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

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing

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The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office works with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

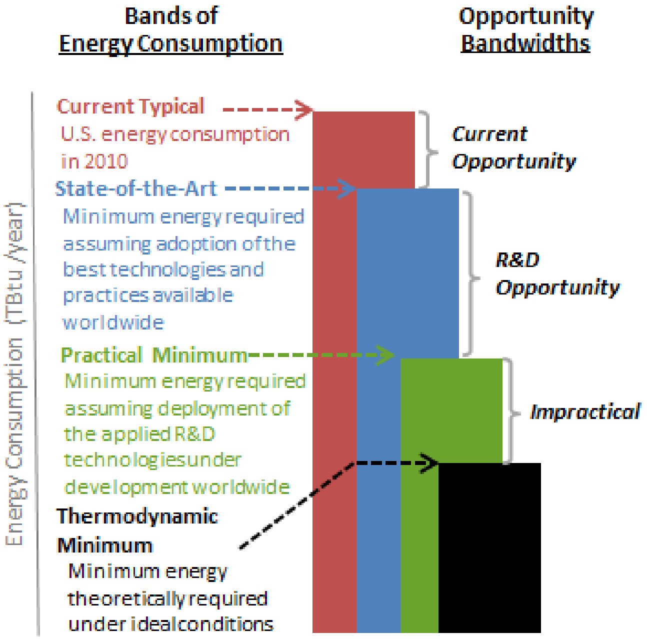
Prepared for DOE / EERE's Advanced Manufacturing Office by Energetics Incorporated

(Sabine Brueske, Caroline Kramer, Aaron Fisher)

Disclaimer

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. The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the processes and products that consume the most energy, and provide hypothetical, technology-based estimates of potential energy savings opportunities. 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. Bandwidth studies using the terminology and methodology outlined below were prepared for the Chemicals, Petroleum Refining, Iron and Steel, and Pulp and Paper industry sectors in 2014.[11]



Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure). **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or

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[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the Office of Industrial Technologies). The first two sector studies—Iron and Steel, and Metal Castings—were completed in 2004. That work was followed by Chemicals and Petroleum Refining studies in 2006, and Aluminum, Glass, and Mining in 2007. A Cement Industry analysis was conducted in 2010 and a Pulp and Paper analysis was conducted in 2011.

theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included in the energy consumption estimates.

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

In each sector studied in the series, the four energy bands are estimated for select individual products or processes, subsectors, 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.

Acknowledgements

AMO wishes to acknowledge the contributions made by Dr. Joe Porcelli of JVP International Inc., and Dr. Peter Akinjiola of Psage Research, LLC, for their work reviewing this study. Also Professor Eric Masanet of Northwestern University and Professor Rakesh Agrawal and Mr. Dharik Mallapragada of Purdue University for their work determining the thermodynamic minimum energy value of each chemical studied.

In addition, AMO recognizes Joseph Cresko of DOE/AMO who lead the conceptual development and publication of the bandwidth study series with the support of Dr. Alberta Carpenter at the National Renewable Energy Laboratory and Dr. Dickson Ozokwelu of DOE/AMO, as well as the important contributions made by Sabine Brueske, Caroline Kramer, and Dr. Aaron Fisher of Energetics Incorporated for conducting the majority of the research and analysis and drafting this study.

Executive Summary

More than 70,000 chemicals are produced in the United States. This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. chemical manufacturing. Industrial, government, and academic data are used to estimate the energy consumed in manufacturing 74 of the most energy intensive and production intensive chemicals. Three different energy consumption *bands* (or levels) are estimated for manufacturing these select chemicals based on referenced energy intensities of current, state of the art, and R&D technologies. A fourth theoretical minimum energy consumption *band* is also estimated. The data from the select individual chemicals studied is extrapolated and aggregated to determine energy consumption for 15 chemical subsectors. The *bandwidth*—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The costs associated with realizing these energy savings was not in the scope of this study.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for chemicals manufacturing subsectors and sector-wide. This is a step toward understanding the chemicals that could most benefit from process and technology efficiency improvements to realize energy savings.

Study Organization and Approach: After providing an overview of the methodology (Chapter 1) and energy consumption in chemicals manufacturing (Chapter 2), the 2010 production volumes (Chapter 3) and current energy consumption (Current typical [CT], Chapter 4) were estimated for 74 select chemicals. In addition, the minimum energy consumption to manufacture these chemicals was estimated assuming the adoption of best technologies and practices available worldwide (state of the art [SOA], Chapter 5) and assuming the deployment of the applied research and development (R&D) technologies available worldwide (practical minimum [PM], Chapter 6). The minimum amount of energy theoretically required to manufacture these chemicals assuming ideal conditions was also estimated (thermodynamic minimum [TM)], Chapter 7); in some cases, this is less than zero. The difference between the energy consumption *bands* (CT, SOA, PM, TM) are the estimated energy savings opportunity *bandwidths* (Chapter 8).

The U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) provides subsector and sector-wide estimates of energy consumption for U.S. chemical manufacturing; this data is referenced as subsector and sector-wide CT energy consumption. In this study, CT energy consumption for 74 *individual* chemicals is estimated from multiple referenced sources. To estimate SOA, PM, and TM energy consumption for the chemical subsectors, the energy consumption data of the 74 chemicals was grouped by subsector and 10 of the 74 chemicals were omitted to avoid duplication when aggregating results; data for 64 chemicals was extrapolated to estimate total subsector SOA, PM, and TM energy consumption. The subsector energy consumption values were summed to determine sector-wide SOA, PM, and TM energy consumption. In 2010, these 64 chemicals corresponded to 31% of the industry's production volume and 57% of the industry's 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.[1] 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 for the 64 chemicals studied and for all of U.S. chemical manufacturing based on extrapolated data. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual chemicals subsectors based on the sector-wide extrapolated data.

Table ES-1. Potential Energy Savings Opportunities in the U.S. Chemical Manufacturing Sector[1]

Opportunity Bandwidths	Estimated Energy Savings Opportunity to Manufacture 64 Select U.S. Chemicals (per year)	Estimated Energy Savings Opportunity to Manufacture All the Chemicals of the U.S. Chemical Industry Based on Extrapolated Data (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	450 TBtu[2] (19% energy savings, where TM is the baseline)	766 TBtu[3] (19% energy savings, where TM is the baseline)
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	757 TBtu[4] (32% energy savings, where TM is the baseline)	1221 TBtu[5] (31% energy savings, where TM is the baseline)

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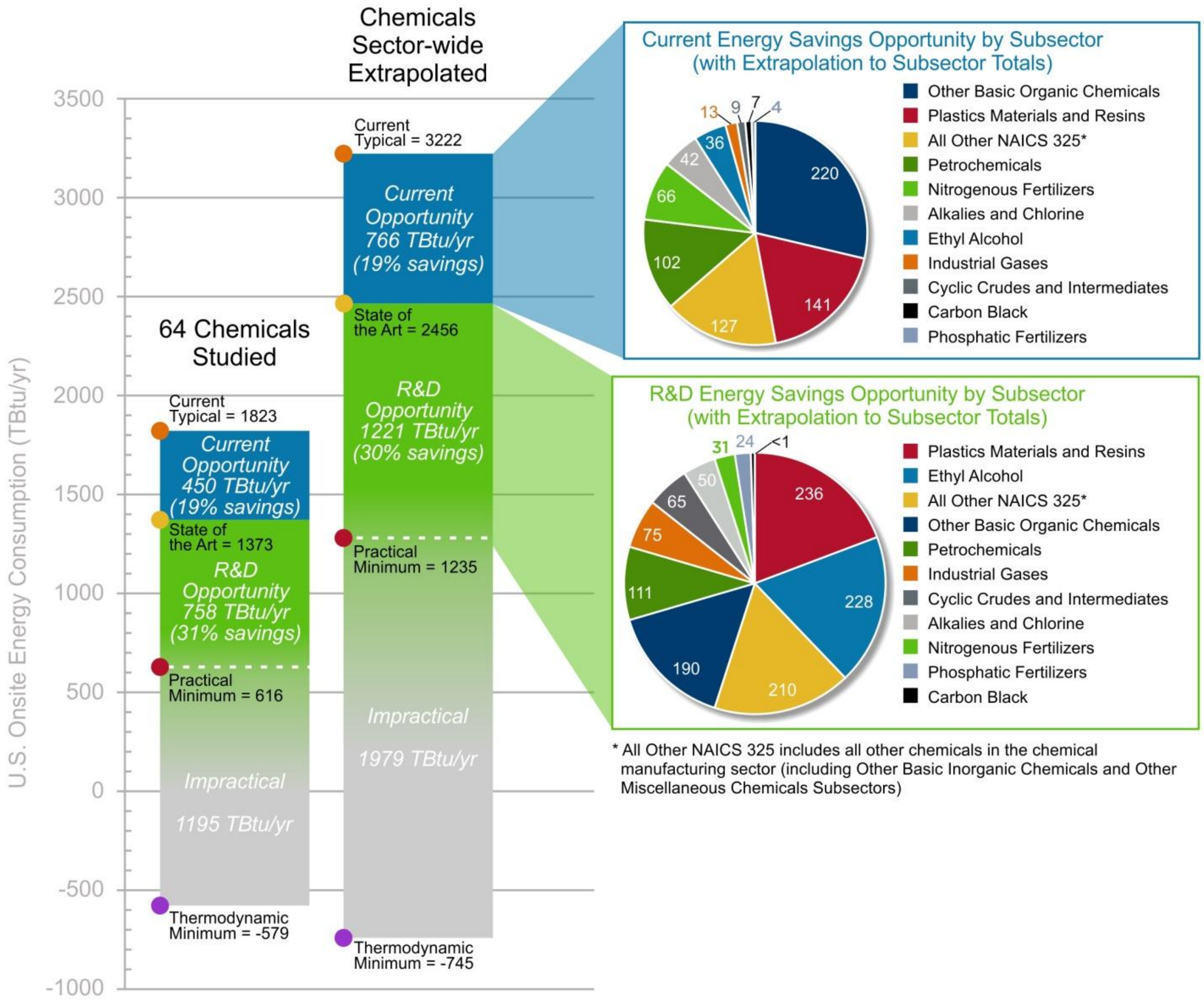
[1] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for onsite energy use (i.e., energy consumed within the manufacturing plant boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

[2] 450 TBtu = 1823 – 1373

[3] 766 TBtu = 3222 – 2456

[4] 757 TBtu = 1373 – 616

[5] 1221 TBtu = 2456 – 1235



* All Other NAICS 325 includes all other chemicals in the chemical manufacturing sector (including Other Basic Inorganic Chemicals and Other Miscellaneous Chemicals Subsectors)

Figure ES-1. Current and R&D Energy Savings Opportunities for the 64 Chemicals Studied and for Chemicals Sector-wide Based on Extrapolated Data

As shown in Figure ES-1, the total TM energy consumption sector-wide is negative because many of the chemicals studied are theoretically net-energy producers (i.e., TM energy intensity less than zero). The percentage energy savings presented considers that the TM value is negative.

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” because with today’s knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

The results presented show that 450 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade chemical production of the 64 chemicals; an additional 757 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

However, if the energy savings potential is estimated for the U.S. chemical industry as a whole, the current energy savings opportunity is 766 TBtu/year and the R&D opportunity increases to 1,221 TBtu per year.

The Current Energy Savings Opportunities for the top four subsectors are as follows:

- Other Basic Organic Chemicals subsector - 220 TBtu (or 29% of the current opportunity)
- Plastic Materials and Resins subsector - 141 TBtu (or 18% of the current opportunity)
- All other NAICS 325[1] subsectors - 127 TBtu (or 17% of the current opportunity) and
- Petrochemicals subsector - 102 TBtu (or 13% of the current opportunity).

The Future Energy Saving Opportunities for the top four subsectors are as follows:

- Plastic Materials and Resins subsector - 236 TBtu (or 19% of the R&D opportunity)
- Ethyl alcohol - 228 TBtu (or 19% of the R&D opportunity)
- All other NAICS 325[1] subsectors - 210 TBtu (or 17% of the R&D opportunity) and
- Other Basic Organic Chemicals subsector - 190 TBtu (or 16% of the R&D opportunity).

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[1] All other NAICS 325 includes all other chemicals in the chemical manufacturing sector including Other Basic Inorganic Chemicals and other Miscellaneous Chemical subsectors.

List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
BAT	Best available technology
BPT	Best practices technology
Btu	British thermal unit
BTX	Benzene, toluene, and xylene
COE	Cost of energy
CT	Current typical
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Agency
EERE	DOE Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
FCC	Fluidized catalytic cracking
LPG	Liquefied petroleum gases
MECS	Manufacturing Energy Consumption Survey
NAICS	North American Industry Classification System
NGL	Natural gas liquids
G	Gibbs Free Energy
GJ	Gigajoules
GJ/t	Gigajoules per ton
ORNL	Oak Ridge National Laboratory
PM	Practical minimum
R&D	Research and development
SEC	Specific energy consumption
SOA	State of the art
TBtu	Trillion British thermal units
TM	Thermodynamic minimum

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1. Introduction

1.1. OVERVIEW

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. chemical manufacturing sector, as defined by classification 325 of the North American Industry Classification System (NAICS). The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for chemicals manufacturing subsectors and chemicals 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.

More than 70,000 chemicals are produced in the United States; 74 of the most energy-intensive and high-volume chemicals were studied. Together, 64 of these chemicals (10 were omitted to avoid double counting and other issues) accounted for 57% of energy consumption and 31% of the total volume of chemicals manufactured by the U.S. chemical sector in 2010.

The four bands of energy consumption estimated in this report include: the onsite energy consumption associated with manufacturing 64 chemicals 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 manufacture a chemical theoretically (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 study builds upon the 2006 DOE bandwidth report *Chemical Bandwidth Study, Exergy Analysis: A Powerful Tool for Identifying Process Inefficiencies in the U.S. Chemical Industry*. The earlier study relied on extensive software simulations to identify the quality of energy consumed in manufacturing chemicals and the amount of energy that could be recovered. In contrast, this study compares diverse industrial, academic and governmental consumption data to analyses[1] of reported plant energy consumption data in the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA) for data year 2010. This study also expands the number of chemical products studied from 44 to 74 and updates energy consumption and production values to the year 2010.

This report is one in a series of bandwidth studies commissioned by DOE's Advanced Manufacturing Office characterizing energy consumption in U.S. manufacturing using a uniform methodology and definitions of energy bands. Other manufacturing sector bandwidth studies

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[1] The relevant analysis was published as the *Manufacturing Energy and Carbon Footprint for the Chemicals Sector* (NAICS 325), based on energy use data from 2010 EIA MECS (with adjustments) in February 2014. Hereafter, this document will be referred to as the "Energy Footprint" and listed in the References section as DOE 2014.

include iron and steel, petroleum refining, and pulp and paper; additional sector studies are under consideration. Collectively, these studies explore the potential energy savings opportunities in manufacturing that are available through existing technology and with investment in research and development (R&D) technologies.

1.3. DEFINITIONS OF ENERGY CONSUMPTION BANDS AND OPPORTUNITY BANDWIDTHS

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 chemical 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).

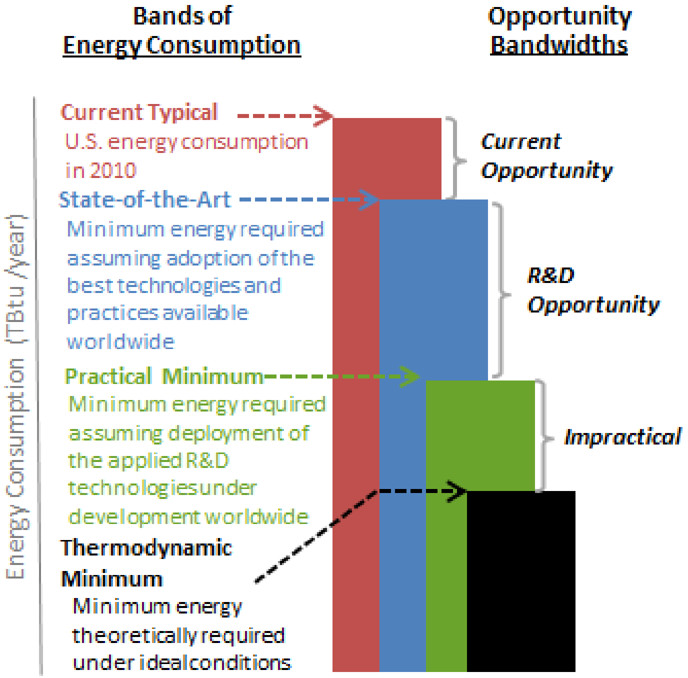

Figure 1-1. Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

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

Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

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

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

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 chemicals in new ways with technologies that are not commercially available.

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 difference between PM and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

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 "onsite energy" or "primary energy" and defined as follows:

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

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

Four bands of energy consumption are quantified for select individual chemicals, chemicals subsectors, and chemical manufacturing sector-wide. **The bands of energy consumption and the opportunity bandwidths presented herein consider onsite energy consumption; feedstocks[2] are excluded.** To determine the total annual onsite CT, SOA, PM, and TM energy consumption values of the chemicals studied (TBtu per year), energy intensity values per unit weight (Btu per pound of chemical manufactured) are estimated and multiplied by the production volumes (pounds per year of chemical manufactured). The year 2010 is used as a base year since it is the most recent year for which consistent subsector and sector-wide energy consumption data are available. Unless otherwise noted, 2010 production data is used. Some chemical 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 chemicals manufacturing. The estimates reported herein are representative of average U.S. chemical 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.

Overview of energy use in chemical manufacturing: Chapter 2 provides an **overview** of the U.S. chemical manufacturing sector and how energy is used in chemicals manufacturing (how much, what type, and for what end use).

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[2] Feedstock energy is the nonfuel use of combustible energy. Feedstocks are converted to chemical products (not used as a fuel). An example of a feedstock is natural gas liquids used to produce petrochemicals.

Estimating production volumes for select chemicals: Chapter 3 presents the **production volumes** for the 74 chemicals (lb per year) in 2010 and the rationale for how the 74 chemicals were selected.

Estimating CT energy consumption: Chapter 4 presents the calculated onsite CT **energy consumption** (TBtu per year) for the 74 chemicals individually, the subsectors, and sector-wide (along with references for the CT energy intensity data and assumptions). The CT energy consumption data is calculated based on this energy intensity data and the production volumes (identified in Chapter 3). The boundary assumptions for the industrial processes considered in this bandwidth study are presented.

MECS provides onsite CT energy consumption data by subsector and sector-wide for 2010 (See Table 4-1). However, MECS does not provide CT energy consumption data for individual chemicals. Calculated CT energy consumption estimates for the chemical subsectors and sector-wide are based on the extrapolated analysis of individual chemicals. The percent coverage of the chemicals studied by subsector (compared to MECS subsector data) is presented and used in calculations discussed later in this report.

Primary CT energy consumption (TBtu per year) estimates are calculated, which include offsite generation and transmission losses associated with bringing electricity and steam to manufacturing facilities. Primary energy consumption estimates are not provided for SOA, PM, or TM because they were outside the scope of this study.

Estimating SOA energy consumption: Chapter 5 presents the estimated onsite **SOA energy consumption** for the 74 chemicals (along with the references for the SOA energy intensity data and assumptions). The SOA energy consumption for 64 of the 74 chemicals studied is extrapolated to estimate the entire SOA energy consumption for each subsector (see inset). The extrapolated data for each subsector is summed to provide an estimate of sector-wide SOA energy consumption. The *current opportunity* bandwidth, the difference between CT energy consumption and SOA energy consumption (also called the SOA energy savings), is presented along with the SOA energy savings percent.

Estimating PM energy consumption: Chapter 6 presents the estimated onsite **PM energy consumption** for the 74 chemicals (along with the references for PM energy intensity data and

Chemicals Subsector Analysis for SOA, PM, and TM Energy Consumption

To estimate SOA, PM, and TM energy consumption for the chemicals subsectors, the energy consumption data for an individual chemical was aligned and grouped with its NAICS-defined subsector. To provide the most accurate aggregate data for the chemicals subsectors, 10 of the 74 chemicals studied were excluded to avoid double counting and other issues (see Table 4-6). As a result, subsector estimates for SOA, PM, and TM energy consumption are based on 64 chemicals (rather than the 74 chemicals studied individually).

The SOA, PM, and TM energy consumption data for the 64 chemicals grouped by subsector is extrapolated to estimate SOA, PM, and TM energy consumption for entire subsectors. A consistent extrapolation method is used. The subsector values are summed to provide sector-wide SOA, PM and TM energy consumption estimates.

assumptions). The range of potentially applicable applied R&D technologies to consider in the PM analysis worldwide is vast. The technologies that were considered are sorted by chemical and described in Appendix A3. The technologies that are considered crosscutting throughout all of chemical manufacturing along with the most energy-saving, chemical-specific R&D technology were used to determine PM energy consumption for each chemical. A weighting method that includes factors such as technology readiness, cost, and environmental impact was developed for all technologies considered; the weighting analysis methodology and summary table provided in Appendix A4 is intended to serve as a resource for continued consideration of all identified R&D opportunities.

The PM energy consumption for 64 of the 74 chemicals studied is extrapolated to estimate the entire PM energy consumption for each subsector (see inset). The extrapolated data for each subsector is summed to provide an estimate of sector-wide PM energy consumption. The *R&D opportunity* bandwidth, the difference between SOA energy consumption and PM energy consumption, is presented along with the PM energy savings percent. PM energy savings is the sum of *current* and *R&D opportunity*.

The technologies considered in the PM analysis are unproven on a commercial scale. As a result, the PM energy consumption is expressed as a range. The upper limit is assumed to be the SOA energy consumption; the lower limit is estimated and shown as a dashed line with color fading in the summary figures because the PM is speculative and depends on unproven R&D technologies. Furthermore, the potential energy savings opportunity could be greater if additional unproven technologies were considered.

Estimating TM energy consumption: Chapter 7 presents the estimated onsite **TM energy consumption** for 74 chemicals (along with the references for the TM energy intensity data and assumptions). The TM energy intensities are based on the most common chemical synthesis pathways. TM energy consumption assumes all of the energy is used productively and there are no energy losses. TM is the minimum amount of energy required; in some cases it is less than zero.

To determine the available potential energy savings opportunities in this bandwidth study, TM energy consumption was used as the baseline for calculating the energy savings potentials for each chemical studied (not zero, as is typically the case in considering energy savings opportunities). The rationale for using TM as the baseline is explained in Chapter 7.

Estimating the energy savings opportunities: Chapter 8 presents the energy savings **opportunity bandwidths** for the chemical subsectors and sector-wide, as well as the top 10 chemicals. The analyses used to derive these values are explained in Chapters 3 to 7.

2. U.S. Chemical Manufacturing Sector Overview

This Chapter presents an overview of the U.S. chemical manufacturing sector, including its impact on the economy and jobs, number of establishments, types of energy consumed, and the end uses of the energy. The convention for reporting energy consumption as either onsite versus primary energy is explained. The data and information in this Chapter provide the basis for understanding the energy consumption estimates.

2.1. U.S. CHEMICAL MANUFACTURING ECONOMIC OVERVIEW

Chemicals are in nearly every product we use. They are essential to modern life and improving safety, health, and productivity. The business of chemistry changes natural raw materials into products we use every day as diverse as automobiles and pharmaceuticals. Innovation plays an important role in chemicals manufacturing. The chemicals industry accounts for 20% of all U.S. patents issued each year.

Chemical manufacturing plays an outsized role in the U.S. manufacturing sector in terms of the economy, jobs, and energy. The business of chemistry supports 25% of the U.S. GDP (ACC 2012). It is the largest U.S. exporting sector, contributing 12% of all exports. The U.S. chemical sector accounts for 15% of the world’s chemical production. The value of chemical goods produced in the United States in 2010 totaled $701 billion and weighed 1.2 billion tons.

Each job in the chemical sector generates an additional 7.6 jobs in other sectors of the economy (ACC 2012). In 2011, the chemicals sector directly employed 788,000 people (ACC 2012). In addition to direct employment, the chemical sector stimulated2.7 million indirect (supply-chain) jobs and 3.2 million payroll-induced jobs (ACC 2012). Using a broader and more detailed definition of dependence, the American Chemistry Council estimates that 31.8 million jobs (or 24% of all U.S. jobs) in the U.S. economy are dependent on the chemicals sector (ACC 2012).

Energy is a significant cost in chemicals manufacturing. The American Chemistry Council has indicated that for some energy intensive chemicals, the cost of fuel, electricity, and feedstocks accounts for up to 85% of total production costs (ACC 2012).

2.2. U.S. CHEMICAL MANUFACTURING ESTABLISHMENTS

In 2007, there were 13,796 chemical manufacturing establishments in the United States (*establishments* is the term used in data tracking by the Department of Commerce). The number of establishments by state is shown in Figure 2-1. Much of basic chemical production is still concentrated in the Gulf Coast area, with Texas and Louisiana producing about 70% of all primary petrochemicals. The business of converting these basic chemicals into plastics, synthetic fibers, rubber, and other chemical products tends to be more diffused throughout the country (ACC 2011).

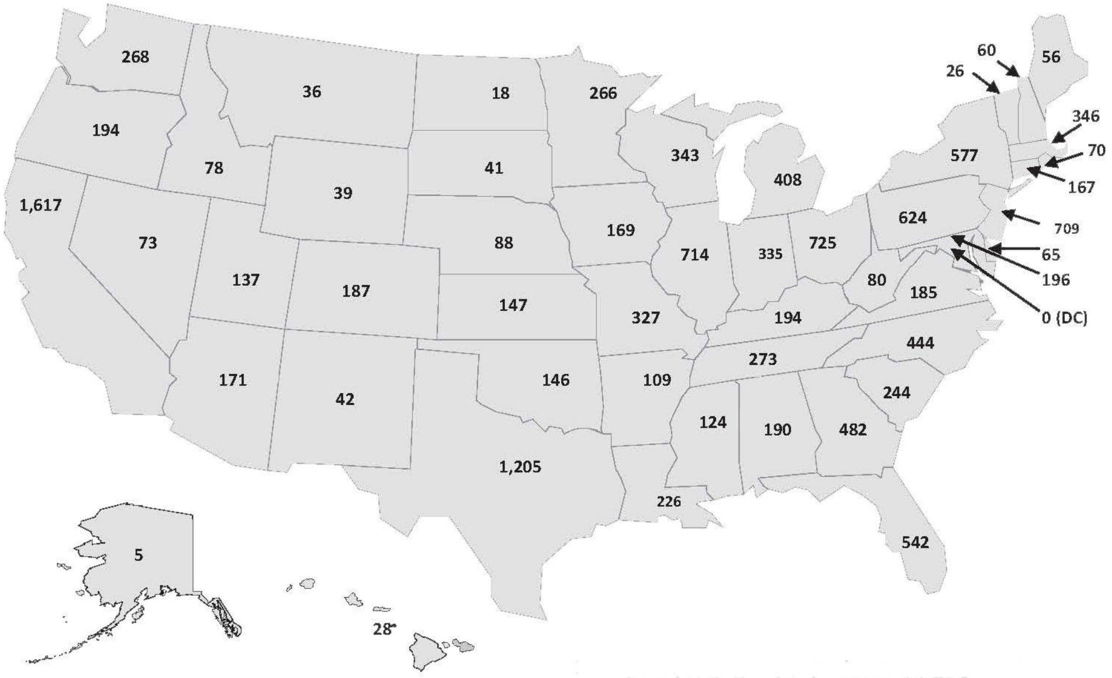


Figure 2-1. Number of U.S. Chemistry Business Establishments by State in 2007 (ACC 2012)

2.3. U.S. CHEMICAL MANUFACTURING ENERGY CONSUMPTION

Onsite energy and primary energy for the U.S. chemical sector are provided in Table 2-1. EIA MECS provides onsite energy consumption data by end use, including onsite fuel and electricity consumption, as well as feedstock energy. Primary energy includes assumptions for offsite losses (DOE 2014).

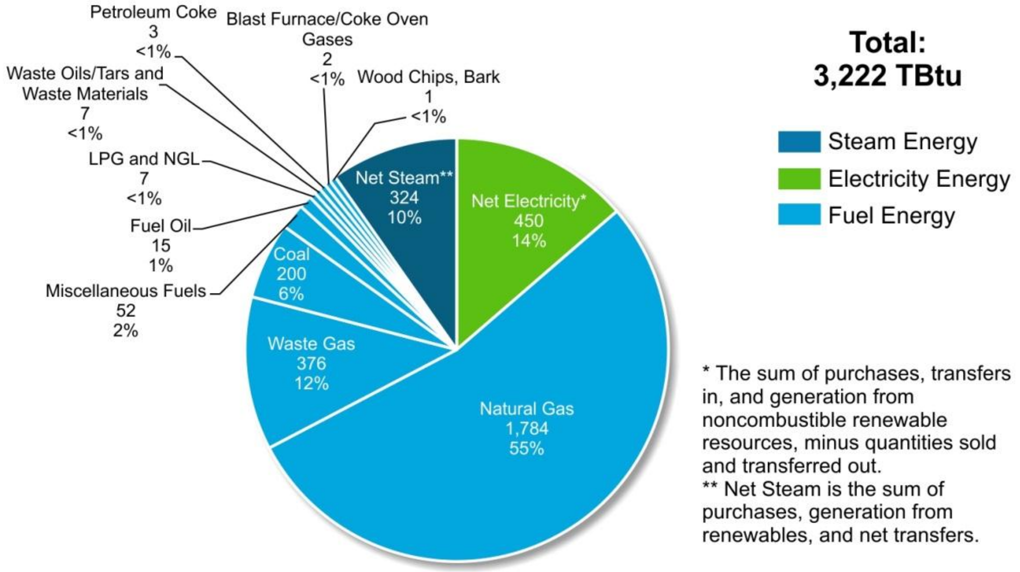
Table 2-1. U.S. Chemical Manufacturing Energy Consumption Sector-Wide, 2010

Onsite Energy Consumption (includes electricity, steam, and fuel energy used onsite at the facility)	3,222 TBtu
Primary Energy Consumption (includes onsite energy consumption, and offsite energy losses associated with generating electricity and steam offsite and delivering to the facility)	4,290 TBtu

Source: DOE 2014

Chemical manufacturing is the single largest consumer of energy in U.S. manufacturing, accounting for 4,290 TBtu (22%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Offsite electricity and steam generation and transmission losses in chemical manufacturing totaled 1,068 TBtu in 2010; onsite energy consumed within the boundaries of U.S. chemical manufacturing facilities totaled 3,222 TBtu.

Figure 2-2 shows the total onsite energy *entering* U.S. chemical facilities; most of the energy entering is in the form of fuel. Over half of this fuel is used onsite in boilers and combined heat and power (CHP) to generate additional electricity and steam (DOE 2014). In contrast, Figure 2-3 shows the total onsite energy at the *point of end use*. Electricity and steam from both offsite and onsite generation are included in Figure 2-3, along with the portion of energy loss that occurs in onsite generation. The data provided in Table 2-1, Figure 2-2, and Figure 2-3 are based on MECS with adjustments to account for withheld and unreported data (DOE 2014).



