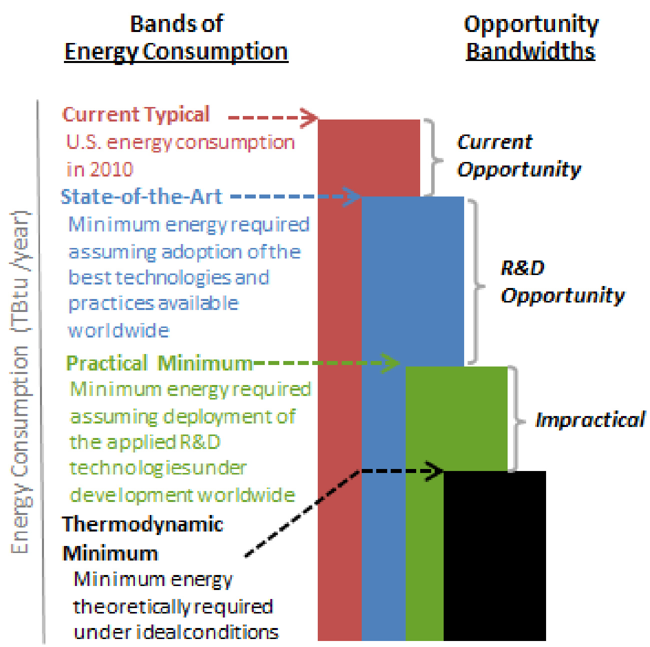
Preface

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.



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

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

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

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List of Acronyms and Abbreviations

Δ	Delta
ABS	Acrylonitrile Butadiene Styrene
ACC	American Chemistry Council
AMO	Advanced Manufacturing Office
ANL	Argonne National Laboratory
Btu	British thermal unit
CIPEC	Canadian Industry Program for Energy Conservation
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
EPS	Expanded Polystyrene
euRECIPE	European Union's Reducing Energy Consumption in Plastics Engineering
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (model)
HPDE	High-Density polyethylene
kWh	Kilowatt hour
lb	Pound(s)
LDPE	Low-Density Polyethylene
LLDPE	Linear Low-Density Polyethylene
MECS	Manufacturing Energy Consumption Survey
MFI	Materials Flows through Industry (tool)
NAICS	North American Industry Classification System
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
PET	Polyethylene Terephthalate
PM	Practical minimum energy consumption or energy intensity
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl Chloride
SBR	Styrene Butadiene Rubber
EPDM	Ethylene Propylene Diene Monomer Rubber
SOA	State of the art energy consumption or energy intensity
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
VSD	Variable Speed Drive
yr	Year

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Executive Summary

This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. plastics and rubber products manufacturing (NAICS [North American Industry Classification System] codes 3261 and 3262). Industrial, government, and academic data are used to estimate the energy consumed in the most energy-intensive manufacturing subareas. Three different energy consumption *bands* are estimated for these select manufacturing subareas based on referenced energy intensities of current, state of the art, and research and development (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 macroscale estimates of energy savings opportunities for each plastics and rubber products manufacturing subarea. Subareas are defined as the major domestic end-use processes for a resin, as categorized by the American Chemistry Council's 2015 Resin Review (ACC 2015). These are categorized by the primary manufacturing processes that materials will undergo (e.g., injection molding, extrusion, blow molding) to be converted into products, and each category identifies all of the on-site energy that is consumed at the facility where the process occurs. This categorization 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 five select subareas and sector-wide.
- Chapter 4 estimates the minimum energy consumption for these processes 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 processes 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 processes, 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 a sector-wide estimate of 2010 energy consumption for U.S. Plastics and Rubber Product Manufacturing (NAICS Code 326). In 2010, the sub-areas studied corresponded to 97% of the industry's energy consumption. In this study, CT, SOA, PM, and TM energy consumption for *individual* sub-areas included in this study is estimated from multiple referenced sources; this data was then extrapolated based on the 97% coverage to estimate total subsector SOA, PM, and TM energy consumption. The subarea energy consumption values were summed to determine sector-wide SOA, PM, and TM energy consumption.

***Study Results**:* Two energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are presented in Table ES-1 and Figure ES-1 for plastics and rubber products manufacturing [data calculated using methods and sources identified in this document].[2] The current opportunity is the difference between the 2010 CT energy consumption and SOA energy consumption; the R&D opportunity is the difference between SOA energy consumption and PM energy consumption. Potential energy savings opportunities are presented as a total and broken down by manufacturing subarea and for all of the U.S. plastics and rubber products manufacturing sector, based on extrapolated data. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual processes based on the sector-wide extrapolated data. The energy savings opportunities presented reflect the estimated production of plastics and rubber products 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. Plastics and Rubber Products Manufacturing Sector[3]

Opportunity Bandwidths	Estimated On-site Energy Savings Opportunity for Five Subareas Studied (per year)	Estimated Energy Savings Opportunity for total U.S. Plastics and Rubber 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	84 TBtu [4] (31% energy savings)[5]	86 TBtu [4] (31% energy savings)[5]
R&D Opportunity: additional on-site energy savings if applied R&D technologies under development worldwide are successfully deployed	22 TBtu [6] (8% energy savings)[7]	22 TBtu [6] (8% energy savings)[7]

[2] Note that the thermodynamic minimum (TM) is used as the baseline (rather than zero) for energy savings percent calculations. The energy estimates presented in this study are for macroscale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for onsite energy use (i.e., energy consumed within the 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 = $\left(\frac{CT - SOA}{CT - TM}\right) x\ 100$, as shown in Table 4-3.

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

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

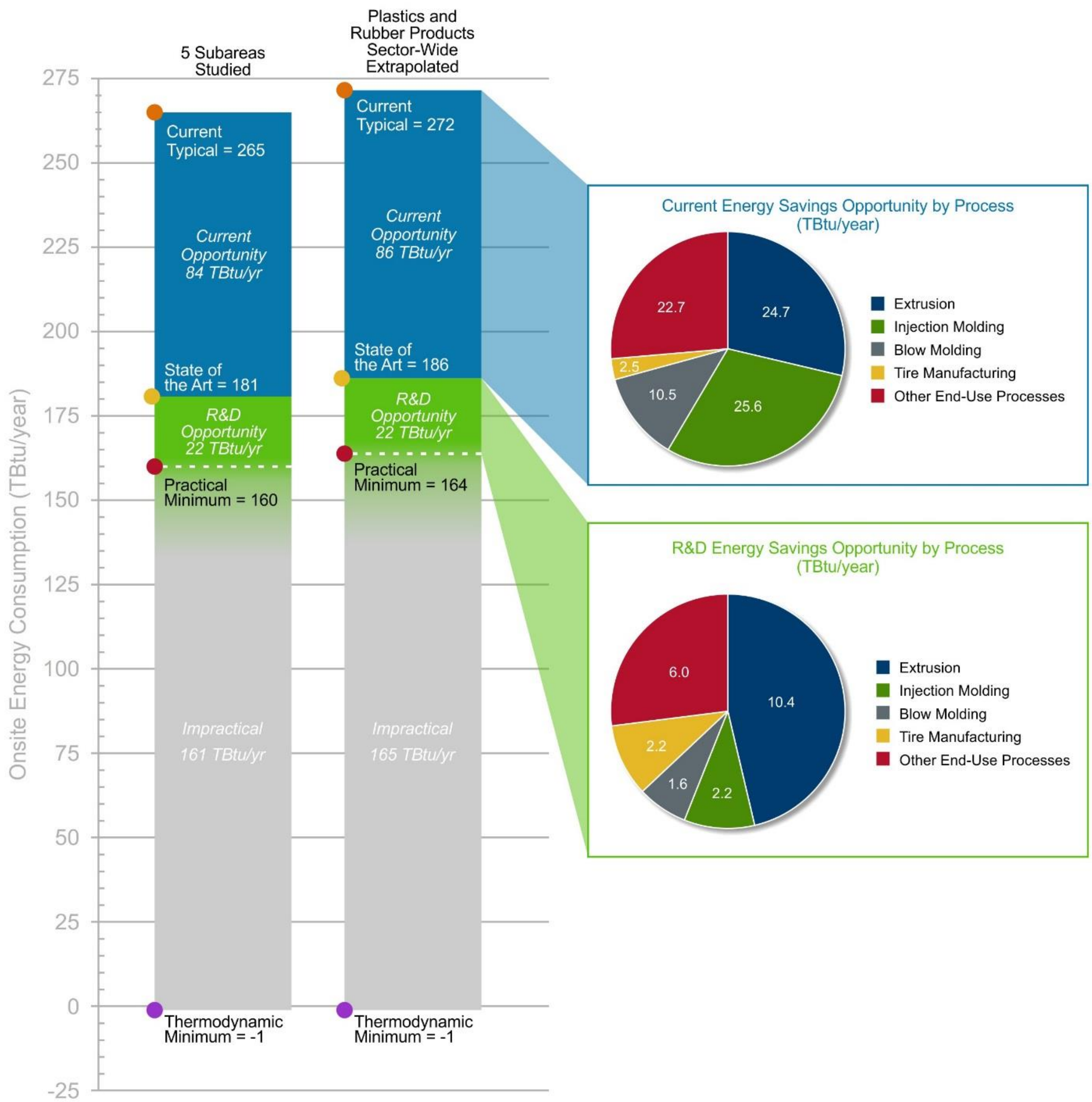

Figure ES-1. Current and R&D energy savings opportunities for the subsectors studied and for plastics and rubber products manufacturing (sector-wide), based on extrapolated data
Source: EERE

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, and 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.

An estimated 272 TBtu of energy was consumed in 2010 to manufacture plastics and rubber products in the United States. Based on the results of this study, an estimated 85.94 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade the plastics and rubber manufacturing subareas studied; an additional 22.38 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:

- Injection Molding: 25.6 TBtu/year (or 30% of the current opportunity)
- Extrusion: 24.7 TBtu/year (or 29% of the current opportunity)
- Blow Molding: 10.5 TBtu/year (or 12% of the current opportunity)

The top three R&D energy savings opportunities for the processes are as follows:

- Extrusion: 10.4 TBtu/year (or 46% of the R&D opportunity)
- Tire Manufacturing: 2.2 TBtu/year (or 10% of the R&D opportunity)
- Injection Molding: 2.2 TBtu/year (or 10% of the R&D opportunity)

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

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1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. plastics and rubber products manufacturing sector, as defined by classifications 3261 and 3262 of the North American Industry Classification System (NAICS). The study focuses on the manufacture of products made from plastics and rubber. It does not include the production of plastic and rubber intermediates or feedstocks, which is covered in the chemicals bandwidth study updated in 2015 (DOE 2015a). The purpose of this analysis is to provide macro-scale estimates of energy savings opportunities in plastics and rubber products manufacturing subareas and sector-wide. In this study, four different energy consumption *bands* (or measures) are estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

Numerous plastics and rubber products are manufactured in the United States; five of the most energy-intensive subareas were studied. Together, these selected subareas accounted for 97% of energy consumption by the U.S. plastics and rubber 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.

1.2. Comparison to Other Bandwidth Studies

This is the first DOE energy bandwidth study prepared specifically for the plastics and rubber 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 cement, food and beverage products, and glass 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.

History of DOE Advanced Manufacturing Office Energy Bandwidth Reports

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

- 2013: Developed and refined a consistent methodology for bandwidth studies such that comparisons could be made across the manufacturing sectors.
- 2015: Published revised reports for four U.S. manufacturing sectors: chemicals, iron and steel, petroleum refining, and pulp and paper.
- 2016: Published six additional bandwidth studies on U.S. 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), following the same analysis methodology and presentation format.
- 2017: Prepared bandwidth studies (including this report) for four additional U.S. manufacturing sectors: cement, food and beverage products, glass, and plastics and rubber products.

