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

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining

June 2015

THE U.S. DEPARTMENT OF ENERGY (DOE)'S ADVANCED MANUFACTURING OFFICE PROVIDED FUNDING FOR THIS ANALYSIS AND REPORT

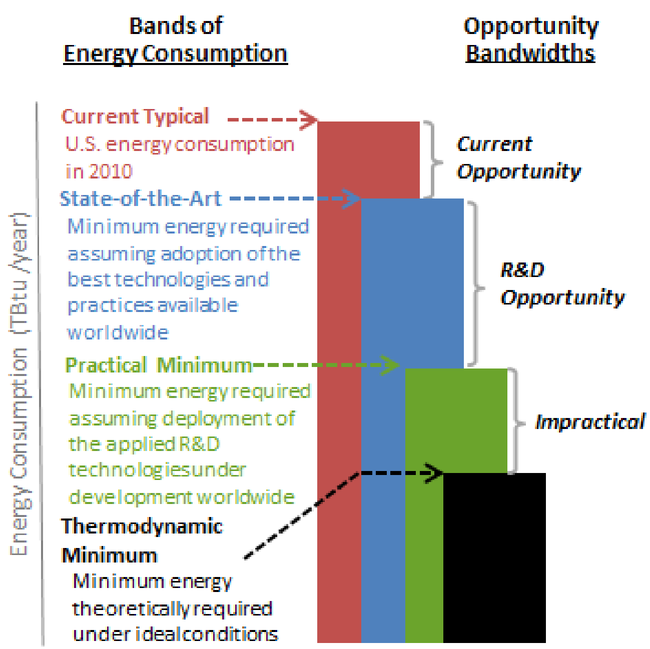
The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office works with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the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

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

(Sabine Brueske, Caroline Kramer, Aaron Fisher)

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.[1]



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

---

[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 R&D 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 Jimmy Kumana of Kumana and Associates for his work reviewing this study. Appreciated is also extended to UOP, a Honeywell Company, for their assistance with estimating research and development savings.

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, 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

The United States was the largest producer of refined petroleum products in 2010, with a net production of a total of over 12.5 million barrels per day (EIA 2013b). This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. petroleum refining. Industrial, government, and academic data are used to estimate the energy consumed in nine of the most energy intensive petroleum refining processes. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing processes 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 processes studied is also extrapolated to determine energy consumption for the entire petroleum refining sector. 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 petroleum refining processes and sector-wide. This is a step toward understanding the processes that could most benefit from technology and efficiency improvements to realize energy savings.

Study Organization and Approach: After providing an overview of the methodology (Chapter 1) and energy consumption in petroleum refining (Chapter 2), the 2010 throughput and production volumes (Chapter 3) and current energy consumption (current typical [CT], Chapter 4) were estimated for nine select processes. In addition, the minimum energy consumption for these processes was estimated assuming the adoption of best technologies and practices available worldwide (state of the art [SOA], Chapter 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 for these processes 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 a sector-wide estimate of energy consumption for U.S. petroleum refining; this data is referenced as sector-wide CT energy consumption. In this study, CT, SOA, PM, and TM energy consumption for nine *individual* processes is estimated from multiple referenced sources. To estimate SOA, PM, and TM energy consumption for the entire sector, the CT, SOA, PM, and TM energy consumption data of the nine processes studied is extrapolated estimate total sector-wide SOA, PM, and TM energy consumption. In 2010, these nine processes corresponded to 68% 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 nine processes studied and for all of U.S. petroleum refining based on extrapolated data. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual processes based on the sector-wide extrapolated data.

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

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Nine Select Petroleum Refining Processes (per year)	Estimated Energy Savings Opportunity for All of the U.S. Petroleum Refining Sector Based on Extrapolated Data (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	286 TBtu[2] (14% energy savings, where TM is the baseline)	420 TBtu[3] (14% energy savings, where TM is the baseline)
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	540 TBtu[4] (26% energy savings, where TM is the baseline)	793 TBtu[5] (26% energy savings, where TM is the baseline)

[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 refinery boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.
[2] 286 TBtu = 2163 – 1877
[3] 420 TBtu = 3176 – 2756
[4] 540 TBtu = 1877 – 1336
[5] 793 TBtu = 2756 – 1963