* The sum of purchases, transfers in, and generation from noncombustible renewable resources, minus quantities sold and transferred out.

** Net Steam is the sum of purchases, generation from renewables, and net transfers.

Figure 2-2. Onsite Energy Entering U.S. Chemical Manufacturing Facilities, 2010 (DOE 2014)

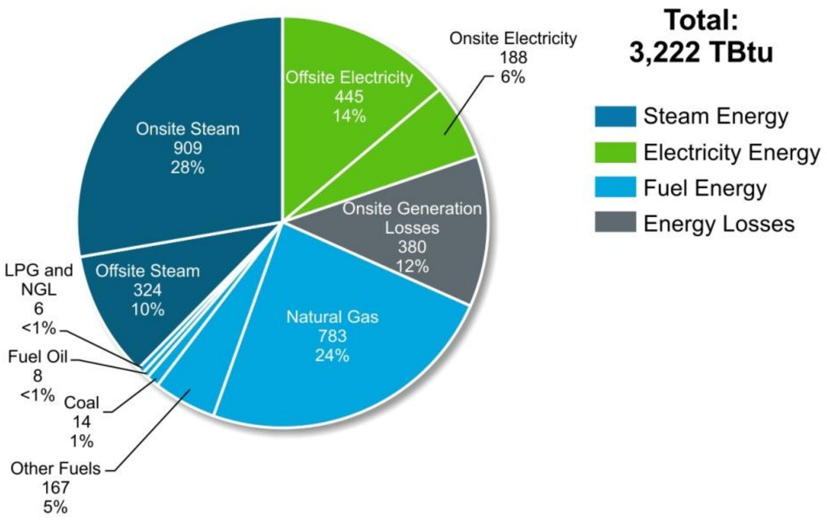


Figure 2-3. Onsite Energy Consumption at Point of End Use in Chemical Manufacturing Facilities, 2010 (DOE 2014)

2.3.1. Fuel and Feedstocks

As shown in Figure 2-2, onsite fuel consumption amounted to 2,447 TBtu in 2010, or about 76% of total onsite energy entering chemical manufacturing facilities (EIA 2013, DOE 2014). Natural gas accounts for the majority of this fuel.

Figure 2-4 provides a breakdown of fuel consumption in the chemicals sector by end use in 2010. The categories of end use are reported by EIA in MECS. A large portion of fuel (60%) is used indirectly in boilers and CHP to generate additional onsite electricity and steam (DOE 2014). Fuel is directly used for other end uses—the majority is used in process heating. Examples of process heating equipment include fired heaters, heated reactors, dryers, and heat exchangers.

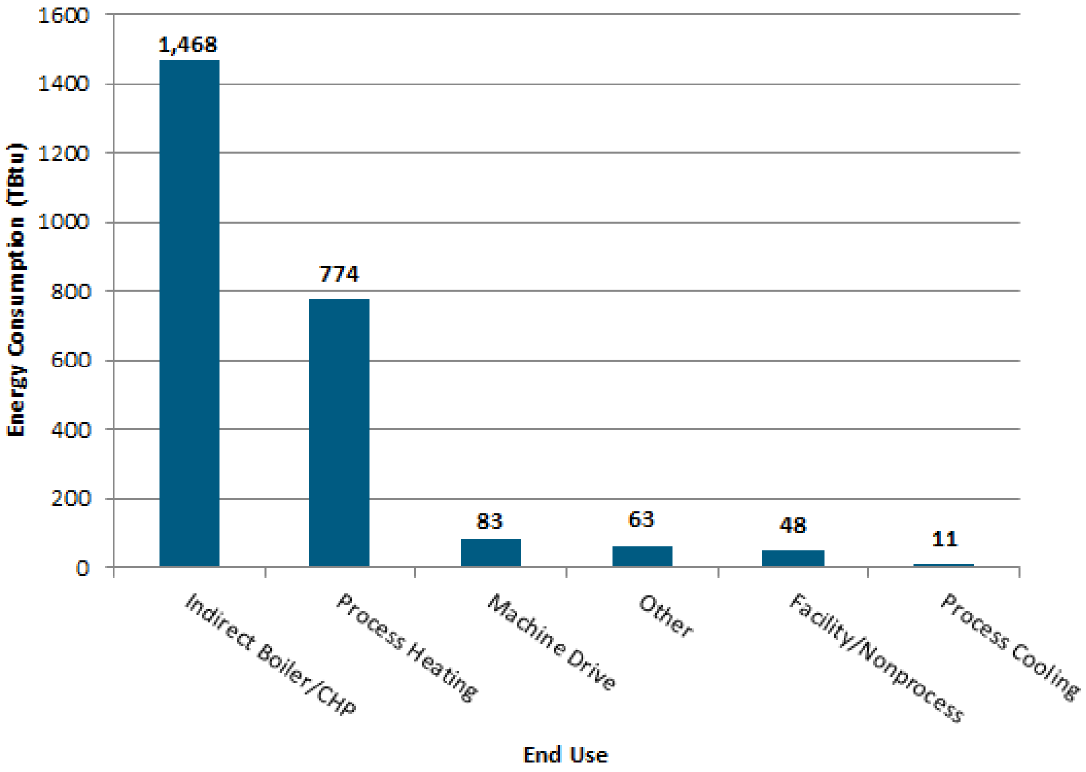


Figure 2-4. Fuel Consumption in the Chemicals Sector by End Use, 2010 (DOE 2014)

Feedstock energy is the nonfuel use of combustible energy. For chemicals manufacturing, feedstock energy is when combustible energy is converted to chemical products instead of being used as a fuel. For the energy bandwidth study, only the fuel use of combustible energy is considered in the opportunity analysis; however, due to the highly connected nature of feedstock and fuel energy, it is important to provide some context around that relationship and some background information on feedstock energy in this sector.

Feedstock energy is a significant portion of energy consumption in U.S. chemical manufacturing (2,665 TBtu) so it is important to consider when analyzing overall chemical sector energy use. However, **feedstock energy is not included in the onsite energy data in the energy consumption bands in this study**. Feedstock energy is excluded in order to be consistent with previous bandwidth studies and because the relative amount of feedstock energy versus fuel energy used in manufacturing is not readily available for individual chemicals.

Figure 2-5 shows feedstock energy use in the U.S. chemical manufacturing sector. The chemicals sector consumed 2,665 TBtu of feedstock energy in 2010. Liquefied petroleum gases (LPG)[3] and natural gas liquids (NGLs) account for 74% of the feedstock energy used, while natural gas provided 18%, and other feedstocks (including fuel oil, coal, coke and breeze, and other fuels) provided the remainder (EIA 2013). Examples of subsectors that use a significant amount of feedstock energy include Petrochemicals (e.g., ethylene), Plastics Materials and Resins, and Other Basic Organic Chemicals (e.g., methanol). Of the 2,665 TBtu of feedstock energy—which is mostly natural gas, LPG, and NGL feedstock used in petrochemicals production—most ends up in the form of finished chemical products while 15% of feedstock energy input (398 TBtu) does not end up as a product. Instead, it is converted to byproduct fuel that is used onsite and accounted for in the onsite fuel consumption values in Figure 2-2 (EIA 2013, DOE 2014).[4]

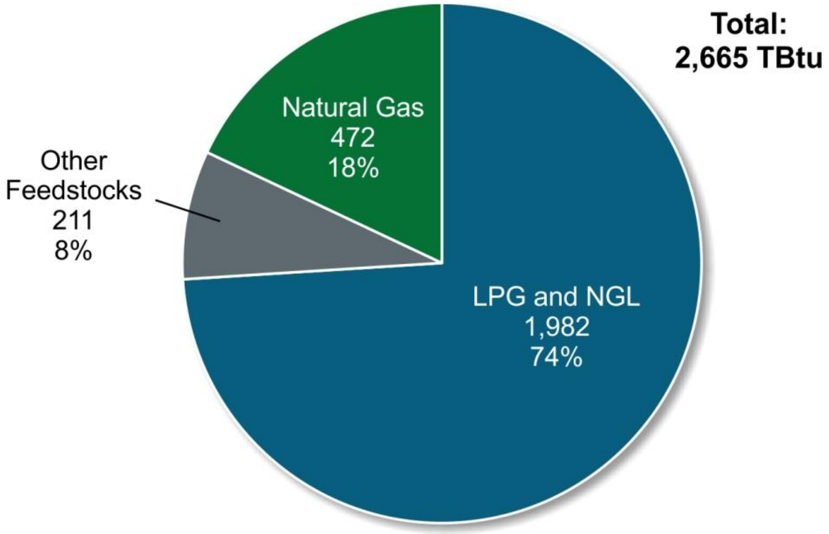


Figure 2-5. Feedstock Energy Consumption in the Chemicals Sector, 2010 (EIA 2013)

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[3] LPG includes propane, propylene, n- and iso-butane, butylene.

[4] EIA reports byproduct fuel as part of onsite energy. The feedstock energy data presented here cannot be summed with onsite energy; otherwise, there would be double counting.

In the case of ethylene manufacturing, ethane (an NGL) is both a feedstock in the dehydrogenation reaction and a source of process fuel. Another example of feedstock energy use is in ammonia manufacturing, where natural gas is both a feedstock in steam refining (which is used to generate hydrogen for the Habor-Bosch process) and a source of process fuel.

Natural gas is relied on as both a fuel and feedstock source for chemicals manufacturing, accounting for 55% of onsite energy entering chemical facilities in 2010 (up from 44% in 2006) as well as 18% of feedstock energy in 2010 (up from 13% in 2006) (EIA 2013). The recent natural gas boom in the United States due to the production of natural gas from shale formations has created an opportunity for the chemical manufacturing industry. Natural gas transport occurs either via energy intensive liquefaction or via pipeline, which makes prices highly localized. U.S. chemical producers close to these sources of natural gas are now at an advantage (especially in the Petrochemicals and Nitrogenous Fertilizer subsectors) because of ready access to the cheaper fuel and feedstock (ACC 2012). Chemical manufacturing is the largest manufacturing consumer of natural gas, accounting for 39% of all U.S. manufacturing natural gas consumption in terms of primary energy (DOE 2014).

Shale gas fits into the chemicals supply chain in a number of different ways. Dry natural gas (methane) is used directly as a feedstock in a number of chemical processes, including the production of ammonia and methanol. These processes stand to benefit from cheaper feedstock. NGLs from shale gas have greatly benefited petrochemicals production (specifically ethylene and propylene). Due to availability and pricing, ethylene and propylene manufacturers have significantly reduced the use of naphtha from petroleum refining as a feedstock and are instead taking advantage of cheap NGLs available in the United States as a feedstock. This shift in feedstock to NGLs adversely affects the co-production of benzene, toluene, and xylene, among others, which are valuable reaction side products formed from naphtha.

The change in feedstock towards shale gas is altering the petrochemicals marketplace and further changes are likely to occur to ensure all chemicals can still be economically produced in sufficient quantities. Besides offering cheaper feedstocks and shifting between known production methods, shale gas offers a unique opportunity to pursue other pathways to chemicals that have not yet been used commercially (Gharibi et al. 2012). The technology improvements associated with shale gas production are not directly accounted for in this energy bandwidth study, although the impacts are both substantial and connected to the opportunities presented herein; energy consumption in the production of fuels and feedstock falls outside of this study’s chemical manufacturing facility boundary.

2.3.2. Electricity

Figure 2-2 shows that onsite net electricity entering chemical facilities totaled 450 TBtu in 2010. The data presented is the *net amount*, which is the sum of purchases and transfers from offsite sources as well as generation from non-combustion renewable resources (e.g., hydroelectric, geothermal, solar, or wind energy) less the amount of electricity that is sold or transferred out of the plant. Figure 2-3 shows that 638 TBtu of total electricity is consumed at the point of end use and includes 188 TBtu of electricity generated onsite.

In Figure 2-6, the breakdown of the 638 TBtu of electricity is shown by end use in 2010 (DOE 2014). There are numerous uses for electricity in chemical manufacturing; the most common use is for machine driven equipment (i.e., motor-driven systems such as compressors, fans, pumps, and materials handling and processing equipment). Electro-chemical processes are another large end use of electricity; in these processes, electricity is used to drive chemical reactions. Some examples of significant electricity use in chemical manufacturing include electro-chemical processing in chlorine manufacturing and refrigeration (motor driven compressors) in industrial gas manufacturing.

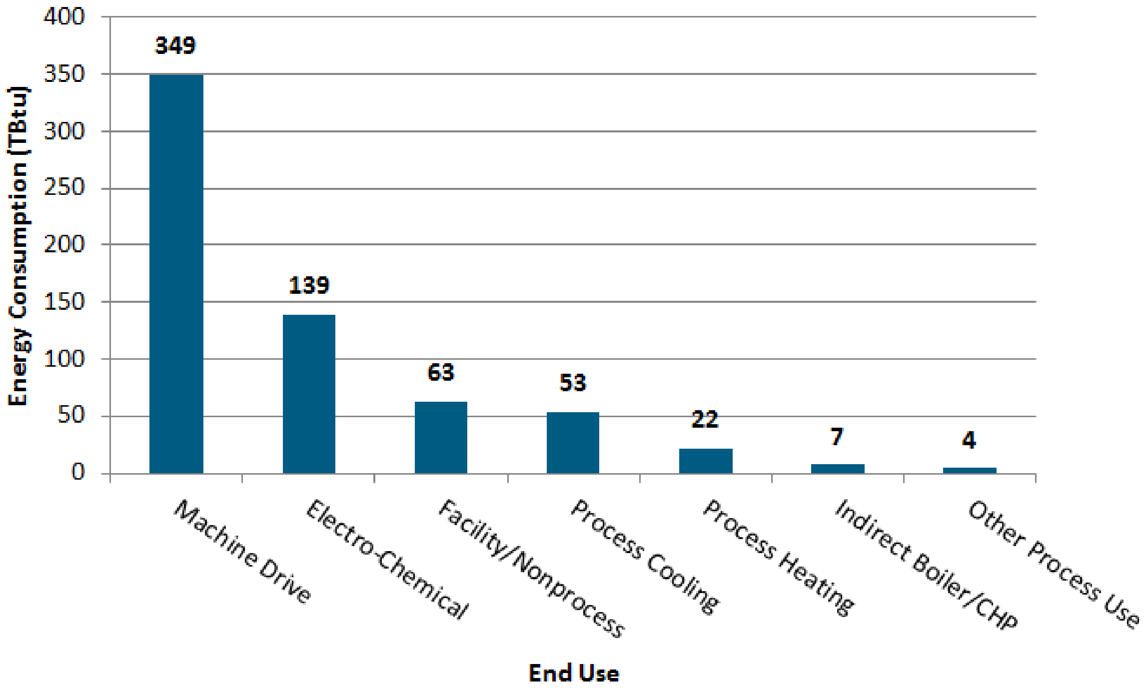


Figure 2-6. Electricity Consumption in the Chemicals Sector by End Use, 2010 (DOE 2014)

2.3.3. Steam

Figure 2-2 shows 324 TBtu of net steam entering chemical facilities in 2010, which is the sum of purchases, generation from renewables, and net transfers. A larger amount of steam is generated onsite. Figure 2-3 shows that 986 TBtu of steam is consumed at the point of end use, including 909 TBtu of steam generated onsite (247 TBtu of purchased and generated steam is lost through distribution to end uses) (DOE 2014).

Figure 2-7 shows the breakdown of 986 TBtu of steam by end use in 2010 (DOE 2014). A majority of the offsite- and onsite-generated steam is used for process heating; other end uses for steam in chemicals manufacturing include machine driven equipment (i.e., steam turbines), facility heating, ventilation, and air conditioning (HVAC), and process cooling and refrigeration. Unlike fuel and electricity end use, steam end use is not reported in MECS. The end use distribution shown here was determined in the Energy Footprint analysis (DOE 2014) based on input from an industry-led working group.

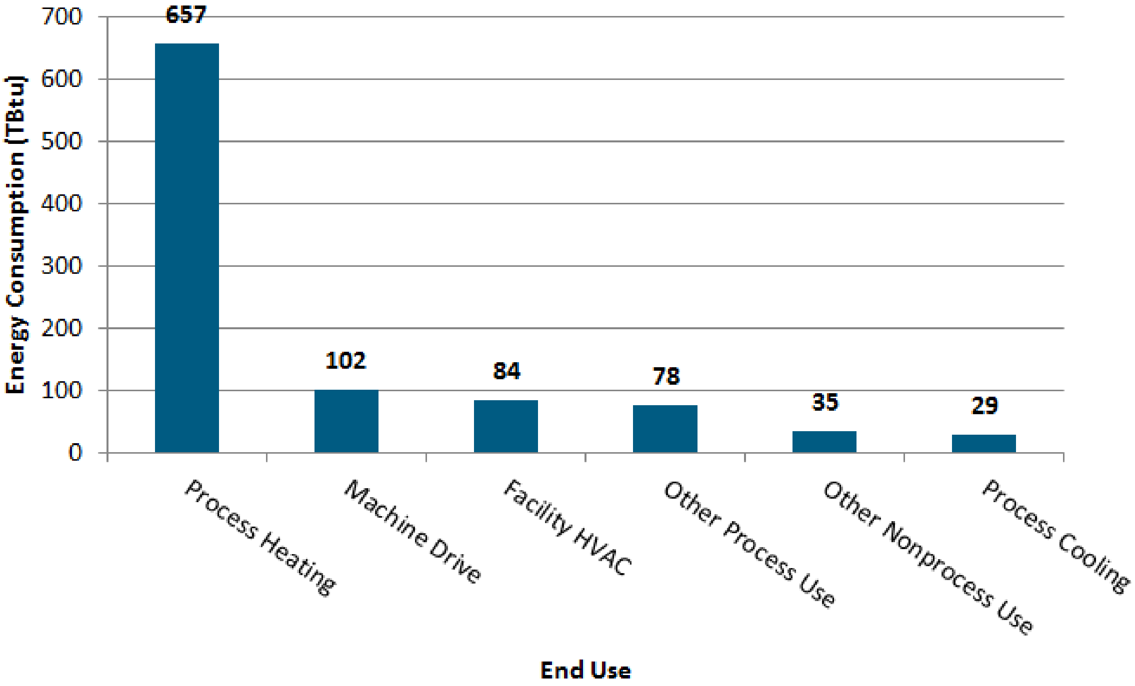


Figure 2-7. Steam Consumption in the Chemicals Sector by End Use, 2010 (DOE 2014)

3. Production Volumes in U.S. Chemical Manufacturing

More than 70,000 chemicals are produced in the United States. Identifying which chemicals are the most energy intensive is a step toward understanding the chemicals that could most benefit from process and technology efficiency improvements.

In this bandwidth study, 74 chemicals were selected for individual analysis. Table 3-1 presents the U.S. production data of the 74 chemicals for the year 2010, unless otherwise noted. The chemicals studied are listed in alphabetical order in Appendix A1a.

The most energy intensive and production intensive chemicals were selected for this study. Other, less intensive chemicals were added to the study to expand the representative coverage of the chemical sector as a whole. In general, the selection of chemicals was largely dependent on the availability of current production and energy consumption data.

The total volume of the 74 chemicals studied amounts to over 900 billion lb of chemicals. The chemical sector as whole produced an estimated 2,400 billion lb of chemicals in 2011 (ACC 2012). The 74 chemicals account for 38% of the total volume of chemicals produced in 2010.

The year 2010 was used for production values to correspond with the latest MECS data, which is also for 2010. Production data was gathered from a variety of sources, including the American Chemistry Council's (ACC) *Guide to the Business of Chemistry*, U.S. Census data, Chemical & Engineering News's Facts & Figures of the Chemical Industry, the *Updated Bandwidth and Energy Use Analysis for the U.S. Chemical Industry: Draft Report*, IHS Chemical Economics Handbook (CEH) product reviews, and various other publications. The ACC's *Guide to the Business of Chemistry* is released annually and provides production data (along with other information on the state of the U.S. chemical industry) for a select group of chemicals which varies from year to year. Appendix A2 provides a complete list of production sources referenced for each chemical. When a source of production data was not available for 2010, the production for certain chemicals was estimated based on plant capacities provided by ICIS Chemical Business and capacity utilization provided by the *Guide to the Business of Chemistry*. When production data for 2010 could not be located or estimated, data for the next most recent year was utilized (no earlier than 2007).

Table 3-1. U.S. Production Volumes in 2010 of 74 Chemicals Selected for the Bandwidth Analysis

Chemical	**2010 Production** (Million lb/Year)	**Chemical**	**2010 Production** (Million lb/Year)
Acetic Acid	4,366	Methanol	2,024
Acetic Anhydride	1,798[a]	Methyl Chloride	1,330[a]
Acetone	3,178	Methyl Methacrylate	1,529
Acrylic Acid	2,723	Methyl tert-Butyl Ether	3,386
Acrylonitrile	2,505	Monoammonium Phosphate	9,245
Aluminum Sulfate	1,906[a]	Nitric Acid	15,280
Ammonia	22,691	Nitrobenzene	3,020
Ammonium Nitrate	15,166	Nitrogen	69,609[a]
Ammonium Phosphates (Other)*	3,053	Oxygen	58,287[a]
Ammonium Sulfate	5,729	Phenol	4,652
Aniline	2,348	Phosphoric Acid	20,678
Benzene	13,274	Polycarbonate	1,862[c]
Bisphenol A	1,610	Polyester	2,525
Butadiene	3,484	Polyethylene Terephthalate	9,230[a]
Butylenes	2,110	Polyethylene, High Density	16,889
Calcium Carbonate	24,282	Polyethylene, Linear Low Density	13,787
Calcium Chloride	2,204[a]	Polyethylene, Low Density	6,741
Caprolactam	1,530	Polypropylene	17,258
Carbon Black	3,415[a]	Polystyrene	5,055
Carbon Dioxide	17,365[a]	Polystyrene, High Impact	1,873[c]
Chlorine	21,465	Polyurethane	4,143
Cumene	7,626	Polyvinylchloride	14,019
Cyclohexane	3,462	Propylene	31,057
Cyclohexanone	3,031[a]	Propylene Oxide	4,470
Diammonium Phosphate	17,503	Soda Ash (Sodium Carbonate)	23,373
Ethanol	66,080	Sodium Hydroxide	16,581
Ethylbenzene	9,349	Sodium Hypochlorite	11,589[a]
Ethylene	52,864	Sodium Silicates	2,624
Ethylene Dichloride	19,426	Styrene	9,179
Ethylene Glycol	2,867	Sulfur	20,123[c]
Ethylene Oxide	5,876	Sulfuric Acid	71,687
Formaldehyde	3,050[b]	Terephthalic Acid	7,221
Hydrogen	6,591	Urea	11,292
Hydrochloric Acid	7,840	Vinyl Acetate	3,054
Hydrogen Peroxide	852	Vinyl Chloride	14,159
Isobutylene	8,769	Xylenes, Mixed	13,869
Isopropanol	1,662	Xylenes, Paraxylene	7,520
Subtotal			903,270
Total Sector-Wide			2,400,000

** Excludes monoammonium and diammonium phosphates*

[a] Data for 2008 (most recent year available)

[b] Data for 2009 (most recent year available)

[c] Data for 2007 (most recent year available)

Source: Appendix A2 provides the sources referenced for U.S. production data of each chemical.

4. Current Typical Energy Consumption for U.S. Chemical Manufacturing

This Chapter presents the energy consumption data for individual chemicals and subsectors in 2010. Energy consumption in a manufacturing process can vary for diverse reasons. The energy intensity estimates reported herein are representative of average U.S. chemicals manufacturing; they do not represent energy consumption in any specific facility or any particular region in the United States.

4.1. BOUNDARIES OF THE CHEMICAL BANDWIDTH STUDY

Estimating energy requirements for an industrial process depends on the boundary assumptions; this is especially true in the chemical industry. The key focus of this bandwidth study is energy consumption within the plant boundary, which is the *onsite* use of process energy (including purchased energy and onsite generated steam and electricity) that is directly applied to manufacturing chemical products.

This study does not consider lifecycle energy consumed during raw material extraction (e.g., natural gas production), off-site treatment, and transportation of materials. Upstream energy, such as the energy required for processing and handling materials outside of the plant is also not included. To be consistent 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.

4.2. SUBSECTOR ENERGY CONSUMPTION DATA

EIA MECS data provides the most complete understanding of manufacturing energy consumption in the United States, including for the chemical manufacturing sector. The most recent set of MECS data is available for 2010. EIA collects U.S. manufacturing subsector energy use data through a mandatory survey (MECS). EIA aggregates plant-level data to represent total subsector and sector-wide data. NAICS categories as classified by the U.S. Census Bureau (USCB 2014) are used in MECS. The U.S. government developed NAICS to collect, analyze, and publish data about the economy. For the chemicals sector, MECS data is available for the chemicals manufacturing sector as a whole (NAICS 325) as well as 15 separate chemicals manufacturing subsectors denoted by six digit NAICS codes beginning with 325. Table 4-1 provides the NAICS codes for chemical manufacturing subsectors and sector-wide, and the Current Typical (CT) energy consumption reported in MECS.

Table 4-1. U.S. Chemicals Subsectors with Onsite Current Typical Energy Consumption Data Reported in MECS, 2010

Subsector	NAICS Code	Onsite CT Energy Consumption (TBtu/year)
Petrochemical Manufacturing	325110	568
Industrial Gas Manufacturing	325120	96
Alkalies and Chlorine Manufacturing	325181	224
Carbon Black Manufacturing	325182	13
Other Basic Inorganic Chemical Manufacturing	325188	214
Cyclic Crudes and Intermediate Manufacturing	325192	52
Ethyl Alcohol Manufacturing	325193	307
Other Basic Organic Chemical Manufacturing	325199	634
Plastics Materials and Resin Manufacturing	325211	462
Synthetic Rubber Manufacturing**	325212	39
Noncellulosic Organic Fibers Manufacturing**	325222	36
Nitrogenous Fertilizer Manufacturing	325311	166
Phosphatic Fertilizer Manufacturing	325312	35
Pharmaceutical and Medicine Manufacturing**	3254	91
Photographic Film, Paper, Plate, and Chemical Manufacturing**	325992	20
All other chemical manufacturing	All other 325 NAICS (data not reported)*	265
Total for Chemicals Sector-wide	**325**	**3,222**

Current Typical (CT)

**Data not provided in MECS.*

*** Subsector not covered in this report; no chemicals in this subsector were studied.*

Source: EIA 2013

Table 4-1 and Figure 4-1 provide a breakdown of the onsite energy consumption by subsector provided by MECS. Table 4-1 shows the onsite energy consumption for 15 specific chemical subsectors; also shown is ‘All other chemical manufacturing,’ which is the balance of the energy consumption data not reported by subsector.

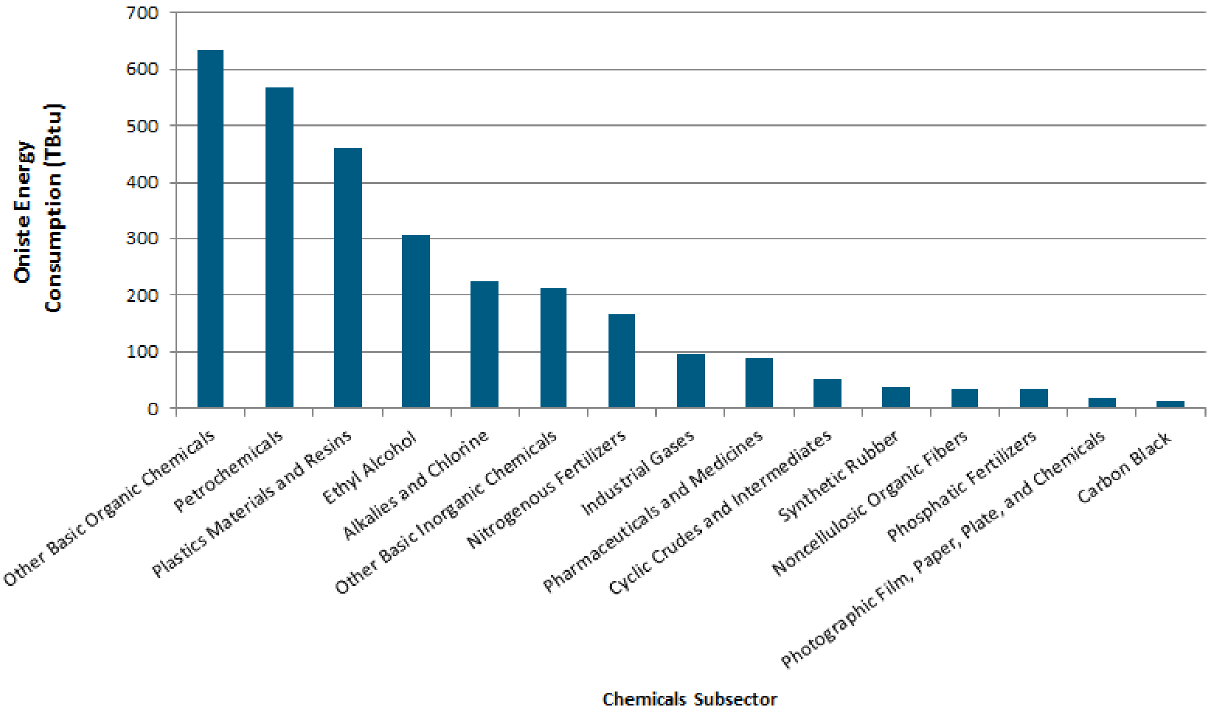


Figure 4-1. Onsite Energy Consumption for Chemicals Subsectors, 2010 (EIA 2013)

4.3. INDIVIDUAL CHEMICALS GROUPED BY SUBSECTOR

When studying energy consumption of a large group of chemicals, it is helpful to group them into their respective subsectors. Grouping the chemical products by subsector helps to identify energy savings opportunities from similar manufacturing processes. The 74 chemicals studied in this report are sorted into subsectors and listed in Table 4-2 by their respective NAICS categories as classified by the U.S. Census Bureau (USCB 2014), along with the onsite CT energy consumption for each subsector and the percentage of sector-wide energy consumption. The sum total of sector-wide (NAICS 325) onsite energy consumption is 3,222 TBtu for 2010 (see Table 4-1 and Table 4-2).

The 11 subsectors that contain chemicals that were analyzed in this report are: Petrochemicals, Industrial Gases, Alkalies and Chlorine, Carbon Black, Other Basic Inorganic Chemicals, Cyclic Crudes and Intermediates, Ethyl Alcohol, Other Basic Organic Chemicals, Plastics Materials and Resins, Nitrogenous Fertilizers, and Phosphatic Fertilizers. These subsectors account for 86% of the sector-wide onsite energy consumption of 3,222 TBtu (EIA 2013). Other Basic Organic Chemicals manufacturing is the most energy consuming subsector, followed by Petrochemicals, Plastics Materials and Resins, Ethanol, and Alkalies and Chlorine.