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

1.3. Definitions of Energy Consumption Bands and Opportunity Bandwidths

The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro scale. There are four energy consumption bands referenced throughout this report: current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy consumption. These bands describe different levels of energy consumption to manufacture products.

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

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If manufacturers use the most efficient technologies and practices available worldwide, 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 capital investments that may not be economically viable for a given facility. Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings. Definitions of the four energy bands are provided in the inset (box at right). Definitions of the two opportunity bandwidths are provided below:

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

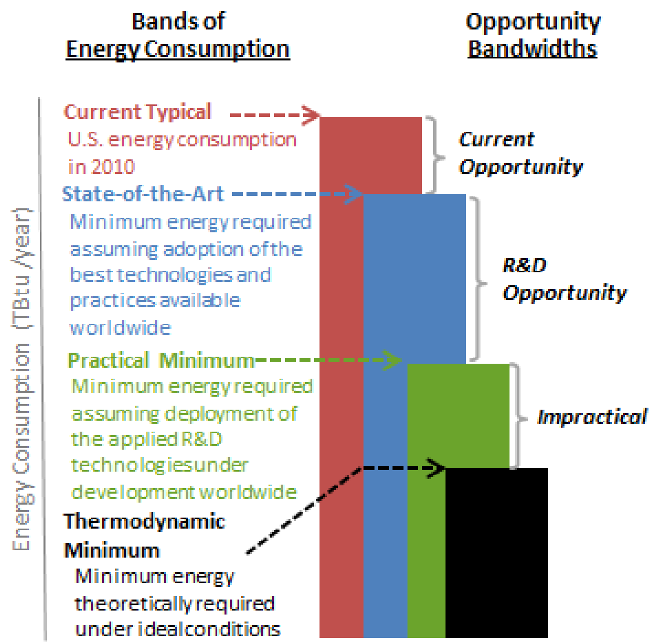

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Definitions of Energy Bands Used in the Bandwidth Studies

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

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

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

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

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

The *R&D opportunity* is the energy savings that is potentially attainable through the applied R&D technologies under development. It is the difference between SOA and PM energy consumption. To attain this energy savings, manufacturers would need to produce plastics and rubber 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. Some production processes are exothermic and are net producers of energy; the net energy was considered in the analysis.

The estimates presented are for macro-scale consideration of energy use in plastics and rubber products manufacturing. The estimates reported herein are representative of average U.S. plastics and rubber 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 pounds per year) for 2010.

Chapter 3 presents the calculated on-site **CT energy intensity** (Btu per pound) and **CT energy consumption** (TBtu per year) for the process subareas studied and material total (along with sources).

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

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per pound) and **PM energy consumption** for the process subareas studied and material total (along with sources). The sector-wide PM energy consumption is estimated based on an extrapolation of the PM energy consumption for the subareas studied.

Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per pound) and **TM energy consumption** for the process subareas studied and material total (along with sources).

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

1.5. Boundaries of the Study

The U.S. plastics and rubber 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 plastics and rubber products often occur *outside* of the products manufacturing 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 plastics and rubber products. 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 plastics and rubber products manufacturing at a production facility.

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

2. U.S. Plastics and Rubber Products Sector Overview

2.1. U.S. Plastics and Rubber Manufacturing Overview

In 2010, the United States consumed 83.3 billion pounds of plastic resins to manufacture plastic products (ACC 2015). This estimate excludes exported resins and is based on the American Chemistry Council (ACC)'s 2015 Resin Review, which reports resin consumption by end-use production process for both thermoplastic and thermoset resins. Rubber consumption for end-use production of rubber products is estimated to be 5.9 billion pounds for 2010. This is based on the total U.S. consumption of natural rubber (Rubber Board 2012) and synthetic rubber (Statista 2016). Based on these sources, for 2010, the total production volume of plastic and rubber materials consumed within the United States to manufacture products is estimated to be 89.2 billion pounds.

2.2. U.S. Plastics and Rubber Manufacturing Sector Description

This study focuses on end-use consumption of plastics and rubber materials as reported by sources representative of the industry. Table 2-1 shows the materials and specific processes considered. For thermoplastics[8] and thermosets (polyurethane), the end-use process categories considered are those defined in the ACC's 2015 Resin Review (ACC 2015). The Resin Review defines an end-use consumption estimate in million pounds for each of the processes listed. Common end-use processes in plastic product manufacturing include injection molding, blow molding, rotational molding, calendaring, and various forms of extrusion. In some cases, the ACC 2015 Resin Review reports an end-use category as "All Other End Uses," "All Other Conversion Processes," or "Other Thermoplastics." These quantities represent nearly a third of total production but are not tracked in detail by industry sources. For the purposes of this study, these quantities are counted under the label "All Other End Uses."

For synthetic and natural rubber, the largest singular category, as defined by the NAICS code 32621, is tire manufacturing. NAICS 32629 (other rubber product manufacturing) is the only other relevant NAICS category devoted to rubber. For this reason, synthetic and natural rubbers are both divided into categories for "Tire Production" and "Other End Uses" in Table 2-1.

[8] Polypropylene (PP), high-density polyethylene (HDPE), linear low-density polyethylene (LLDPE), polyvinyl chloride (PVC), polystyrene and expanded polystyrene (PS and EPS), low-density polyethylene (LDPE), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET).

Table 2-1. Plastic and Rubber Products Manufacturing Process Areas Considered in Bandwidth Analysis

Materials	End-Use Processes
Polypropylene (PP)	Injection Molding Fiber and Filament Production Film Production Sheet Production Blow Molding Other End Uses
High-Density Polyethylene (HDPE)	Blow Molding Injection Molding Film Production Pipe and Conduit Sheet Production Other End Uses
Linear Low-Density Polyethylene (LLDPE)	Film Production Injection Molding Rotational Molding Other Extruded Products (May Include Sheet, Blow Molding, and Pipe/Conduit Production) Other End Uses
Polyvinyl Chloride (PVC)	Wire and Cable Production Film and Sheet Production Siding Production Rigid Pipe and Tubing Production Window and Door Production Fencing and Decking Production Calendaring Molding Other End Uses
Polystyrene (PS and EPS)	Food Packaging and Food Service/Packaging and One-Time Use All Other End Uses/Conversion Processes
Low-Density Polyethylene (LDPE)	Film Production Other Extruded Products (Includes Pipe/Conduit Production) Injection Molding Blow Molding Other End Uses
Other Thermoplastics (acrylonitrile butadiene styrene [ABS], polyethylene terephthalate [PET], etc.)	All Processes
Polyurethanes[9]	Rigid Foam Flexible Foam Slabstock Flexible Foam Molded
Synthetic Rubber	Tire Production Other End Uses
Natural Rubber	Tire Production Other End Uses

[9] This category of polyurethanes refers to thermosets. As the ACC Resin Review 2015 does not specify a category for thermoplastic polyurethane, it is assumed that this is included in the "Other Thermoplastics" category.

The categories identified in Table 2-1 are based on the ACC's classification of end uses. While these definitions are based on the material-forming step, the energy intensity and consumption analyses in this report account for additional energy used in batching and post-forming steps. The major resin forming processes identified include:

- *Injection Molding* is used to produce high-quality, three-dimensional products. Resin is extruded and heated into a molten form, which is then pushed into a mold at high pressure. The resin cools in the mold to form a solid product.
- *Rotational Molding* is used to make products that have a uniform layer of plastic around a hollow center. Resin is placed in a mold, which is then rotated and heated to distribute the resin in a uniform coating around the inside of the mold. The resin cools and is removed from the mold to produce a solid product with a hollow center.
- *Blow Molding* is used to produce uniform hollow products in one piece (e.g., water bottles). A molten tube or injection-molded preform of resin is expanded into a mold using compressed air. The finished product is hollow and takes on the shape of the mold.
- *Film or Sheet Extrusion* is used to produce products in the shape of a flat film or sheet. Material is fed through an extruder and heated as it is forced through a flat opening. The extruded product is then cooled either by blowers or by water immersion. The extruded film or sheet may go through additional forming steps such as thermoforming.
- *Thermoforming* is not identified separately in Table 2-1 because it is typically used in conjunction with film extrusion processes. A flat film is heated and either pulled by a vacuum or pushed by a plug to take the shape of the mold.
- *Pipe or Profile Extrusion* is similar to film or sheet extrusion: the material is pushed through an extruder and heated to produce a pipe or other shape that is not flat.
- *Sheet Calendaring* involves using polished rollers to shape an extruded product into thick sheets (0.005 to 0.500 inches thick).

2.3. U.S. Plastics and Rubber Manufacturing Energy Consumption

On-site energy and primary energy for the U.S. plastics and rubber 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).

Plastics and rubber manufacturing accounted for 586 TBtu (3.0%) 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.

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)**	272 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)**	586 TBtu

Source: DOE 2014

* Primary energy accounts for off-site electricity generation and transmission losses. Off-site electrical losses are based on published grid efficiency. The Energy Information Administration (EIA) Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from off-site sources including generation and transmission losses is determined to be 10,553 Btu/kWh. See Appendix A2 for energy mix assumptions.

2.4. U.S. Plastics and Rubber Manufacturing Production Values

In this report, production data refers to the amount of resin produced in the United States that is consumed in a particular end-use process. Energy intensity values represent the energy that the end-use process requires to convert a pound of resin into plastic or rubber products. 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 thermoplastics and thermosets is the ACC's 2015 Resin Review, which recorded the values in Table 2-3 as end-use domestic consumption by process or product type. These values are organized into major process types, and insignificant production quantities for which little or no energy intensity data are available, were removed. The excluded processes represent less than 7% (by weight) of the plastic and rubber materials used to make products in the United States, and were removed to avoid attributing inaccurate energy intensities to the processes they represent, which may skew the final bandwidth results.

For natural and synthetic rubber, consumption in tire manufacturing is estimated using 2010 U.S. unit production data of tires for passenger vehicles, buses, and trucks. To estimate the total amounts of synthetic and natural rubber used in tire production, this analysis calculated the total weight of each type of tire produced in the United States and applied the typical compositions of synthetic and natural rubber in tires to that weight. The data for this calculation came from the United Soybean Board's 2011 report titled *Rubber Compounds: A Market Opportunity Study* (USB 2011). Production values for tire production are then subtracted from the total U.S. consumption of natural rubber (Rubber Board 2012) and synthetic rubber (Statista 2016) to estimate rubber consumption in other end-use processes.