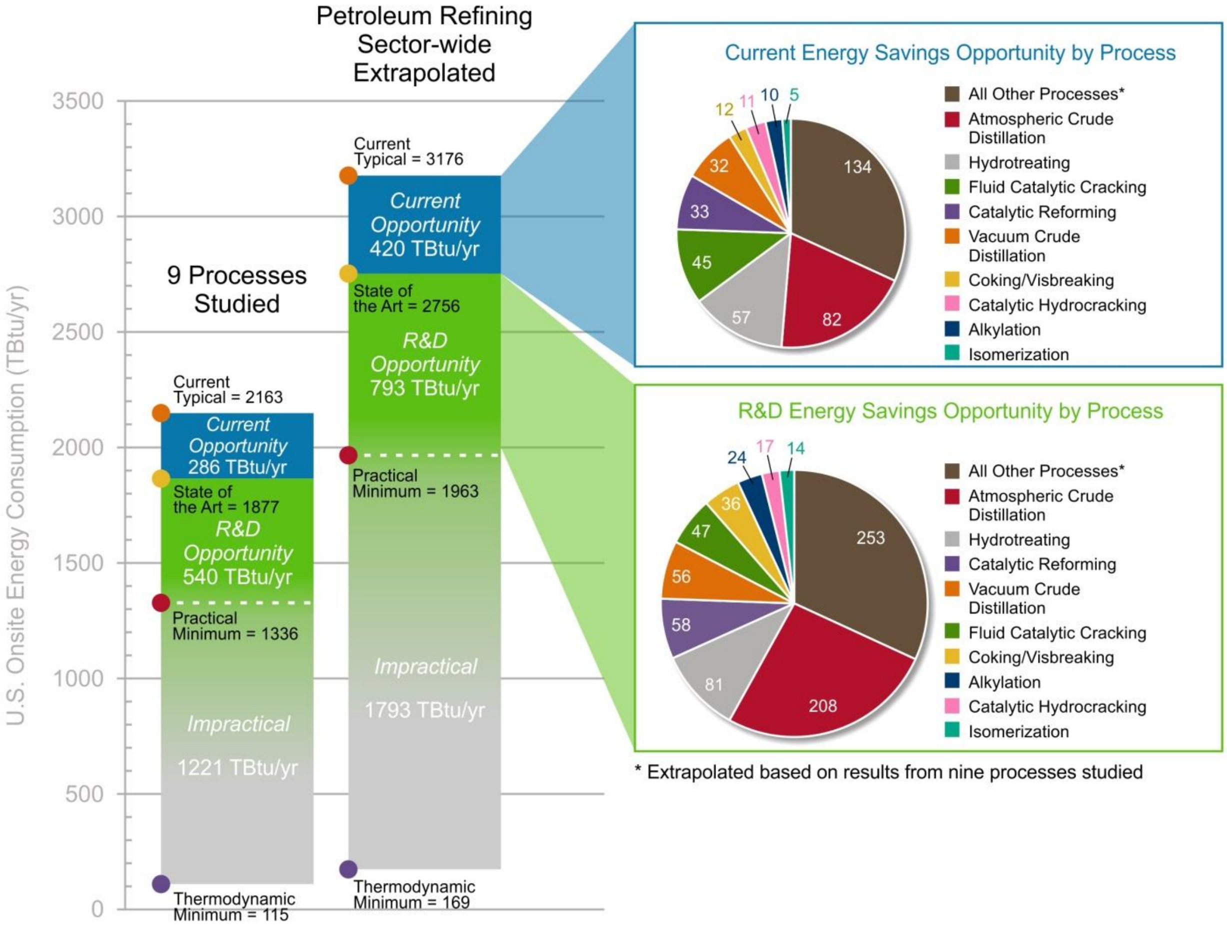


Figure ES-1. Current and R&D Energy Savings Opportunities for the Nine Processes Studied and for Petroleum Refining Sector-wide Based on Extrapolated Data

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 286 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade nine petroleum refining processes; an additional 540 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. petroleum refining industry as a whole, the current energy savings opportunity is 420 TBtu per year and the R&D opportunity increases to 793 TBtu per year.

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

- All other NAICS 324110[1] processes - 134 TBtu (or 32% of the current opportunity)
- Atmospheric Crude Distillation - 82 TBtu (or 20% of the current opportunity)
- Hydrotreating - 57 TBtu (or 14% of the current opportunity) and
- Fluid Catalytic Cracking - 45 TBtu (or 11% of the current opportunity).

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

- All other NAICS 324110[2] processes - 253 TBtu (or 32% of the R&D opportunity)
- Atmospheric Crude Distillation - 208 TBtu (or 26% of the R&D opportunity)
- Hydrotreating - 81 TBtu (or 10% of the R&D opportunity) and
- Catalytic Reforming - 58 TBtu (or 7% of the R&D opportunity).

[1] All other NAICS 324110 includes all other processes in the petroleum refining sector other than the nine processes studied.
[2] All other NAICS 324110 includes all other processes in the petroleum refining sector other than the nine processes studied.