Among the subsectors, Alkalies and Chlorines (NAICS 325181) are heavily dependent on electricity. The production of chlorine occurs by the electrolysis of a salt solution and also results in the production of sodium hydroxide and hydrogen gas. Petrochemicals (NAICS 325110) and

Nitrogenous Fertilizers (NAICS 325311) are heavily reliant on fuel for their manufacturing processes. The synthesis of these chemicals is done at high temperatures and pressures, often over catalysts, and energy from fuel helps create and maintain these reaction conditions.

In general, the synthesis of Other Basic Organic Chemicals (NAICS 325199) requires large amounts of energy to manufacture. However, there is less of a requirement for extreme reaction conditions (high temperature and pressure). Some organic chemicals are net energy generators since they are formed by exothermic reactions, including many of the reactions that form Plastics Materials and Resins (NAICS 325211). The final properties of a plastic depend on the length of the polymer molecule's chain. The chain length is directly related to the conditions, especially the production temperature. Because heat is generated by the process, cooling to maintain a constant temperature becomes a significant energy demand.

Table 4-2. 74 Chemicals Grouped by Subsector with Total Subsector Energy Consumption and Subsector Percentage of Sector-wide Energy Consumption

Chemical Subsector	NAICS Code	Onsite CT Energy Consumption by Subsector (TBtu/year)	Subsector Percent of Sector-wide Energy Consumption	Chemicals Studied in Bandwidth Analysis
Petrochemicals	325110	568	18%	Benzene Butadiene Butylenes Cumene Ethylbenzene Ethylene Propylene Styrene Xylenes, Mixed Xylenes, Paraxylene
Industrial Gases	325120	96	3%	Carbon Dioxide Hydrogen Nitrogen Oxygen
Alkalies and Chlorine	325181	224	7%	Chlorine Soda Ash (Sodium Carbonate) Sodium Hydroxide
Carbon Black	325182	13	<1%	Carbon Black
Other Basic Inorganic Chemicals	325188	214	7%	Aluminum Sulfate Calcium Carbonate Calcium Chloride Hydrochloric Acid Hydrogen Peroxide Sodium Hypochlorite

Table 4-2. 74 Chemicals Grouped by Subsector with Total Subsector Energy Consumption and Subsector Percentage of Sector-wide Energy Consumption

Chemical Subsector	NAICS Code	Onsite CT Energy Consumption by Subsector (TBtu/year)	Subsector Percent of Sector-wide Energy Consumption	Chemicals Studied in Bandwidth Analysis
				Sodium Silicates
				Sulfur
				Sulfuric Acid
Cyclic Crudes and Intermediates	325192	52	2%	Aniline
				Bisphenol A
				Cyclohexane
				Cyclohexanone
				Nitrobenzene
				Phenol
Ethyl Alcohol	325193	307	10%	Ethanol
Other Basic Organic Chemicals	325199	634	20%	Acetic Acid
				Acetic Anhydride
				Acetone
				Acrylic Acid
				Acrylonitrile
				Caprolactam
				Ethylene Dichloride
				Ethylene Glycol
				Ethylene Oxide
				Formaldehyde
				Isobutylene
				Isopropanol
				Methanol
				Methyl Chloride
				Methyl Methacrylate
				Propylene Oxide
				Terephthalic Acid
				Vinyl Acetate
				Vinyl Chloride
Plastics Materials and Resins	325211	462	14%	Polycarbonate
				Polyester
				Polyethylene Terephthalate
				Polyethylene, High Density
				Polyethylene, Linear Low Density
				Polyethylene, Low Density
				Polypropylene
				Polystyrene
				Polystyrene, High Impact
				Polyurethane

Table 4-2. 74 Chemicals Grouped by Subsector with Total Subsector Energy Consumption and Subsector Percentage of Sector-wide Energy Consumption

Chemical Subsector	NAICS Code	Onsite CT Energy Consumption by Subsector (TBtu/year)	Subsector Percent of Sector-wide Energy Consumption	Chemicals Studied in Bandwidth Analysis
				Polyvinylchloride
Nitrogenous Fertilizers	325311	166	5%	Ammonia
				Ammonium Nitrate
				Ammonium Sulfate
				Nitric Acid
				Urea
Phosphatic Fertilizers	325312	35	1%	Ammonium Phosphates (Other)
				Diammonium Phosphate
				Monoammonium Phosphate
				Phosphoric Acid
Subtotal		2,771	86%	
All other NAICS 325 Chemicals		451	14%	Methyl tert-Butyl Ether
Total for Chemicals Sector-wide (NAICS 325)		3,222	100%	

Current Typical (CT)

Source: Subsector and sector-wide energy consumption and percent of sector-wide energy consumption are from MECS 2010/Energy Footprint analysis (DOE 2014)

4.4. ESTIMATED ENERGY INTENSITY FOR INDIVIDUAL CHEMICALS

Energy intensity data are needed to calculate bands of energy consumption in this study. This Section presents the estimated energy intensities of 74 chemical products.

Most chemicals have a unique manufacturing process. The specific energy needed to make a pound of chemical can vary significantly between chemicals, and also between facilities. Energy intensity is a common measure of energy performance in manufacturing. Energy intensity is reported in units of energy consumption (typically Btu) per unit of manufactured product (typically pounds, tons, or metric tons) and, therefore, reported as Btu per pound (Btu/lb). Energy intensity estimates are available for specific equipment performance, process unit performance, or even plant-wide performance. Energy intensity can be estimated by chemical product, both in the United States and other global regions, based on average, representative process and plant performance.

Appendix A1a presents the CT energy intensities and energy consumption for the 74 chemicals studied in alphabetical order; Appendix A1b presents the energy intensities and energy consumption for the 74 chemicals grouped by subsector. Table 4-3 presents a summary of the references consulted to identify CT energy intensity by chemical. Appendix A2 provides the references used for each particular chemical.

Because the chemicals manufacturing sector is diverse, covering tens of thousands of products, a wide range of data sources were considered (see Table 4-3). Often multiple references were considered for each chemical; in these cases, the authors were contacted for clarification and peer reviewers were consulted for guidance to determine the best energy intensity estimates.

Chemicals are produced in different scales and sometimes by multiple processes; thus, it is difficult to ascertain an exact amount of energy necessary to produce a certain volume of a chemical. Consequently, the values for energy intensity provided should be regarded as estimates based on the best available information. Also, there are certain processes (e.g., steam cracking) that produce multiple chemicals simultaneously and in different amounts depending upon feedstock type.

Many of the references consulted did not provide a breakdown of feedstock and fuel energy consumed during the production of specific chemicals. When the energy had to be apportioned to the two categories, the authors of the studies were contacted and assumptions were made to estimate how much of the raw material was apportioned to fuel verses feedstock.

Table 4-3. Published Sources Reviewed to Identify Current Typical Energy Intensities for 74 Select Chemicals

Source	Description
EIA 2013	Manufacturing Energy Consumption Survey (MECS) data released by EIA every four years; this data comes from a survey that is taken by U.S. manufacturers. The data is scaled up to cover the entirety of U.S. manufacturing and for individual manufacturing subsectors
Energetics 2000	The *Energy and Environmental Profile of the U.S. Chemical Industry*, published by DOE in 2000 and focused on the U.S., provides a detailed breakdown (including total processing energy) for six chemical chains which consume a significant amount of energy in the sector and produce numerous products
HP 2010	Hydrocarbon Processing publishes the *Petrochemical Processes* Handbook every few years which provides utility consumption data (electricity, steam, and fuel) for specific licensed chemical processing technologies. In some cases, multiple technologies are listed for a specific chemical, allowing for comparison
IEA 2009	This paper explores the best practice technologies (BPT) for 57 processes that produce 66 chemicals, mostly petrochemicals, and compares these values to the current specific energy consumption (SEC) of electricity, feedstock, fuel, and steam in these processes and chemicals in Western Europe. A newer version of the work of these authors was published in 2011, but the average current SEC values remain largely unchanged and do not include electricity use
LBNL 2008	This report focuses on the U.S.; specific energy consumption and feedstock energy is listed for select key chemicals
Neelis et al. 2005	This report compares average energy use for a selection of chemicals with the best available technology (BAT) energy use and with a focus on the Netherlands, Western Europe, and the world. In some cases, data for multiple processes used to produce a chemical (such as ammonia, ethylene, or chlorine) are provided. The electricity, fuel, steam, and total primary energy use are provided separately, as well as data for energy and carbon losses and efficiencies. An updated version of the authors' work was published in 2007, but the values for current average energy remained largely unchanged
PEP 2002	IHS (formerly SRI) publishes PEP Yearbooks. 2002 Yearbook was referenced.
Other scientific papers	Maruoka et al. 2010, Ozalp 2008 (As indicated in Appendix A2)

When available, energy intensity values specific to the United States were used in calculating CT energy consumption for the 74 select chemicals. For certain chemicals, the energy intensity data was only available for non-U.S. regions, such as Western Europe, the Netherlands, or the world average. This data was used with the understanding that energy consumption and chemicals processes can vary from country to country and from region to region.

The average energy intensity of a chemical varies depending on the feedstock mix and the corresponding process energy. The feedstock mix used varies worldwide, depending on the availability and price of feedstocks. A comparison of global average energy intensity values for the production of select chemicals is provided in Table 4-4, along with energy sources, including feedstocks. Note that these numbers are ***not*** the energy intensity data used in this report; this data is instead provided to show regional variability. North American crackers, for example, are typically less efficient than those in Europe and Asia (IEA 2007). (As mentioned in Section 4.1, feedstock energy is excluded from the onsite energy consumption data and the opportunity bandwidths presented in this study.)

Table 4-4. Examples of Average Energy Intensities by Country for Select Chemicals (Btu/lb)

	United States	Germany	China	India	World
Steam cracking, Ethylene et al. (fuel & steam)	7,868	6,750	7,180	7,180	7,266
Ammonia (fuel, feedstock & steam)	16,337	16,036	21,324	17,283	17,885
Methanol (fuel & steam)	4,901	5,331	6,449	4,686	4,686
Chlorine (fuel & steam)	2,021	989	1,161	258	1,247
Chlorine (electricity)	4,557	4,729	6,191	4,815	4,643

Source: IEA 2009, Estimated country specific energy consumption (SEC) for the production of key chemicals, 2006 (original data provided in gigajoules/metric ton)

4.5. CALCULATED CURRENT TYPICAL ENERGY CONSUMPTION FOR INDIVIDUAL CHEMICALS

Table 4-5 presents the calculated onsite CT energy consumption for the 74 select chemicals. To calculate onsite CT energy consumption, energy intensity for each chemical (presented initially in Appendix A1a) is multiplied by the 2010 chemical production data (presented initially in Table 3-1). Feedstock energy is excluded from the consumption values. The CT energy consumption for these 74 chemicals is estimated to account for 1,969 TBtu of onsite energy, or 61% of the sector-wide onsite energy use in 2010. Appendix A1a presents the onsite CT energy consumption for the 74 chemicals individually in alphabetical order; Appendix A1b presents the onsite CT energy consumption for the 74 chemicals grouped by subsector.

Calculated primary CT energy consumption by chemical product is also reported in Table 4-5. Primary energy includes offsite energy generation and transmission losses associated with electricity and steam from offsite sources. To determine primary energy, the net electricity and net steam portions of onsite energy are scaled to account for offsite losses and added to onsite energy (see the footnote in Table 4-5 for details on the scaling method). For the few chemicals where onsite energy is negative and the process is exothermic in nature, it is assumed that there is no offsite sourced electricity or steam and primary energy remains the same as onsite energy.

Table 4-5. Calculated U.S. Onsite Current Typical Energy Consumption for 74 Chemicals in 2010 with Calculated Primary Energy Consumption and Offsite Losses

Chemical	Energy Intensity (Btu/lb)	Production (million lb/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated (TBtu/year)[1]	Primary CT Energy Consumption, Calculated (TBtu/year)
Acetic Acid	2,552	4,366	11	2	13
Acetic Anhydride	2,785	1,798	5	1	6
Acetone	7,717	3,178	25	4	28
Acrylic Acid	9,009	2,723	25	4	28
Acrylonitrile	626	2,505	2	<0.5	2
Aluminum Sulfate	1,250	1,906	2	2	4
Ammonia	5,847	22,691	133	25	158
Ammonium Nitrate	341	15,166	5	1	6
Ammonium Phosphates (Other)	323	3,053	1	<0.5	1
Ammonium Sulfate	4,000	5,729	23	4	27
Aniline	-980	2,348	-2	0	-2
Benzene	7,868	13,274	104	13	117
Bisphenol A	9,410	1,610	15	6	21
Butadiene	7,868	3,484	27	3	31
Butylenes	1,677	2,110	4	<0.5	4
Calcium Carbonate	2,046	24,282	50	43	92
Calcium Chloride	3,882	2,204	9	7	16
Caprolactam	13,185	1,530	20	3	23
Carbon Black	3,845	3,415	13	3	16
Carbon Dioxide	320	17,365	6	8	14
Chlorine	6,578	21,465	141	48	189
Cumene	520	7,626	4	<0.5	4
Cyclohexane	-559	3,462	-2	0	-2
Cyclohexanone	68	3,031	<0.5	<0.5	<0.5
Diammonium Phosphate	323	17,503	6	2	7
Ethanol	4,646	66,080	307	64	371
Ethylbenzene	1,174	9,349	11	1	12
Ethylene	7,071	52,864	374	45	419
Ethylene Dichloride	3,410	19,426	66	10	76
Ethylene Glycol	2,045	2,867	6	1	7
Ethylene Oxide	1,916	5,876	11	2	13
Formaldehyde	-2,514	3,050	-8	0	-8
Hydrogen	949	6,591	6	9	15
Hydrochloric Acid	178	7,840	1	1	3
Hydrogen Peroxide	6,965	852	6	5	11
Isobutylene	3261	8,769	29	4	33

Table 4-5. Calculated U.S. Onsite Current Typical Energy Consumption for 74 Chemicals in 2010 with Calculated Primary Energy Consumption and Offsite Losses

Chemical	Energy Intensity (Btu/lb)	Production (million lb/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated (TBtu/year)[1]	Primary CT Energy Consumption, Calculated (TBtu/year)
Isopropanol	4,693	1,662	8	1	9
Methanol	4,901	2,024	10	1	11
Methyl Chloride	839	1,330	1	<0.5	1
Methyl Methacrylate	3,483	1,529	5	1	6
Methyl tert-Butyl Ether	1,871	3,386	6	2	8
Monoammonium Phosphate	323	9,245	3	1	4
Nitric Acid	267	15,280	4	1	5
Nitrobenzene	576	3,020	2	1	2
Nitrogen	774	69,609	54	80	134
Oxygen	774	58,287	45	67	112
Phenol	3,661	4,652	17	7	24
Phosphoric Acid	482	20,678	10	3	13
Polycarbonate	6,707	1,862	12	4	17
Polyester	12,128	2,525	31	10	41
Polyethylene Terephthalate	2,291	9,230	21	7	28
Polyethylene, High Density	1,037	16,889	18	6	24
Polyethylene, Linear Low Density	871	13,787	12	4	16
Polyethylene, Low Density	1,143	6,741	8	3	10
Polypropylene	616	17,258	11	4	14
Polystyrene	2,264	5,055	11	4	15
Polystyrene, High Impact	636	1,873	1	<0.5	2
Polyurethane	138	4,143	1	<0.5	1
Polyvinyl Chloride	1,463	14,019	21	7	28
Propylene	1,351	31,057	42	5	47
Propylene Oxide	2,567	4,470	11	2	13
Soda Ash	2,966	23,373	69	23	93
Sodium Hydroxide	3,765	16,581	62	21	84
Sodium Hypochlorite	592	11,589	7	6	13
Sodium Silicates	2,298	2,624	6	5	11
Styrene	3,777	9,179	35	4	39
Sulfur	-2,414	20,123	-49	0	-49
Sulfuric Acid	-900	71,687	-65	0	-65
Terephthalic Acid	2,217	7,221	16	2	18
Urea	843	11,292	10	2	11
Vinyl Acetate	3,611	3,054	11	2	13
Vinyl Chloride	2,103	14,159	30	4	34

Table 4-5. Calculated U.S. Onsite Current Typical Energy Consumption for 74 Chemicals in 2010 with Calculated Primary Energy Consumption and Offsite Losses

Chemical	Energy Intensity (Btu/lb)	Production (million lb/year)	Onsite CT Energy Consumption, Calculated (TBtu/year)	Offsite Losses, Calculated (TBtu/year)[1]	Primary CT Energy Consumption, Calculated (TBtu/year)
Xylenes, Mixed	1,255	13,869	17	2	19
Xylenes, Paraxylene	2,541	7,520	19	2	21
Total for Chemicals Studied			**1,969**	**617**	**2,585**

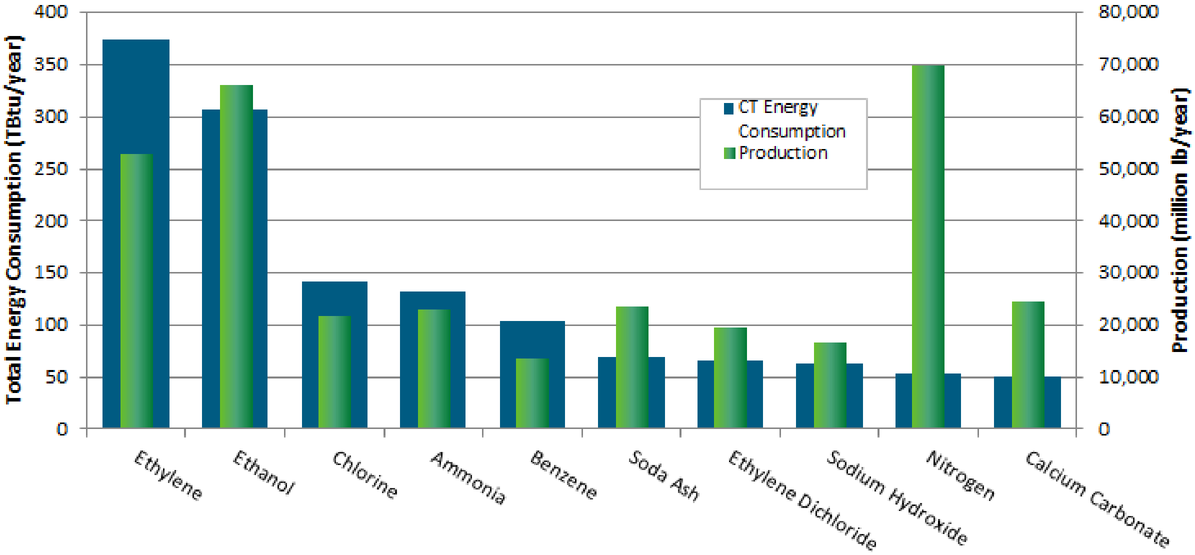
Current Typical (CT)

[1] Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and offsite steam transmission losses are estimated to be 10% (DOE 2007, Technical Guidelines Voluntary Reporting of Greenhouse Gases and EPA 2011, ENERGY STAR Performance Ratings Methodology).

References for production data and energy intensity data are provided by chemical in Appendix A2. The other values are calculated as explained in the text.

4.5.1. Top 10 Energy Consuming Chemicals

The 10 most energy consuming chemicals examined in this bandwidth study are (in descending order): ethylene, ethanol, chlorine, ammonia, benzene, soda ash, ethylene dichloride, sodium hydroxide, nitrogen, and calcium carbonate. Figure 4-2 shows the CT energy consumption and 2010 production volumes (million lb/year) of these 10 chemicals. Nitrogen ranks ninth in CT energy consumption, even though it leads the list in production. This is a function of the low energy intensity per unit weight to produce nitrogen. Alternatively, ethanol ranks second highest in production and in CT energy consumption, thereby indicating a relatively large energy reduction opportunity. In 2010, the ethanol subsector consumed nearly 10% of all energy in U.S. chemical manufacturing.



Current Typical (CT)

Figure 4-2. Current Typical Energy Consumption vs. Production Volume for the Top 10 Energy Consuming Chemicals, 2010

4.5.2. Area Graphs for Top 10 Energy Consuming Chemicals

Another informative visual approach for comparing the 10 most energy consuming chemicals is an area graph. Figure 4-3 shows the specific energy intensity (Btu/lb) of these chemicals plotted relative to the 2010 annual production, pictured in increments of 50 billion pounds. The area (e.g., the width times the height) of the resulting colored rectangles is equivalent to the annual energy consumption of the chemical; the chemicals are shown from left to right in order of energy consumption. The energy intensity to manufacture calcium carbonate is almost twice that of nitrogen, although the overall energy consumption is relatively equivalent. Benzene, the fifth most energy-consuming chemical to manufacture in the United States, has a relatively high energy intensity and relatively low production volume.

The area graph highlights the importance of energy intensity in considering energy savings opportunities. Even incremental 1 or 2 percent improvements in energy intensity can alter the energy consumption, especially in cases where energy intensity is high and production is low (e.g., benzene).

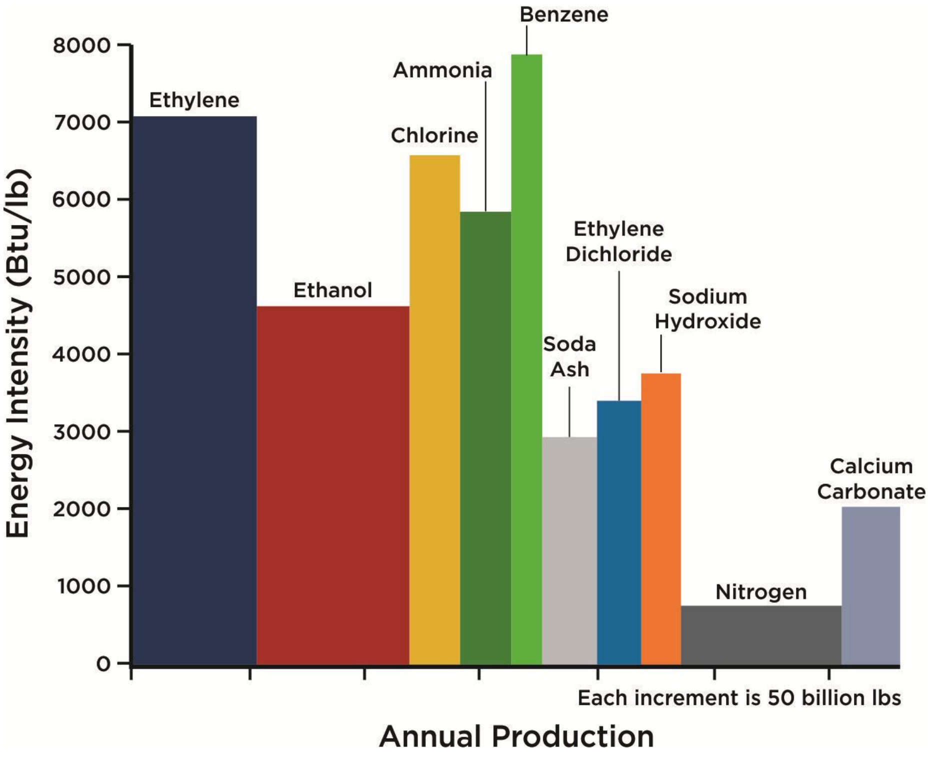


Figure 4-3. Current Typical Energy Intensity vs. Production Volume for the Top 10 Energy Consuming Chemicals, 2010

4.6. CURRENT TYPICAL ENERGY CONSUMPTION BY SUBSECTOR AND SECTOR-WIDE

In this Section, the CT energy consumption estimates for 74 individual chemicals are grouped and presented by subsector. In aligning and grouping the 74 chemicals into subsectors, 10 chemicals were excluded to provide the most accurate extrapolated subsector values. Table 4-6 lists these 10 chemicals along with the rationale for exclusion. All the subsector and sector-wide onsite CT energy consumption values presented in this chapter and subsequent chapters are based on 64 of the 74 chemicals studied in this bandwidth analysis.

Table 4-6. Chemicals Excluded from Subsector and Sector-wide Aggregate Data with Rationale

Excluded Chemical	Rationale
Butadiene	*Avoids double counting with benzene*
Cumene, sulfur, formaldehyde, and nitric acid	*Anomalies exist in calculating TM*
Paraxylene	*Avoids double counting with mixed xylenes*
Styrene	*Secondary intermediate*
Oxygen	*Coproduced with nitrogen*
Sodium hydroxide	*Byproduct of chlorine production*
Ammonium nitrate	*Produced downstream of ammonia*

Table 4-7 presents the onsite CT energy consumption by subsector and sector-wide for U.S. chemical manufacturing. As shown in the first column of Table 4-7, the subsector onsite CT energy consumption is provided in the MECS data. The data in the second column shows the onsite CT energy consumption for the 64 chemicals studied. The 64 chemicals studied account for 57% of all onsite energy consumption by the U.S. chemical manufacturing sector in 2010.

As shown in the last column of Table 4-7, the percentage of coverage of the chemicals studied in each subsector is calculated. This indicates how well the chemicals studied represent total MECS-reported energy consumption in the subsector. The Ethyl Alcohol (ethanol) and Carbon Black subsectors have 100% coverage because the subsectors only include one chemical each. The Petrochemicals and Nitrogenous Fertilizers subsectors have the best coverage (97% and 99% respectively) of the other subsectors that were analyzed. This coverage is helped by the fact that energy consumption is concentrated into a few chemicals: ethylene and benzene dominate Petrochemicals and ammonia dominates Nitrogenous Fertilizers. The lowest subsector coverage is the Other Basic Inorganic Chemicals at 8%. This percentage of coverage for the subsectors is used later in this study to determine the extrapolated total subsector SOA, PM, and TM energy consumption.

Table 4-7 also presents CT primary energy consumption by subsector. Primary energy is calculated from onsite CT energy consumption databased on an analysis of MECS data (DOE 2014) as well as the 64 chemicals studied, with scaling to include offsite electricity and steam generation and transmission losses (DOE 2014).

Table 4-7. Onsite and Primary Current Typical Energy Consumption for the 64 Chemicals Studied by Subsector in 2010, with Percent of Subsector Coverage and Comparison to MECS and Energy Footprints

Subsector	**Onsite CT Energy Consumption, MECS** (TBtu/year)	**Onsite CT Energy Consumption for 64 Chemicals Studied**[1] (TBtu/year)	**Primary CT Energy Consumption, MECS/Energy Footprints**[2] (TBtu/year)	**Primary CT Energy Consumption for 64 Chemicals Studied**[1] (TBtu/year)	**Percent Coverage** (Onsite CT for 64 Chemicals Studied as a % of Subsector and Sector-wide Total)[3]
Petrochemicals	568	552	636	618	97%
Industrial Gases	96	66	238	163	68%
Alkalies and Chlorine	224	211	299	282	94%
Carbon Black	13	13	16	16	100%
Other Basic Inorganic Chemicals	214	16	398	86	8%
Cyclic Crudes and Intermediates	52	30	73	44	58%
Ethyl Alcohol	307	307	371	371	100%
Other Basic Organic Chemicals	634	291	728	334	46%
Plastics Materials and Resins	462	146	620	196	32%
Nitrogenous Fertilizers	166	165	198	197	99%
Phosphatic Fertilizers	35	20	45	25	56%
Total for Chemicals Studied	**2,771**	**1,817**	**3,622**	**2,331**	**66%**
All Other NAICS 325 Chemicals	451	6	667	8	1%
Total for Chemicals Sector-wide	**3,222**	**1,823**	**4,290**	**2,339**	**57%**

Current Typical (CT)

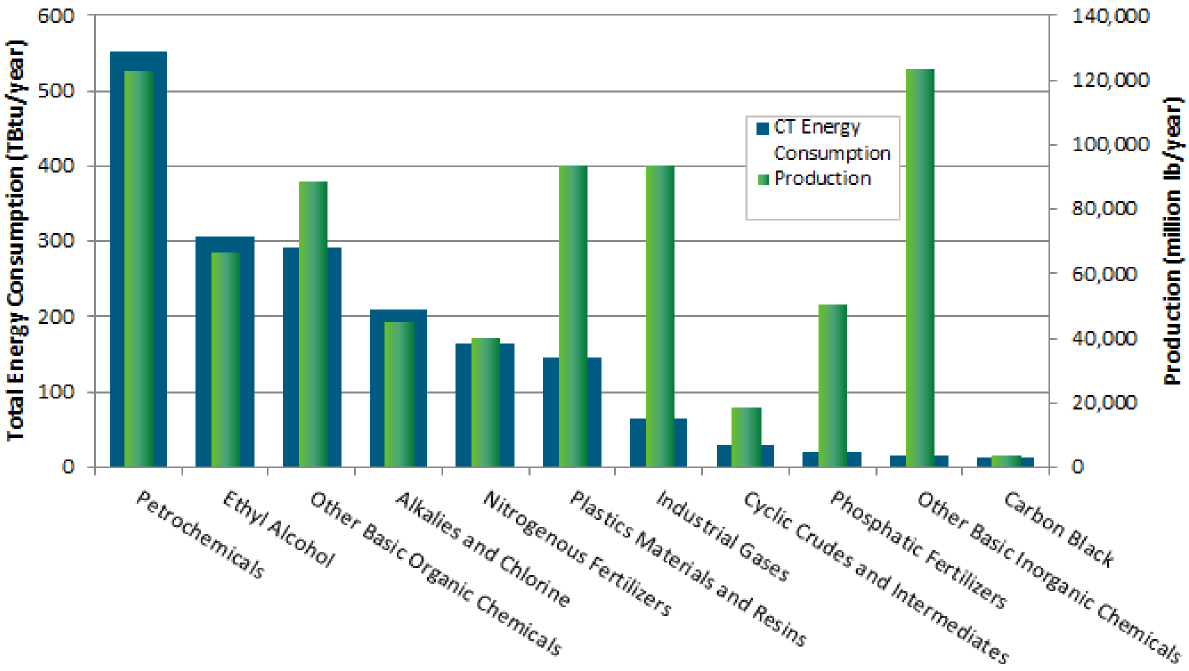
[1] *Certain chemicals are omitted from the subsector sum because: butadiene is double counted with benzene; there were issues with determining the TM of cumene, sulfur, formaldehyde and nitric acid; paraxylene is double counted with mixed xylenes; styrene is a secondary intermediate; oxygen is coproduced with nitrogen; sodium hydroxide is a byproduct of chlorine production; and ammonium nitrate is produced downstream of ammonia. Onsite CT energy consumption for the chemicals studied is calculated from energy intensity and production data for individual chemicals. Primary energy is calculated from onsite energy consumption data, with scaling to include offsite electricity and steam generation and transmission loss.*

[2] *DOE 2014 is the source for MECS/Energy Footprints data.*

[3] *Calculated by dividing the onsite CT energy consumption for the 64 chemicals studied by MECS onsite CT energy consumption.*

4.6.1. Subsector Profiles

Figure 4-4 shows the onsite CT energy consumption and production volumes for each subsector. As noted in Table 4-6, 10 chemicals studied are not included in the sums shown in this figure. The Other Basic Inorganic Chemicals subsector has a large annual production coupled with a low CT energy consumption; this is due to the fact that sulfuric acid accounts for nearly 58% of the subsector's total production and is largely an exothermic process. The Petrochemicals, Ethyl Alcohol (ethanol), and Other Basic Organic Chemicals subsectors have larger annual production volumes coupled with the three highest CT energy consumptions.