Table 2-3. U.S. Plastics and Rubber Resin Production for Each Domestic End-Use Production Process in 2010

Materials	End-Use Processes	2010 Total Resin Production for Domestic End-Use Processes (million lb)
Polypropylene (PP)	Injection Molding	5,136
	Fiber and Filament Production	2,822
	Film Production	1,545
	Sheet Production	1,296
	Blow Molding	252
	Other End Uses	4,919
	Total	***15,970***
High-Density Polyethylene (HDPE)	Blow Molding	4,307
	Injection Molding	2,178
	Film Production	2,087
	Pipe and Conduit	1,876
	Sheet Production	568
	Other End Uses	2,653
	Total	***13,669***
Linear Low-Density Polyethylene (LLDPE)	Film Production	6,479
	Injection Molding	569
	Rotational Molding	264
	Other Extruded Products (May Include: Sheet, Blow Molding and Pipe/Conduit Production)	702
	Other End Uses	1,885
	Total	***9,899***
Polyvinyl Chloride (PVC)	Wire and Cable Production	395
	Film and Sheet Production	534
	Siding Production	924
	Rigid Pipe and Tubing Production	3,808
	Window and Door Production	482
	Fencing and Decking Production	280
	Calendaring	751
	Molding	316
	Other End Uses	105
	Total	***7,595***
Polystyrene (PS and EPS)	Food Packaging and Food Service/Packaging and One-Time Use	5,154

Table 2-3. U.S. Plastics and Rubber Resin Production for Each Domestic End-Use Production Process in 2010

Materials	End-Use Processes	2010 Total Resin Production for Domestic End-Use Processes (million lb)
	All Other End Uses/Conversion Processes	282
	Total	***5,436***
Low-Density Polyethylene (LDPE)	Film Production	2,372
	Other Extruded Products (Includes Pipe/Conduit Production)	615
	Injection Molding	244
	Blow Molding	59
	Other End Uses	1,390
	Total	***4,680***
Other Thermoplastics (Acrylonitrile butadiene styrene [ABS], Polyethylene terephthalate [PET])	All Processes	
	Total	**14,822**
Polyurethanes	Rigid Foam	2,254
	Flexible Foam Slabstock	1,397
	Flexible Foam Molded	716
	Total	***4,367***
Synthetic Rubber	Tire Production	1,118
	Other End Uses	2,769
	Total	***3,887***
Natural Rubber	Tire Production	871
	Other End Uses	1,170
	Total	***2,041***

3. Current Typical Energy Intensity and Energy Consumption for U.S. Plastics and Rubber Products Manufacturing

This chapter presents current typical (CT) energy intensities and energy consumption data for plastics and rubber products manufacturing subareas. The subareas identified are listed by material type and primary process. Energy intensities were identified for each material and process and applied to the production values reported in the previous chapter to determine U.S. 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 subareas studied. Table 3-1 presents a summary of the main references consulted to identify CT energy intensity by subarea.

The plastics and rubber sector incorporates a wide range of products whose manufacture 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 and material 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., injection molding, extrusion, blow molding).

Table 3-1. Published Sources Reviewed to Identify Current Typical Energy Intensities for Subarea and Material Total

Source Abbreviation	Description
NREL 2016	Data were provided by the National Renewable Energy Laboratory (NREL) from the *Materials Flows through Industry (MFI)* tool. This source provides energy intensity values applicable to the United States for various material and process pairings.
NREL 2012	The *U.S. Life Cycle Inventory Database,* compiled by NREL, contains energy flow data on select material and process pairings. Energy intensity values per pound of resin were calculated from this data and used for some processes. In most cases, the results overlapped or agreed with data from NREL's *Materials Flows through Industry (MFI)* tool.
Keoleian et al. 2012	This University of Michigan report details values used to update Argonne National Laboratory (ANL)'s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model. This report notes that it was necessary to fill in some data gaps using European sources, indicating that some process energy intensities are similar in the United States and Europe. Based on this justification, some European sources are used to fill in energy intensity data gaps in this bandwidth study.
euRECIPE 2005	The *2005 European Benchmarking Survey of Energy Consumption and Adoption of Best Practice,* produced by euRECIPE, summarizes typical energy intensity values by process type using surveys on manufacturers in European countries. For processes for which both U.S. and European data were available, energy intensity values were similar, indicating similarities between industries in the United States and Europe. For some processes, if U.S. data were not available, energy intensity values from this study were used.
Khripko et al. 2016	This source provides energy intensity data for injection molding, profile extrusion, blown film, and monofilament extrusion plants in Germany and Western Australia. Data from this source were used only for cases where no better U.S. source was available (e.g., for estimating typical energy intensities for fiber and filament extrusion).
ANL 2010	This ANL report provides energy intensity values for the processing of plastic and rubber parts for vehicle component manufacturing. Data from this source were used to estimate the energy intensity of sheet calendaring and tire manufacturing.
Euromap 2011	The European Commission's report, *Energy Efficiency: Plastics and Rubber Machines Well Placed*, provides typical energy intensity values for European plastics converters. Some process energy intensity values from this report were used in cases in which U.S. data were not available.
IFC 2007	This World Bank report cites typical industry values for energy intensities of some plastics and rubber products manufacturing processes. These data were used to fill in data gaps in cases in which U.S. data was not available.

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 plastics and rubber product manufacturing subareas studied. Feedstock energy is excluded from the consumption values. The energy intensities are presented in terms of Btu per pound of plastic resin used for production. The CT energy consumption for these subareas is estimated to account for 265 TBtu of on-site energy and 585 TBtu of primary energy in 2010.

While multiple process types may be included at a single plastics or rubber products manufacturing facility, the energy intensity data collected are selected based on the primary process at the facility and matched to the process identified for end-use consumption of the resin (see Production Values in the previous chapter). For example, polypropylene injection molding uses a source for its production value representative of all of the polypropylene resin that is used in production via injection molding. This amount (in million pounds) is multiplied by the CT energy intensity value for polypropylene injection molding (in Btu/lb.) to calculate energy consumption (in TBtu/year).

In most cases, primary energy is calculated from on-site CT energy intensity data. In a few cases, primary energy intensity data are provided by the source and used to calculate the on-site energy intensity. When calculating the off-site energy lost during conversion from primary to on-site energy, the study used an energy mix of electricity and fuel based on the MECS Plastics and Rubber Manufacturing Energy and Carbon Footprint (DOE 2014).

Plastics and rubber products manufacturing accounted for 586 TBtu (3.0%) 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 plastics and rubber products manufacturing totaled 315 TBtu in 2010; on-site energy consumed within the boundaries of U.S. plastics and rubber products manufacturing plants totaled 272 TBtu.

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Plastics and Rubber Products Manufacturing Subareas Studied and Sector Wide in 2010, with Percent of Sector Coverage

Subarea	On-site CT Energy Intensity for Processes Studied (Btu/lb resin)	Production (Million lb)	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 Sector-wide total)**
Polypropylene (PP)						
Injection Molding	4,065	5,136	20.88	25.19	46.06	
Fiber and Filament Production	2,729	2,822	7.70	9.29	16.99	
Film Production	5,420	1,545	8.37	10.10	18.48	
Sheet Production	1,141	1,296	1.48	1.78	3.26	
Blow Molding	3,451	252	0.87	1.05	1.92	
Other End Uses	3,556	4,919	17.49	21.11	38.60	
Subtotal		**15,970**	**56.79**	**68.52**	**125.31**	**21%**
High-Density Polyethylene (HDPE)						
Blow Molding	3,081	4,307	13.27	16.01	29.28	
Injection Molding	3,594	2,178	7.83	9.45	17.27	
Film Production	1,626	2,087	3.39	4.09	7.49	
Pipe and Conduit	985	1,876	1.85	2.23	4.08	
Sheet Production	1,141	568	0.65	0.78	1.43	
Other End Uses	2,450	2,653	6.50	7.84	14.34	
Subtotal		**13,669**	**33.49**	**40.40**	**73.89**	**12%**
Linear Low-Density Polyethylene (LLDPE)						
Film Production	2,126	6,479	13.78	16.62	30.40	
Injection Molding	4,127	569	2.35	2.83	5.18	

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Plastics and Rubber Products Manufacturing Subareas Studied and Sector Wide in 2010, with Percent of Sector Coverage

Subarea	On-site CT Energy Intensity for Processes Studied (Btu/lb resin)	Production (Million lb)	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 Sector-wide total)**
Rotational Molding	9,020	264	2.38	2.87	5.25	
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	2,331	702	1.64	1.97	3.61	
Other End Uses	2,513	1,885	4.74	5.72	10.45	
Subtotal		**9,899**	**24.88**	**30.02**	**54.90**	**9%**
Polyvinyl Chloride (PVC)						
Wire and Cable Production	1,316	395	0.52	0.63	1.15	
Film and Sheet Production	938	534	0.50	0.60	1.11	
Siding Production	2,331	924	2.15	2.60	4.75	
Rigid Pipe and Tubing Production	949	3,808	3.61	4.36	7.97	
Window and Door Production	2,331	482	1.12	1.36	2.48	
Fencing and Decking Production	2,331	280	0.65	0.79	1.44	
Calendaring	634	751	0.48	0.57	1.05	
Molding	2,210	316	0.70	0.84	1.54	
Other End Uses	1,300	105	0.14	0.16	0.30	
Subtotal		**7,595**	**9.87**	**11.91**	**21.79**	**4%**
Polystyrene (PS and EPS)						
Food Packaging and Food Service/ Packaging and One-Time Use	2,970	5,154	15.31	18.47	33.78	

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Plastics and Rubber Products Manufacturing Subareas Studied and Sector Wide in 2010, with Percent of Sector Coverage

Subarea	On-site CT Energy Intensity for Processes Studied (Btu/lb resin)	Production (Million lb)	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 Sector-wide total)**
All Other End Uses/ Conversion Processes	2,970	282	0.84	1.01	1.85	
Subtotal		**5,436**	**16.15**	**19.48**	**35.63**	**6%**
Low-Density Polyethylene (LDPE)						
Film Production	4,127	2,372	9.79	11.81	21.60	
Other Extruded Products (Includes Pipe/Conduit Production)	2,331	615	1.43	1.73	3.16	
Injection Molding	4,826	244	1.18	1.42	2.60	
Blow Molding	3,451	59	0.20	0.25	0.45	
Other End Uses	3,831	1,390	5.33	6.43	11.75	
Subtotal		**4,680**	**17.93**	**21.63**	**39.56**	**7%**
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)						
All Processes	5,057	14,822	74.95	90.43	165.39	**28%**
Polyurethanes						
Rigid Foam	2,814	2,254	6.34	7.65	14.00	
Flexible Foam Slabstock	313	1,397	0.44	0.53	0.96	
Flexible Foam Molded	313	716	0.22	0.27	0.49	
Subtotal		**4,367**	**7.00**	**8.45**	**15.45**	**0.3%**
Synthetic Rubber						
Tire Production	8,067	1,118	9.02	10.88	19.90	
Other End Uses	2,126	2,769	5.89	7.10	12.99	
Subtotal		**3,887**	**14.91**	**17.98**	**32.89**	**5%**
Natural Rubber						
Tire Production	8,067	871	7.03	8.48	15.50	
Other End Uses	1,865	1,170	2.18	2.63	4.82	
Subtotal		**2,041**	**9.21**	**11.11**	**20.32**	**3%**

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Plastics and Rubber Products Manufacturing Subareas Studied and Sector Wide in 2010, with Percent of Sector Coverage

Subarea	On-site CT Energy Intensity for Processes Studied (Btu/lb resin)	Production (Million lb)	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 Sector-wide total)**
Total for Process Subareas Studied		82,367	265.18	319.95	585.13	97%
Total for Plastics and Rubber Manufacturing Sector-wide		N/A	272	315	586	100%

Current Typical (CT)
** DOE 2014 is the source for MECS/Energy Footprints data and approaches. Primary energy is calculated from on-site energy consumption data, with scaling to include off-site electricity and steam generation and transmission loss.*

4. State of the Art Energy Intensity and Energy Consumption for U.S. Plastics and Rubber Products Manufacturing

This chapter estimates energy savings possible in plastics and rubber products manufacturing plants to achieve state of the art (SOA) energy consumption levels. SOA 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 injection molding, extrusion, and blow molding, as well as measures more widely applicable to plastics and rubber 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 subareas 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 that maximize yield, even though these types of process improvements can help minimize the energy used to produce a pound of product. The on-site SOA energy consumption estimates exclude feedstock energy.