List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
bbl	Barrel
BPSD	Barrels per stream day
Btu	British thermal unit
C	Carbon
C_p	Specific heat
CDU	Crude (oil) distillation unit
CHP	Combined heat and power
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EERE	DOE Office of Energy Efficiency and Renewable Energy
FCC	Fluid catalytic cracking
G	Gibbs free energy
GEMS	Global Energy Management System
H	Enthalpy or hydrogen
HEN	Heat exchanger network
HVAC	Heating, ventilation, and air conditioning
K	degrees Kelvin (as suffix to numerical temperature measure)
LPG	Liquefied petroleum gases
MECS	Manufacturing Energy Consumption Survey
NAICS	North American Industry Classification System
NGL	Natural gas liquids
PM	Practical minimum energy consumption or energy intensity
ppm	Parts per million
R&D	Research and development
S	Entropy
scf	Standard cubic feet
SOA	State of the art energy consumption or energy intensity
T	Temperature
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
Wt%	Weight percent

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. petroleum refining sector, as defined by classification 324110 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 petroleum refining processes and petroleum refining 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.

The United States produces a wide range of refined petroleum products using multiple processes; nine of the most energy-intensive petroleum refining processes were studied. Together, these processes accounted for 68% of the onsite energy consumption of the U.S. petroleum refining sector in 2010.

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

1.2. Comparison to Other Bandwidth Studies

This study builds upon the 2006 DOE bandwidth report *Energy Bandwidth for Petroleum Refining Processes*. The earlier study relied on slightly different energy consumption bands. 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 petroleum refining processes studied from six to nine 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 include chemicals, iron and steel, and pulp and paper; additional sector studies are under

[1] The relevant analysis was published as the *Manufacturing Energy and Carbon Footprint for the Petroleum Refining Sector* (NAICS 324110), 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.

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 for petroleum refining processes.

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).

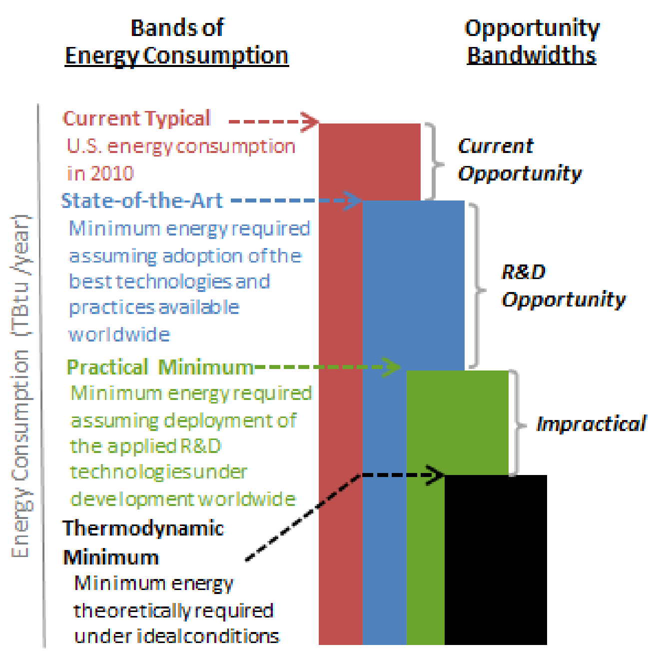


Figure 1-1. Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

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 or 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:

Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption for a *specific manufacturing process 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 *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, petroleum refineries would need to produce refined products in new ways with technologies that are not commercially available.

The difference between PM and TM energy consumption is labeled as *impractical*. The term *impractical* is used because 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 processes and petroleum refining 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 processes studied (TBtu per year), energy intensity values per unit of output or feed (Btu per barrel) are estimated and multiplied by the output or feed volumes (barrels per year). The year 2010 is used as a base year since it is the most recent year for which consistent sector-wide energy consumption data are available. Unless otherwise noted, 2010 capacity and throughput or production data is used. Some petroleum refining 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 petroleum refining. The estimates reported herein are representative of average U.S. petroleum refining; 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 R&D 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 petroleum refining: Chapter 2 provides an **overview** of the U.S. petroleum refining sector and how energy is used in petroleum refining (how much, what type, and for what end uses).

Estimating throughput or production volumes for select processes: Chapter 3 presents the relevant **throughput or production volumes** for the nine processes (bbl per year) in 2010 and the rationale for how the nine processes were selected.

[2] Feedstock energy is the nonfuel use of combustible energy. Feedstocks are converted to refined petroleum products (not used as a fuel); MECS values reported as "feedstocks" exclude feedstocks converted to other energy products (e.g., crude oil converted to residual and distillate fuel oils).