Current Typical (CT)

Figure 4-4. Current Typical Energy Consumption vs. Production Volume by Subsector for the Chemicals Studied, 2010

5. State of the Art Energy Consumption for U.S. Chemical Manufacturing

As plants age, manufacturing processes and equipment are updated and replaced by newer, more energy-efficient technologies. This results in a range of energy intensities among U.S. facilities that produce each chemical. Some individual chemicals can be manufactured with a number of different processes using varying feedstocks. Chemical plants, therefore, vary widely in size, age, energy consumption, and types and amounts of chemicals produced. Modern chemical plants can benefit from more energy-efficient technologies and practices, including new chemicals manufacturing pathways that may not be the industry standard.

This Chapter estimates the energy savings possible if U.S. chemical manufacturers adopt the best technologies and practices available worldwide. State of the art (SOA) energy consumption is the minimum amount of energy that could be used in a specific chemical production process using existing technologies and practices.

5.1. CALCULATED STATE OF THE ART ENERGY CONSUMPTION FOR INDIVIDUAL CHEMICALS

Appendix A1a presents the onsite SOA energy consumption for the 74 chemicals considered in this bandwidth study in alphabetical order. Appendix A1b presents the onsite SOA energy consumption for the 74 chemicals grouped by subsector. The SOA energy consumption for each chemical is calculated by multiplying the SOA energy intensity for each chemical by the chemical’s 2010 production volume (the energy intensity and production data are also presented in Appendix A1a and Appendix A1b).

The onsite SOA energy consumption values are the net energy consumed in the production of each chemical using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a pound of product. The onsite SOA energy consumption estimates exclude feedstock energy.

Table 5-1 presents the published sources referenced to identify the SOA energy intensities. Appendix A2 provides the references for the SOA energy intensity data for each individual chemical.

Table 5-1. Published Sources Referenced to Identify State of the Art Energy Intensities for 74 Select Chemicals

Source Abbreviation	Description
DOE 2011b	Average savings of 12.6% identified from assessment implementation results.
DOE 2001	This 2001 report examined the energy intensity of 5 chemical processes; however, only the values for acetic anhydride were used in this bandwidth study.
Exxon 2011	This report describes how Exxon achieved greater than 12% energy savings.
Ferland 2010	Average achieved energy savings was estimated to be 6 - 14%over a period of 2 to 3 years.
IEA 2009[5]	This paper explores the best practice technologies (BPT) for 57 processes that produce 66 chemicals, mostly petrochemicals, and compares the energy values to the current specific energy consumption (SEC) of electricity, feedstock, fuel, and steam in these processes and chemicals in Western Europe.
IPPC 2003, 2007a-c[6]	This series of reports examined the best available techniques of a wide range of manufacturing processes with specific emphasis on reducing environmental impacts.
Maruoka et al. 2010	This report examined the energy efficiency in hydrogen production by methane steam reforming which is used in steelmaking

Two methods were used for determining the SOA energy intensity values. If available, the energy intensity for ‘Best Practice Technology’ (BPT) was used (IEA 2009). As defined in this IEA report, “BPT represents the most advanced technologies that are currently in use at industrial scale, and therefore, by definition, economically viable.” These processes are not necessarily currently commercialized in the U.S. chemical sector, but are in practice somewhere in the world. Several sources also considered the ‘Best Available Technology’ (BAT) for manufacturing a chemical (IPPC 2003, 2007a-c). They used a similar definition citing implementation of those technologies that are “technologically and economically viable.” The definitions of terms vary between sources. Where a range was given for energy usage, the minimum of the range was defined as the SOA process in terms of energy consumption. Energy feed stream values were converted to process energy values (Btu) using the conversion factors presented in Table 5-2 (EPA 2013). Where presented separately, the energy used to create

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[5] In *Chemical and Petrochemical Sector: Potential of best practice technology and other measures for improving energy efficiency* (IEA 2009), the specific energy consumption values in this paper were estimated by examining the energy inputs and outputs of processes at operational plants. The data is sourced from a combination of benchmarking studies and a survey of industry experts. However, the energy intensity values did not include energy gains outside of the process (such as heat cascading and process integration across the plant) or nonprocess energy uses (such as lighting). For electricity, an overall savings potential of 20% was estimated, of which ~65% is attributable to more efficient motors and motor systems. In this source, the energy data for propylene extraction in a fluidized catalytic cracking (FCC) process was not available and was estimated in the report from the data on aromatics extraction. Feedstock energy was added by means of accounting for the calorific value of the basic chemicals; thus, efficiency improvements due to changes in the feedstock would not be included in these values. In the U.S., soda ash is primarily produced by mining; yet the quoted SOA energy value in this source is for the energy intensity of its chemical production. Toluene is largely used as a raw material in other aromatics production; therefore, the end feedstock value of toluene is corrected by its consumption by 50% (IEA 2009).

[6] The IPPC sources do not provide references for energy values.

cooling water was ignored. Technologies identified that are in a pre-commercial stage of development or that are extremely expensive were not considered in the SOA analysis (instead they were considered in Chapter 6 on the practical minimum (PM) energy consumption).

Table 5-2. Energy Conversion Factors Used in Calculations

Energy Type	Process Energy (Btu)
1 kWh Electricity	3,412
1 Nm^3 Natural Gas	36,339
1 lb Steam	1,194
1 kg CO Fuel Gas	13,281
1 liter Fuel Gas	36,060

In the studies referenced, a number of chemicals had either no SOA energy intensity or had outdated SOA energy intensity values that did not agree with the onsite CT energy intensity values. In these cases, the onsite SOA energy intensity was assumed to be 12.5% lower than onsite CT energy intensity. This 12.5% value is based on data from plant assessments conducted by the DOE's Energy Savings Assessment (ESA) Program and ExxonMobil's Global Energy Management Systems (GEMS) studies (DOE 2011b, Exxon 2011). The ESA program identified an aggregate energy savings of 12.56% for the top 10 most common energy saving technologies for chemical plants (discussed more in the next paragraph). GEMS identified savings of greater than 12% in ExxonMobil's chemical manufacturing. These energy savings values also agree with the energy savings of 6-14% from early certification results of DOE's Superior Energy Performance (SEP) program (Ferland 2010).

The ESAs identified a number of energy savings opportunities. Most of the opportunities were related to management of the steam systems or process heating. The technologies identified with steam were related to reducing leaks, adjusting the boilers, improving insulation, and improving steam traps. The other large source of energy savings came from improving boilers by upgrading the heat exchangers or by increasing their efficiency. Many of these simple yet straightforward changes result in savings over CT energy consumption with reasonable capital investment and short payback periods (less than 2 years).

5.2. STATE OF THE ART ENERGY CONSUMPTION BY SUBSECTOR AND SECTOR-WIDE

Table 5-3 presents the onsite SOA energy consumption for U.S. chemical manufacturing by subsector for the 64 chemicals studied. The 64 chemicals were sorted into subsectors and the onsite SOA energy consumption for these chemicals studied was sub-totaled by subsector; 10 chemicals were excluded as explained in Table 4-6. Table 5-3 also presents the onsite SOA energy savings, which is the difference between CT energy consumption and SOA energy consumption. The SOA energy savings is also called the *current opportunity* bandwidth for the 64 chemicals studied.

Table 5-3. Onsite State of the Art Energy Consumption and Energy Savings for the 64 Chemicals Studied by Subsector

Subsector	NAICS Code	Onsite CT Energy Consumption for 64 Chemicals Studied (TBtu/year)	Onsite SOA Energy Consumption for 64 Chemicals Studied (TBtu/year)	SOA Energy Savings for 64 Chemicals Studied[†] (CT-SOA) (TBtu/year)
Petrochemicals	325110	552	453	99
Industrial Gases	325120	66	56	9
Alkalies and Chlorine	325181	211	171	39
Carbon Black	325182	13	7	7
Other Basic Inorganic Chemicals	325188	16	-25	41
Cyclic Crudes and Intermediates	325192	30	25	5
Ethyl Alcohol	325193	307	271	36
Other Basic Organic Chemicals	325199	291	190	101
Plastics Materials and Resins	325211	146	101	45
Nitrogenous Fertilizers	325311	165	100	66
Phosphatic Fertilizers	325312	20	17	2
All Other Miscellaneous Chemicals*		6	6	1
Total for Chemicals Studied		1,823	1,373	450

Current Typical (CT), State of the Art (SOA), Thermodynamic Minimum (TM)

[†] When generalized to the full subsector, SOA energy savings is called Current Opportunity.

**MTBE was the only chemical studied in this subsector.*

In Table 5-4, data from Table 5-3 is extrapolated to estimate the total SOA subsector opportunity. SOA subsector energy savings, which is the *current opportunity*, is expressed as a percent in Table 5-4. This is also shown in Figure 5-1. It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. In Figure 5-1, the percent savings is the percent of the overall energy consumption bandwidth, with CT energy consumption as the upper benchmark and TM as the lower baseline. In Figure 5-2, the *current* energy savings opportunity is shown in terms of TBtu/year savings for each subsector. The pie chart in Figure 5-2 captures the blue portions of the bar chart shown in Figure 5-1. The greatest *current opportunity* in terms of percent energy savings is Nitrogenous Fertilizers at 40% energy savings; the greatest *current opportunity* in terms of TBtu savings is Other Basic Organic Chemicals at 220 TBtu/year savings.

To extrapolate the data presented in Table 5-4 and Figure 5-1, the SOA energy consumption of each individual chemical studied within a subsector is summed, and the sum is divided by the percent coverage for the entire subsector. The percent coverage of chemicals studied compared to the total CT energy consumption of the subsector is shown in Table 4-7. Percent coverage is the ratio of the sum of all the CT energy consumption for the individual chemicals studied in the subsector to the CT energy consumption for the subsector provided by MECS (see Table 4-7). The extrapolated number is the estimated SOA energy consumption for the entire subsector. This method is used to extrapolate data for 10 subsectors that include the chemicals analyzed in this study.

Table 5-4 also presents the SOA energy savings percent which is used to extrapolate the data for subsectors with limited coverage in the chemicals studied (this is explained later in this Section). To calculate the onsite SOA energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with SOA technologies and practices compared to CT energy consumption, considering that the TM may not be zero. As will be explained in Chapter 7, the TM reaction energy for some chemicals is a negative value. When comparing energy savings percent from one chemical product to another (or one subsector to another), the absolute savings is the best measure of comparison. The equation for calculating onsite SOA energy savings percent is:

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

Table 5-4. Onsite State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for the Chemicals Subsectors and Sector-wide Based on Extrapolated Data from the 64 Chemicals Studied

Subsector	Onsite SOA Energy Consumption for 64 Chemicals Studied (TBtu/year)	Onsite SOA Energy Consumption for Total Subsector (extrapolated) (TBtu/year)	SOA Energy Savings for Total Subsector (extrapolated)† (CT-SOA) (TBtu/year)	SOA Energy Savings Percent (CT-SOA)/ (CT-TM)*
Petrochemicals	453	466†	102	21%
Industrial Gases	56	83†	13	6%
Alkalies and Chlorine	171	182†	42	21%
Carbon Black	7	7†	6	41%
Cyclic Crudes and Intermediates	25	43†	9	6%
Ethyl Alcohol	271	271†	36	9%
Other Basic Organic Chemicals	190	414†	220	28%
Plastics Materials and Resins	101	321†	141	18%
Nitrogenous Fertilizers	100	100†	66	40%
Phosphatic Fertilizers	17	31†	4	7%
All Other NAICS 325 Chemicals	-19**	538***	127	19%
Total for Chemicals Studied	**1,373**			
Total for Chemicals Sector-wide		**2,456**	**766**	**19%**

State of the art (SOA)

† Estimates for the entire subsector were extrapolated by dividing the total onsite SOA energy consumption for all the chemicals studied within the subsector by the % coverage.

** SOA energy savings percent is the SOA energy savings opportunity from transforming chemicals manufacturing process. Energy savings percent is calculated using TM energy consumption shown in Table 7-2 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT- SOA)/(CT- TM)*

*** Estimate includes Other Basic Inorganic Chemicals (NAICS 325188) because of underrepresentation of chemicals studied in this subsector, as well as All Other Miscellaneous Chemicals (NAICS 325998) because the energy consumption for this subsector is not identified in MECS*

**** All Other NAICS 325 Chemicals includes underrepresented subsectors (Other Basic Inorganic Chemicals and All Other Miscellaneous Chemicals). Estimates were extrapolated by applying the sector-wide SOA energy savings percent (19%); CT energy consumption was multiplied by 81% (100%-19%) to calculate extrapolated SOA energy consumption. Consequently, All Other NAICS 325 Chemicals extrapolated SOA energy consumption is 19% less than the CT energy consumption.*

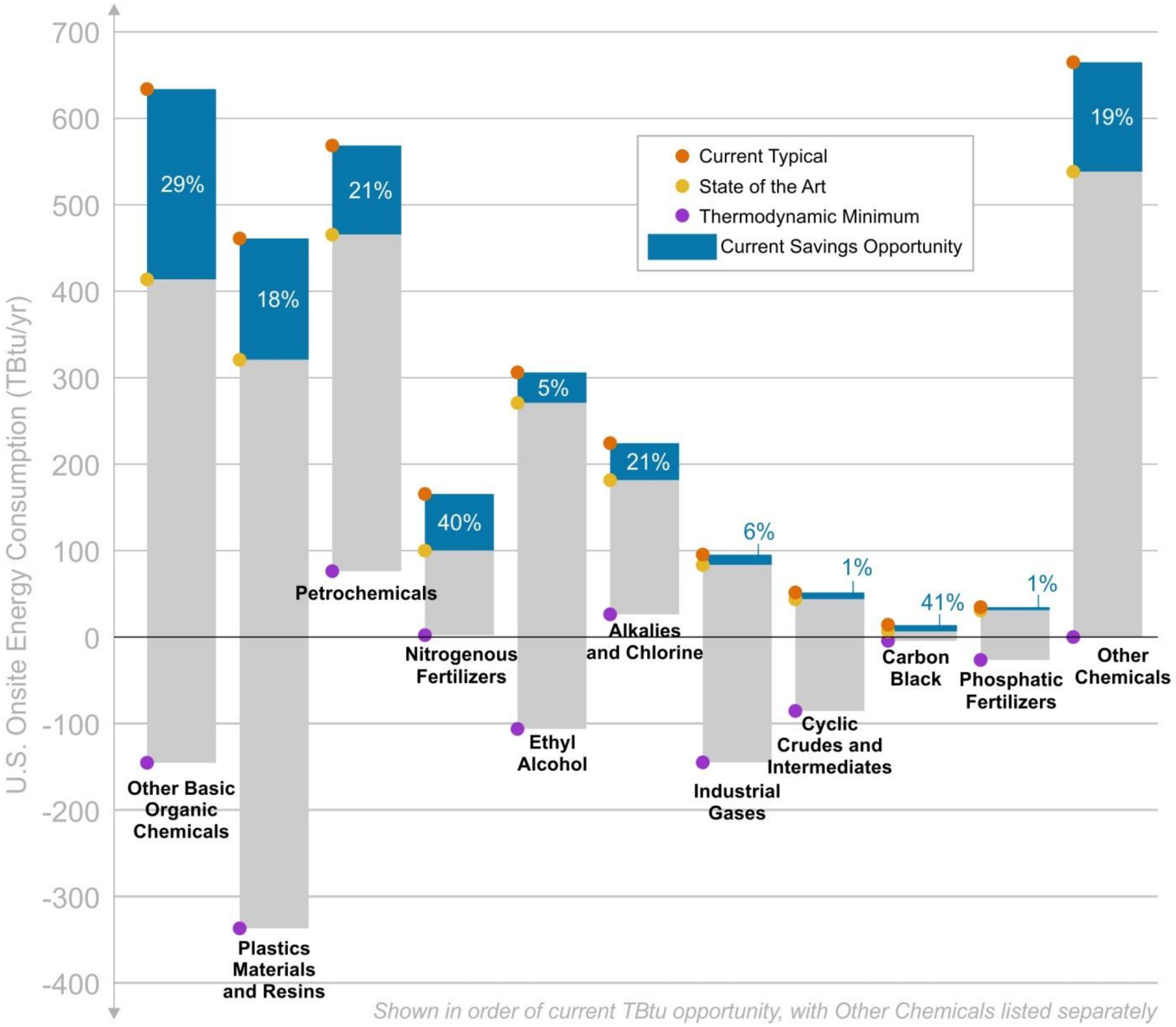
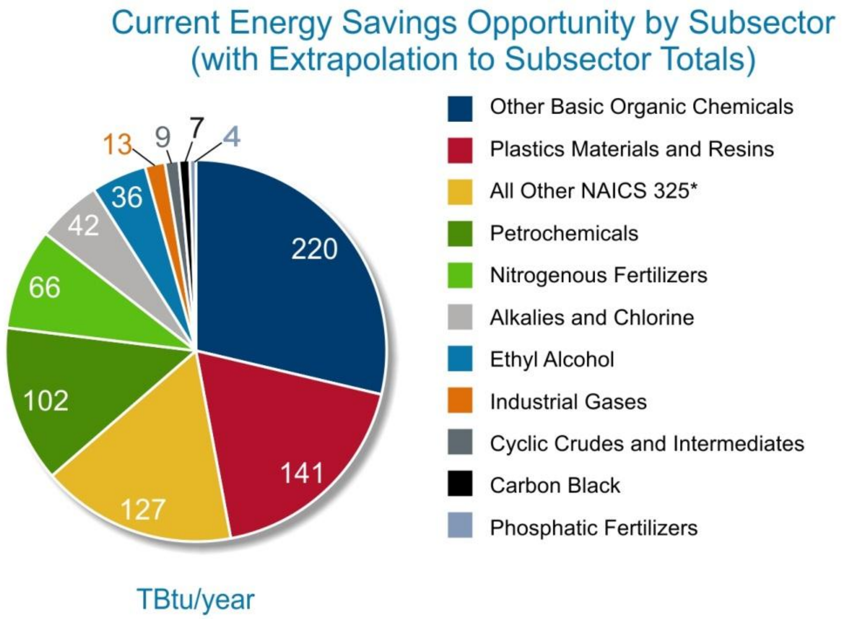


Figure 5-1. Current Opportunity Energy Savings Bandwidths for Chemicals Subsectors Based on Extrapolated Data from the 64 Chemicals Studied (with Percent of Overall Energy Consumption Bandwidth)

The Other Basic Inorganic Chemicals subsector and the All Other Miscellaneous Chemicals subsector have insufficient percent coverage among the chemicals studied and, therefore, a different extrapolation method was used. Additionally, the SOA energy consumption was estimated for the remainder of the chemicals sector (i.e., all chemicals that are not included in these two subsectors and the 10 subsectors referenced above). These additional chemicals, as well as the Other Basic Inorganic Chemicals subsector and the All Other Miscellaneous Chemicals subsector, are together referred to as All Other NAICS 325 Chemicals in Table 5-4.



* All Other NAICS 325 includes all other chemicals in the chemical manufacturing sector (including Other Basic Inorganic Chemicals and Other Miscellaneous Chemicals Subsectors)

Figure 5-2. Current Energy Savings Opportunity by Chemical Subsectors Based on Extrapolated Data from the 64 Chemicals Studied (Energy Savings Per Year in TBtu)

5.2.1. Comparing State of the Art and Current Typical Energy Data

If all U.S. chemical manufacturing facilities were able to attain onsite SOA energy intensities, it is estimated that 450 TBtu/year of energy could be saved from the production of these 64 chemicals alone, corresponding to a 19% energy savings sector-wide. This estimated annual energy savings is equivalent to 78 million barrels of oil or 464 billion cubic feet of natural gas. This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D.

Delving deeper, certain subsectors and chemicals have relatively large available energy savings opportunities. In the following Sections, several subsectors and chemicals are highlighted and the nature of the onsite SOA energy savings is discussed. Appendix A1b provides detailed data for each individual chemical studied by subsector.

5.2.1.1. Petrochemicals (Ethylene via steam cracking)

Of the 99 TBtu/year in identified SOA energy savings in Petrochemicals, 47 TBtu/year or about half of the energy savings comes from ethylene production alone. Most ethylene production occurs by steam cracking where the feedstock (mostly ethane, sometimes naphtha or propane) is heated to high temperatures over a catalyst that promotes the formation of double bonds.

Because of its high manufacturing temperature, heat recovery is essential to minimize the energy consumption in ethylene production.

5.2.1.2. Nitrogen-based Chemicals (Ammonia)

The energy consumption in the Nitrogenous Fertilizers subsector can predominantly be attributed to ammonia production. Of the 66 TBtu/year of SOA energy savings for the subsector, 62TBtu/year or 93% of the available subsector SOA energy savings are from ammonia. Similar to ethylene, ammonia is manufactured at high temperatures and pressures. Recovery of the invested energy is essential to minimize the energy intensity of ammonia production.

5.2.1.3. Alkalies and Chlorine

Chlorine production is generally cited as an energy intensive process where there are opportunities for energy efficiency improvements. The energy savings opportunities for this chemical are in line with other subsectors; moving from CT energy consumption to SOA energy consumption results in an expected 20% SOA energy savings. A significant amount of process energy must go into oxidizing brine to chlorine, and this is reflected by the process's endergonic nature. Since electrolysis is a critical step in chlorine production, efficiency gains in grid electricity generation would benefit the total energy footprint of chlorine production; however, offsite electricity generation falls outside the scope of this bandwidth (it is considered in primary energy). The remainder of the energy goes towards process heating and recovery of heat from the process stream, which are the main areas where the energy intensity of chlorine production could be reduced.

5.2.1.4. Carbon Black

While not representing a large absolute energy savings opportunity (only 7 TBtu/year), the production of carbon black is estimated to gain a 41% energy savings with SOA energy consumption. Production of carbon black occurs through the incomplete combustion of petrochemicals. Heat recovery from process streams is largely responsible for the energy savings. If the recuperation processes significantly improved, carbon black production could be a net creator of energy.

5.2.1.5. Other Basic Organic Chemicals

The Other Basic Organic Chemicals subsector, which accounts for 20% of all chemical sector CT energy consumption, spans a wide variety of output products and processes. The chemicals studied in this subsector accounted for 46% of this subsector's CT energy consumption. Among chemicals studied, acetone (11 TBtu/year), caprolactam (21 TBtu/year), ethylene dichloride (24 TBtu/year), and vinyl chloride (11 TBtu/year) have the largest identified SOA energy savings. Similar to the other subsectors, the production of chemicals in this subsector can benefit from better steam management and heat recovery.

6. Practical Minimum Energy Consumption for U.S. Chemical Manufacturing

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway that can be used to make chemicals in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. chemical manufacturing. In this Chapter, the future energy savings made possible through R&D advancements in chemicals manufacturing are estimated. Practical minimum (PM) is the minimum amount of energy required assuming the deployment of applied R&D technologies under development worldwide.

6.1. R&D IN THE CHEMICALS INDUSTRY

The United States was an early leader in developing a chemical industry. Historic investment in R&D has positioned the U.S. chemical manufacturing sector as the second-largest supplier of chemicals in the world (second to China, which surpassed the United States in 2009) (ACC 2011).

Investing in R&D in the short term ensures long term future prosperity. Increasing the energy efficiency of an existing process often requires capital investment and taking manufacturing equipment offline to perform the necessary updates. The risks and rewards of this type of business decision needs to be clearly assessed. A study of public commodity and specialty chemical companies sponsored by the Council for Chemical Research found that every dollar invested in chemical R&D returned $2 in operating income over six years, which is a 17% return on investment in R&D (CRC 2005). Investment in R&D is a commitment of resources with a high degree of risk; however, rates of return on successful innovations can be quite high, often in the range of 25 to 35% (ACC 2011). In 2010, the combined revenue from new products in the chemical manufacturing sector totaled approximately 18% of total revenue (ACC 2011). The chemicals sector dedicated $55.4 million toward R&D in 2010; most chemical companies typically allocate 1-3% of their annual sales toward R&D (ACC 2011). In segments such as pharmaceuticals, companies may allocate as much as 25%.

6.2. CALCULATED PRACTICAL MINIMUM ENERGY CONSUMPTION FOR INDIVIDUAL CHEMICALS

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

R&D progress is difficult to predict and potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a broad search of R&D activities in the chemical industry was conducted. A large number and range of potential technologies were identified.

The focus of this study's search was applied research, which was defined as investigating new technology with the intent of accomplishing a particular objective. Basic research, the search for unknown facts and principles without regard to commercial objectives, was not considered. Many of the technologies identified were disqualified from consideration due a lack of data from which to draw energy savings conclusions.

Appendix A1a presents the onsite PM energy consumption for the 74 chemicals considered in this bandwidth study in alphabetical order. Appendix A1b presents the onsite PM energy consumption for the 74 chemicals grouped by subsector. The PM energy consumption for each chemical is calculated by multiplying the estimated PM energy intensity for each chemical by the chemical's 2010 production volume (the energy intensity and production data are also presented in Appendix A1a and A1b).These values exclude feedstock energy. The lower limit for onsite PM energy intensity and onsite PM energy consumption are presented in Appendix A1a and A1b.The upper limit of the PM range is assumed to be the SOA energy consumption. The PM energy consumption for each chemical is expressed as a range because the energy savings impacts are speculative and based on unproven technologies.

Table 6-1 presents the key sources consulted to identify PM energy intensities in chemicals manufacturing. Additionally, numerous fact sheets, case studies, reports, and award notifications were referenced; a more detailed listing of references is provided in Appendix A3 (Table A3 and References for Table A3).

Table 6-1. Key Published Sources Reviewed to Identify Practical Minimum Energy Intensities for 74 Select Chemicals

Reference Abbreviation	Source
DOE 2011a	"Grand Challenge Portfolio: Driving Innovations in Industrial Energy Efficiency," U.S. Department of Energy, Industrial Technologies Program. 2011.
Martin et al. 2000	"Emerging Energy-Efficient Industrial Technologies," Martin et al. for LBNL, 2000.
Ren et al. 2006	"Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes," *Energy*. Ren at al. 2006.
RET n.d.	"Energy Efficiency Opportunities," Australian Government, Department of Resources Energy and Tourism, 2008 to 2010.

Numerous fact sheets, case studies, reports, and award notifications were referenced. Details of all of the practical minimum sources consulted can be found in Appendix A-3.

Table 6-2 presents a summary of the energy intensities and the energy savings range for select chemicals and process areas considered in this PM analysis. Data in this table was used to estimate PM energy intensity and PM energy consumption for individual chemicals.

Table 6-2. Summary of Practical Minimum Energy Intensities and Energy Savings Range for Select Chemicals and Process Areas

Chemical or Process Area	Practical Minimum Energy Intensity (Btu/lb) or Energy Savings (% or Btu/lb) (low end of range*)
Ethylene	5,159 Btu/lb
Propylene	878 Btu/lb
Chlorine	4,932 Btu/lb
Ammonia	2,457 Btu/lb
Nitrogen and Oxygen	403 Btu/lb
All Industrial Gases	15 Btu/lb energy savings over CT applies to all Industrial Gases
Ammonium Nitrate	35 Btu/lb
Methyl Methacrylate	1,742 Btu/lb
Methyl Chloride	420 Btu/lb
Butadiene	4,997 Btu/lb
Plastics Materials and Resins	70% energy savings over CT applies to all Plastics Materials and Resins
Styrene	2,266 Btu/lb
Isopropanol	2,205 Btu/lb
Methanol	3,921 Btu/lb
Sodium Hydroxide	802 Btu/lb
Nitric Acid	-1,075 Btu/lb
Distillation/Separation - 40% of energy consumption for these chemicals is used in distillation/separation technologies[1, 2]	18% energy savings over CT applies to only chemicals with distillation/separation
Utilities (applied to all chemicals including those above) [1]	2.7% energy savings over CT applies to all 74 chemicals studied
Crosscutting Technologies[1]	43% energy savings over CT applies to those chemicals not listed or referenced above

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

[1] *These percent energy savings are assumed to be additive for the relevant chemicals.*

[2] *Technologies impacted include the following 25 chemicals: acetic acid, acetone, acrylonitrile, ammonia, benzene, butadiene, cumene, ethanol, ethylbenzene, ethylene, ethylene glycol, ethylene oxide, formaldehyde, isopropanol, methanol, nitrogen, oxygen, p-xylene, phenol, propylene, propylene oxide, styrene, vinyl acetate, vinyl chloride monomer, and xylene. (Humphrey 1997)*

** Upper end of PM is assumed to be the lower end of SOA.*

Appendix A3 presents details on the R&D technologies that were selected and used to estimate the PM energy intensities. Energy savings from R&D advancements were directly estimated for 15 chemicals (including the highest energy consuming chemicals), as well as for the subsectors Industrial Gases and Plastics Materials and Resins. These 15 chemical products are ethylene, propylene, chlorine, ammonia, nitrogen, oxygen, ammonium nitrate, methyl methacrylate, methyl chloride, butadiene, styrene, isopropanol, methanol, sodium hydroxide, and nitric acid. Energy savings from R&D advancements were also estimated for three process areas: distillation/separation, utilities, and crosscutting technologies.

In Appendix A3, technologies are aligned with the most representative chemical product. Some of the technologies have applicability to more than one chemical product. The broad impact of these technologies is due to the fact that many common unit processes are used in the manufacturing of a wide range of chemicals. In addition, some chemicals are co-produced and process energy savings can apply to all co-produced chemicals.

Analysis of the range of energy savings offered by groups of technologies is complicated in that the savings offered by multiple technologies may or may not be additive. One example would be that developing a superior catalyst that works at lower temperatures would limit the gains made by more efficient heat recovery of an exit stream. Each technology contributes discrete or compounding savings that increase the ultimate savings of the group and some energy savings may be duplicative. As a result, all values are presented as sourced from the literature and energy savings were not aggregated for multiple technologies. A separate study of the individual technologies would be necessary to verify and validate the savings estimates and interrelationships between the technologies. If more than one technology was considered for a particular chemical, the technology that resulted in the lowest energy intensity was conservatively selected for the PM energy intensity.

R&D in some process areas (as identified in Table 6-2) is more broadly applicable, such as utility/power generation improvements, separations/distillation technologies, and crosscutting technologies. The estimated energy savings from utility improvements were assumed to be applicable to all 74 chemical products studied. To calculate PM energy consumption, the difference between CT energy intensity and TM energy intensity was multiplied by the estimated savings for utility improvements (2.7%) and subtracted from the CT energy consumption.