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

Table 4-1. Published Sources Reviewed to Identify SOA Energy Intensities by Process Area and Material Total

Source Abbreviation	Description
Kanungo & Yong 2012	This report, titled *Opportunities and Barriers in the Implementation of Energy Efficiency Measures in Plastic Manufacturing*, provides energy savings estimates for measures applicable to processes such as injection molding, extrusion, and blow molding.
CIPEC 2007	This report, titled *Guide to Energy Efficiency Opportunities in the Canadian Plastics Processing Industry*, provides potential savings estimates for several measures as well as processes broken down by percentage of total on-site energy for each process area.
DOE 2005	This report, produced by DOE and the Society of the Plastics Industry, summarizes realized and potential energy savings at 11 plastics manufacturing plants, demonstrating potential energy savings in the plastics industry using best practices.
Khripko et al. 2016	This source provides energy intensity data for injection molding, profile extrusion, blown film, and monofilament extrusion plants in Germany and Western Australia. The source provides an estimate of typical best-practice savings from switching from natural gas to all-electric blow molders. This contributed to the savings estimate for SOA blow molding operations. Data from this source were used only for cases in which no better U.S. source was available.
MidAmerican Energy n.d.	This document summarizes energy consumption by plastics and rubber products manufacturing in Iowa and provides a typical range of savings possible in manufacturing facilities by incorporating energy efficiency best practices. This savings estimate was used for cases in which more process-specific energy savings data were not available.

Table 4-1. Published Sources Reviewed to Identify SOA Energy Intensities by Process Area and Material Total

Source Abbreviation	Description
Focus on Energy 2010	This case study reports energy savings from the use of radiant heater bands on plastic sheet extrusion machines.
Focus on Energy 2006	Published by the state of Wisconsin's Focus on Energy service, this report provides energy savings estimates and other metrics to quantify the impact of best practices for processes in plastics manufacturing.
Rauwendaal 2010	Published in *Plastics Technology*, this article provides energy savings estimates for measures applicable to plastics extrusion.

4.2. State of the Art Energy Intensity and Energy Consumption

SOA energy intensities were based on a literature review of existing technologies used in plastics and rubber products manufacturing. The technologies that represent the largest savings potential were categorized by their applicability to processes (e.g., injection molding, extrusion, blow molding, etc.), and their savings potentials were quantified as a percentage from either a subarea of a process or from the total on-site energy.

Energy savings from multiple technologies were combined such that the savings from a particular technology were applied only to the subareas of the process affected by that technology (e.g., forming, compressed air, process cooling). Competing technologies were excluded if they had lower potential for energy savings or were incompatible with the selected technologies. In some cases, multiple energy-saving technologies were applied to the same process subarea. For these cases, the percentage energy savings estimates were combined using the formula at the end of Appendix A3.

The sets of SOA technologies selected for injection molding, extrusion, and blow molding cover the majority of the energy consumption of the plastics and rubber products manufacturing industry. For other process types, the study used generalized estimates representative of typical savings possible in plastics and rubber products manufacturing by applying best practices. Appendix A3 provides a summary of the technologies considered, the energy savings percentages used in calculations, and their applicability to individual processes or subareas. The SOA technologies included in this analysis and their estimated energy savings were:

- **Switching from hydraulic to all-electric injection molding machines:** 74% energy savings from the machine (Kanungo and Yong 2012)
- **Insulation on barrel heaters:** 20%–22% energy savings from the barrel heating component of the machine (Kanungo and Yong 2012)
- **Variable speed drive (VSD) on chilled water pump:** 33% energy savings applied to process chilling systems (Kanungo and Yong 2012)
- **Low-pressure drying:** 50%–80% energy savings applied to material drying systems (Focus on Energy 2006)
- **High-efficiency motors for extruder drive system:** 20% energy savings applied to the extruder drive (CIPEC 2007)
- **Compressed air system operation:** 20% energy savings applied to compressed air systems (CIPEC 2007)
- **Radiant heater bands for plastic extrusion:** 33% energy savings applied to extrusion machines (Focus on Energy 2010)
- **Extruding material directly after drying:** 25% energy savings applied to extrusion machines (Rauwendaal 2010)

- **Extrusion barrel heating using electrically heated thermal oil and insulation:** 30%–40% energy savings applied to the facility (Khripko et al. 2016).

Table 4-2 presents the on-site SOA energy intensities and energy consumption for the plastics and rubber products manufacturing subareas studied. The SOA energy intensities are presented as Btu per pound of resin, and the on-site SOA energy consumption is presented as TBtu per year.

Table 4-3 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each subarea and as a total. This is presented as the SOA energy savings (or current opportunity) and SOA energy savings percent. It is useful to consider both TBtu energy savings and energy savings percentage 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 percentage energy savings is replacing hydraulic injection molding machines with all-electric machines at 74% energy savings (Kanungo & Yong 2012).

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site SOA Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Polypropylene (PP)			
Injection Molding	1,659	5,136	8.52
Fiber and Filament Production	1,923	2,822	5.43
Film Production	3,820	1,545	5.90
Sheet Production	804	1,296	1.04
Blow Molding	1,917	252	0.48
Other End Uses	1,934	4,919	9.51
Subtotal		**15,970**	**30.89**
High-Density Polyethylene (HDPE)			
Blow Molding	1,711	4,307	7.37
Injection Molding	1,467	2,178	3.19
Film Production	1,146	2,087	2.39
Pipe and Conduit	694	1,876	1.30
Sheet Production	804	568	0.46
Other End Uses	1,332	2,653	3.53
Subtotal		**13,669**	**18.25**
Linear Low-Density Polyethylene (LLDPE)			
Film Production	1,498	6,479	9.71
Injection Molding	1,684	569	0.96
Rotational Molding	7,216	264	1.91

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site SOA Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	1,643	702	1.15
Other End Uses	1,713	1,885	3.23
Subtotal		**9,899**	**16.95**
Polyvinyl Chloride (PVC)			
Wire and Cable Production	771	395	0.30
Film and Sheet Production	550	534	0.29
Siding Production	1,366	924	1.26
Rigid Pipe and Tubing Production	556	3,808	2.12
Window and Door Production	1,366	482	0.66
Fencing and Decking Production	1,366	280	0.38
Calendaring	507	751	0.38
Molding	816	316	0.26
Other End Uses	755	105	0.08
Subtotal		**7,595**	**5.74**
Polystyrene (PS and EPS)			
Food Packaging and Food Service/ Packaging and One-Time Use	2,376	5,154	12.25
All Other End Uses/ Conversion Processes	2,376	282	0.67
Subtotal		**5,436**	**12.92**
Low-Density Polyethylene (LDPE)			
Film Production	2,909	2,372	6.90
Other Extruded Products (Includes Pipe/Conduit Production)	1,643	615	1.01
Injection Molding	1,969	244	0.48

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site SOA Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Blow Molding	1,917	59	0.11
Other End Uses	2,585	1,390	3.59
Subtotal		**4,680**	**12.10**
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)			
All Processes	4,046	14,822	59.96
Polyurethanes			
Rigid Foam	1,649	2,254	3.72
Flexible Foam Slabstock	183	1,397	0.26
Flexible Foam Molded	183	716	0.13
Subtotal		**4,367**	**4.10**
Synthetic Rubber			
Tire Production	6,857	1,118	7.67
Other End Uses	1,807	2,769	5.00
Subtotal		**3,887**	**12.67**
Natural Rubber			
Tire Production	6,857	871	5.97
Other End Uses	1,585	1,170	1.86
Subtotal		**2,041**	**7.83**
Total for Process Subareas Studied			**181.40**

State of the Art (SOA)

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)	SOA Energy Savings* (CT - SOA) (TBtu/year)	SOA Energy Savings Percent** (CT - SOA) / (CT - TM)
Polypropylene (PP)				
Injection Molding	20.88	8.52	12.36	59%
Fiber and Filament Production	7.70	5.43	2.27	30%

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)	SOA Energy Savings* (CT - SOA) (TBtu/year)	SOA Energy Savings Percent** (CT - SOA) / (CT - TM)
Film Production	8.37	5.90	2.47	30%
Sheet Production	1.48	1.04	0.44	30%
Blow Molding	0.87	0.48	0.39	44%
Other End Uses	17.49	9.51	7.98	46%
High-Density Polyethylene (HDPE)				
Blow Molding	13.27	7.37	5.90	44%
Injection Molding	7.83	3.19	4.63	59%
Film Production	3.39	2.39	1.00	30%
Pipe and Conduit	1.85	1.30	0.55	30%
Sheet Production	0.65	0.46	0.19	30%
Other End Uses	6.50	3.53	2.97	46%
Linear Low-Density Polyethylene (LLDPE)				
Film Production	13.78	9.71	4.07	30%
Injection Molding	2.35	0.96	1.39	59%
Rotational Molding	2.38	1.91	0.48	20%
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	1.64	1.15	0.48	30%
Other End Uses	4.74	3.23	1.51	32%
Polyvinyl Chloride (PVC)				
Wire and Cable Production	0.52	0.30	0.22	41%
Film and Sheet Production	0.50	0.29	0.21	41%
Siding Production	2.15	1.26	0.89	41%
Rigid Pipe and Tubing Production	3.61	2.12	1.50	41%
Window and Door Production	1.12	0.66	0.47	41%
Fencing and Decking Production	0.65	0.38	0.27	41%
Calendaring	0.48	0.38	0.10	20%
Molding	0.70	0.26	0.44	63%
Other End Uses	0.14	0.08	0.06	42%

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)	SOA Energy Savings* (CT - SOA) (TBtu/year)	SOA Energy Savings Percent** (CT - SOA) / (CT - TM)
Polystyrene (PS and EPS)				
Food Packaging and Food Service/ Packaging and One-Time Use	15.31	12.25	3.06	20%
All Other End Uses/ Conversion Processes	0.84	0.67	0.17	20%
Low-Density Polyethylene (LDPE)				
Film Production	9.79	6.90	2.89	30%
Other Extruded Products (Includes Pipe/Conduit Production)	1.43	1.01	0.42	30%
Injection Molding	1.18	0.48	0.70	59%
Blow Molding	0.20	0.11	0.09	44%
Other End Uses	5.33	3.59	1.73	33%
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)				
All Processes	74.95	59.96	14.99	20%
Polyurethanes				
Rigid Foam	6.34	3.72	2.63	39%
Flexible Foam Slabstock	0.44	0.26	0.18	26%
Flexible Foam Molded	0.22	0.13	0.09	26%
Synthetic Rubber				
Tire Production	9.02	7.67	1.35	15%
Other End Uses	5.89	5.00	0.88	15%
Natural Rubber				
Tire Production	7.03	5.97	1.05	15%
Other End Uses	2.18	1.86	0.33	15%
Total for Process Subareas Studied	**265.18**	**181.40**	**83.78**	**31%**
Total for Plastics and Rubber Manufacturing Sector-Wide* **	**272**	**186.1**	**85.9**	**31%**

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)	SOA Energy Savings* (CT - SOA) (TBtu/year)	SOA Energy Savings Percent** (CT - SOA) / (CT - TM)

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)
* SOA energy savings is also called current opportunity.
** SOA energy savings percentage is the SOA energy savings opportunity from transforming plastics and rubber production processes through the adoption of SOA equipment and practices. Energy savings percentage is calculated using the TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percentage, with TM as the minimum, is calculated as follows: SOA Energy Savings Percentage = (CT - SOA)/(CT - TM).
*** The sector-wide SOA energy consumption was an extrapolated value, calculated by dividing the total on-site SOA energy consumption for the processes studied by the overall percent coverage from Chapter 3 (97%).