Estimating CT energy consumption: Chapter 4 presents the calculated onsite **CT energy consumption** (TBtu per year) for the nine processes individually 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 throughput or 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 sector-wide for 2010 (See Table 4-1). However, MECS does not provide CT energy consumption data for individual processes. The percent coverage of the processes studied (compared to MECS sector-wide 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 nine processes (along with the references for the SOA energy intensity data and assumptions). The sector-wide SOA energy consumption is estimated based on an extrapolation of the SOA energy consumption for the nine processes studied. 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 nine processes (along with the references for PM energy intensity data and 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 process and described in Appendix A3. The technologies that are considered crosscutting throughout all of petroleum refining along with the most energy-saving, process-specific R&D technologies were used to determine PM energy consumption for each process. 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 sector-wide PM energy consumption is estimated based on an extrapolation of the PM energy consumption for the nine processes studied. 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 the nine processes (along with the references for the TM energy intensity data and assumptions). The TM energy intensities are based on the commercial process 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 process 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 processes and sector-wide. The analyses used to derive these values are explained in Chapters 3 to 7.

2. U.S. Petroleum Refining Sector Overview

This Chapter presents an overview of the U.S. petroleum refining 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. Petroleum Refining Economic Overview

Petroleum refining products are an essential part of the world economy, providing a large source of energy as well as other high value products. The petroleum refining sector produces many high value outputs (e.g., gasoline, jet fuel, etc.) that are essential to our economy. Petroleum is the largest source of primary energy use for the U.S., accounting for 35.3 quadrillion Btu in 2011 (EIA 2012e). About 71% of petroleum is consumed in transportation, making that sector particularly vulnerable to changes in production and pricing (EIA 2012d). Petroleum refining-derived products are also relied upon throughout the manufacturing supply chain, both as fuels and as chemical building blocks in the production of consumer goods.

Petroleum refining plays an outsized role in the U.S. manufacturing sector in terms of the economy, jobs, and energy. The U.S. was the largest producer of refined petroleum products in 2010, with a net production of a total of over 12.5 million barrels per day (EIA 2013b). The petroleum refining industry is closely connected to the chemicals industry as certain petroleum products (e.g., naphtha) are used as feedstocks (or inputs) for the production of petrochemicals, an important subsector of the chemicals industry. In 2011, the total value of petroleum refining products shipped in the United States amounted to $753 billion and direct employment of the petroleum refining sector numbered about 62,000 (USCB 2012b).

2.2. U.S. Petroleum Refining Products, Establishments, and Processes

Petroleum refining is a complex industry that generates a diverse slate of fuel and chemical products, from gasoline to heating oil. Numerous outputs are produced by petroleum refineries each year in the United States; Table 2-1 shows the type and amount of products produced by U.S. refineries in 2010.

Table 2-1. U.S. Petroleum Refinery Products, 2010	
Product	**Production** (million barrels)
Distillate Fuel Oil *	1,538
Motor Gasoline	1,142
Jet Fuel	521
Petroleum Coke *	296
Still Gas *	245
Liquefied Refinery Gases (LRG) *	240
Residual Fuel Oil *	210
Asphalt and Road Oil	139
Petrochemical Feedstocks	119
Lubricants	60
Miscellaneous	28
Special Naphthas	14
Kerosene	6
Aviation Gasoline	5
Waxes	3
Total	**4,568**

Source: EIA 2013b

** A portion of some refining products are used as fuel at the refinery. Approximately 90% of still gas, 28% of petroleum coke, and <1% of distillate fuel oil, residual fuel oil, and LRG are consumed onsite as fuel (EIA 2013f)*

As of January 1, 2012, there were 144 operable petroleum refineries (both operating and idle) in the U.S. (EIA 2012c). About 44% of refineries were located in three states: Texas (which had 27 refineries), Louisiana (19 refineries), and California (18 refineries) (EIA 2012c). Most of the larger refineries are concentrated along the coast due to the access to sea transportation and shipping routes. Figure 2-1 shows the current geographic distribution of petroleum refineries in the U.S. As can be seen, there is a concentration of refineries along the Gulf Coast, in close proximity to shipping channels and crude oil supply sources.

Figure 2-1. Geographic Distribution of Petroleum Refineries in the United States
(created from EIA 2013d)

The refining process involves separating, cracking, restructuring, treating, and blending hydrocarbon molecules to generate petroleum products. Figure 2-2 shows the typical overall refining process. The specific processes implemented will vary from refinery to refinery, and depend upon the refinery's capacity and feedstock makeup or quality as well as specific products. As seen in Figure 2-2 petroleum refinery operations generally start with the atmospheric crude distillation unit. Heavier products from the bottom of the atmospheric distillation tower continue to the vacuum crude distillation unit where heat is applied under vacuum conditions to further separate products. To simplify the bandwidth analysis, coking and visbreaking were combined as one process area, where coking includes both delayed coking and fluid coking. Also, the isomerization process category includes isobutane, isopentane, and isohexane production, and the alkylation process includes both sulfuric acid and hydrofluoric acid catalyst.