Separation processes account for about 40% of total energy consumption in the chemical process industries (Humphrey 1997). The following chemicals were identified as having “key distillation separations” and, therefore, have significant separation/distillation energy use: acetic acid, acetone, acrylonitrile, ammonia, benzene, butadiene, cumene, ethanol, ethylbenzene, ethylene, ethylene glycol, ethylene oxide, formaldehyde, isopropanol, methanol, nitrogen, oxygen, p-xylene, phenol, propylene, propylene oxide, styrene, vinyl acetate, vinyl chloride monomer, and xylene (Humphrey 1997). To calculate the PM energy consumption for these 25 chemicals, the 18% energy savings over CT energy consumption from R&D advancements in separations/distillation technologies was applied to the difference between CT and TM energy consumption, multiplied by 40% (the assumed percentage of the energy for these chemicals used in distillation/separation technologies) and subtracted from the CT.

Cross-cutting technologies applied during the PM analysis included new high-temperature, low-cost ceramic media for natural gas combustion burners, the application of modeling and process analysis, and advanced energy and water recovery technology from low-grade waste heat. The estimated energy savings from R&D advancement of crosscutting technologies (43%) was applied to 45 of the chemicals studies. To calculate PM energy consumption, the difference between CT and TM for these 45 chemicals was multiplied by the estimated saving (43%) and subtracted from the CT.

In Appendix A3, the range of technologies considered offer a corresponding range of estimated energy savings. Brief descriptions of the technologies are followed by reported savings in terms of dollars, Btu, and percent savings. The technology developers' estimated savings were taken at face value and adjusted to represent the overall average energy savings potential.

For each technology, Appendix A3 presents a brief explanation of the energy savings and a summary of adjustments necessary to determine the overall average energy savings potential and PM energy intensity. Research savings are speculative in nature. The energy savings will vary depending on the source; they can be reported in terms of primary energy savings, plant-wide energy savings, process energy savings, or energy-type savings. In each case, the reported energy savings were adjusted to determine PM energy intensity.

6.2.1. Weighting of Technologies

The technologies described in Appendix A3 can be weighted differently depending on the audience. Plant managers may primarily be interested in productivity and quality implications; business managers may primarily be interested in relative cost and payback; technology investors may primarily be interested in market impact, technology readiness, and development risk factors; and government regulators may primarily be interested in environmental impacts. Each factor plays heavily into R&D investment considerations.

Appendix A4 (Table A4) considers how to weigh these various perspectives. Six technology weighting factors were considered for each technology:

A	Technology Readiness
B	Market Impact
C	Relative Cost and Savings Payback
D	Technical Risk
E	Productivity/Product Quality Gain
F	Environmental Impacts

Appendix A4 (Table A4) presents the PM technology weighting factors that could be applied to the technologies for the production of specific chemicals (as identified in Appendix A3). Best engineering judgment was employed to rate each of the technologies with these weighting factors. A score of High, Medium, or Low was assigned to each factor along with a brief explanation for the score. The parameters referenced in scoring are detailed in Appendix A4 (Table A4). An overall importance rating for the technology was determined based on the weighting factor scores. Each weighting factor is assigned a DOE importance level of “1.”This importance level can be altered; for example, if Technology Readiness and Market Impact carry higher importance, the importance level for these factors can be changed to “2” or “3” and the resulting Overall Importance Rating would change accordingly.

The weighting factors presented in Appendix A4 can be used for further study of the R&D technologies identified in Appendix A3. The weighting factor study was part of the analysis of the R&D technologies, and serves as a guide for prioritizing the technologies. However, the weighting factors were not utilized to estimate onsite PM energy intensity or consumption.

6.3. PRACTICAL MINIMUM ENERGY CONSUMPTION BY SUBSECTOR AND SECTOR-WIDE

Table 6-3 presents the onsite PM energy consumption for the 64 chemicals studied by subsector. The 64 chemicals were sorted into subsectors and onsite PM energy consumption for the chemicals studied was sub-totaled by subsector. The onsite PM energy savings is the difference between CT energy consumption and PM energy consumption. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings.

Table 6-3. Onsite Practical Minimum Energy Consumption and Energy Savings by Subsector for the 64 Chemicals Studied

Subsector	NAICS Code	Onsite CT Energy Consumption for 64 Chemicals Studied (TBtu/year)	Onsite PM Energy Consumption for 64 Chemicals Studied (TBtu/year)	PM Energy Savings for 64 Chemicals Studied[†] (CT-PM) (TBtu/year)
Petrochemicals	325110	552	345-453	99-207
Industrial Gases	325120	66	5-56	9-60
Alkalies and Chlorine	325181	211	124-171	39-87
Carbon Black	325182	13	6-7	7
Other Basic Inorganic Chemicals	325188	16	(-101) - (-25)	41-118
Cyclic Crudes and Intermediates	325192	30	(-12) - 25	5-42
Ethyl Alcohol	325193	307	43-271	36-264
Other Basic Organic Chemicals	325199	291	103-190	101-189
Plastics Materials and Resins	325211	146	27-101	45-119
Nitrogenous Fertilizers	325311	165	69-100	66-96
Phosphatic Fertilizers	325312	20	4-17	2-16
All Other Miscellaneous Chemicals*		6	4-6	1-3
Total for Chemicals Studied		1,823	616-1,373	450-1,209

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

[†] *When generalized to the full subsector, PM energy savings is the Current Opportunity plus the R&D Opportunity.*

* *MTBE was the only chemical studied in this subsector.*

In Table 6-4 , data from Table 6-3 is extrapolated to estimate the total PM subsector opportunity. PM energy consumption for the individual chemicals studied is grouped by subsector and the data is extrapolated to estimate subsector totals. PM subsector energy savings is expressed as a percent in Table 6-4. This is also shown in Figure 6-1. It is useful to consider both TBtu energy savings and energy savings percent when comparing energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same.

Table 6-4. Onsite Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for the Chemicals Subsectors and Sector-wide Based on Extrapolated Data from the 64 Chemicals Studied

Subsector	**Onsite PM Energy Consumption for 64 Chemicals Studied** (TBtu/year)	**Onsite PM Energy Consumption for Total Subsector (extrapolated)** (TBtu/year)	**PM Energy Savings for Total Subsector (extrapolated)**[††] (CT-PM) (TBtu/year)	**PM Energy Savings Percent** (CT-PM)/ (CT-TM)*
Petrochemicals	345-453	355-466[†]	102-213	21-43%
Industrial Gases	5-56	8-83[†]	13-88	6-37%
Alkalies and Chlorine	124-171	132-182[†]	42-92	21-47%
Carbon Black	6-7	6-7[†]	6-7	41-42%
Cyclic Crudes and Intermediates	(-12)-25	(-21)-43[†]	9-73	6-53%
Ethyl Alcohol	43-271	43-271[†]	36-264	9-64%
Other Basic Organic Chemicals	103-190	224-414[†]	220-410	25-53%
Plastics Materials and Resins	27-101	84-321[†]	141-378	18-47%
Nitrogenous Fertilizers	69-100	69-100[†]	66-97	40-59%
Phosphatic Fertilizers	4-17	7-31[†]	4-28	7-46%
All Other NAICS 325 Chemicals	(-98) - (-19)**	332-538***	127-333	
Total for Chemicals Studied	**629-1,373**			19-50%
Total for Chemicals Sector-wide		**1,235-2,456**	**766-1,988**	19-50%

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

† Estimates for the entire subsector were extrapolated by dividing the onsite SOA energy consumption for the chemicals studied within the subsector by the % coverage.

[††]When generalized to the full subsector, PM energy savings is the Current Opportunity plus the R&D Opportunity.

** Calculated using TM from Table 7-2 as the minimum energy of production. This accounts for the energy necessary to perform the chemical transformation occurring during the production process. Potential opportunity reflects the difference between CT and TM. Calculation: (CT- PM)/(CT- TM).*

***Estimate includes Other Basic Inorganic Chemicals (NAICS 325188) because of underrepresentation of chemicals studied in this subsector, as well as All Other Miscellaneous Chemicals (NAICS 325998) because the energy consumption for this subsector is not identified in MECS*

**** All Other NAICS 325 Chemicals includes underrepresented subsectors (Other Basic Inorganic Chemicals and All Other Miscellaneous Chemicals). Estimates were extrapolated by applying the sector-wide PM energy savings percent (50% PM Energy Savings); CT was multiplied by 50% (100%-50%) to calculate extrapolated PM energy consumption. Consequently, All Other NAICS 325 Chemicals extrapolated PM energy consumption is 50% less than the CT energy consumption.*

Figure 6-1 presents the *current opportunity* and the *R&D opportunity* for each subsector based on the extrapolated data; the *current opportunity* is the difference between CT energy consumption and SOA energy consumption (shown in blue) and the *R&D opportunity* is the difference between the SOA energy consumption and the PM energy consumption (shown in green). In Figure 6-1, the percent savings is the percent of the overall energy consumption bandwidth where TM is the lower baseline. The greatest *current opportunity* in terms of percent savings is Nitrogenous Fertilizers at 40% energy savings; the greatest *R&D opportunity* is Ethyl Alcohol at 55% energy savings. In Figure 6-2, the *current* and *R&D* savings opportunity is shown in terms of TBtu/year savings. The pie chart in Figure 6-2 captures the blue and green portions of the bar chart shown in Figure 6-1, each in a separate pie chart. The greatest *current opportunity* in terms of TBtu savings is Other Basic Organic Chemicals at 220 TBtu/year savings; the greatest *R&D opportunity* in terms of TBtu savings is Ethyl Alcohol at 228 TBtu/year savings. In terms of both percent energy savings and TBtu/year savings, Ethyl Alcohol shows the greatest overall opportunity.

To extrapolate the data in Table 6-4 and Figure 6-2, the PM energy consumption of each individual chemical studied within a subsector is summed, and the sum is divided by the percent coverage for the entire subsector. The percent coverage of chemicals studied compared to the total CT energy consumption of the subsector is shown in the last column of Table 4-7. Percent coverage is the ratio of the sum of all the CT energy consumption for the individual chemicals studied in the subsector to the CT energy consumption for the subsector provided by MECS (see Table 4-1). The extrapolated number is the estimated lower limit of the PM energy consumption for the entire subsector. This method is used to extrapolate data for the 10 subsectors that include the chemicals analyzed in this study.

Table 6-4 also presents the PM energy savings percent which is used to extrapolate the data in subsectors with limited coverage in the chemicals studied (this is explained later in this Section). To calculate the onsite PM energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with PM energy consumption (i.e., the deployment of R&D technologies under development worldwide) compared to CT energy consumption, considering that the TM energy consumption may not be zero (i.e., the TM energy consumption may be negative). As will be explained in Chapter 7, in some cases, the TM reaction energy is a negative value. When comparing energy savings percent from one chemical product to another (or one subsector to another), the absolute savings is the best measure of comparison. The equation for calculating onsite PM energy savings percent is:

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

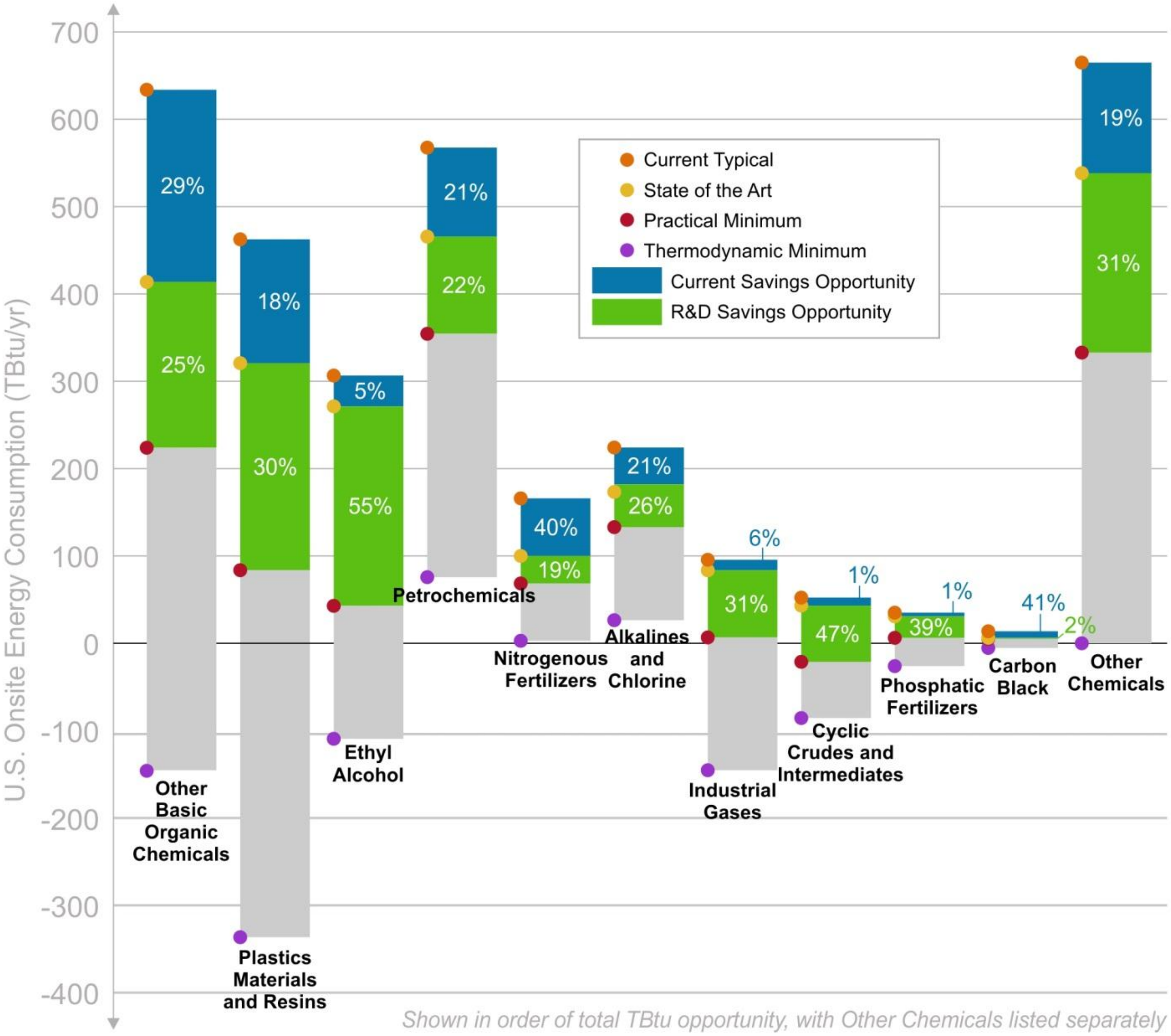
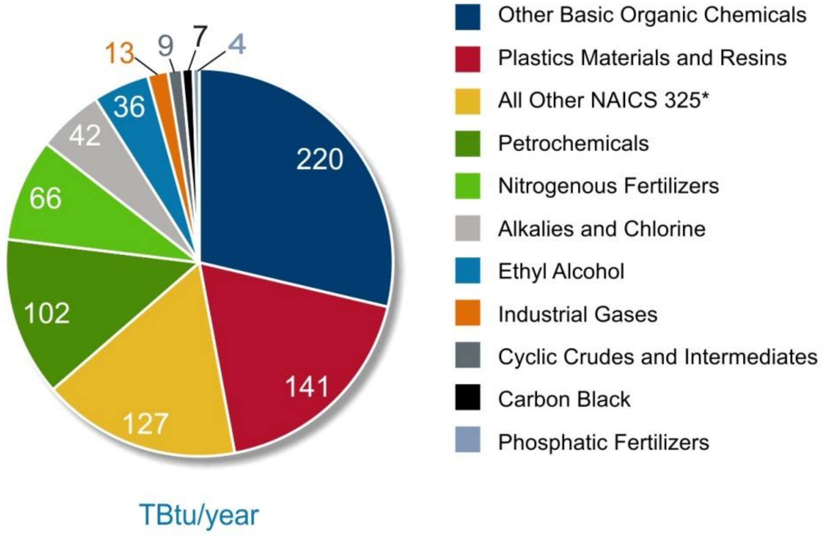
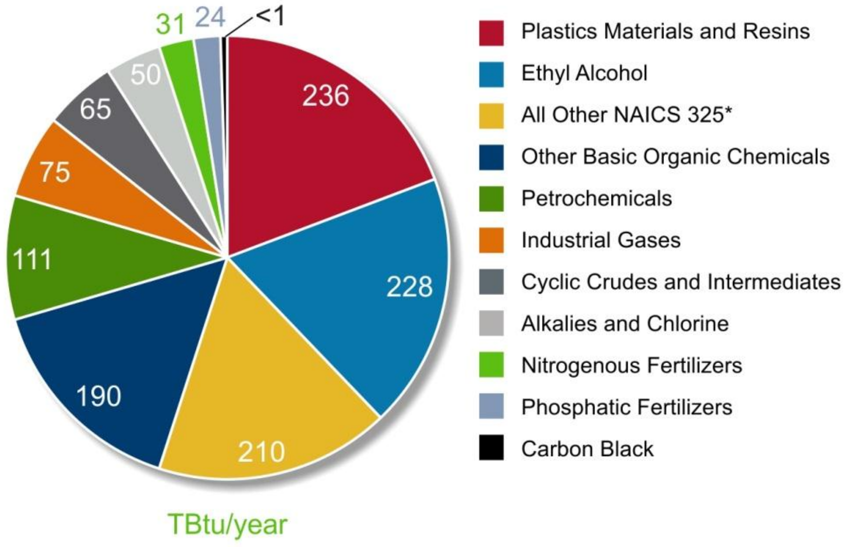


Figure 6-1. Current and R&D Opportunity Energy Savings Bandwidths for the Subsectors Based on Extrapolated Data from the 64 Chemicals Studied
(with Percent of Overall Energy Consumption Bandwidth)



Current Energy Savings Opportunity by Subsector (with Extrapolation to Subsector Totals)



R&D Energy Savings Opportunity by Subsector (with Extrapolation to Subsector Totals)

* All Other NAICS 325 includes all other chemicals in the chemical manufacturing sector (including Other Basic Inorganic Chemicals and Other Miscellaneous Chemicals Subsectors)

Figure 6-2. Current and R&D Energy Savings Opportunities by Chemical Subsector Based on Extrapolated Data from the 64 Chemicals Studied (Energy Savings Per Year in TBtu)

The PM energy savings opportunity is different than SOA energy savings opportunity in that the scope of the R&D technologies contributing energy savings can essentially be boundless. Putting aside obvious financial, timing, and resource limitations, the process improvements and increased energy efficiency that can be gained through unproven technology is speculative. For this reason, a range is used to represent the potential onsite PM energy consumption, PM energy savings, and PM energy savings percent in Table 6-4. The upper limit of the PM energy consumption range is assumed to be equal to the SOA energy consumption. The lower limit of the PM energy consumption range was estimated using the method explained in Section 6.2. The lower limit is shown as a dashed line with color fading in the summary figures that present subsector and sector-wide data. This is done because the PM is speculative and depends on unproven R&D technologies; furthermore, the potential energy savings opportunity could be bigger if additional unproven technologies were considered.

The Other Basic Inorganic Chemicals subsector and the All Other Miscellaneous Chemicals subsector have insufficient percent coverage among the chemicals studied and, therefore, a different extrapolation method was used. Additionally, the PM energy consumption was estimated for the remainder of the chemicals sector (i.e., the chemicals that are not included in these two subsectors and the 10 subsectors referenced above). These additional chemicals, as well as the Other Basic Inorganic Chemicals subsector and the All Other Miscellaneous Chemicals subsector, are together referred to as All Other NAICS 325 Chemicals in **Table 6-4**.

The extrapolation for All Other NAICS 325 Chemicals was done by applying the overall PM energy savings percent (see Table 6-4, 50% PM energy savings percent) to the CT energy consumption (multiplying CT energy consumption by 50% (100%-50%)) in order to calculate the extrapolated lower limit of PM energy consumption. Thus, the extrapolated PM energy consumption of All Other NAICS 325 Chemicals shown in Table 6-4 is 50% less than the CT energy consumption.

Also in Table 6-4, the subsectors are summed to provide an estimated sector-wide onsite PM energy consumption range based on extrapolated data from the chemicals studied. The estimated overall onsite PM energy savings opportunity for U.S. chemical manufacturing ranges from 19-49% over onsite CT energy consumption.

6.3.1. Ethylene Savings

Steam cracking is the most energy intensive chemical manufacturing process. Its energy intensity depends on the feedstock (whether ethane or naphtha) and which product petrochemicals are favored. The major chemical produced is generally ethylene, but propylene, butylenes, benzene, toluene and xylenes can all be produced by this process. Within a steam cracker, there are three major processes: pyrolysis, primary fractionation, and product recovery/fractionation. The ethylene energy savings opportunities and values presented below in this Section are summarized from (Ren et al. 2006); the savings presented by Ren et al. 2006 below do not appear in the bandwidth intensity and consumption values in Appendix A1a and Appendix A1b.

Catalytic processes are being investigated to reduce energy consumption of ethylene production. In these novel catalytic pyrolysis processes, the feed stream is heated before passing over a catalyst which causes the molecules to break up resulting in lighter olefin molecules. The energy consumption of the pyrolysis section could be reduced with circulating beds, greater control of the radiant coils, coatings that reduce coking, and the use of advanced furnace materials. Coupled together, these technologies could result in savings of 860-1,290 Btu/lb of ethylene over the CT values (Ren et al. 2006). Gas turbines can also be integrated into the process to generate steam, electricity and hot combustion gases. By itself, it would save 1,290 Btu/lb of ethylene over SOA, and 1,620 Btu/lb if combined with advanced furnace materials (Ren et al. 2006).

In primary fractionation/compression, which only occurs with naphtha and gas oil feeds, the olefins are separated from the unreacted feed streams by cooling and compression. Additionally, liquid benzene, toluene, and xylene (BTX) is also collected separately in this process. In product recovery/fractionation, the remaining gaseous olefins are separated using distillation and refrigeration. The use of mechanical vapor recompression could lead to savings of about 430 Btu/lb of ethylene. Advanced distillation columns, such as the Heat Integrated Distillation Column (HiDiC), which improve heat transfer can save between 60-90% of the energy consumed in a distillation column with heat pumps (amounts to 6.5Btu/lb of ethylene) (Ren et al. 2006). Membranes can also be used for separation with a projected energy savings of 645 Btu/lb of ethylene (Ren et al. 2006). Lastly, plant integration of the refrigeration step with cryogenic fractionation of gases could save 430 Btu/lb of ethylene (Ren et al. 2006). Given decreasing returns from the efficiency overlaps, these savings are expected to save 1,290 Btu/lb of ethylene over SOA.

Alternative technology improvements can also be made to steam cracking. Ethane oxidative dehydrogenation can reduce total energy by 35% (~1,290-2,150 Btu/lb) compared to SOA, including the cost of oxygen production (Ren et al. 2006). However, this process does produce 15% more carbon dioxide emissions, which could likely be offset by cleaner electricity production used to produce oxygen. The catalytic pyrolysis process could save approximately 20% of SOA (1,620 Btu/lb) because of its lower operational temperature and the lack of need to produce naphtha feedstock(Ren et al. 2006).When this 20% savings over SOA is applied, the resulting ethylene PM energy intensity value is 5,159 Btu/lb.

7. Thermodynamic Minimum Energy Consumption for U.S. Chemical Manufacturing

Real world chemical manufacturing does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture a chemical can provide a more complete understanding of opportunities for energy savings. This baseline can be used to establish more realistic projections of what future energy savings can be achieved. This Chapter presents the thermodynamic minimum (TM) energy consumption required to manufacture the chemicals studied and for the entire sector.

7.1. THERMODYNAMIC MINIMUM ENERGY

TM energy consumption is the calculated minimum amount of energy theoretically needed to produce a chemical product assuming ideal conditions that are typically unachievable in real-world applications; in some cases, it is less than zero. TM energy consumption assumes all the energy is used productively and there are no energy losses. It is based on the Gibbs Free Energy (ΔG) equation under ideal conditions for a chemical reaction. Some chemical production processes are net producers of energy (i.e., exothermic processes); this created energy was considered in this analysis.

While TM energy intensity is process independent, it is directly related to the relative energy levels of the substrate reactants and the products. All elemental forms are assigned to zero energy (reference state), with lower energy values being more favored thermodynamically. Those with negative values are exothermic processes that generate energy when they are formed. However, they do not form spontaneously because there are higher energy state intermediates limiting the formation of the chemical. The production of these chemicals can be favored by any number of mechanisms including, but not limited to, acids/bases, temperature, or catalysts.

7.2. CALCULATED THERMODYNAMIC MINIMUM FOR INDIVIDUAL CHEMICALS

Appendix A1a presents the onsite TM energy consumption for the 74 chemicals considered in this bandwidth study in alphabetical order. Appendix A1b presents the onsite TM energy consumption for the 74 chemicals grouped by subsector. The TM energy intensities are based on the most common chemical synthesis pathway. For a given chemical product, the TM energy intensity is multiplied by the annual U.S. production to determine the total onsite TM energy consumption (the energy intensity and production data are also presented in Appendix A1a and A1b). Table 7-1 presents the references for the TM energy intensity values. Appendix A2 provides the references for the TM energy intensity data for each individual chemical.

Table 7-1. Published Sources Reviewed to Identify Thermodynamic Minimum Energy Intensities for the 74 Chemicals Studied

Source	Description
DOE 2006	Based on calculations of ΔG from data in Aspen models and exergy studies.
Updated calculations from peer reviewer	Based on calculations of ΔG from data in Aspen models
Calculations from Dharik Mallapragada and Dr. Rakesh Agrawal at Purdue University	Calculated from calculations of ΔG from data in HSC Chemistry 5.1 and Aspen Properties
Internal calculations	Calculations based on change in ΔG of bonds

Chemical production can at times result in net energy gain through exothermic processes; this is the case for several chemicals studied (e.g., sulfuric acid). For exothermic chemical processes, a zero baseline would result in negative percent savings, a physical impossibility. TM energy consumption was instead referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for SOA and PM are as follows:

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

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

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

7.3. Thermodynamic Minimum Energy Consumption By Subsector and Sector-wide

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

Table 7-2 provides the TM energy consumption for the 64 chemicals studied grouped by subsector (excluding feedstock energy); 10 chemicals are omitted to avoid double counting and other issues as explained in Table 4-6. In theory, if heat generating processes could be carefully coupled with heat consuming processes, this could greatly offset the energy usage in chemical manufacturing overall. It is an imperative to keep in mind that ideal conditions are largely unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities.

Table 7-2 also presents the TM energy consumption extrapolated to provide estimates for the entire subsector. The extrapolation for all of the subsectors listed in Table 7-2, except for the All Other NAICS 325 Chemicals, is done with the same methodology as for SOA energy consumption and PM energy consumption (as explained in Section 5.3 and 6.3). For All Other NAICS 325 Chemicals, the TM energy consumption is assumed to be zero (therefore, the TM energy savings percent for the subsectors and sector-wide was not calculated).

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 chemicals studied have a negative TM energy intensity.

Table 7-2. Thermodynamic Minimum Energy Consumption by Subsector and Sector-wide for the 64 Chemicals Studied and Extrapolated to Subsector Total

Subsector	NAICS Code	Onsite TM Energy Consumption for 64 Chemicals Studied (TBtu/year)	Onsite TM Energy Consumption for Total Subsector (extrapolated) (TBtu/year)
Petrochemicals	325110	75	77†
Industrial Gases	325120	-99	-145†
Alkalies and Chlorine	325181	25	27†
Carbon Black	325182	-3	-3†
Cyclic Crudes and Intermediates	325192	-49	-85†
Ethyl Alcohol	325193	-107	-107†
Other Basic Organic Chemicals	325199	-67	-146†
Plastics Materials and Resins	325211	-107	-338†
Nitrogenous Fertilizers	325311	2	2†
Phosphatic Fertilizers	325312	-15	-27†
All Other NAICS 325 Chemicals		-235*	0**
Total for 64 Chemicals Studied		**-579**	
Total for Chemicals Sector-wide	**325**		**-745**

Thermodynamic minimum (TM)

† Estimates for the entire subsector were extrapolated by dividing the onsite TM energy consumption for the chemicals studied within the subsector by the % coverage.

**Estimate includes Other Basic Inorganic Chemicals (NAICS 325188) because of underrepresentation of chemicals studied in this subsector, as well as All Other Miscellaneous Chemicals (NAICS 325998) because the energy consumption for this subsector is not identified in MECS.*

*** TM energy consumption is assumed to be 0 for All Other NAICS 325 Chemicals.*

8. U.S. Chemical Manufacturing Energy Bandwidth Summary

This Chapter presents the energy savings bandwidths for chemicals subsectors and sector-wide based on the analysis and data presented in the previous Chapters and the Appendices. Data is presented for the 64 chemicals studied and extrapolated to estimate the energy savings potential for all of U.S. chemical manufacturing.

8.1. CHEMICAL BANDWIDTH PROFILE

Table 8-1 presents the *current opportunity* and *R&D opportunity* energy savings by subsector for the 64 chemicals studied and extrapolated to estimate the subsector totals. The subsector totals are summed to provide a sector-wide estimate. The data for the 64 chemicals was aggregated into subsectors. The energy savings data was extrapolated to account for the chemicals in a subsector that were not studied, as explained in Section 5.2 (SOA) and 6.3 (PM). Each row in Table 8-1 shows the opportunity bandwidth for a specific chemicals subsector and sector-wide. Opportunity bandwidths for individual chemicals can be calculated from the data in Appendix A1a or Appendix A1b.

As shown in Figure 8-1, four hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). To manufacture the 64 chemicals studied, the analysis shows the following:

- *Current Opportunity* – 450 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 758 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

To manufacture all the chemicals of the U.S. chemicals sector (based on extrapolated data), the analysis shows the following:

- *Current Opportunity* – 766 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 1,221 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 8-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual chemicals subsectors based on extrapolated data. The area between *current* and *R&D opportunity* is shown as a dashed line with color fading because the PM energy savings impacts are speculative and based on unproven technologies.