If U.S. plastics and rubber products manufacturing were able to attain on-site SOA energy intensities, it is estimated that 85.9 TBtu per year of energy could be saved from the subareas alone, corresponding to a 31% 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 is not inferred that all existing plants could achieve these SOA values or that the improvements would prove to be cost-effective in all cases.

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. Plastics and Rubber Products Manufacturing

For the plastics and rubber products industry, the majority of the practical energy savings potential comes from SOA products 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 economic growth for the United States. This chapter determines the R&D opportunity for the plastics and rubber 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 plastics or rubber products 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 literature review of R&D activities in the plastics and rubber 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 owing to 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 plastics and rubber products manufacturing.

Table 5-1. Published Sources Reviewed to Identify SOA Energy Intensities by Process Area and Material Total

Source Abbreviation	Description
Lu et al. 2012	This report presents the results of a study on multi-objective process parameter optimization for energy savings in injection molding processes. The report includes the energy savings results from eight experiments using this method for optimization in injection molding.
Vera-Sorroche 2013	This study investigates energy intensity of extrusion using in-process monitoring techniques to determine how optimizations to screw geometry, screw speed, and temperature can be used to minimize the energy intensity of extrusion processes.
Njobet 2012	This report investigates energy savings potential in high-throughput extrusion, demonstrating the potential energy savings that can be achieved at higher extrusion speeds.
Lovrec & Tic 2010	This study presents a highly efficient cooling unit for plastic molding machines designed using computational fluid dynamic simulations. The unit is intended to reduce the energy consumption of processes that typically use compressed air for cooling.

5.2. Practical Minimum Energy Intensity and Energy Consumption

Energy savings estimates for PM technologies were compiled using considerations similar to those outlined for SOA technologies in the previous chapter. The literature review showed that computational parameter optimization is one of the primary areas of quantifiable energy savings potential in R&D for the plastics and rubber products manufacturing industry. This describes methods used to optimize parameters such as extrusion speed, mold temperature, and packing pressure to minimize energy consumption per part produced. Process heating was another technology area that was considered, but this area presented a lack of data from which to draw energy savings conclusions across the industry. Appendix A3 provides a summary of the technologies considered. The PM technologies included in this analysis and their estimated energy savings were:

- **Multi-objective process parameter optimization to reduce energy consumption in injection molding processes:** 11% energy savings from the machine (Lu et al. 2011)
- **Optimal high-throughput extrusion to reduce energy consumption:** A conservative estimate of 20% energy savings from extrusion processes (Njobet 2012)
- **Computational fluid dynamics to optimize cooling unit designs:** 50% savings from compressed air systems (Lovrec & Tic 2010)

Table 5-2 presents the on-site PM energy intensities and energy consumption for the plastics and rubber products manufacturing subareas studied. The PM energy intensities are presented as Btu per pound resin, and the on-site PM energy consumption is presented as TBtu per year.

Table 5-2. On-site Practical Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site PM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site PM Energy Consumption, Calculated (TBtu/year)
Polypropylene (PP)			
Injection Molding	1,580	5,136	8.12
Fiber and Filament Production	1,507	2,822	4.25
Film Production	2,993	1,545	4.62
Sheet Production	630	1,296	0.82
Blow Molding	1,784	252	0.45
Other End Uses	1,652	4,919	8.13
Subtotal		**15,970**	**26.39**
High-Density Polyethylene (HDPE)			
Blow Molding	1,593	4,307	6.86
Injection Molding	1,397	2,178	3.04
Film Production	898	2,087	1.87
Pipe and Conduit	544	1,876	1.02
Sheet Production	630	568	0.36
Other End Uses	1,190	2,653	3.16
Subtotal		**13,669**	**16.31**

Table 5-2. On-site Practical Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site PM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site PM Energy Consumption, Calculated (TBtu/year)
Linear Low-Density Polyethylene (LLDPE)			
Film Production	1,174	6,479	7.61
Injection Molding	1,605	569	0.91
Rotational Molding	6,753	264	1.78
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	1,287	702	0.90
Other End Uses	1,398	1,885	2.64
Subtotal		**9,899**	**13.84**
Polyvinyl Chloride (PVC)			
Wire and Cable Production	620	395	0.24
Film and Sheet Production	442	534	0.24
Siding Production	1,099	924	1.02
Rigid Pipe and Tubing Production	447	3,808	1.70
Window and Door Production	1,099	482	0.53
Fencing and Decking Production	1,099	280	0.31
Calendaring	474	751	0.36
Molding	773	316	0.24
Other End Uses	619	105	0.07
Subtotal		**7,595**	**4.70**
Polystyrene (PS and EPS)			
Food Packaging and Food Service/ Packaging and One-Time Use	2,224	5,154	11.46
All Other End Uses/ Conversion Processes	2,224	282	0.63
Subtotal		**5,436**	**12.09**
Low-Density Polyethylene (LDPE)			
Film Production	2,279	2,372	5.41

Table 5-2. On-site Practical Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site PM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site PM Energy Consumption, Calculated (TBtu/year)
Other Extruded Products (Includes Pipe/Conduit Production)	1,287	615	0.79
Injection Molding	1,876	244	0.46
Blow Molding	1,784	59	0.11
Other End Uses	2,055	1,390	2.86
Subtotal		**4,680**	**9.62**
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)			
All Processes	3,786	14,822	56.12
Polyurethanes			
Rigid Foam	1,327	2,254	2.99
Flexible Foam Slabstock	147	1,397	0.21
Flexible Foam Molded	147	716	0.11
Subtotal		**4,367**	**3.30**
Synthetic Rubber			
Tire Production	5,760	1,118	6.44
Other End Uses	1,518	2,769	4.20
Subtotal		**3,887**	**10.64**
Natural Rubber			
Tire Production	5,760	871	5.02
Other End Uses	1,331	1,170	1.56
Subtotal		**2,041**	**6.58**
Total for Process Subareas Studied			**159.58**

Practical Minimum (PM)

Table 5-3 presents a comparison of the on-site CT energy consumption and PM energy consumption for each subarea and as a total. This is presented as the PM energy savings (the difference between CT energy consumption and PM energy consumption) and PM energy savings percentage. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings. Table 5-4 calculates the R&D opportunity for the processes studied and sector-wide opportunity.

It is useful to consider both TBtu energy savings and energy savings percentage 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 percentage energy savings is in injection molding at 61% energy savings; the greatest *current* plus *R&D opportunity* in terms of TBtu savings is extrusion at 35.0 TBtu per year savings. Section 7 explores *current opportunity* and *R&D opportunity* for each process subarea in more detail.

If U.S. plastics and rubber products manufacturing (for 2010 production levels) were able to attain on-site PM energy intensities, it is estimated that 108.3 TBtu per year of energy could be saved from the subareas alone, corresponding to a 40% 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.

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site PM Energy Consumption, Calculated (TBtu/year)	PM Energy Savings* (CT - PM) (TBtu/year)	PM Energy Savings Percent** (CT - PM) / (CT - TM)
Polypropylene (PP)				
Injection Molding	20.88	8.12	12.76	61%
Fiber and Filament Production	7.70	4.25	3.45	45%
Film Production	8.37	4.62	3.75	45%
Sheet Production	1.48	0.82	0.66	45%
Blow Molding	0.87	0.45	0.42	48%
Other End Uses	17.49	8.13	9.37	54%
High-Density Polyethylene (HDPE)				
Blow Molding	13.27	6.86	6.41	48%
Injection Molding	7.83	3.04	4.78	61%
Film Production	3.39	1.87	1.52	45%
Pipe and Conduit	1.85	1.02	0.83	45%
Sheet Production	0.65	0.36	0.29	45%
Other End Uses	6.50	3.16	3.34	51%
Linear Low-Density Polyethylene (LLDPE)				
Film Production	13.78	7.61	6.17	45%
Injection Molding	2.35	0.91	1.44	61%
Rotational Molding	2.38	1.78	0.60	25%

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site PM Energy Consumption, Calculated (TBtu/year)	PM Energy Savings* (CT - PM) (TBtu/year)	PM Energy Savings Percent** (CT - PM) / (CT - TM)
Other Extruded Products (May include Sheet, Blow Molding and Pipe/Conduit Production)	1.64	0.90	0.73	45%
Other End Uses	4.74	2.64	2.10	44%
Polyvinyl Chloride (PVC)				
Wire and Cable Production	0.52	0.24	0.27	53%
Film and Sheet Production	0.50	0.24	0.26	53%
Siding Production	2.15	1.02	1.14	53%
Rigid Pipe and Tubing Production	3.61	1.70	1.91	53%
Window and Door Production	1.12	0.53	0.59	53%
Fencing and Decking Production	0.65	0.31	0.34	53%
Calendaring	0.48	0.36	0.12	25%
Molding	0.70	0.24	0.45	65%
Other End Uses	0.14	0.07	0.07	52%
Polystyrene (PS and EPS)				
Food Packaging and Food Service/ Packaging and One-Time Use	15.31	11.46	3.85	25%
All Other End Uses/ Conversion Processes	0.84	0.63	0.21	25%
Low-Density Polyethylene (LDPE)				
Film Production	9.79	5.41	4.38	45%
Other Extruded Products (Includes Pipe/Conduit Production)	1.43	0.79	0.64	45%
Injection Molding	1.18	0.46	0.72	61%
Blow Molding	0.20	0.11	0.10	48%
Other End Uses	5.33	2.86	2.47	46%

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Plastics and Rubber Products Manufacturing in Subareas Studied and Sector-Wide

Subarea	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site PM Energy Consumption, Calculated (TBtu/year)	PM Energy Savings* (CT - PM) (TBtu/year)	PM Energy Savings Percent** (CT - PM) / (CT - TM)
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)				
All Processes	74.95	56.12	18.84	25%
Polyurethanes				
Rigid Foam	6.34	2.99	3.35	50%
Flexible Foam Slabstock	0.44	0.21	0.23	33%
Flexible Foam Molded	0.22	0.11	0.12	33%
Synthetic Rubber				
Tire Production	9.02	6.44	2.58	29%
Other End Uses	5.89	4.20	1.68	28%
Natural Rubber				
Tire Production	7.03	5.02	2.01	29%
Other End Uses	2.18	1.56	0.62	28%
Total for Process Subareas Studied	**265.18**	**159.58**	**105.60**	**40%**
Total for Plastics and Rubber Manufacturing Sector-Wide* **	**272**	**163.7**	**108.3**	**40%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
* PM energy savings is the current opportunity plus the R&D opportunity.
** PM energy savings percentage is the PM energy savings opportunity from transforming plastics and rubber production processes through the adoption of SOA equipment and practices. Energy savings percentage is calculated using the 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: PM Energy Savings Percent = (Current-PM)/(Current-TM).
*** The sector-wide PM energy consumption was an extrapolated value, calculated by dividing the total on-site SOA energy consumption for the processes studied by the overall percent coverage from Chapter 3 (97%).

The R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. The PM energy savings percentage is the percentage of energy saved with PM energy consumption compared to CT energy consumption, while referencing the TM as the baseline energy consumption. 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). TM is not necessarily equal to zero for manufacturing processes that entail 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); 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 percentage provides the most accurate measure of absolute savings potential. The equation for calculating on-site R&D opportunity and PM energy savings percentage are:

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

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

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

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

Subareas	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 Process Areas Studied	181.40	159.58	22	8%
Total for Plastics and Rubber Products Sector-wide	186.1†	163.7†	22	8%

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

* Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (SOA - PM)/(CT - TM).

6. Thermodynamic Minimum Energy Intensity and Energy Consumption for U.S. Plastics and Rubber Products Manufacturing

Real-world plastics and rubber products production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture a plastic or rubber 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 plastics and rubber 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 PM (see Chapter 5).