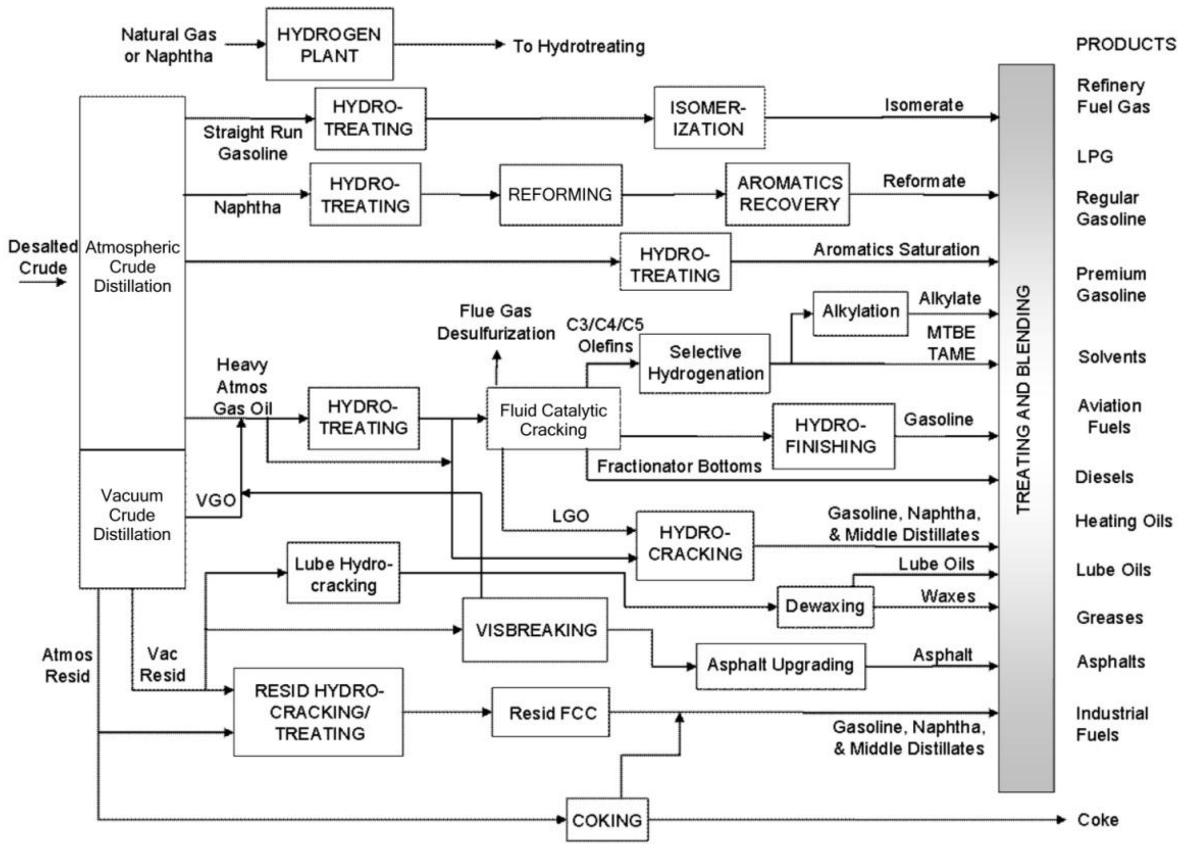


Figure 2-2. Typical Petroleum Refinery Flow Diagram *(DOE 2007)*

Of the numerous processes involved in petroleum refining, nine were selected for this analysis on the basis of production volume and energy intensity, including three (coking/visbreaking, hydrocracking, and isomerization) that were not considered in the previous bandwidth (DOE 2006). This makes the present report more representative of the petroleum refining sector as a whole. The nine processes studied in this bandwidth analysis are listed in Table 2-2 in alphabetical order.

Table 2-2. Petroleum Refining Processes Selected for Bandwidth Analysis
Alkylation
Atmospheric Crude Distillation
Catalytic Hydrocracking
Catalytic Reforming
Coking/Visbreaking
Fluid Catalytic Cracking (FCC)
Hydrotreating
Isomerization
Vacuum Crude Distillation

2.3. U.S. Petroleum Refining Energy Consumption

Onsite energy and primary energy for the U.S. petroleum refining sector are provided in Table 2-3. 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 2-3. U.S. Petroleum Refining Energy Consumption Sector-Wide, 2010	
Onsite Energy Consumption (includes electricity, steam, and fuel energy used onsite at the facility)	3,176 TBtu
Primary Energy Consumption (includes onsite energy consumption, and offsite energy losses associated with generating electricity and steam offsite and delivering to the facility)	3,555 TBtu

Source: DOE 2014

Petroleum refining is the second largest consumer of energy in U.S. manufacturing, accounting for 3,555 TBtu (18%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Offsite electricity and steam generation and transmission losses in petroleum refining totaled 379 TBtu in 2010; onsite energy consumed within the boundaries of U.S. petroleum refineries totaled 3,176 TBtu.