Table 8-1. Current Opportunity and R&D Opportunity Energy Savings by Subsector for the 64 Chemicals Studied and Extrapolated to Subsector Total

Subsector	NAICS Code	Current Opportunity for 64 Chemicals Studied (CT-SOA) (TBtu/year)	Current Opportunity for Total Subsector (extrapolated) (CT-SOA) (TBtu/year)	R&D Opportunity for 64 Chemicals Studied (SOA-PM) (TBtu/year)	R&D Opportunity for Total Subsector (extrapolated) (SOA-PM) (TBtu/year)
Petrochemicals	325110	99	102	108	111
Industrial Gases	325120	9	13	51	75
Alkalies and Chlorine	325181	39	42	47	50
Carbon Black	325182	7	7	<1	<1
Cyclic Crudes and Intermediates	325192	5	9	37	65
Ethyl Alcohol	325193	36	36	228	228
Other Basic Organic Chemicals	325199	101	220	87	190
Plastics Materials and Resins	325211	45	141	75	236
Nitrogenous Fertilizers	325311	66	66	31	31
Phosphatic Fertilizers	325312	2	4	13	24
All Other NAICS 325 Chemicals		42*	127	79*	210
Total for Chemicals Studied		**450**		**758**	
Total for Chemicals Sector-wide	**325**		**766**		**1,221**

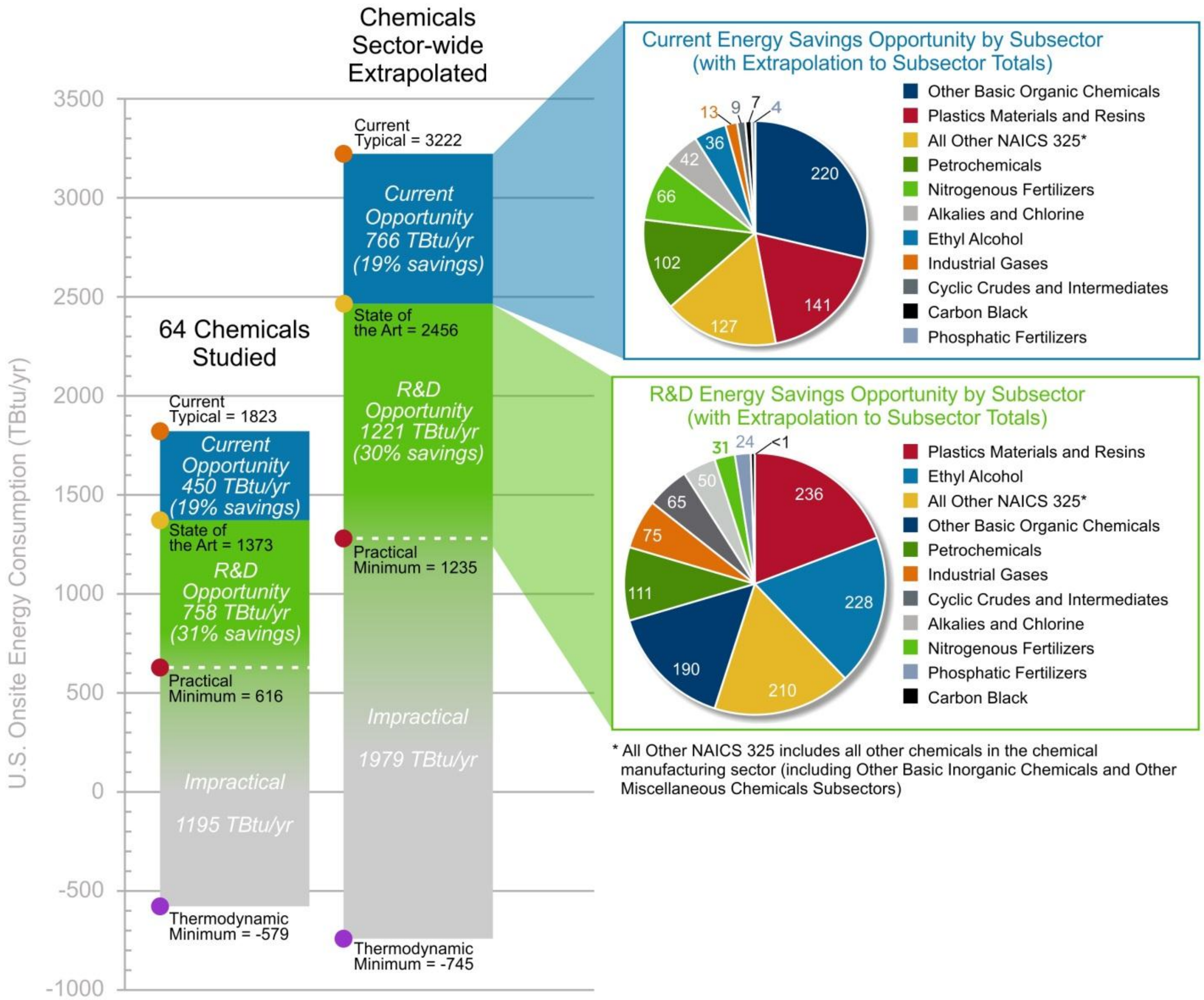
Current Typical (CT), State of the Art (SOA),Practical Minimum (PM)

**All Other NAICS 325 Chemicals includes underrepresented subsectors (Other Basic Inorganic Chemicals and All Other Miscellaneous Chemicals).*

The greatest *current* energy savings opportunity for chemicals comes from upgrading production methods in the Other Basic Organic Chemicals and Petrochemicals subsectors. The greatest *R&D* energy savings opportunity for chemicals comes from the Ethyl Alcohol (ethanol) and Plastics Materials and Resins subsectors.

The *impractical* bandwidth represents the energy savings potential that would require fundamental changes in the formation of chemical products. It is the difference between PM energy consumption and TM energy consumption. The term *impractical* is used because the significant research investment required based on today's knowledge would no longer be practical because of the thermodynamic limitations.

Because many of chemicals studied have negative TM energy intensities, the TM energy consumption needed to manufacture chemicals sector-wide is negative (as shown in Figure 8-1). 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.



* All Other NAICS 325 includes all other chemicals in the chemical manufacturing sector (including Other Basic Inorganic Chemicals and Other Miscellaneous Chemicals Subsectors)

Figure 8-1. Current and R&D Energy Savings Opportunities in U.S. Chemical Manufacturing for the 64 Chemicals Studied and for Sector-Wide based on Extrapolated Data

Figure 8-2 shows the bandwidth summaries for the top 10 energy consuming chemicals. The TM energy consumption for five of the 10 chemicals (ethanol, benzene, soda ash, ethylene dichloride, and sodium hydroxide) is a negative value. For most of these chemicals, there is a large range between PM energy consumption and TM energy consumption (representing the *impractical*). Although the TM energy consumption is negative for some, the PM energy consumption is positive.

For the *current opportunity* (or the energy savings between CT and SOA), ammonia has the greatest energy savings opportunity. The largest area for *R&D opportunity* (or energy savings between SOA energy consumption and PM energy consumption), exists for the production of ethanol. There is a relatively small difference between CT energy consumption and PM energy consumption for nitrogen. The reason why nitrogen is a part of the top 10 energy consuming chemicals is due to the large annual production volumes.

Figure 8-3 shows the bandwidth summaries for the chemicals subsectors (extrapolated values) presented in order of highest CT energy consumption. As explained in Table 4-6, 10 of the chemicals studied were excluded in these totals. The Petrochemicals subsector is the largest energy consuming subsector in chemicals manufacturing. If the lower limit of PM energy consumption could be reached, this would save about 207 TBtu/year compared to CT, amounting to 6% of CT energy consumption for the entire chemicals sector. Other subsectors, such as Carbon Black, Phosphatic Fertilizers, Industrial Gases, and Cyclic Crudes and Intermediates, have a much smaller difference between CT energy consumption and the PM energy consumption. Figure 8-3 shows the relative size of the *current* and *R&D opportunity* energy savings potential for each subsector.

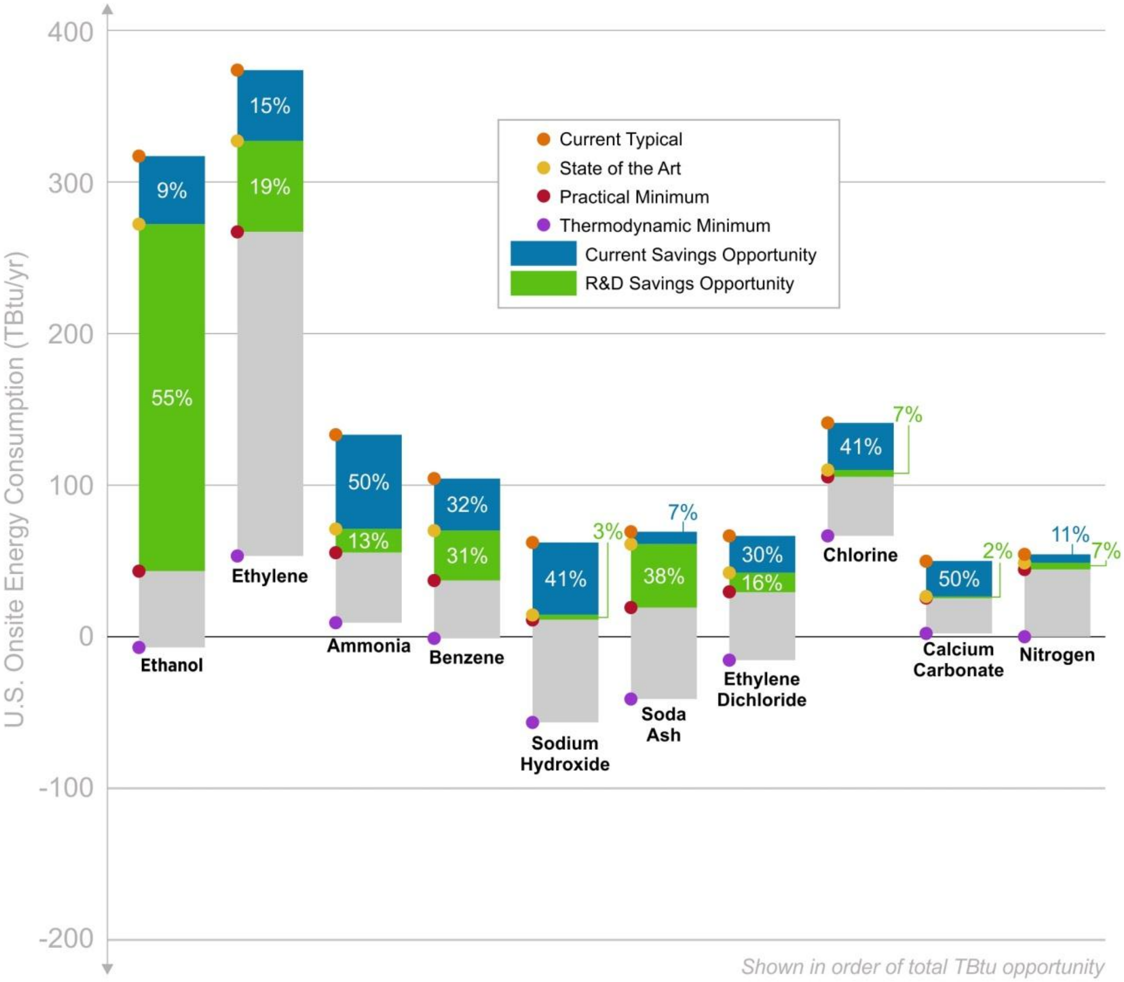


Figure 8-2. Energy Band Summaries for the Top 10 Energy Consuming Chemicals

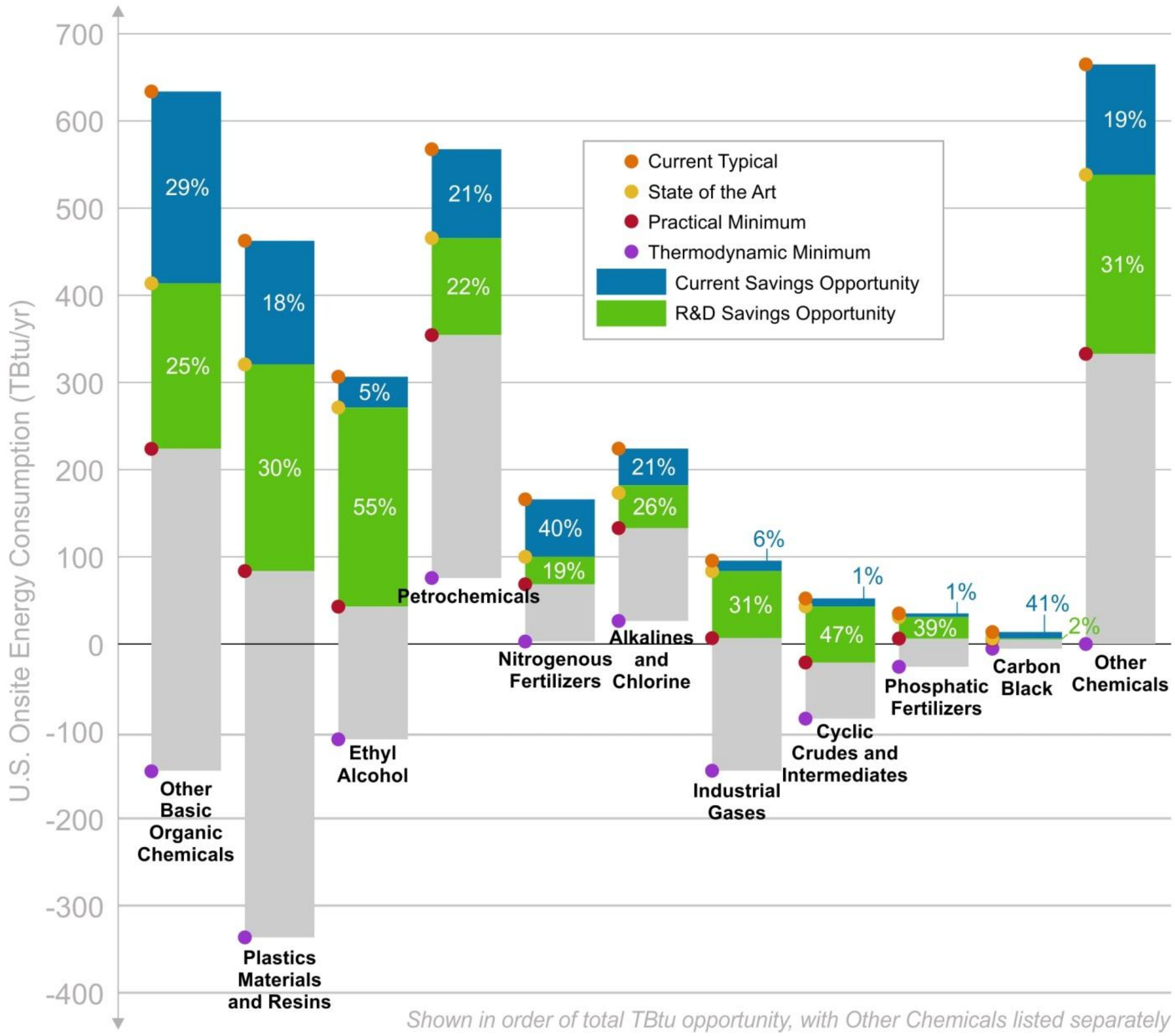


Figure 8-3. Current and R&D Opportunity Energy Savings Bandwidths for the Chemical Subsectors Based on Extrapolated Data from the 64 Chemicals Studied (with Percent of Overall Energy Consumption Bandwidth)

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USCB 2014	North American Industry Classification System, U.S. Census Bureau. 2014. www.census.gov/eos/www/naics/index.html

Appendix A1a: Master Chemicals Table – by Chemical

Table A1a. U.S. Production Volume of 74 Select Chemicals in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

NAICS Code	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy Consumption (TBtu/year)			
			CT	SOA	PM Lower Limit	TM[a]	CT	SOA	PM Lower Limit	TM
325199	Acetic Acid	4,366	2,552	1,978	1,204	436	11	9	5	2
325199	Acetic Anhydride	1,798	2,785	2,450	578	-2,045	5	4	1	-4
325199	Acetone	3,178	7,717	4,299	2,073	-1,143	25	14	7	-4
325199	Acrylic Acid	2,723	9,009	7,883	4,073	-1,792	25	21	11	-5
325199	Acrylonitrile	2,505	626	-2,021	-3,286	-5,516	2	-5	-8	-14
325188	Aluminum Sulfate	1,906	1,250	1,094	608	-156	2	2	1	0
325311	Ammonia	22,691	5,847	3,138	2,402	414	133	71	55	9
325311	Ammonium Nitrate	15,166	341	39	21	-502	5	1	<0.5	-8
325312	Ammonium Phosphates (Other)	3,053	323	283	66	-240	1	1	<0.5	-1
325311	Ammonium Sulfate	5,729	4,000	3,500	1,849	-706	23	20	11	-4
325192	Aniline	2,348	-980	-1,120	-1,489	-2,093	-2	-3	-3	-5
325110	Benzene	13,274	7,868	5,288	2,812	-69	104	70	37	-1
325192	Bisphenol A	1,610	9,410	8,234	4,885	-491	15	13	8	-1
325110	Butadiene	3,484	7,868	5,288	2,534	-505	27	18	9	-2
325110	Butylenes	2,110	1,677	989	681	-502	4	2	1	-1
325188	Calcium Carbonate	24,282	2,046	1,069	1,043	100	50	26	25	2
325188	Calcium Chloride	2,204	3,882	3,396	981	-2,465	9	7	2	-5
325199	Caprolactam	1,530	13,185	-344	-345	-366	20	-1	-1	-1
325182	Carbon Black	3,415	3,845	1,935	1,861	-803	13	7	6	-3
325120	Carbon Dioxide	17,365	320	280	-1,587	-3,854	6	5	-28	-67
325181	Chlorine	21,465	6,578	5,116	4,882	3,086	141	110	105	66
325110	Cumene	7,626	520	-430	N/A	N/A	4	-3	N/A	N/A

Table A1a. U.S. Production Volume of 74 Select Chemicals in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

NAICS Code	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy Consumption (TBtu/year)			
			CT	SOA	PM Lower Limit	TM[a]	CT	SOA	PM Lower Limit	TM
325192	Cyclohexane	3,462	-559	-688	-1,382	-2,360	-2	-2	-5	-8
325192	Cyclohexanone	3,031	68	60	-2,656	-5,893	<0.5	<0.5	-8	-18
325312	Diammonium Phosphate	17,503	323	283	66	-240	6	5	1	-4
325193	Ethanol	66,080	4,646	4,105	652	-1,624	307	271	43	-107
325110	Ethylbenzene	9,349	1,174	1,027	600	273	11	10	6	3
325110	Ethylene	52,864	7,071	6,187	5,047	998	374	327	267	53
325199	Ethylene Dichloride	19426	3,410	2,150	1,493	-784	66	42	29	-15
325199	Ethylene Glycol	2,867	2,045	1,935	478	-415	6	6	1	-1
325199	Ethylene Oxide	5,876	1,916	1,419	1,163	734	11	8	7	4
325199	Formaldehyde	3,050	-2,514	-2,873	N/A	N/A	-8	-9	N/A	N/A
325188	Hydrochloric Acid	7,840	178	156	-417	-1,124	1	1	-3	-9
325120	Hydrogen	6,591	949	568	-1,713	-4,876	6	4	-11	-32
325188	Hydrogen Peroxide	852	6,965	6,094	3,084	-1,528	6	5	3	-1
325199	Isobutylene	8,769	3,261	2,853	1,795	54	29	25	16	<0.5
325199	Isopropanol	1,662	4,693	4,600	2,144	-50	8	8	4	<0.5
325199	Methanol	2,024	4,901	4,041	3,167	802	10	8	6	2
325199	Methyl Chloride	1,330	839	734	401	-250	1	1	1	<0.5
325199	Methyl Methacrylate	1,529	3,483	3,048	1,523	-6,359	5	5	2	-10
325998	Methyl tert-Butyl Ether	3,386	1,871	1,637	1,073	124	6	6	4	<0.5
325312	Monoammonium Phosphate	9,245	323	283	66	-240	3	3	1	-2
325311	Nitric Acid	15,280	267	-1,032	N/A	N/A	4	-16	N/A	N/A
325192	Nitrobenzene	3,020	576	504	184	-281	2	2	1	-1
325120	Nitrogen	69,609	774	688	635	0	54	48	44	0
325120	Oxygen	58,287	774	688	635	0	45	40	37	0

Table A1a. U.S. Production Volume of 74 Select Chemicals in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

NAICS Code	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy Consumption (TBtu/year)			
			CT	SOA	PM Lower Limit	TM[a]	CT	SOA	PM Lower Limit	TM
325192	Phenol	4,652	3,661	3,203	-936	-3,556	17	15	-4	-17
325312	Phosphoric Acid	20,678	482	422	82	-394	10	9	2	-8
325211	Polycarbonate	1,862	6,707	4,944	1,444	46	13	9	3	<0.5
325211	Polyester	2,525	12,128	10,612	3,069	-1,044	31	27	8	-3
325211	Polyethylene Terephthalate	9,230	2,291	897	234	-1,044	21	8	2	-10
325211	Polyethylene, High Density	16,889	1,037	817	191	-1,744	18	14	3	-30
325211	Polyethylene, Linear Low Density	13,787	871	860	221	-1,122	12	12	3	-16
325211	Polyethylene, Low Density	6,741	1,143	602	129	-1,744	8	4	1	-12
325211	Polypropylene	17,258	616	430	94	-1,163	11	7	2	-20
325211	Polystyrene	5,055	2,264	387	100	-470	11	2	1	-2
325211	Polystyrene, High Impact	1,873	636	557	150	-470	1	1	<0.5	-1
325211	Polyurethane	4,143	138	121	30	188	1	1	<0.5	-1
325211	Polyvinyl Chloride	14,019	1,463	1,161	313	-969	21	16	4	-14
325110	Propylene	31,057	1,351	989	985	846	42	31	31	26
325199	Propylene Oxide	4,470	2,567	2,246	966	54	11	10	4	<0.5
325181	Soda Ash	23,373	2,966	2,623	809	-1,754	69	61	19	-41
325181	Sodium Hydroxide	16,581	3,765	835	690	-3,349	62	14	11	-56
325188	Sodium Hypochlorite	11,589	592	518	311	-23	7	6	4	<0.5
325188	Sodium Silicates	2,624	2,298	332	-1,114	-5,168	6	1	-3	-14
325110	Styrene	9,179	3,777	3,697	2,214	340	35	34	20	3
325188	Sulfur	20,123	-2,414	-2,759	N/A	N/A	-49	-56	N/A	N/A
325188	Sulfuric Acid	71,687	-900	-1,024	-1,814	-2,900	-65	-73	-130	-208
325199	Terephthalic Acid	7,221	2,217	1,247	-138	-2,937	16	9	-1	-21
325311	Urea	11,292	843	731	326	-289	10	8	4	-3

Table A1a. U.S. Production Volume of 74 Select Chemicals in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

NAICS Code	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy Consumption (TBtu/year)			
			CT	SOA	PM Lower Limit	TM[a]	CT	SOA	PM Lower Limit	TM
325199	Vinyl Acetate	3,054	3,611	2,494	1,656	-1,060	11	8	5	-3
325199	Vinyl Chloride	14,159	2,103	1,333	948	142	30	19	13	2
325110	Xylenes, Mixed	13,869	1,255	989	249	-324	17	14	3	-4
325110	Xylenes, Paraxylene	7,520	2,541	2,223	926	5	19	17	7	<0.5

[a] *Based on previous bandwidth, peer review, and author calculations*

The four bandwidth measures are Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), and Thermodynamic Minimum (TM).

Appendix A1b: Master Chemicals Table – by Subsector

Table A1b. U.S. Production Volume of 74 Select Chemicals in 2010 Grouped by Subsector with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Energy Used as Feedstocks)

Subsector	**Chemical**	**2010 Production** (million lb)	**Energy Intensity** (Btu/lb)				**Calculated Onsite Energy** (TBtu/year)			
			CT	**SOA**	**PM (lower limit)**	**TM**	**CT**	**SOA**	**PM (lower limit)**	**TM**
Petrochemicals (NAICS 325110)	Benzene	13,274	7,868	5,288	2,812	-69	104	70	37	-1
	Butadiene	3,484	7,868	5,288	2,534	-505	27	18	9	-2
	Butylenes	2,110	1,677	989	681	-502	4	2	1	-1
	Cumene	7,626	520	-430	N/A	N/A	4	-3	N/A	N/A
	Ethylbenzene	9,349	1,174	1,027	600	273	11	10	6	3
	Ethylene	52,864	7,071	6,187	5,047	998	374	327	267	53
	Propylene	31,057	1,351	989	249	846	42	31	3	26
	Styrene	9,179	3,777	3,697	985	340	35	34	31	3
	Xylenes, Mixed	13,869	1,255	989	926	-324	17	14	7	-4
	Xylenes, Paraxylene	7,520	2,541	2,223	2,214	5	19	17	20	<0.5
	Total for Subsector, Chemicals Studied (excludes butadiene, cumene, xylenes – p, styrene) *						552	453	345	75
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						568	466	355	77
Industrial Gases (NAICS 325120)	Carbon Dioxide	17,365	320	280	-1,587	-3,854	6	5	-28	-67
	Hydrogen	6,591	949	568	-1,713	-4,876	6	4	-11	-32
	Nitrogen	69,609	774	688	635	0	54	48	44	0
	Oxygen	58,287	774	688	635	0	45	40	37	0
	Total for Subsector, Chemicals Studied (excludes oxygen) *						66	56	5	-99
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						96	83	8	-145

Table A1b. U.S. Production Volume of 74 Select Chemicals in 2010 Grouped by Subsector with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Energy Used as Feedstocks)

Subsector	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy (TBtu/year)			
			CT	SOA	PM (lower limit)	TM	CT	SOA	PM (lower limit)	TM
Alkalies and Chlorine (NAICS 325181)	Chlorine	21,465	6,578	5,116	4,882	3,086	141	110	105	66
	Soda Ash	23,373	2,966	2,623	809	-1,754	69	61	19	-41
	Sodium Hydroxide	16,581	3,765	835	690	-3,349	62	14	11	-56
	Total for Subsector, Chemicals Studied (excludes sodium hydroxide) *						211	171	124	25
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						224	182	132	27
Carbon Black (NAICS 325182)	Carbon Black	3,415	3,845	1,935	1,861	-803	13	7	6	-3
	Total for Subsector, Chemicals Studied						13	7	6	-3
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						13	7	6	-3
Other Basic Inorganic Chemicals (NAICS 325188)	Aluminum Sulfate	1,906	1,250	1,094	608	-156	2	2	1	<0.5
	Calcium Carbonate	24,282	2,046	1,069	1,043	100	50	26	25	2
	Calcium Chloride	2,204	3,882	3,396	981	-2,465	9	7	2	-5
	Hydrochloric Acid	7,840	178	156	-417	-1,124	1	1	-3	-9
	Hydrogen Peroxide	852	6,965	6,094	3,084	-1,528	6	5	3	-1
	Sodium Hypochlorite	11,589	592	518	311	-23	7	6	4	<0.5
	Sodium Silicates	2,624	2,298	332	-1,114	-5,168	6	1	-3	-14
	Sulfur	20,123	-2,414	-2,759	N/A	N/A	-49	-56	N/A	N/A
	Sulfuric Acid	71,687	-900	-1,024	-1,814	-2,900	-65	-73	-130	-208
	Total for Subsector, Chemicals Studied (excludes sulfur) *						16	-25	-101	-235
	Subsector Not Extrapolated Due to Insufficient Coverage						NA	NA	NA	NA

Table A1b. U.S. Production Volume of 74 Select Chemicals in 2010 Grouped by Subsector with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Energy Used as Feedstocks)

Subsector	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy (TBtu/year)			
			CT	SOA	PM (lower limit)	TM	CT	SOA	PM (lower limit)	TM
Cyclic Crudes and Intermediates (NAICS 325192)	Aniline	2,348	-980	-1,120	-1,489	-2,093	-2	-3	-3	-5
	Bisphenol A	1,610	9,410	8,234	4,885	-491	15	13	8	-1
	Cyclohexane	3,462	-559	-688	-1,382	-2,360	-2	-2	-5	-8
	Cyclohexanone	3,031	68	60	-2,656	-5,893	<0.5	<0.5	-8	-18
	Nitrobenzene	3,020	576	504	184	-281	2	2	1	-1
	Phenol	4,652	3,661	3,203	-936	-3,556	17	15	-4	-17
	Total for Subsector, Chemicals Studied						30	25	-12	-49
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						52	43	-21	-85
Ethyl Alcohol (NAICS 325193)	Ethanol	66,080	4,646	4,105	652	-1,624	307	271	43	-107
	Total for Subsector, Chemicals Studied						307	271	43	-107
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						307	271	43	-107
Other Basic Organic Chemicals (NAICS 325199)	Acetic Acid	4,366	2,552	1,978	1,204	436	11	9	5	2
	Acetic Anhydride	1,798	2,785	2,450	578	-2,045	5	4	1	-4
	Acetone	3,178	7,717	4,299	2,073	-1,143	25	14	7	-4
	Acrylic Acid	2,723	9,009	7,883	4,073	-1,792	25	21	11	-5
	Acrylonitrile	2,505	626	-2,021	-3,286	-5,516	2	-5	-8	-14
	Caprolactam	1,530	13,185	-344	-345	-366	20	-1	-1	-1
	Ethylene Dichloride	19426	3,410	2,150	1,493	-784	66	42	29	-15
	Ethylene Glycol	2,867	2,045	1,935	478	-415	6	6	1	-1
	Ethylene Oxide	5,876	1,916	1,419	1,163	734	11	8	7	4
	Formaldehyde	3,050	-2,514	-2,873	N/A	N/A	-8	-9	N/A	N/A

Table A1b. U.S. Production Volume of 74 Select Chemicals in 2010 Grouped by Subsector with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Energy Used as Feedstocks)

Subsector	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy (TBtu/year)			
			CT	SOA	PM (lower limit)	TM	CT	SOA	PM (lower limit)	TM
	Isobutylene	8,769	3,261	2,853	1,795	54	29	25	16	<0.5
	Isopropanol	1,662	4,693	4,600	2,144	-50	8	8	3	<0.5
	Methanol	2,024	4,901	4,041	3,167	802	10	8	6	2
	Methyl Chloride	1,330	839	734	401	-250	1	1	1	<0.5
	Methyl Methacrylate	1,529	3,483	3,048	1,523	-6,359	5	5	2	-10
	Propylene Oxide	4,470	2,567	2,246	966	54	11	10	4	<0.5
	Terephthalic Acid	7,221	2,217	1,247	-138	-2,937	16	9	-1	-21
	Vinyl Acetate	3,054	3,611	2,494	1,656	-1,060	11	8	5	-3
	Vinyl Chloride	14,159	2,103	1,333	948	142	30	19	13	2
	Total for Subsector, Chemicals Studied (excludes formaldehyde) *						291	190	103	-67
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						634	414	224	-146
Plastics Materials and Resins (NAICS 325211)	Polycarbonate	1,862	6,707	4,944	1,444	46	12	9	3	<0.5
	Polyester	2,525	12,128	10,612	3,069	-1,044	31	27	8	-3
	Polyethylene Terephthalate	9,230	2,291	897	234	-1,044	21	8	2	-10
	Polyethylene, High Density	16,889	1,037	817	191	-1,744	18	14	3	-30
	Polyethylene, Linear Low Density	13,787	871	860	221	-1,122	12	12	3	-16
	Polyethylene, Low Density	6,741	1,143	602	129	-1,744	8	4	1	-12
	Polypropylene	17,258	616	430	94	-1,163	11	7	2	-20
	Polystyrene	5,055	2,264	387	100	-470	11	2	1	-1
	Polystyrene, High Impact	1,873	636	557	150	-470	1	1	<0.5	-1

Table A1b. U.S. Production Volume of 74 Select Chemicals in 2010 Grouped by Subsector with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Energy Used as Feedstocks)

Subsector	Chemical	2010 Production (million lb)	Energy Intensity (Btu/lb)				Calculated Onsite Energy (TBtu/year)			
			CT	SOA	PM (lower limit)	TM	CT	SOA	PM (lower limit)	TM
	Polyurethane	4,143	138	121	30	-188	1	1	<0.5	1
	Polyvinyl Chloride	14,019	1,463	1,161	313	-969	21	16	4	-14
	Total for Subsector, Chemicals Studied						146	101	27	-107
	Total for Subsector, CT from MECS, Extrapolated for SOA, PM, TM						462	321	84	-338
Nitrogenous Fertilizers (NAICS 325311)	Ammonia	22,691	5,847	3,138	2,402	414	133	71	55	9
	Ammonium Nitrate	15,166	341	39	21	-502	5	1	<0.5	-8
	Ammonium Sulfate	5,729	4,000	3,500	1,849	-706	23	20	11	-4
	Nitric Acid	15,280	267	-1,032	N/A	N/A	4	-16	N/A	N/A
	Urea	11,292	843	731	326	-289	10	8	4	-3
	Total for Subsector, Chemicals Studied (excludes ammonium nitrate, nitric acid) *						165	100	69	2
	Subsector, CT from MECS, Extrapolated for SOA, PM, TM						166	100	69	2
Phosphatic Fertilizers (NAICS 325312)	Ammonium Phosphates (Other)	3,053	323	283	66	-240	1	1	<0.5	-1
	Diammonium Phosphate	17,503	323	283	66	-240	6	5	1	-4
	Monoammonium Phosphate	9,245	323	283	66	-240	3	3	1	-2
	Phosphoric Acid	20,678	482	422	82	-394	10	9	2	-8
	Total for Subsector, Chemicals Studied						20	17	4	-15
	Subsector, CT from MECS, Extrapolated for SOA, PM, TM						35	31	7	-27
All Other Miscellaneous Chemical Products (NAICS 325998)	Methyl tert-Butyl Ether	3,386	1,871	1,637	1,073	124	6	6	4	<0.5
	Total for Subsector, Chemicals Studied						6	6	4	<0.5
	Subsector Not Extrapolated Due to Insufficient Coverage									

** Excluded due to double-counting and other anomalies as explained in Chapter 1*

The four bandwidth measures are Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), and Thermodynamic Minimum (TM).