TM is not necessarily equal to zero for manufacturing processes that entail 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); 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 Plastics and Rubber Products

The TM energy intensity was calculated for each plastic and rubber product by determining the Gibbs free energy associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[10] The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[11]

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 more or fewer process steps. Note that for processes that involve no net chemical changes or reactions, the TM energy intensity is *zero* because all energy expended is assumed to be perfectly recovered. The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic. It is important to note that a negative TM value does not imply that the reaction will occur without being forced by a manufacturing process.

Two subareas of this sector involved chemical reactions: polyurethane product manufacturing and vulcanization of rubber (both natural and synthetic). The TM for polyurethane products manufacturing is based on the net Gibbs free energy change in the reaction of a polyol and an isocyanate to form a polyurethane that then undergoes a foaming reaction with water, as described in another bandwidth study (DOE 2016).

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[10] Unless otherwise noted, "ideal conditions" means a pressure of 1 atmosphere and a temperature of 77°F.
[11] Exergonic (reaction is favorable) and endogonic (reaction is not favorable) are thermodynamic terms for total change in Gibbs free energy (ΔG). This differs from exothermic (reaction is favorable) and endothermic (reaction is not favorable) terminology used in describing change in enthalpy (ΔH).

The TM for both natural and synthetic rubber products is based on the net Gibbs free energy change in the vulcanization process detailed in a National Institute of Standards and Technology (NIST) study (Bekkedahl and Weeks 1969), assuming 2% sulfur by weight in the process.

In this report, TM energy consumption is referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings 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 plastics and rubber products requiring an energy-intensive transformation (e.g., injection molding), this percent energy savings approach results in 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 percentage. 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 plastics and rubber products manufacturing subarea is its TM energy consumption. If all the 2010 levels of plastics and rubber 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 6-1 provides the TM energy intensities and energy consumption for the subareas studied (excluding feedstock energy). It is important to keep in mind that ideal conditions are unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities. As mentioned, the TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero). The total TM energy consumption sector-wide is negative because many of the products studied have a zero TM energy intensity (i.e., no chemical transformation), while some have negative TM energy intensity.

TM energy intensity values of zero are reported for the majority of processes because the definition of TM energy intensity used in this study accounts for only chemical transformations. Much of the thermal energy required for processes such as injection molding, blow molding, or extrusion is from melting and reshaping the resin. This energy is not counted under the definition of TM energy intensity used here. The processes with negative TM energy intensities include the polymerization of polyurethane and the vulcanization of rubber: two exothermic reactions.

Table 6-1. Thermodynamic Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site TM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site TM Energy Consumption, Calculated (TBtu/year)
Polypropylene (PP)			
Injection Molding	0	5,136	0.00
Fiber and Filament Production	0	2,822	0.00
Film Production	0	1,545	0.00
Sheet Production	0	1,296	0.00
Blow Molding	0	252	0.00
Other End Uses	0	4,919	0.00
Subtotal		**15,970**	**0.00**
High-Density Polyethylene (HDPE)			
Blow Molding	0	4,307	0.00
Injection Molding	0	2,178	0.00
Film Production	0	2,087	0.00
Pipe and Conduit	0	1,876	0.00
Sheet Production	0	568	0.00
Other End Uses	0	2,653	0.00
Subtotal		**13,669**	**0.00**
Linear Low-Density Polyethylene (LLDPE)			
Film Production	0	6,479	0.00
Injection Molding	0	569	0.00
Rotational Molding	0	264	0.00
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	0	702	0.00
Other End Uses	0	1,885	0.00
Subtotal		**9,899**	**0.00**
Polyvinyl Chloride (PVC)			
Wire and Cable Production	0	395	0.00
Film and Sheet Production	0	534	0.00
Siding Production	0	924	0.00
Rigid Pipe and Tubing Production	0	3,808	0.00

Table 6-1. Thermodynamic Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site TM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site TM Energy Consumption, Calculated (TBtu/year)
Window and Door Production	0	482	0.00
Fencing and Decking Production	0	280	0.00
Calendaring	0	751	0.00
Molding	0	316	0.00
Other End Uses	0	105	0.00
Subtotal		**7,595**	**0.00**
Polystyrene (PS and EPS)			
Food Packaging and Food Service/ Packaging and One-Time Use	0	5,154	0.00
All Other End Uses/ Conversion Processes	0	282	0.00
Subtotal		**5,436**	**0.00**
Low-Density Polyethylene (LDPE)			
Film Production	0	2,372	0.00
Other Extruded Products (Includes Pipe/Conduit Production)	0	615	0.00
Injection Molding	0	244	0.00
Blow Molding	0	59	0.00
Other End Uses	0	1,390	0.00
Subtotal		**4,680**	**0.00**
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)			
All Processes	0	14,822	*0.00*
Polyurethanes			
Rigid Foam	-188	2,254	-0.42
Flexible Foam Slabstock	-188	1,397	-0.26
Flexible Foam Molded	-188	716	-0.13
Subtotal		**4,367**	**-0.82**
Synthetic Rubber			
Tire Production	-18	1,118	-0.02

Table 6-1. Thermodynamic Minimum Energy Intensities and Calculated On-site Energy Consumption for Plastics and Rubber Products Manufacturing Subareas Studied

Subarea	On-site TM Energy Intensity (Btu/lb resin)	Production (Million lb)	On-site TM Energy Consumption, Calculated (TBtu/year)
Other End Uses	-18	2,769	-0.05
Subtotal		**3,887**	**-0.07**
Natural Rubber			
Tire Production	-18	871	-0.02
Other End Uses	-18	1,170	-0.02
Subtotal		**2,041**	**-0.04**
Total for Process Subareas Studied		**N/A**	**-0.93**

Thermodynamic Minimum (TM)

7. U.S. Plastics and Rubber Products Manufacturing Current and R&D Opportunity Analysis/Bandwidth Summary

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

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings for the plastics and rubber products industry subareas studied. Each row in Table 7-1 shows the opportunity bandwidth for a specific plastics and rubber products process area and as a total. As previously noted, the energy savings opportunities presented reflect the estimated production of plastics and rubber products *in baseline year 2010*.

As shown in Figure 7-1, two hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). The analysis shows the following:

- *Current Opportunity:* 86 TBtu per year of energy savings could be obtained if SOA technologies and practices are deployed.
- *R&D Opportunity:* 22 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 PM).

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

Table 7-1. Current and R&D Opportunity for Plastics and Rubber Products Manufacturing

Subarea	Current Opportunity (CT - SOA) (TBtu/year)	R&D Opportunity (SOA - PM) (TBtu/year)
Polypropylene (PP)		
Injection Molding	12.36	0.40
Fiber and Filament Production	2.27	1.18
Film Production	2.47	1.28
Sheet Production	0.44	0.23
Blow Molding	0.39	0.03
Other End Uses	7.98	1.39
Totals	*25.91*	*4.50*
High-Density Polyethylene (HDPE)		
Blow Molding	5.90	0.51

Table 7-1. Current and R&D Opportunity for Plastics and Rubber Products Manufacturing

Subarea	**Current Opportunity** (CT - SOA) (TBtu/year)	**R&D Opportunity** (SOA - PM) (TBtu/year)
Injection Molding	4.63	0.15
Film Production	1.00	0.52
Pipe and Conduit	0.55	0.28
Sheet Production	0.19	0.10
Other End Uses	2.97	0.37
Totals	*15.24*	*1.93*
Linear Low-Density Polyethylene (LLDPE)		
Film Production	4.07	2.10
Injection Molding	1.39	0.05
Rotational Molding	0.48	0.12
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	0.48	0.25
Other End Uses	1.51	0.59
Totals	*7.93*	*3.11*
Polyvinyl Chloride (PVC)		
Wire and Cable Production	0.22	0.06
Film and Sheet Production	0.21	0.06
Siding Production	0.89	0.25
Rigid Pipe and Tubing Production	1.50	0.41
Window and Door Production	0.47	0.13
Fencing and Decking Production	0.27	0.07
Calendaring	0.10	0.02
Molding	0.44	0.01
Other End Uses	0.06	0.01
Totals	*4.14*	*1.03*
Polystyrene (PS and EPS)		
Food Packaging and Food Service/ Packaging and One-Time Use	3.06	0.79
All Other End Uses/ Conversion Processes	0.17	0.04
Totals	*3.23*	*0.83*
Low-Density Polyethylene (LDPE)		
Film Production	2.89	1.49
Other Extruded Products (Includes Pipe/Conduit Production)	0.42	0.22

Table 7-1. Current and R&D Opportunity for Plastics and Rubber Products Manufacturing

Subarea		Current Opportunity (CT - SOA) (TBtu/year)	R&D Opportunity (SOA - PM) (TBtu/year)
Injection Molding		0.70	0.02
Blow Molding		0.09	0.01
Other End Uses		1.73	0.74
Totals		*5.83*	*2.48*
Other Thermoplastics (Acrylonitrile Butadiene Styrene [ABS], Polyethylene Terephthalate [PET], etc.)			
All Processes		14.99	3.85
Polyurethanes			
Rigid Foam		2.63	0.73
Flexible Foam	Slabstock	0.18	0.05
Flexible Foam	Molded	0.09	0.03
Totals		*2.90*	*0.80*
Synthetic Rubber			
Tire Production		1.35	1.23
Other End Uses		0.88	0.80
Totals		*2.24*	*2.03*
Natural Rubber			
Tire Production		1.05	0.96
Other End Uses		0.33	0.30
Totals		*1.38*	*1.25*
Total for Process Subareas Studied		**83.78**	**21.82**
Total for Plastics and Rubber Manufacturing Sector-Wide (extrapolated)*		**85.9**	**22.4**

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM)
* The sector-wide energy SOA and PM values are extrapolated values, calculated by dividing the total on-site SOA and PM energy consumptions for the processes studied by the overall percent coverage from Chapter 3 (97%).