Figure 2-3 shows the total onsite energy *entering* U.S. petroleum refineries; most of the energy entering is in the form of fuel. About 30% 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 2-4 shows the total onsite energy at the *point of end use*. Electricity and steam from both offsite and onsite generation are included in Figure 2-4, along with the portion of energy loss that occurs in onsite generation. The data provided in Table 2-3, Figure 2-3, and Figure 2-4 are based on MECS with adjustments to account for withheld and unreported data (DOE 2014).

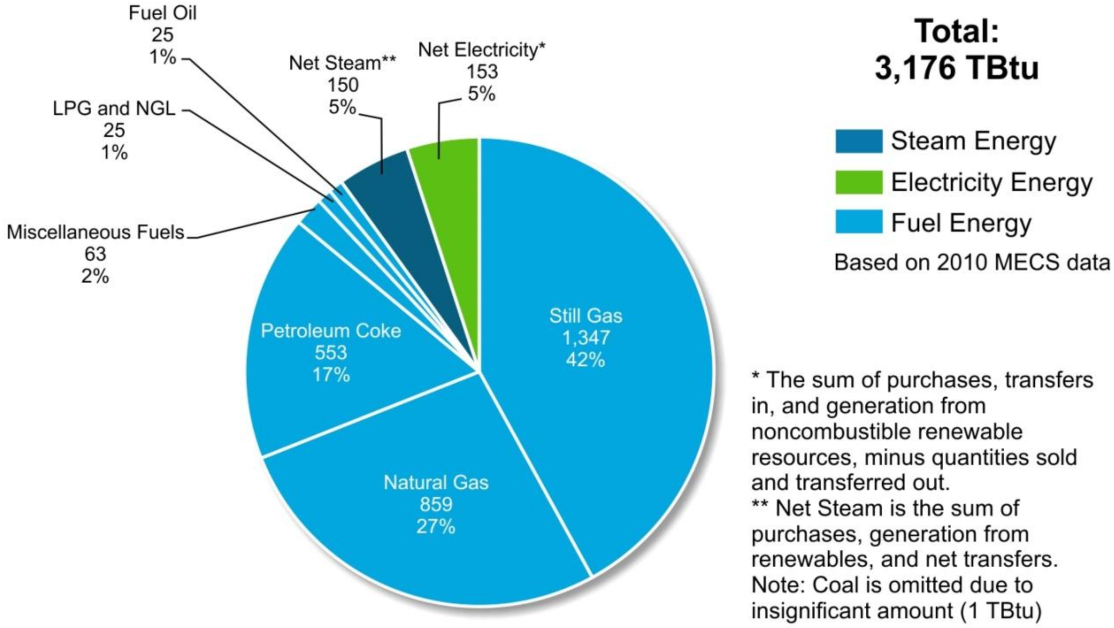


Figure 2-3. Onsite Energy Entering U.S. Petroleum Refineries, 2010 *(DOE 2014)*

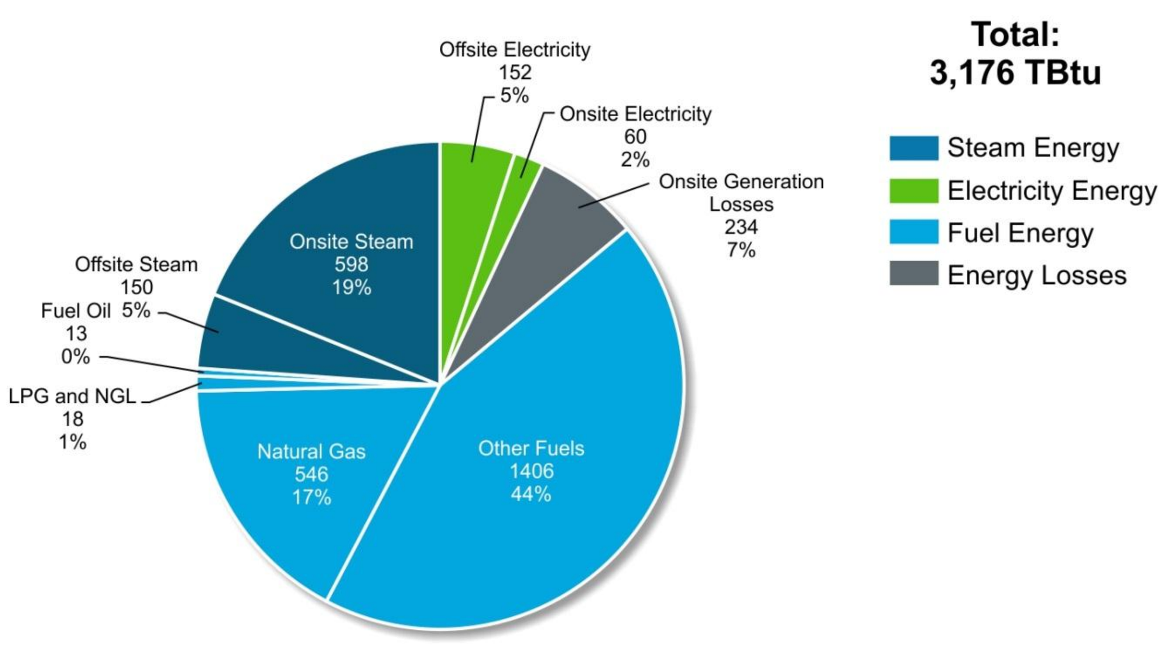


Figure 2-4. Onsite Energy Consumption at Point of End Use in U.S. Petroleum Refineries, 2010 *(DOE 2014)*

2.3.1. Fuel and Feedstocks

As shown in Figure 2-3, onsite fuel consumption amounted to 2,873 TBtu in 2010, or about 90% of total onsite energy entering petroleum refineries (EIA 2013). Still gas (also referred to as refinery fuel gas or waste gas) accounts for nearly half (46%) of the sector's fuel consumption. Still gas, the most commonly used byproduct fuel, is produced and captured in process off-gases and is typically made up of hydrogen, methane, ethane, and other light-end gases. The hydrogen content in still gas improves the enthalpy of combustion which allows for greater transfer of heat into the process compared to purchased natural gas.