Appendix A2: References for U.S. Production Data of the 74 Select Chemicals Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

Table A2. References for U.S. Production Data of the 74 Select Chemicals Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

NAICS Code	Chemical	Production Reference	CT Energy Intensity Reference	SOA Energy Intensity Reference	TM Energy Intensity Reference
325199	Acetic Acid	Estimate based on ACC 2012 and CEH 2011a	LBNL 2008	IEA 2009	DOE 2006
325199	Acetic Anhydride	CEH 2010a (data for 2008)	DOE 2001	DOE 2001	Internal Calculations
325199	Acetone	CEH 2011a	LBNL 2008	IEA 2009	Internal Calculations
325199	Acrylic Acid	CEH 2011b	PEP 2002	Calculated as 12.5% savings on CT	Internal Calculations
325199	Acrylonitrile	ACC 2011	LBNL 2008	IEA 2009	Internal Calculations
325188	Aluminum Sulfate	ACC 2009 (data for 2008)	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations
325311	Ammonia	ACC 2012	Neelis et al. 2005	IEA 2009	DOE 2006
325311	Ammonium Nitrate	C&EN 2011	Energetics 2000	IPPC 2007a	DOE 2006
325312	Ammonium Phosphates (Other)	USCB 2011a	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations
325311	Ammonium Sulfate	C&EN 2011	Energetics 2000	Calculated as 12.5% savings on CT	DOE 2006
325192	Aniline	ACC 2012	Neelis et al. 2005	Calculated as 12.5% savings on CT	DOE 2006
325110	Benzene	ACC 2012	IEA 2009	IEA 2009	Internal Calculations
325192	Bisphenol A	Estimate based on ACC 2012 and ICIS 2011b	Energetics 2000	Calculated as 12.5% savings on CT	DOE 2006
325110	Butadiene	ACC 2012	IEA 2009	IEA 2009	Internal Calculations
325110	Butylenes	CEH 2011c	IEA 2009	IEA 2009	Internal Calculations
325188	Calcium Carbonate	CEH 2011d	IPPC 2007b	IPPC 2007b	Internal Calculations

Table A2. References for U.S. Production Data of the 74 Select Chemicals Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands					
NAICS Code	**Chemical**	**Production Reference**	**CT Energy Intensity Reference**	**SOA Energy Intensity Reference**	**TM Energy Intensity Reference**
325188	Calcium Chloride	CEH 2009a (data for 2008)	Estimate based on SOA	IPPC 2007b	Internal Calculations
325199	Caprolactam	Estimate based on ICIS 2010a and Porcelli 2011	Energetics 2000	IEA 2009	Internal Calculations
325182	Carbon Black	Porcelli 2011 (2008 data)	EIA 2013	IEA 2009	DOE 2006
325120	Carbon Dioxide	CEH 2010b (data for 2008)	Ozalp 2008	Calculated as 12.5% savings on CT	Internal Calculations
325181	Chlorine	ACC 2012	IEA 2009	IEA 2009	DOE 2006
325110	Cumene	ACC 2012	HP 2010	IEA 2009	Internal Calculations
325192	Cyclohexane	Estimate based on ICIS 2010b	IEA 2009	IEA 2009	DOE 2006
325192	Cyclohexanone	CEH 2009b (data for 2008)	PEP 2002	Calculated as 12.5% savings on CT	Internal Calculations
325312	Diammonium Phosphate	USCB 2011a	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations
325193	Ethanol	ACC 2011	EIA 2013	Calculated as 12.5% savings on CT	Internal Calculations
325110	Ethylbenzene	ACC 2012	LBNL 2008	Calculated as 12.5% savings on CT	DOE 2006
325110	Ethylene	ACC 2012	HP 2010; Weighted average of propane, ethane, naphtha, and gas oil feedstock routes	Calculated as 12.5% savings on CT	Internal Calculations
325199	Ethylene Dichloride	ACC 2012	Energetics 2000	IEA 2009	DOE 2006
325199	Ethylene Glycol	ACC 2012	Energetics 2000	IEA 2009	DOE 2006
325199	Ethylene Oxide	ACC 2012	LBNL 2008	IEA 2009	DOE 2006
325199	Formaldehyde	CEH 2010c (data for 2009)	IPPC 2003; Average of silver catalyst/oxide process	Calculated as 12.5% savings on CT	Internal Calculations
325120	Hydrogen	Markets and Markets 2011	Maruoka, Purwanto, & Akiyama 2010	Maruoka, Purwanto, & Akiyama 2010	Internal Calculations
325188	Hydrochloric Acid	C&EN 2011	SRI 1979	Calculated as 12.5% savings on CT	DOE 2006
325188	Hydrogen Peroxide	ACC 2011	PEP 2002	Calculated as 12.5% savings on CT	Internal Calculations
325199	Isobutylene	Estimate based on EIA and Porcelli 2011	PEP 2002	Calculated as 12.5% savings on CT	DOE 2006

Table A2. References for U.S. Production Data of the 74 Select Chemicals Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

NAICS Code	Chemical	Production Reference	CT Energy Intensity Reference	SOA Energy Intensity Reference	TM Energy Intensity Reference
325199	Isopropanol	Estimate based on ICIS 2010c and ICIS 2012a	Energetics 2000	IEA 2009	DOE 2006
325199	Methanol	CMAI 2011	IEA 2009	IEA 2009	DOE 2006
325199	Methyl Chloride	Porcelli 2011 (data for 2008)	PEP 2002	Calculated as 12.5% savings on CT	DOE 2006
325199	Methyl Methacrylate	Estimate based on ICIS 2012b	PEP 2002	Calculated as 12.5% savings on CT	DOE 2006
325998	Methyl tert-Butyl Ether	ACC 2012	LBNL 2008	Calculated as 12.5% savings on CT	DOE 2006
325312	Monoammonium Phosphate	USCB 2011a	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations
325311	Nitric Acid	USCB 2011b	Energetics 2000	IPPC 2007a	Internal Calculations
325192	Nitrobenzene	CEH 2011e	Neelis et al. 2005	Calculated as 12.5% savings on CT	Internal Calculations
325120	Nitrogen	Porcelli 2011 (data for 2008)	LBNL 2000	IEA 2009	DOE 2006
325120	Oxygen	Porcelli 2011 (data for 2008)	LBNL 2000	IEA 2009	DOE 2006
325192	Phenol	ACC 2012	HP 2010	Calculated as 12.5% savings on CT	DOE 2006
325312	Phosphoric Acid	C&EN 2011	Bhattacharjee 2006	Calculated as 12.5% savings on CT	DOE 2006
325211	Polycarbonate	CEH 2008b (data for 2007)	IEA 2009	IEA 2009	Internal Calculations
325211	Polyester	ACC 2011	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations
325211	Polyethylene Terephthalate	CEH 2009d (data for 2008)	IEA 2009; IPPC 2007c	IPPC 2007c	Internal Calculations
325211	Polyethylene, High Density	ACC 2012	HP 2010	IEA 2009	Internal Calculations
325211	Polyethylene, Linear Low Density	ACC 2012	HP 2010	IEA 2009	Internal Calculations
325211	Polyethylene, Low Density	ACC 2012	HP 2010	IEA 2009	Internal Calculations
325211	Polypropylene	ACC 2012	HP 2010	IEA 2009	Internal Calculations
325211	Polystyrene	ACC 2012	LBNL 2008	IEA 2009	Internal Calculations
325211	Polystyrene, High Impact	CEH 2008c (data for 2007)	IPPC 2007c	Calculated as 12.5% savings on CT	Internal Calculations
325211	Polyurethane	CPI 2010; ACC 2010	Energetics 2000	Calculated as 12.5% savings on CT	Internal Calculations

Table A2. References for U.S. Production Data of the 74 Select Chemicals Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

NAICS Code	Chemical	Production Reference	CT Energy Intensity Reference	SOA Energy Intensity Reference	TM Energy Intensity Reference
325211	Polyvinyl Chloride	ACC 2012	LBNL 2008	IPPC 2007c	Internal Calculations
325110	Propylene	ACC 2012	Energetics 2000	IEA 2009	DOE 2006
325199	Propylene Oxide	Estimate based on ICIS 2011e	LBNL 2008	Calculated as 12.5% savings on CT	DOE 2006
325181	Soda Ash	ACC 2012	IEA 2009	IPPC 2007b	DOE 2006
325181	Sodium Hydroxide	C&EN 2011	Energetics 2000	IEA 2009	Internal Calculations
325188	Sodium Hypochlorite	CEH 2009c (data for 2008)	PEP 2002	Calculated as 12.5% savings on CT	Internal Calculations
325188	Sodium Silicates	ACC 2011	IPPC 2007b; water glass method	IPPC 2007b	Internal Calculations
325110	Styrene	ACC 2012	LBNL 2008	IEA 2009	DOE 2006
325188	Sulfur	CEH 2009e (data for 2007)	PEP 2002	Calculated as 12.5% savings on CT	Internal Calculations
325188	Sulfuric Acid	C&EN 2011	Energetics 2000	IPPC 2007a	DOE 2006
325199	Terephthalic Acid	Estimate based on ACC 2012 and ICIS 2011c	LBNL 2008	IEA 2009	DOE 2006
325311	Urea	USCB 2011b	Energetics 2000	IPPC 2007a	DOE 2006
325199	Vinyl Acetate	ACC 2012	IEA 2009	IEA 2009	DOE 2006
325199	Vinyl Chloride	Estimate based on ICIS 2011e	LBNL 2008	IEA 2009	DOE 2006
325110	Xylenes, Mixed	ACC 2012	LBNL 2008	IEA 2009	Internal Calculations
325110	Xylenes, Paraxylene	Estimate based on CEH 2010e and ICIS 2012d	HP 2010	Calculated as 12.5% savings on CT	DOE 2006

The four bandwidth measures are Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), and Thermodynamic Minimum (TM).

Appendix A3: Technologies Analyzed to Estimate Practical Minimum Energy Intensities with References

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ethylene							
Primary Fractionation	In primary fractionation/compression, which only occurs with naphtha and gas oil feeds, the olefins are separated from the unreacted feed streams by cooling and compression. Additionally, liquid BTX (benzene, toluene, xylene) is also collected separately in this process.	Ethylene	Ren, Patel & Blok 2006	Savings from SOA: Advanced Distillation Columns - 64.5Btu/lb; Membranes - 645 Btu/lb; Integrate refrig. with cryogenic fractionation - 430 Btu/lb	Use of mechanical vapor recompression would save ~1 GJ/t ethylene. Advanced distillation columns such as the Heat Integrated Distillation Column (can save 60-90% of the energy consumed in a distillation column with heat pumps (0.15 GJ/t ethylene). Membranes can also be used for separation with projected savings of 1.5 GJ/t ethylene. Plant integration of refrigeration with cryogenic fractionation of gases could save 1 GJ/ethylene.	This is an absolute value; PM savings were estimated in the cited report. Interested readers are directed to this in depth report. Joint savings are shown for all technologies (Primary Fractionation, Pyrolysis, Alternative Ethylene Technology and Product Recovery/Fractionation).	5,159
Pyrolysis	In the catalytic pyrolysis of naphtha feedstock, the feed stream is heated before passing over a catalyst which causes the molecules to break up resulting in lighter olefin molecules. The energy consumption of the pyrolysis section could be reduced with circulating beds, greater control of the radiant coils, coatings that reduce coking and the use of advanced furnace materials.	Ethylene	Ren, Patel & Blok 2006	Turbines alone save 1,290 Btu/lb, when combined with advanced furnace materials. 1,720 Btu/lb are saved over SOA	Coupled together these technologies could result in savings of 2-3 GJ/MT of ethylene over the CT values. Gas turbines can also be integrated into the process generating steam, electricity and hot combustion gases. By itself it would save 3 GJ/MT ethylene over SOA, and 4 GJ/MT if combined with advanced furnace materials	This is an absolute value; PM savings were estimated in the cited report. Interested readers are directed to this in depth report. Joint savings are shown for all technologies (Primary Fractionation, Pyrolysis, Alternative Ethylene Technology and Product Recovery/Fractionation).	5,159

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ethylene (continued)							
Alternative Ethylene Technology	Ethane oxidative dehydrogenation can reduce total energy 35% (~3-5 GJ/t) from SOA including the cost of oxygen production. This can be coupled with catalytic pyrolysis process, which could save approximately 20% of SOA (4 GJ/t) because of its lower operational temperature and the lack of need to produce naphtha feedstock.	Ethylene	Ren, Patel & Blok 2006	Ethane oxidative dehydrogenation: 1,290-2,150 Btu/lb in savings; Catalytic pyrolysis process: 1,720 Btu/lb in savings	Ethane oxidative dehydrogenation can reduce total energy 35% (~3-5 GJ/t) from SOA including the cost of oxygen production. But this process produces 15% more CO_2 emissions, which could likely be offset by cleaner electricity production to produce O_2. The catalytic pyrolysis process could save about 20% of SOA (4 GJ/t) because of lower operational temperature and no need to produce naphtha feedstock.	This is an absolute value; PM savings were estimated in the cited report. Interested readers are directed to this in depth report. Joint savings are shown for all technologies (Primary Fractionation, Pyrolysis, Alternative Ethylene Technology and Product Recovery/Fractionation).	5,159
Product Recovery/ Fractionation	In product recovery/fractionation the remaining gaseous olefins are separated using distillation and refrigeration.	Ethylene	Ren, Patel & Blok 2006	This is related to Alternate Ethylene Technology, the savings are the two individually	See the corresponding process in Alternate Ethylene Technology. Technologies discussed individually, joint savings reported.	This is an absolute value; PM savings were estimated in the cited report. Interested readers are directed to this in depth report. Joint savings are shown for all technologies (Primary Fractionation, Pyrolysis, Alternative Ethylene Technology and Product Recovery/Fractionation).	5,159

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ethylene (continued)							
Enhanced Separation Efficiency in Olefin/ Paraffin Distillation	Develop technologies to enhance separation efficiencies by replacing the conventional packing materials with hollow fiber membranes, which have a high specific area and separated channels for both liquid and vapor phases. This new type of packing materials can result in high separation efficiency and high capacity.	Ethylene, Propylene industries	DOE 2011; GPRA 2011	Initial claims were for savings of 10-50 TBtu/yr	Analysis shows 30.4 TBtu/yr, but not until 2035	Estimated savings of 10 TBtu/yr. Ethylene CT = 374TBtu/yr. Therefore 3% savings. Ethylene energy intensity = 7071 Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 6,881 Btu/lb.**	6,881
Elongating the Reactor to Increase the Residency Time of the Feed Stream	BOP Furnace Energy Improvement in Steam Cracking	Ethylene	Gandler 2010	2.4% improvement of the reactor by changing run length and steam/ hydrocarbon ratio	The 2.4% efficiency gains for ethylene is 366.3 billion Btu/lb over CT or 185.7 billion Btu/lb over SOA.	Estimated savings of 2.4% or 185.7 Btu/lb over SOA. Ethylene SOA energy intensity = 6,187 Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 6,001 Btu/lb.**	6,001

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	Technology Description	Applicability (Product, process, sector)	Source (See Reference list at end)	Reported Energy Savings (Literature-reported savings, Btu, %, etc.)	Explanation of Savings Baseline, or Reference (Adjustment, conversion, scale up of reported savings)	Calculated Product/ Process Savings (Savings compared to SOA or CT energy use. PM savings estimate.)	PM Energy Intensity Btu/lb or % savings
Ethylene (continued)							
Heat Integrated Distillation through Use of Micro-channel Technology	A breakthrough distillation process using Microchannel Process Technology (MPT) to integrate heat transfer and separation into a single unit operation. The project focuses on the application of MPT in a fractionation section of an ethylene plant, the C_2 splitter.	Although specific to ethylene, this application could presumably be used for propylene or other cracking distillation based chemical production	DOE 2009a; Velocys 2010; GPRA 2011	Energy savings of 13 TBtu/yr in 2020 in the ethylene industry.	GPRA 2011 analysis shows13TBtu/yr savings in 2020 Velocys 2010 indicates that distillation via microchannels may not be significantly effective on the large scale to displace conventional systems.	Estimated savings of 13 TBtu/yr. Ethylene CT energy consumption = 374TBtu/yr. 3.5% savings over CT equals 245.8 Btu/lb. Applied to the ethylene CT value of7,071 Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 6,771 Btu/lb.**	6,771
Develop-ment of Highly Selective Oxidation Catalysts by Atomic Layer Deposition	This project uses atomic layer deposition (ALD) to build nano-structured catalysts to oxidatively dehydrogenate alkanes.	Applicable to ethylene and propylene production directly, and to their derivatives	DOE 2009b; GPRA 2011	Energy savings of 25 TBtu/yr by 2020.	GPRA 2011 analysis shows 2.2 TBtu/yr savings in 2020. 25 TBtu may include derivatives. Final (or interim) report in OSTI not available.	Estimated savings of 25 TBtu/yr. Ethylene CT energy consumption = 374TBtu/yr. Therefore 6.7% savings over CT. Ethylene CT energy intensity = 7,071 Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 6,598 Btu/lb.**	6,598

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	Technology Description	Applicability (Product, process, sector)	Source (See Reference list at end)	Reported Energy Savings (Literature-reported savings, Btu, %, etc.)	Explanation of Savings Baseline, or Reference (Adjustment, conversion, scale up of reported savings)	Calculated Product/ Process Savings (Savings compared to SOA or CT energy use. PM savings estimate.)	PM Energy Intensity Btu/lb or % savings
Ethylene (continued)							
New Catalyst	New catalysts; 80% of chemical processes depend on catalysts. In the case of ethylene, catalytic pyrolysis would be used in place of thermal pyrolysis	Ethylene	LBNL 2000	A savings of 246Btu/lb or 4% on SOA	Estimated savings of 13.64 TBtu of energy on only ethylene based on 27.74 million tons of ethylene produced. Equates to 246Btu/lb savings over SOA, or 4% savings over SOA.	Estimated savings of 20% or 246 Btu/lb over SOA. Ethylene SOA energy intensity = 6,187Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 5,941 Btu/lb.**	5,941
Microwave Enhanced Direct Cracking of Hydro-carbon Feedstock for Production of Ethylene and Propylene	Definition of concepts to enable direct microwave treatment of HCs to replace indirect heating processes to make ethylene and propylene. Modeling of microwave-based mechanisms.	Ethylene and propylene directly; their polymers (plastic materials and resins) and derivatives (other basic organic chemicals) indirectly	DOE 2011b; Ceralink 2012	Reduction "by at least" 50% of the energy required for cracking. Also reduces reactor skin temperature and minimizes coke, thus prolonging cracker efficiency	Industry wide, 750 TBtu is used to heat feedstock for cracking, a 45% efficient process, thus about 420 TBtu of waste heat. Ceralink 2012 claims that direct microwave heating will save 195 TBtu/yr by 2020 (equivalent to 16 crackers). This is based on a conversion of 10% of ethylene plants. The estimate works out to about 12.2 TBtu energy savings per plant, with each plant producing about 150,000 tonnes/yr. This estimate seems very high; converted for all the plants (160) it is more than the total energy that is used by the cracking sector	Estimated industry-wide ethylene cracking energy = 750 TBtu/yr (does not agree with bandwidth CT energy estimate). Estimated savings for this technology = 195 TBtu/yr. Therefore 26% savings over CT. (Overall Btu/yr may not be in agreement with bandwidth CT, but % savings is relative). Ethylene CT energy intensity = 7,071Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 5,192 Btu/lb.**	5,192

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ethylene (continued)							
Catalyst-Assisted Production of Olefins from Natural Gas Liquids	An innovative catalytic coating material could significantly reduce surface deposits on ethylene steam cracker furnace coils. Proposed technology can be installed during normal maintenance cycle and with growing availability of shale gas, has the potential to help U.S. maintain leadership in olefins production.	Ethylene	DOE 2012	A 6-10% reduction in energy consumption per plant would save an estimated 20-35 TBtu/year.	Innovative catalytic coating for ethylene steam cracker; saves 20-35 TBtu/yr	Estimated savings of 6% (or 20-35 TBtu/yr). Ethylene CT = 374TBtu/yr and CT energy intensity = 7071Btu/lb. Therefore 6% equates to 4721Btu/lb savings. **Practical minimum energy intensity for ethylene employing this technology = 6,596 Btu/lb.**	6,596
Novel Membranes for Olefin/ Paraffin Separation	Initial reference is very limited. Separation process for ethylene and propylene. (Compact Membrane Systems, Newport, DE)	Ethylene, Propylene and their derivatives	DOE 2011c; SBIR 2011	Claims 40 TBtu/yr in retrofit application.	Taken as claimed in source	Estimated savings of 40 TBtu/yr. Ethylene CT = 374TBtu/yr. Therefore 10.6% savings. Ethylene energy intensity = 7,071Btu/lb. **Practical minimum energy intensity for ethylene employing this technology = 6,266 Btu/lb.**	6,266

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Propylene							
Advanced Nanostructured Molecular Sieves for Energy Efficient Industrial Separations	Developing mesoporous zeolite containing adsorbents for use in moving bed or Pressure swing Adsorption (PSA) systems to replace energy/cost intensive distillation processes. This study focuses on separation of propane from propylene - a very energy intensive and high-volume process. (Rive Technology, Monmouth Junction, NJ).	There is obvious applicability to propylene and to its derivatives, but it may also apply to other chemical industry material that has an expensive energy intensive distillation step - although it is assumed modification would be needed in the process.	DOE 2011b; Rive 2011; ICIS 2012	Estimates 50% increase in diffusivity and 40% improvements in selectivity	Estimates 50% increase in diffusivity and 40% improvements in selectivity and rate of adsorption over a zeolite without mesopores. Second report gives overall reduction; 800 Btu/lb for microporous sieves. Report # 1033219 from Rive shows the standard propylene separation from propane requires 2790 Btu /lb of propylene. Rive states a typical plant using the mesoporous zeolite process would produce 40 million lb of propylene. Propylene production is dynamic right now, according to the ICIS article with less propylene being made during refining of the increasing amount of petroleum from shale.	CT Propylene production = 31,057 Million lb/yr. The standard process step requires 31,057 Million lb/yr x 2,790 Btu/lb = 87 TBtu/yr. For the microporous sieves process, which averages 800 Btu/lb propylene, 31,057 Million lb/yr x 800 Btu/lb = 25 TBtu/yr. This is an energy savings of 62 TBtu/yr over CT industry wide. However, only about half of the propylene goes through the distillation process. The rest is made in ethylene cracking and would not be included as a candidate here. Thus the numbers are halved, resulting in energy savings of 31 TBtu/yr or 35% savings over CT. Propylene CT energy intensity = 1,351 Btu/lb. **PM energy intensity for propylene employing this technology = 878 Btu/lb.**	878

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Propylene (continued)							
Millisecond Oxidation of Alkanes	a production process for propylene and acrylic acid from propane using A catalytic auto-thermal oxydehydrogenation process that reduces reaction times by requiring a very short reactant contact period. (Rohm and Haas, Spring House, PA; BASF Catalysts, Iselin, NJ; University of Connecticut, Storrs, CT)	This is geared to energy reduction for propylene and acrylic acid, but would also affect downstream chemicals.	DOE 2009c; GPRA 2011; Rohm and Haas & BASF 2011	Conservatively estimated savings of 10TBtu/yr.	The GPRA 2011 analysis for propylene using this technology yielded 6.50 TBtu/yr savings in 2020, increasing to 14.21 TBtu/yr by 2025. However, the original R&H plan was really concentrating on producing acrylic acid directly from propane (a separate reaction from propane to propylene.) Project stopped due to a turnover in management at R&H. They seemed to have some success in making propylene. However, the technology will not be deployed unless someone picks it up. There is need for making propylene because shale gas does not yield propylene directly, so processes that make it via dehydrogenation will become more valuable. A conservative estimate of 10 TBtu/yr savings is estimated.	Propylene CT = 42 TBtu/yr. 10 Btu/yr savings = 24% savings. Propylene CT energy intensity = 1,351 Btu/lb. **Practical minimum energy intensity for propylene employing this technology = 1,027 Btu/lb.**	1,027

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Chlorine							
Hydrogen Fuel Cells	In a traditional membrane cell hydrogen is generated, which could then be fed into a fuel cell. A fuel cell would oxidize the hydrogen and generate electricity. This technology would offset 20% of the energy consumed, compared to the 17% for merely burning hydrogen to produce electricity. This technology using polymer electrolyte membrane fuel cells (PEMFCs) has been demonstrated in 2007 at an AkzoNobel plant and in 2011 at a Solvin plant	Chlorine	IPPC 2011	20% of the technology compared to 17% for merely hydrogen burning	Assume that SOA is burning hydrogen to produce electricity. CT energy intensity for chlorine = 6544 Btu/lb. 17% savings estimated for SOA = 6544 x 0.17= 1112 Btu/lb savings. 20% savings estimated for this technology = 6544 x 0.20 = 1309 Btu/lb savings. Calculated SOA for chlorine = 6544 - 1112 = 5432 Btu/lb. Calculated PM for this technology = 6544 - 1309 = 5235 Btu/lb. Relative savings = 3.6% over SOA.	SOA chlorine intensity = 5,116 Btu/lb. Estimated savings of 3.6% over SOA = 5,116 x 0.036 = 184 Btu/lb savings. **Practical minimum energy intensity for chlorine employing this technology = 5,116 - 184 = 4,932 Btu/lb.**	4,932
Fuel Cells	Fuel cells are more efficient electricity generators especially when coupled with h2 gas production; 80-83% theoretical limit, closer to 50-60% for actual cells	Chlorine from H2 production	LBNL 2000	No effect on final energy only on primary energy	Primary energy savings of 33%, equaling 185 TBtu of savings, all electricity	See Hydrogen Fuel Cells with chlorine production for more information	N/A

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Chlorine (continued)							
Oxygen Depolarized Cathodes in Membrane Cells	In chlorine production using membrane cells it is possible to replace the common metal cathodes in membrane cells with oxygen depolarized cathodes (ODC). These new cathodes produce hydroxide instead of hydrogen and hydroxide. The ODC is a gas diffusion electrode wherein oxygenated water is catalytically reduced to hydroxide. The electrons for this reaction come from the oxidation of chlorine in NaCl to Cl_2.	Chlorine	IPPC 2011	15-30% compared to standard cells	CT energy intensity for chlorine = 6544 Btu/lb. 15-30% savings, assume 20%. 20% savings over CT = 6544 x 0.20 = 1309 Btu/lb.	Practical minimum savings estimated to be CT = 1,309 Btu/lb. CT energy intensity = 6,544 Btu/lb. **Practical minimum energy intensity for chlorine employing this technology = 5,234 Btu/lb.**	5,234

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ammonia							
Integrated Ammonia Reactor and Ammonia Pressure Swing Adsorption (PSA) Recovery	Using a newly developed recovery system and an "enhanced ammonia reactor" to produce higher volume of ammonia and decrease energy usage and cost. Reduces product loss by improved separation and recycling. There is no need to recompress or reheat the recycled steam.	Ammonia is the main application (also applies to products of ammonia, e.g., ammonium sulfate, ammonium nitrate, nitric acid, urea)	DOE 2011b; Smart Koncept 2010	70% reduction in plant capital cost and energy use	A 70% reduction in both energy use and capital cost is estimated for each ammonia plant, presumably including ammonia used in power and utility plants. Using this technology to retrofit existing ammonia plants: There are 27 significantly sized ammonia plants in the U.S. according to the EPA. Ammonia production is 22,691 million lb, so the average production per plant is 22,691/27 = 840 million lb. According to SmartKoncept 2010, these plants consume an industry total of 750 TBtu/year of energy.	The source claims 40% energy reduction using the new PSA process for retrofitted plants. Using the 40% reduction, this would be a reduction of 300 million Btu/yr industry wide, or 11.1 TBtu per plant. CT ammonia= 133TBtu/yr. Industry wide, 40% reduction in energy amounts to savings of53TBtu/yr, or 4.1 TBtu per plant. Assuming 40% savings, practical minimum energy consumption for ammonia employing this technology = 133 - 53TBtu/yr = 80TBtu/yr. Ammonia production = 22,691 Million lb/yr in 2010. **Practical minimum energy intensity for ammonia employing this technology = 7,403 Btu/lb.**	3,525