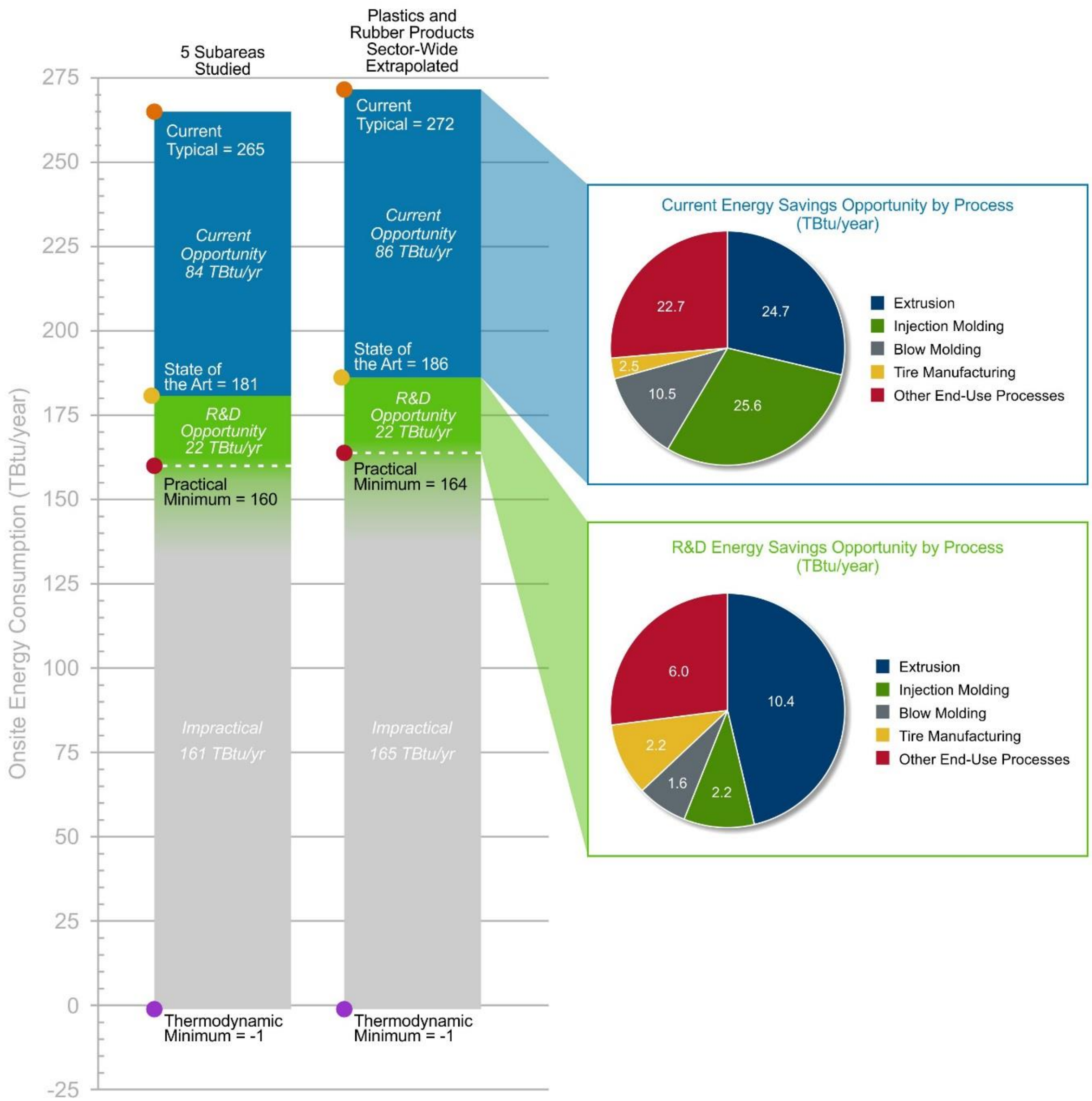

Figure 7-1. Current and R&D energy savings opportunities for the subsectors studied and for plastics and rubber products manufacturing (sector-wide), based on extrapolated data
Source: EERE

From the subareas studied, the greatest *current* and *R&D* energy savings opportunity for plastics and rubber products manufacturing comes from upgrading extrusion processes—largely because 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 plastics and rubber 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.

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Appendix A1. Master Plastics and Rubber Products Manufacturing Summary Table

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

Subarea	2010 Production (million lb)	On-site Energy Intensity (Btu/lb. resin)				Calculated On-site Energy Consumption (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Polypropylene (PP)									
Injection Molding	5,136	4,065	1,659	1,580	0	20.88	8.52	8.12	0.00
Fiber and Filament Production	2,822	2,729	1,923	1,507	0	7.70	5.43	4.25	0.00
Film Production	1,545	5,420	3,820	2,993	0	8.37	5.90	4.62	0.00
Sheet Production	1,296	1,141	804	630	0	1.48	1.04	0.82	0.00
Blow Molding	252	3,451	1,917	1,784	0	0.87	0.48	0.45	0.00
Other End Uses	4,919	3,556	1,934	1,652	0	17.49	9.51	8.13	0.00
Totals	*15,970*					*56.79*	*30.89*	*26.39*	*0.00*
High-Density Polyethylene (HDPE)									
Blow Molding	4,307	3,081	1,711	1,593	0	13.27	7.37	6.86	0.00
Injection Molding	2,178	3,594	1,467	1,397	0	7.83	3.19	3.04	0.00
Film Production	2,087	1,626	1,146	898	0	3.39	2.39	1.87	0.00
Pipe and Conduit	1,876	985	694	544	0	1.85	1.30	1.02	0.00
Sheet Production	568	1,141	804	630	0	0.65	0.46	0.36	0.00
Other End Uses	2,653	2,450	1,332	1,190	0	6.50	3.53	3.16	0.00
Totals	*13,669*					*33.49*	*18.25*	*16.31*	*0.00*
Linear Low-Density Polyethylene (LLDPE)									
Film Production	6,479	2,126	1,498	1,174	0	13.78	9.71	7.61	0.00
Injection Molding	569	4,127	1,684	1,605	0	2.35	0.96	0.91	0.00
Rotational Molding	264	9,020	7,216	6,753	0	2.38	1.91	1.78	0.00

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

Subarea	2010 Production (million lb)	On-site Energy Intensity (Btu/lb. resin)				Calculated On-site Energy Consumption (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	702	2,331	1,643	1,287	0	1.64	1.15	0.90	0.00
Other End Uses	1,885	2,513	1,713	1,398	0	4.74	3.23	2.64	0.00
Totals	*9,899*					*24.88*	*16.95*	*13.84*	*0.00*
Polyvinyl Chloride (PVC)									
Wire and Cable Production	395	1,316	771	620	0	0.52	0.30	0.24	0.00
Film and Sheet Production	534	938	550	442	0	0.50	0.29	0.24	0.00
Siding Production	924	2,331	1,366	1,099	0	2.15	1.26	1.02	0.00
Rigid Pipe and Tubing Production	3,808	949	556	447	0	3.61	2.12	1.70	0.00
Window and Door Production	482	2,331	1,366	1,099	0	1.12	0.66	0.53	0.00
Fencing and Decking Production	280	2,331	1,366	1,099	0	0.65	0.38	0.31	0.00
Calendaring	751	634	507	474	0	0.48	0.38	0.36	0.00
Molding	316	2,210	816	773	0	0.70	0.26	0.24	0.00
Other End Uses	105	1,300	755	619	0	0.14	0.08	0.07	0.00
Totals	*7,595*					*9.87*	*5.74*	*4.70*	*0.00*
Polystyrene (PS and EPS)									
Food Packaging and Food Service/Packaging and One-Time Use	5,154	2,970	2,376	2,224	0	15.31	12.25	11.46	0.00
All Other End Uses/Conversion Processes	282	2,970	2,376	2,224	0	0.84	0.67	0.63	0.00
Totals	*5,436*					*16.15*	*12.92*	*12.09*	*0.00*
Low-Density Polyethylene (LDPE)									
Film Production	2,372	4,127	2,909	2,279	0	9.79	6.90	5.41	0.00

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

Subarea	2010 Production (million lb)	On-site Energy Intensity (Btu/lb. resin)				Calculated On-site Energy Consumption (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Other Extruded Products (Includes Pipe/Conduit Production)	615	2,331	1,643	1,287	0	1.43	1.01	0.79	0.00
Injection Molding	244	4,826	1,969	1,876	0	1.18	0.48	0.46	0.00
Blow Molding	59	3,451	1,917	1,784	0	0.20	0.11	0.11	0.00
Other End Uses	1,390	3,831	2,585	2,055	0	5.33	3.59	2.86	0.00
Totals	*4,680*					*17.93*	*12.10*	*9.62*	*0.00*
Other Thermoplastics (acrylonitrile butadiene styrene [ABS], polyethylene terephthalate [PET], etc.)									
All Processes	14,822	5,057	4,046	3,786	0	74.95	59.96	56.12	0.00
Polyurethanes									
Rigid Foam	2,254	2,814	1,649	1,327	-188	6.34	3.72	2.99	-0.42
Flexible Foam Slabstock	1,397	313	183	147	-188	0.44	0.26	0.21	-0.26
Flexible Foam Molded	716	313	183	147	-188	0.22	0.13	0.11	-0.13
Totals	*4,367*					*7.00*	*4.10*	*3.30*	*-0.82*
Synthetic Rubber									
Tire Production	1,118	8,067	6,857	5,760	-18	9.02	7.67	6.44	-0.02
Other End Uses	2,769	2,126	1,807	1,518	-18	5.89	5.00	4.20	-0.05
Totals	*3,887*					*14.91*	*12.67*	*10.64*	*-0.07*
Natural Rubber									
Tire Production	871	8,067	6,857	5,760	-18	7.03	5.97	5.02	-0.02
Other End Uses	1,170	1,865	1,585	1,331	-18	2.18	1.86	1.56	-0.02
Totals	*2,041*					*9.21*	*7.83*	*6.58*	*-0.04*
Total for Process Subareas Studied	**82,367**	**N/A**	**N/A**	**N/A**	**N/A**	**265.18**	**181.40**	**159.58**	**-0.93**
Total for Plastics and Rubber Manufacturing Sector-Wide (extrapolated)	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**272**	**186.1**	**163.4**	**-0.95**

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. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Polypropylene (PP)					
Injection Molding	ACC 2015	NREL 2016	Kanungo & Yong 2012, CIPEC 2007	Kanungo & Yong 2012, CIPEC 2007, Lu et al. 2011, Lovrec and Tic 2010	Set to zero owing to minimal chemical conversions
Fiber and Filament Production	ACC 2015	Average of Monofilament and Fiber Extrusion from 2 sources: euRECIPE 2005 (Fibre Extrusion, On-site), Khripko, et al. 2016 (Monofilament Extrusion, On-site)	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Film Production	ACC 2015	Average of 3 values: NREL 2016 (Polypropylene film, biaxially oriented) (Polypropylene film, unoriented) (Polypropylene film, microporous)	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Sheet Production	ACC 2015	Boustead 2002 and Marks & Spencer PLC 2003 (PVC value from Boustead 2002 was modified using assumption in Marks & Spencer 2003 to represent PP)	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Blow Molding	ACC 2015	Euromap 2011	KEMA 2012, CIPEC 2007	KEMA 2012, CIPEC 2007	Set to zero owing to minimal chemical conversions
Other End Uses	ACC 2015	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin
High-Density Polyethylene (HDPE)					
Blow Molding	ACC 2015	Keoleian et al. 2012	KEMA 2012, CIPEC 2007	KEMA 2012, CIPEC 2007	Set to zero owing to minimal chemical conversions
Injection Molding	ACC 2015	Keoleian et al. 2012	Kanungo & Yong 2012, CIPEC 2007	Kanungo & Yong 2012, CIPEC 2007, Lu et al. 2011, Lovrec and Tic 2010	Set to zero owing to minimal chemical conversions
Film Production	ACC 2015	NREL 2016	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Pipe and Conduit	ACC 2015	Keoleian et al. 2012	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Sheet Production	ACC 2015	Boustead 2002 and Marks & Spencer PLC 2003 (PVC value from Boustead 2002 was modified using assumption in Marks	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
		& Spencer 2003 to represent PP/HDPE)			
Other End Uses	ACC 2015	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin	Production-weighted energy intensity average of other processes for this resin
Linear Low-Density Polyethylene (LLDPE)					
Film Production	ACC 2015	NREL 2016	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Injection Molding	ACC 2015	NREL 2016	Kanungo & Yong 2012, CIPEC 2007	Kanungo & Yong 2012, CIPEC 2007, Lu et al. 2011, Lovrec and Tic 2010	Set to zero owing to minimal chemical conversions
Rotational Molding	ACC 2015	euRECIPE 2005	DOE 2005	DOE 2005, Lu et al. 2011	Set to zero owing to minimal chemical conversions
Other Extruded Products (May Include Sheet, Blow Molding and Pipe/Conduit Production)	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Other End Uses	ACC 2015	Production-weighted energy intensity average of other	Production-weighted energy intensity average of other	Production-weighted energy intensity average of other	Production-weighted energy intensity average of other