Many refineries are self-sufficient in fuel consumption, using a mixture of byproduct off-gases and fuel oil. In some cases, however, it is more profitable to process the gas-oil fractions further into higher-value refined products than to burn them as fuel oil and purchase cheaper natural gas (and sometimes coal) to supplement the available off gases. Figure 2-5 provides a breakdown of fuel consumption in the petroleum refining sector by end use in 2010. The categories of end use are reported by EIA in MECS. The majority of the fuel (64%) is used directly for process heating; some examples of process heating equipment include fired heaters, heated reactors, and heat exchangers. A significant portion of fuel (30%) is used indirectly in boilers and CHP to generate additional onsite electricity and steam (DOE 2014).

The process heating end use is limited to direct-fired fuel used in furnaces for distillation columns, reactors, and hot oil loops. The indirect boiler and CHP end use includes fuel used for steam and electricity generation. The values in Figure 2-5 represent total fuel consumption, not absorbed duty in the process, and therefore boiler, furnace, and turbine efficiency effects are already accounted for.

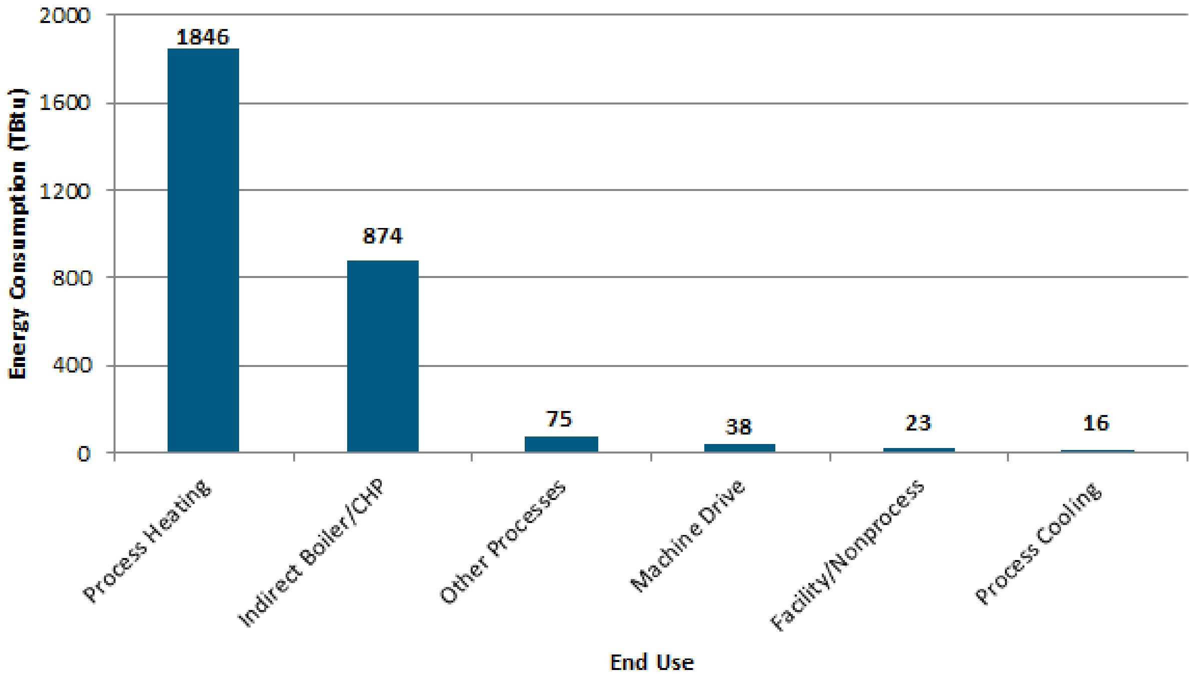


Figure 2-5. Fuel Consumption in the Petroleum Refining Sector by End Use, 2010 *(DOE 2014)*