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ammonia (continued)							
Cold Insulation of Syngas Compressor Suction Pipe	The assessment identified a section of cold piping before a compressor which was not insulated and was absorbing energy from ambient conditions increasing the load on the compressor	Ammonia	RET n.d.	2,600 GJ/yr savings with a production capacity of 300,000 tonnes/yr	2,600 GJ/yr savings with a production capacity of 300,000 Mt/yr. Equals 0.008 GJ/tonne, which then equals 3.72 Btu/lb plus additional production.	**Practical minimum energy intensity savings of 3.72 Btu/lb is negligible, therefore not included in high/low range for PM.**	N/A
Auto-thermal Reforming	Autothermal reforming process in which heat from partial combustion of methane is used to promote the formation of syngas	Ammonia (also applies to methanol, included below)	LBNL 2000	Save 37.8 TBtu of energy on 18 Million tons of production	Estimated savings of 37.8 TBtu of energy on 18 Million tons of production equaling 21.7% savings on primary energy.	Ammonia SOA energy intensity = 3,138 Btu/lb. Savings of 681.3 Btu/lb based on a savings of 21.7% savings over SOA. **Practical minimum energy intensity for ammonia employing this technology (21.7% savings over SOA) = 2,457 Btu/lb.**	2,457

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Nitrogen/Oxygen							
Impellers on Nitrogen Compressor for Pipeline	Dynamic matching of supply and demand to reduce oversupply issues by the installation of impellers with lower flow capacity for Nitrogen compressor to better match reduced pipeline demand.	Industrial Gases - Nitrogen and Oxygen	RET n.d.	$65,700/yr	2008 Price of electricity in Australia=18.3 cents/kWh. Means that AUD$65,700 is 359,000 kWh of power. This equals 1,225 million Btu/yr of energy saved. Unclear how many lb/yr are produced at this site and if it is all N_2.	Medium sized N_2/O_2 plant consumes approximately 100 kW power. Assuming plant operates ~7,500 hrs/yr, this equates to 750,000 kWh per plant or 2,559 million Btu/yr. 1,225 million Btu/yr savings = 48% savings. Nitrogen CT energy intensity = 774 Btu/lb. **PM energy intensity for nitrogen employing this technology = 403 Btu/lb.**	403
All Industrial Gases							
Nitrogen Liquefier Unit Cooling System Upgrading	Savings potential has been identified in the Nitrogen Liquefier Unit (NLU) cooling system. While the NLU runs intermittently the cooling system often remains in continuous operation, but an change can be made to automate the process.	Industrial Gases	RET n.d.	375,400 kWh/year savings from annual cost of $42,000	Plant capacity of 100 tonnes of LNG per day. The energy savings is 375,400 kWh/yr from annual cost of AU$42k. This leads to an energy savings of 10.28 kWh/tonne= .036 GJ/tonne=15.48 Btu/lb over SOA.	Plant capacity of 100 tonnes of LNG per day. Energy savings of 375,400 kWh/yr leads to a savings of 10.28 kWh/tonne=15.48 Btu/lb over SOA. **Practical minimum energy intensity savings of 15 Btu/lb over SOA.**	Savings of 15.48 Btu/lb over CT applies to all Industrial Gases

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Ammonium Nitrate							
Drying Techniques	Different Drying Techniques: Plate bank cooler and rotary cooler	Ammonium Nitrate, Ammonium Phosphate, Ammonium Sulfates	IPPC 2007	Savings: Using a Plate Bank Cooler 0.6 kWh/tonne Using a Rotary Cooler: 3 kWh/tonne	Using a Plate Bank Cooler 0.6 kWh/tonne Rotary Cooler: 3 kWh/tonne Combined Savings 2.4 kWh/tonne or **3.72 Btu/lb savings** over SOA, other factors went in to this combined number which comes from the reference	Ammonium Nitrate SOA energy intensity = 39 Btu/lb. Technology estimated to save 3.72 Btu/lb from the relevant salt processes, or 9.5% savings over SOA. **Practical minimum energy intensity for Ammonium Nitrate employing this technology = 35 Btu/lb.**	35
Methyl Methacrylate							
New Catalyst	Use of Pd-catalyzed process, still needs to be distilled but no acid handling	Methyl methacrylate	Sheldon 1997	Resulting in an energy savings around 50%	Increase molecular efficiency from 46% to 100%; likely resulting in an energy savings around 50%	Energy savings will likely increase at least 50% due to molecular efficiency increase. Also, energy expended in separation from unwanted byproducts would be significantly reduced. Methyl Methacrylate CT energy intensity = 3483 Btu/lb. 50% savings over CT for PM estimate. **Practical minimum energy intensity for Methyl Methacrylate employing this technology = 1,742 Btu/lb.**	1,742

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Methyl Chloride							
Methyl Chloride from Direct Methane Partial Oxidation	Single-step low temp (<300°C) partial oxidation process converts low grade natural gas to Methyl Chloride directly. "Designer" ionic liquids and Shilov-like partial oxidation catalysts are used for the conversion.	Methyl Chloride. (also applies to silicones and polystyrene)	DOE 2011b	Reduces energy intensity and GHG emissions 50-60% (assume savings for energy intensity)	Replaces multistep process that involves >500°C syngas production step. Reduces "energy intensity and greenhouse gas emissions by 50-60%" Not totally clear in what 50-60% refers to.	Methyl Chloride CT energy intensity = 839 Btu/lb. 50% savings over CT for PM estimate. **Practical minimum energy intensity for Methyl Chloride employing this technology = 419.5 Btu/lb.**	420
Butadiene							
Predictive Process Control	Butadiene Dynamic Matrix Control	Butadiene	Exxon Mobil 2010	112,000 million Btu/yr savings	112,000 million Btu/yr savings by modeling and greater control of butadiene process. 175,000 tonnes/yr of capacity at the plant (ICIS 2010), this means a savings of 291 Btu/lb.	Butadiene SOA energy intensity = 5,288 Btu/lb. 291 Btu/lb savings equals 5.5% relative to SOA. **Practical minimum energy intensity for Butadiene employing this technology = 4,997 Btu/lb.**	4,997

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Plastics/Resins[1]							
Plastics Recycling	Better Plastics Recycling- Looking at automobile shredder residue; only 7% of plastics are recycled. Recycling of all plastics materials and types. Life cycle considerations to expedite sorting and reprocessing.	Thermoplastic polymers (all bandwidth plastics and resins are thermoplastics)	LBNL 2000	70% energy savings by recycling	The possibility is 50-75 million Btu/ton recycled leading to a total of 4 TBtu of savings. This leads to savings of **70% of primary energy.** The base case is predicated on 0.1 million tons of plastics at 20,000 ton plant. For more detailed information see source	70% energy savings by producing plastic via recovery as opposed to new. **Practical minimum energy intensity for all plastics is estimated to be 70% lower than CT.** See footnote.	70% savings over CT applies to all plastics[1]
Styrene							
Auto-thermal Styrene Manu-facturing	A new processing technology for manufacturing styrene monomer. Involves new catalyst(s) and a new processing facility design	Styrene	DOE 2011b	25% energy reduction for styrene	25% life cycle process energy reduction from conventional technology for monomer production.	Styrene CT energy intensity = 3,777 Btu/lb. 25% savings applied to CT to determine PM. **Practical minimum energy intensity for styrene employing this technology = 2,833 Btu/lb.**	2,833
Launching A New Route to Styrene Monomer	A new process using a "breakthrough" catalyst	Styrene	DOE n.d.	40% or more energy reduction from standard styrene monomer production	Energy savings and greenhouse gas reduction of 40% or more from use of breakthrough catalyst material in new process. Corresponding cost savings of 30% for styrene monomer production.	Styrene CT energy intensity = 3,777 Btu/lb. 49% savings applied to CT to determine PA. **Practical minimum energy intensity for Styrene employing this technology = 2,266 Btu/lb.**	2,266

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Isopropanol							
Liquid Membranes for Liquid-Liquid Extractions	Liquid Membrane for liquid-liquid extractions and are limited by their high specificity; incredibly large opportunity because of low market penetration	Isopropanol	LBNL 2000	53% savings on primary energy	53% primary energy savings over CT.	Isopropanol CT energy intensity = 4,693 Btu/lb. 53% savings applied to CT to determine PM. **Practical minimum energy intensity for Isopropanol employing this technology = 2,205 Btu/lb.**	2,205
Isopropanol (continued)							
Gas Membranes	Gas Membrane can be used an alternative to liquid-liquid extraction	Isopropanol (also applies to methanol, included below, and others l-l extractions)	LBNL 2000	20% primary energy savings over CT.	20% primary energy savings over CT.	Isopropanol CT energy intensity = 4,693 Btu/lb. 20% savings applied to CT to determine PM. **Practical minimum energy intensity for Isopropyl Alcohol employing this technology = 3,680 Btu/lb.**	3,754

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	Technology Description	Applicability (Product, process, sector)	Source (See Reference list at end)	Reported Energy Savings (Literature-reported savings, Btu, %, etc.)	Explanation of Savings Baseline, or Reference (Adjustment, conversion, scale up of reported savings)	Calculated Product/ Process Savings (Savings compared to SOA or CT energy use. PM savings estimate.)	PM Energy Intensity Btu/lb or % savings
Methanol							
Auto-thermal Reforming	Autothermal reforming process in which heat from partial combustion of methane is used to promote the formation of syngas	Methanol (also applies to ammonia, included above)	LBNL 2000	20% savings on primary energy	20% savings on primary energy. Baseline case is saving 37.8 TBtu of energy on 18 million tons of production	Methanol CT energy intensity = 4,901Btu/lb. **Practical minimum energy intensity for methanol employing this technology (20% savings over CA) = 3,921Btu/lb.**	3,921
Gas Membranes	Gas Membrane can be used an alternative to liquid-liquid extraction	Methanol (also applies to Isopropanol, included above)	LBNL 2000	20% primary energy savings over CT.	20% primary energy savings over CT.	Methanol CT energy intensity = 4,901Btu/lb. 20% savings applied to CT to determine PM. **Practical minimum energy intensity for methanol employing this technology = 3,921Btu/lb.**	3,921

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Sodium Hydroxide							
Heat Recovery in Harsh Environments	Heat Recovery Technologies for Harsh Environments- printed circuit heat exchanges made of nickel can be used to recover energy from these applications where normal conditions do not allow for heat exchangers	Sodium Hydroxide (also applies to Nitric acid, included below)	LBNL 2000	4% savings on SOA	4% savings over SOA This model assumed 30% adoption in all Nitric Acid and Sodium Hydroxide plants. 8.1 TBtu equaling 4% of primary energy on 613.2 TBtu of the base case	Sodium Hydroxide SOA energy intensity = 835 Btu/lb. 4% savings applied to SOA to determine PM. This is done to SOA because it is not currently possible to do. **Practical minimum energy intensity for Sodium Hydroxide employing this technology = 801.6 Btu//lb**	802
Nitric Acid							
Heat Recovery in Harsh Environments	Heat Recovery Technologies for Harsh Environments- printed circuit heat exchanges made of nickel can be used to recover energy from these applications where normal conditions do not allow for heat exchangers	Nitric acid (also applies to Sodium Hydroxide, included above)	LBNL 2000	4% savings on SOA	4% savings over SOA from reference. This model assumed 30% adoption in all Nitric Acid and Sodium Hydroxide plants. 8.1 TBtu equaling 4% of primary energy on 613.2 TBtu of the base case	Nitric Acid SOA energy intensity = -1032 Btu/lb. 4% savings applied to SOA to determine PM. This is done to SOA because it is not currently possible to do **Practical minimum energy intensity for Nitric Acid employing this technology = -1075 Btu/lb**	-1075

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Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Distillation/Separation[2]							
Refining Column Packing	The distillation section of this methanol plant uses packed columns, rather than ordinary tray columns. The flow characteristics and cleanliness of the packing affects column efficiency and so impacts on energy consumption (i.e., steam). While it was possible to remove the existing packing, clean it, and then re-install, the plant has elected to install a new and improved packing design. This packing design is expected to improve mass transfer characteristics leading to increased column efficiency through the elimination of additional steam use in distillation. Accordingly, less energy will be required for the same amount of product made.	Distillation Columns	RET n.d.	10,000 GJ/yr savings with a production capacity of 80,000 tonnes/yr	10,000 GJ/yr savings with a production capacity of 80,000 tonnes/yr (their website). Equals 0.125 GJ/tonne, which then equals 53.74 Btu/lb savings	53.74 Btu/lb over SOA. Methanol's SOA is 4,041 Btu/lb. These savings represent an energy savings of 1.3%. This energy savings can be applied to CT.	1% savings over SOA for all distilled chemicals
Reactive Distillation	As its name suggests the reaction and the separation occur in the same structure. Commercialized by CDTech and Sulzer	Distillation Columns	Harmsen 2007; Sulzern.d.	Reduction of distilled chemicals by 20%	Can reduce energy by 20%, as per the sources	Reduced 20% below CT. From here multiply 40% by 20% to get 8% energy savings.	8% savings over SOA for all distilled chemicals

Table A3. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Distillation/Separation[2] (continued)							
Hybrid Distillation	Hybrid distillation column mixed with other separation processes (membranes or adsorption)	Distillation Columns	Sorin et al. 2007	44% recovery of the lost exergy	**Exergy recovery of 44% for separation of ethylene and ethane**. SOA is 5,352 Btu/lb. TM is 1,538 Btu/lb. A 44% recovery of the lost exergy is 1,678 Btu/lb in savings or a PM of 3,674 Btu/lb or a true savings of 32% relative to SOA	A 44% savings of distillation energy multiplied by 40% of all energy is distillation equals 18% of total energy savings due to a hybrid distillation column	18% savings over SOA for all chemicals
Advanced Distillation Technologies circa 2003	Implementation of advanced distillation methods at a conservative 25% of distillation plants in California	Distillation Columns	CEC 2003	25% savings of distillation energy	It would save 25% of distillation energy. This value is calculated in the reference to be 52 TBtu/yr for all distillation applications.	A 25% savings of distillation energy multiplied by 40% of all energy is distillation equals 10% of total energy savings due to advanced distillation columns	10% savings over SOA for all chemicals
Distributive Distillation Enabled by Micro-channel Process Technology	Improving efficiency of the distillation process by replacing a single distillation column with several smaller ones using microchannel processing. They have already verified efficient separation but need to determine economic viability of commercial scale microchannel distillation units.	Application could include all processes that include distillation across the chemical industry.	DOE 2011b; Engineer Live n.d.	40% energy usage reduction over conventional distillation	Estimates up to 40% energy savings over conventional distillation.	According to Engineer Live, the technology is much more suitable for fine chemicals than bulk chemicals due to scale up problems. **This will likely have no impact on bulk chemicals. Ignored for PM Calculations**	N/A

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Utilities - CHP, Boilers, Pumps, etc.							
Micro-turbines	Microturbines 26-30% efficient; 40% recovery and can push CHP up to 80% efficiency	w/CHP	LBNL 2000	14% increase in efficiency over typical CHP efficiency by adding microturbines	14% increase in efficiency of CHP Systems	Referencing Chemicals Energy Footprint, 604 TBtu of direct end use is from CHP systems, which equates to 19% of plant wide energy use. 14% savings of 19% results in a **practical minimum energy intensity savings of 2.7% over CT applied to all chemicals.**	2.7% savings over CT for all chemicals
Crosscutting Technologies							
New High-Temp., Low-Cost Ceramic Media for Natural Gas Combustion Burners	Combining four different technologies into a single radiant burner package that functions as both a burner and a catalyst support. (3M, St. Paul, MN).	Could potentially apply when electric or natural gas radiant heaters used in process heating.	DOE 2011b	25% reduction in energy for process heat	Potential to reduce energy consumption by 25% for process heat.	Referencing Chemicals Energy Footprint, 1,268 TBtu of direct end use for process heating. This equates to 52% of direct end use. 25% savings of 52% energy use results in 13% average savings. **Practical minimum energy intensity savings of 13% over CT applied to all chemicals.**	13% savings over CT for all chemicals

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Technology Name	**Technology Description**	**Applicability** (Product, process, sector)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** Btu/lb or % savings
Crosscutting Technologies (continued)							
Modeling and Process Analysis	Use of in-silico models and process analysis	All chemicals	Krause 2008	10% energy improvement	10% energy improvement, by reducing off-spec material	10% off nearly all processes solely by computer modeling and process integration. Practical minimum energy intensity reduced by 10% over CT for all chemicals.	10% savings over SOA for all chemicals
Advanced Energy and Water Recovery Technology from Low-Grade Waste Heat	Recovery of high purity water and energy from low grade heat, high moisture waste streams using nanoporous membranes. Will prove concept in laboratory and evaluate in "two different types of industrial environments.	Applies to any chemical process step that produces sufficient low-grade waste heat to make the process viable	DOE 2011b; GTI 2011	20-30% greater energy efficiency in recovery from low grade waste heat.	The amount of energy savings would depend on the amount of waste heat could be recovered. Using the nanoporous membrane technology could increase heat recovery by 20-30% it would appear.	The second report 1031483 which shows a lot more detail indicates much more applicability to other non-chemical industries, and shows styrene as the major chemical industry where this may be of use.	20% savings over SOA for all chemicals

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

[1] *Specific PM savings for plastics over CA: Polycarbonate 2,012 TBtu/yr; Polyester 3,638 TBtu/yr; Polyethylene terephthalate 687 TBtu/yr; Polyethylene, High Density 311 TBtu/yr; Polyethylene, Linear Low Density 261 TBtu/yr; Polyethylene, Low Density 343 TBtu/yr; Polypropylene 185 TBtu/yr; Polystyrene 679 TBtu/yr; Polystyrene, High Impact 191 TBtu/yr; Polyurethane 41 TBtu/yr; and Polyvinyl Chloride 439 TBtu/yr*

[2] *Separations/distillation technology savings identified in this appendix were applied to 40% of the current typical energy use for the chemicals identified. Separation processes account for about 41% of total energy consumption in the chemical process industries (Humphrey & Keller 1997). The following chemicals were identified as having "key distillation separations" and therefore the separations/distillation savings were applied: Acetic acid, Acetone, Acrylonitrile, Ammonia, Benzene, Butadiene, Cumene, Ethanol, Ethylbenzene, Ethylene, Ethylene glycol, Ethylene oxide, Formaldehyde, Isopropanol, Methanol, Nitrogen, Oxygen, P-xylene, Phenol, Propylene, Propylene oxide, Styrene, Vinyl acetate, Vinyl chloride, Xylene. (Humphrey & Keller 1997).*

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Appendix A4: Practical Minimum Technology Weighting Factors

METHODOLOGY TO DETERMINE WEIGHTING FACTORS

In this section the practical minimum technology weighting factors methodology is explained. The application of this methodology is presented in Table A4.

Six Weighting Factors, A through F, are considered for each technology and scored as shown (High (H) = 3, Medium (M) = 2, Low (L) = 1, Not Available (NA) = 0). The factors are also scaled according to DOE Importance Level, e.g., an importance level of 2 carries twice the weight of an importance level of 1. For the chemicals bandwidth, factors A-F each carried a DOE Importance Level of 1.

The DOE Importance Level is multiplied by the score for each factor and divided by the total possible score to determine overall weighting of technology. The NA score of 0 is excluded from overall weighting.

Factor A - Technology Readiness

- High = Technology Readiness Level (TRL) 7-9
- Medium = TRL 4-6
- Low = TRL 1-3

Factor B - Market Impact

- High = widely applicable to all establishments
- Medium = applicable to many establishments
- Low = applicable to select few establishments or unique process

Factor C - Relative Cost and Savings Payback

- High = implementation cost >90% of reference technology, or payback > 10 years
- Medium = cost <90% and >40% of reference technology, payback <10 years
- Low = cost <40% of reference, payback < 2 years

Note: the score is reversed such that H = 1 and L = 3

Factor D – Technical Risk

- High = high likelihood of technology success and deployment, minimal risk factors
- Medium = insufficient evidence of technology success, some risk factors
- Low = low likelihood of success, multiple and significant risk factors

Note: the score is reversed such that H = 1 and L = 3

Factor E – Productivity/Product Quality Gain

- High = significant gain in productivity, either quantity or quality of product produced
- Medium = moderate gain in productivity
- Low = no gain in productivity

Factor F – Environmental Benefits

- High = multiple and significant environmental benefits,
- Medium = some environmental benefits,
- Low = little or no environmental benefit

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Ethylene													
Primary Fractionation	M	Engineering Judgment - TRL 6	H	Wide ranging applications	H	Major capital investment	H	Large process change	L	Engineering judgment	H	Improvement on energy intensive process	61%
Pyrolysis	H	Engineering Judgment - TRL 7	H	Wide ranging applications	H	Major capital investment	H	Large process change	M	Engineering judgment	H	Improvement on energy intensive process	72%
Alternative Ethylene Technology	M	Engineering Judgment - TRL 5	H	Wide ranging applications	H	Major capital investment	H	Large process change	NA	Engineering judgment	NA	15% more CO_2 emissions	58%
Product Recovery/ Fractionation	M	Engineering Judgment - TRL 6	H	Wide ranging applications	H	Major capital investment	H	Large process change	L	Engineering judgment	H	Improvement on energy intensive process	61%
Enhanced Separation Efficiency in Olefin/ Paraffin Distillation	L	Engineering Judgment - TRL 3	M	It is specific to olefins, but they make up a large share of chemicals	M	It is only reducing current by 2-10%.	M	Not enough data to make this high	M	Engineering Judgment,	M	0.1 M Ton CO_2 reduction according to fact sheet	61%
Elongating the Reactor to Increase the Residency Time of the Feed Stream	H	Engineering Judgment - TRL 8	L	Small targeted application	M	Moderate capital investment	L	Small well understood process change	L	Engineering judgment	H	Improvement on energy intensive process	72%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Ethylene (continued)													
Heat Integrated Distillation through Use of Microchannel Technology	M	Based on OSTI report - TRL 5	L	Final report indicates scale up limitations	H	Not cost effective for scale up of ethylene according to final report.	H	Technical risk would be great. Report already states that scale up would not work.	L	Based on it not being able to reasonably affect the large ethylene market, productivity benefits would be minimal	L	Engineering Judgment	39%
Development of Highly Selective Oxidation Catalysts by Atomic Layer Deposition	M	Engineering Judgment - TRL 6	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	L	Does not appear to address environmental benefits	61%
New Catalyst	H	Engineering Judgment - TRL 9	H	Wide ranging applications	H	Payback 7.9 years	H	Large process change	NA	Engineering judgment	H	Improvement on energy intensive process	73%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
	Technology Weighting Factors												
Technology Name	**A – Technology Readiness**		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		**Overall Importance Rating**
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Ethylene (continued)													
Microwave Enhanced Direct Cracking of Hydrocarbon Feedstock for Production of Ethylene and Propylene	M	According to OSTI report appears to be at a TRL5	H	It is process specific, but it's the biggest process for the biggest product and other large-volume products such as propylene.	L	OSTI report says it is directly related to energy savings. Estimating nearly \$900 M/yr	M	Engineering Judgment	H	Engineering Judgment	H	Estimate in OSTI report is for about 1 B tons CO_2 emission reduction	89%
Catalyst-Assisted Production of Olefins from Natural Gas Liquids: Prototype Development and Full-Scale Testing	M	From proposal - TRL 6	H	Engineering Judgment and from proposal estimates.	M	23% reduction in conversion costs according to proposal	M	Engineering Judgment	M	No estimate in proposal; engineering judgment only	M	2 M tons CO_2, reductions in NO_x From proposal	72%
Novel Membranes for Olefin/ Paraffin Separation	M	Judgment from project summary description: TRL 4-5	H	Separation widely applicable in this industry	L	Project summary shows Payback in 1.3 years and ROI of 67%	M	Engineering Judgment	M	Engineering Judgment	M	Engineering Judgment	78%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Propylene													
Advanced Nano-structured Molecular Sieves for Energy Efficient Industrial Separations	M	Engineering Judgment	H	Separations technologies are widely applicable	M	Cost is 40-50% of reference technology	M	Engineering Judgment	M	Moderate	M	Applicability to propylene and maybe other chemicals	72%
Millisecond Oxidation of Alkanes	L	Engineering Judgment - TRL 3	M	Only propylene and its derivatives	L	Cost is only about 5% of reference	H	Low likelihood of success (unless someone picks it up)	H	Significance of this increasing. Direct propylene from cracking predicted to diminish.	NA	No information available	67%
Chlorine													
Hydrogen Fuel Cells	M	Engineering Judgment - TRL 6	L	Small targeted application	M	Moderate capital investment	H	Large process change	NA	No information available	L	Minor energy savings; fuel cells require more metals than just combusting H_2	39%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Chlorine (continued)													
Fuel Cells	M	Engineering Judgment - TRL 6	L	Small targeted application	H	Major capital investment	H	Large process change	NA	No information available	H	Improvement on energy intensive process	44%
Oxygen Depolarized Cathodes in Membrane Cells	H	Engineering Judgment - TRL 7	L	Small targeted application	L	Minor capital investment	M	Moderate process change	NA	No information available	NA	No information available	50%
Ammonia													
Integrated Ammonia Reactor and Ammonia Pressure Swing Adsorption Recovery	M	Engineering Judgment - TRL 6	L	Small targeted application	L	Minor capital investment	M	Moderate process change	M	Engineering judgment	M	Ammonia and its derivatives	67%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Ammonia (continued)													
Cold Insulation of Syngas Compressor Suction Pipe	H	Engineering Judgment - TRL 8	H	Wide ranging applications	L	Minor capital investment	L	Small well understood process change	H	Engineering judgment	H	Improvement on energy intensive process	100%
Autothermal Reforming	H	Engineering Judgment - TRL 9	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	NA	Engineering judgment	H	Improvement on energy intensive process	72%
Nitrogen/Oxygen													
Impellers on Nitrogen Compressor for Pipeline	H	Engineering Judgment - TRL 9	L	Small targeted application	M	Moderate capital investment	L	Small, well understood process change	M	Engineering judgment	H	Large energy savings	78%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
All Industrial Gases													
Nitrogen Liquefier Unit Cooling System Upgrading	H	Engineering Judgment - TRL 7	L	Small targeted application	L	Minor capital investment	L	Small, well understood process change	NA	Engineering judgment	H	Large energy savings	72%
Ammonium Nitrate													
Drying Techniques	M	Engineering Judgment - TRL 5	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	H	Engineering judgment	L	Small energy savings	72%
Methyl Methacrylate													
New Catalyst	H	Engineering Judgment - TRL 8	L	Small targeted application	L	Minor capital investment	M	Moderate process change	H	Engineering judgment	L	Small energy savings	72%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Methyl Chloride													
Methyl Chloride from Direct Methane Partial Oxidation	M	Engineering Judgment - TRL 5	H	Wide ranging applications	M	Moderate capital investment	H	Large process change	L	Engineering judgment	H	Large energy savings	67%
Butadiene													
Predictive Process Control	H	Engineering Judgment - TRL 7	L	Small targeted application	L	Minor capital investment	L	Small, well understood process change	H	Engineering judgment	H	Large energy savings	89%
Plastics/Resins													
Plastics Recycling	H	Engineering Judgment - TRL 9	M	Applicable to multiple processes with moderate energy savings	M	Moderate capital investment	M	Moderate process change	M	Engineering judgment	H	Recycling	78%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Styrene													
Autothermal Styrene Manu-facturing	M	Engineering Judgment - TRL 6	L	Small targeted application	H	Major capital investment	H	Large process change	H	Engineering judgment	H	Large energy savings	61%
Launching A New Route to Styrene Monomer	H	Engineering Judgment - TRL 7	L	Small targeted application	M	Moderate capital investment	M	Moderate process change	M	Engineering judgment	H	Large energy savings	72%
Isopropanol													
Liquid Membranes for Liquid-Liquid Extractions	H	Engineering Judgment - TRL 8	H	Wide ranging applications	H	Major capital investment	H	Large process change	H	Engineering judgment	M	Moderate energy savings	72%
Gas Membranes	H	Engineering Judgment - TRL 7	H	Wide ranging applications	H	Major capital investment	H	Large process change	H	Engineering judgment	H	Large energy savings	78%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Methanol													
Autothermal Reforming	H	Engineering Judgment - TRL 9	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	NA	Engineering judgment	H	Improvement on energy intensive process	72%
Gas Membranes	H	Engineering Judgment - TRL 7	H	Wide ranging applications	H	Major capital investment	H	Large process change	H	Engineering judgment	H	Large energy savings	78%
Sodium Hydroxide													
Heat Recovery in Harsh Environments	H	Engineering Judgment - TRL 9	M	Applicable to multiple processes with moderate energy savings	M	Moderate capital investment	L	Small, well understood process change	NA	Engineering judgment	M	Moderate energy savings	67%
Nitric Acid													
Heat Recovery in Harsh Environments	H	Engineering Judgment - TRL 9	M	Applicable to multiple processes with moderate energy savings	M	Moderate capital investment	L	Small, well understood process change	NA	Engineering judgment	M	Moderate energy savings	67%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Distillation/Separation													
Refining Column Packing	H	Engineering Judgment - TRL 8	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	NA	Engineering judgment	M	Moderate energy savings	67%
Reactive Distillation	M	Engineering Judgment - TRL 4	H	Wide ranging applications	H	Major capital investment	H	Large process change	H	Engineering judgment	L	Small energy savings	61%
Hybrid Distillation	M	Engineering Judgment - TRL 6	H	Wide ranging applications	M	Moderate capital investment	H	Large process change	M	Engineering judgment	H	Large energy savings	72%
Advanced Distillation Technologies circa 2003	M	Engineering Judgment - TRL 6	H	Wide ranging applications	H	Major capital investment	M	Moderate process change	H	Engineering judgment	M	Moderate energy savings	72%
Distributive Distillation Enabled by Microchannel Process Technology	M	Engineering Judgment - TRL 5	H	Wide ranging applications	H	Major capital investment	H	Large process change	L	Scale-up issues	M	Large energy savings but with scale-up issues	56%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Utilities - CHP, Boilers, etc.													
Microturbines	H	Engineering Judgment - TRL 9	L	Small targeted application	H	Major capital investment	M	Moderate process change	NA	Engineering judgment	H	Large energy savings	56%
Crosscutting Technologies													
New High-Temperature, Low-Cost Ceramic Media for Natural Gas Combustion Burners	H	Engineering Judgment - TRL 7	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	M	Better heating	H	Large energy savings	83%
Modeling and Process Analysis	M	Engineering Judgment - TRL 5	H	Wide ranging applications	L	Minor capital investment	L	Small, well understood process change	L	Engineering judgment	H	Reducing waste	83%

Table A4. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Crosscutting Technologies (continued)													
Advanced Energy and Water Recovery Technology from Low-Grade Waste Heat	M	Engineering Judgment - TRL 4	H	Wide ranging applications	H	Major capital investment	H	Large process change	L	Engineering judgment	H	Waste water recovery	61%

Appendix A4 provides the methodology used to identify the weighting factors and the definitions for the abbreviations.

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