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
		processes for this resin	processes for this resin	processes for this resin	processes for this resin
Polyvinyl Chloride (PVC)					
Wire and Cable Production	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Film and Sheet Production	ACC 2015	NREL 2016	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Siding Production	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Rigid Pipe and Tubing Production	ACC 2015	Keoleian et al. 2012	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Window and Door Production	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Fencing and Decking Production	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Calendaring	ACC 2015	Boustead 2002	DOE 2005	DOE 2005, Lu et al. 2011	Set to zero owing to minimal chemical conversions
Molding	ACC 2015	Keoleian et al. 2012	Kanungo & Yong 2012, Focus on Energy 2006, CIPEC 2007	Kanungo & Yong 2012, Focus on Energy 2006, CIPEC 2007, Lu et al. 2011, Lovrec and Tic 2010	Set to zero owing to minimal chemical conversions
Other End Uses	ACC 2015	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.
Polystyrene (PS and EPS)					
Food Packaging and Food Service/Packaging and One-Time Use	ACC 2015	Suwanmanee et al. 2013	DOE 2005	DOE 2005, Lu et al. 2011	Set to zero owing to minimal chemical conversions

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
All Other End Uses/ Conversion Processes	ACC 2015	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.
Low-Density Polyethylene (LDPE)					
Film Production	ACC 2015	NREL 2016	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Other Extruded Products (Includes Pipe/Conduit Production)	ACC 2015	euRECIPE 2005	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	Set to zero owing to minimal chemical conversions
Injection Molding	ACC 2015	euRECIPE 2005 (Injection Molding, On-site)	Kanungo & Yong 2012, CIPEC 2007	Kanungo & Yong 2012, CIPEC 2007, Lu et al. 2011, Lovrec and Tic 2010	Set to zero owing to minimal chemical conversions
Blow Molding	ACC 2015	Euromap 2011	KEMA 2012, CIPEC 2007	KEMA 2012, CIPEC 2007	Set to zero owing to minimal chemical conversions
Other End Uses	ACC 2015	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.	Production-weighted energy intensity average of other processes for this resin.
Other Thermoplastics (acrylonitrile butadiene styrene [ABS], polyethylene terephthalate [PET], etc.)					

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
All Processes	ACC 2015	Average of 3 values NREL 2016 (Process Energy) (Microporous PET film, Biaxially oriented PET film, and PET bottles by injection stretch blow-mold process)	DOE 2005	DOE 2005, Lu et al. 2011	Set to zero owing to minimal chemical conversions
Polyurethanes					
Rigid Foam	ACC 2015	NREL 2016	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	DOE 2016
Flexible Foam Slabstock	ACC 2015	NREL 2016	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	DOE 2016
Flexible Foam Molded	ACC 2015	NREL 2016	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007	Focus on Energy 2010, Focus on Energy 2006, Rauwendaal 2010, Kanungo & Yong 2012, CIPEC 2007, Vera-Sorroche et al. 2013	DOE 2016
Synthetic Rubber					
Tire Production	USB 2011	ANL 2010	MidAmerican Energy n.d.	MidAmerican Energy n.d., Njobet 2012	Bekkedahl and Weeks 1969

Table A2-1. Sources Used to Calculate Production and Energy Intensities for the Four Bandwidth Measures

Subarea	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Other End Uses	USB 2011, Statista 2016	Average of 2 values: NREL 2016 (Synthetic SBR, and Synthetic EPDM)	MidAmerican Energy n.d.	MidAmerican Energy n.d., Njobet 2012	Bekkedahl and Weeks 1969
Natural Rubber					
Tire Production	USB 2011	ANL 2010	MidAmerican Energy n.d.	MidAmerican Energy n.d., Njobet 2012	Bekkedahl and Weeks 1969
Other End Uses	USB 2011, Rubber Board 2012 [Data used was from: Rubber Industry Report (January-March 2012), of the International Rubber Study Group]	IFC 2007	MidAmerican Energy n.d.	MidAmerican Energy n.d., Njobet 2012	Bekkedahl and Weeks 1969

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

Appendix A3. State of the Art and Practical Minimum (R&D) Technologies Considered

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
Switching from hydraulic to all-electric injection molding machines	Electric injection molding machines can be a direct replacement for hydraulic injection molding machines and are typically significantly more energy efficient.	Injection molding	Electric injection molding machines use high-speed electric servo motors. These use less energy than their hydraulic equivalents and eliminate the need to cool the hydraulic oil, resulting in additional savings. Kanungo & Yong 2012 estimates 74% energy savings from the injection molding machine is possible by switching from a hydraulic to electric system.	74%	Yes	Yes	Kanungo & Yong 2012
Insulation on barrel heaters	Barrel insulation jackets can be applied to barrel heaters to reduce wasted heat.	Injection molding	The application of an insulation jacket to the injection molding barrel can reduce the loss of energy and minimize energy required for heating the polymer. Kanungo & Yong 2012 estimates 20%–22% energy savings from the from the barrel heating component of the machine.	21%	Yes	Yes	Kanungo & Yong 2012
Low pressure drying	A vacuum is applied to the dryer cabinet to accelerate drying.	Injection molding, extrusion, and blow molding where material drying is required (polypropylene,	The application of a vacuum reduced the boiling point of water, and water vapor is driven out of the polymer granules, reducing drying times.	65%	Yes	Yes	Focus on Energy 2006

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
		polyethylene, and polystyrene are excluded).	Focus on Energy 2006 estimates 50%–80% energy savings applied to material drying systems.				
Variable speed drive (VSD) on chilled water pump	A VSD modulates the speed of the chilled water pump based on chilled water tank temperature.	Injection molding, extrusion, blow molding	VSD modulation of the pump speed allows it to draw less energy when lower drive speeds are required. Kanungo & Yong 2012 estimates 33% energy savings applied to process chilling systems.	33%	Yes	Yes	Kanungo & Yong 2012
High-efficiency motors for extruder drive system	Using higher-efficiency motors and choosing the correct size and speed of the motor for the application.	Injection molding, extrusion, blow molding	Higher-efficiency motors require less energy, and avoiding over-sizing motors can reduce unnecessary energy use. CIPEC 2007 estimates 20% energy savings applied to the extruder drive.	20%	Yes	Yes	CIPEC 2007
Compressed air system operation	Correct sizing of the compressed air system, regular maintenance, and use of staged compressors.	Injection molding, extrusion, blow molding	Excess energy use can be avoided by properly scaling the system and minimizing leaks. Staged compressors reduce the energy work required to compress air, saving energy. CIPEC 2007 estimates 20% energy savings applied to compressed air systems.	20%	Yes	Yes	CIPEC 2007
Radiant heater bands for plastic extrusion	Insulated heater bands can be applied to extrusion machines for better thermal management.	Extrusion	Radiant heater bands reduce heat loss by adding insulation and allow for a more efficient heat transfer to the polymer.	33%	Yes	Yes	Focus on Energy 2010

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
			Focus on Energy 2010 estimates 33% energy savings applied to extrusion machines.				
Extruding polymer directly after drying	Minimizing the time between drying and extrusion of the polymer to save energy.	Extrusion where material drying is required (polypropylene, polyethylene, and polystyrene are excluded)	Extruding the polymer soon after drying means that some of the thermal energy from drying can be used to get the polymer to the necessary temperature for extrusion. If the polymer is allowed to cool down after drying, additional energy is required to reheat it to the temperature required for extrusion. Rauwendaal 2010 estimates 25% energy savings applied to extrusion machines.	25%	Yes	Yes	Rauwendaal 2010
Extrusion barrel heating using electrically heated thermal oil and insulation	An electrically heated thermal oil system circulates thermal oil to manage extrusion barrel temperatures.	Extrusion	Thermal oil allows for more precise control of extrusion barrel heating and cooling to minimize waste heat. Combined with insulated extrusion barrels, this can further minimize heat loss. Khripko et al. 2016 estimates 30%–40% energy savings applied to the facility.	35%	Yes	Yes	Khripko et al. 2016
Average energy savings from DOE best practices	This savings estimate is used for processes where more specific SOA energy savings information is not available.	Plastic products manufacturing	This estimate is from a study in which DOE made best-practice energy savings recommendations at 11 plastics manufacturing plants. Major energy-saving measures included	20%	Yes	Yes	DOE 2005

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
			recovering compressor waste heat, insulating molding machine surfaces, and barrel heater temperature control. DOE 2005 estimates 20% energy savings applied to the facility.				
Average energy savings potential for rubber products manufacturing	This savings estimate is used for processes where more specific SOA energy savings information is not available.	Rubber products manufacturing	This is a general estimate of energy savings potential for rubber products manufacturing facilities. BRE 1999 estimates that 10%–20% savings are possible through measures that improve the overall energy management of the facility including waste heat recovery, insulation, high-efficiency motors and drives, and boiler efficiency.	15%	Yes	Yes	BRE 1999
Multi-objective process parameter optimization to reduce energy consumption in injection molding processes	Using computational optimization methods such as the Taguchi Method, analysis of variance, artificial neural networks, and genetic algorithms, key process parameters can be optimized to reduce energy consumption while maintaining part quality.	Injection molding	Computational methods were used to optimize parameters such as part weight, mold temperature, nozzle melt temperature, packing time, and packing pressure across several experiments. Lu et al. 2011 estimates an average of 11% energy savings from the machine. based on a set of 8 experiments.	11%	No	Yes	Lu et al. 2011, Fei et al. 2013, Bharti et al. 2010, Park and Nguyen 2014, Biglione et al. 2015
Optimal high-throughput extrusion to reduce energy consumption	Computational/ experimental optimization and in-process monitoring techniques can be	Extrusion	In-process monitoring techniques can be used to identify an optimal extrusion speed that maximizes the heat from mechanical work	40%	No	Yes	Njobet 2012, Vera-Sorroche et al. 2013,

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
	used to identify high-throughput levels of extrusion that minimize energy consumption.		and minimizes the amount of additional heating required to melt the polymer. Njobet 2012 estimates that 40% energy savings are possible from the extrusion process. Vera-Sorroche et al. 2013 found similar efficiency gains at higher extrusion speeds.				Yu et al. 2004
Computational fluid dynamics to optimize cooling unit designs	Computational fluid dynamics is used to optimize cooling units, which can reduce energy consumption by compressed air used for plastics molding.	Blow molding	Computational fluid dynamics are used to make more efficient cooling units. Cleaning and cooling processes using compressed air are particularly wasteful, and the system design outlined in Lovrec and Tic 2010 shows that up to 50% savings can be achieved on compressed air systems used in plastics molding. This applies specifically to different types of blow molding processes.	50%	No	Yes	Lovrec and Tic 2010
Advanced modeling and optimization of an infrared oven for injection stretch blow molding	An optimization model is developed to identify the relationship between infrared oven lamp power settings and the output temperature profile of plastics products.	Blow molding	Adjusting the parameters of an infrared oven to minimize the energy used to heat preforms for blow molding can reduce unnecessary energy consumption.	Unspecified	No	While this process could potentially contribute to achieving the practical minimum, actual energy savings of this emerging technology as applied to plastics and	Yang et al. 2014

Table A3-1. Details of State of the Art and Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Percent Savings Estimate	Included in SOA Calculations	Included in PM Calculations	References
						rubber processing are currently unclear.	
Microwave processing of thermoplastic composites	Microwave process heating can be applied to the heating, drying, and curing of plastic polymers.	Thermoplastics processing	Microwave systems benefit from having lower energy requirements and reduced processing times compared to conventional process heating.	Unspecified	No	While this process could potentially contribute to achieving the practical minimum, actual energy savings of this emerging technology as applied to plastics and rubber processing are currently unclear.	Ku and Yusaf 2008, DOE 2007

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