Feedstock energy is the nonfuel use of combustible energy. For petroleum refining, feedstock energy is converted to 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. In MECS, EIA reports feedstock energy used for the production of non-energy products (e.g., asphalt, waxes, lubricants) and as a petrochemical feedstock only; feedstock energy used for the production of other energy products (e.g., motor gasoline, fuel oil) is excluded. A detailed breakdown of feedstock by energy type is not available from MECS; instead, all feedstock energy is classified as 'other' fuel. EIA excludes inputs and feedstock that were converted to other types of energy products from this reported feedstock number, so total feedstock energy consumed in refining is significantly greater than 2,746 TBtu when accounting for these additional feedstocks (e.g., crude oil converted into gasoline).

Feedstock energy is a significant portion of energy consumption in U.S. petroleum refining (2,746 TBtu) so it is important to consider when analyzing overall petroleum refining 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 processes.

2.3.2. Electricity

Figure 2-3 shows that onsite net electricity entering petroleum refineries totaled 153 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 2-4 shows that 213 TBtu of total electricity is consumed at the point of end use and includes 60 TBtu of electricity generated onsite.

In Figure 2-6, the breakdown of the 213 TBtu of electricity is shown by end use in 2010 (DOE 2014). There are numerous uses for electricity in petroleum refining; 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). Motors used for cooling water circulation pumps and fans, however, are accounted for in process cooling end use. Other end uses of electricity for petroleum refining are less significant, but include nonprocess facility related end uses (e.g., facility heating, ventilation, and air conditioning (HVAC), facility lighting, cooking, office equipment, etc.) and other end uses.

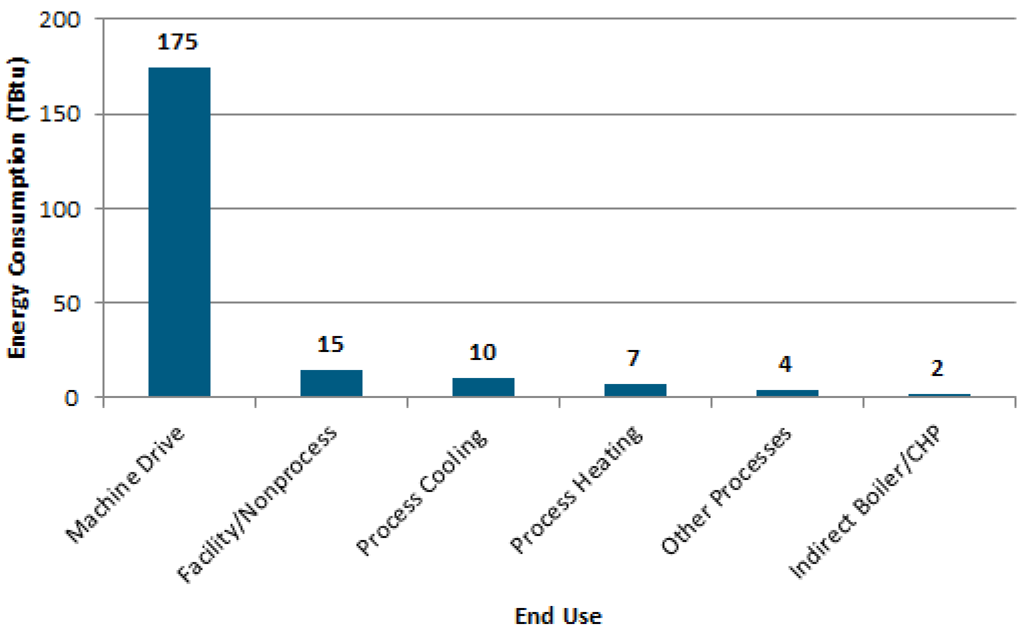


Figure 2-6. Electricity Consumption in the Petroleum Refining Sector by End Use, 2010 *(DOE 2014)*

2.3.3. Steam

Figure 2-3 shows 150 TBtu of net steam entering petroleum refineries in 2010. The data presented is the *net amount*, which is the sum of purchases, generation from renewables, and net transfers. A larger amount of steam is generated onsite. Figure 2-4 shows that 748 TBtu of steam is consumed at the point of end use, including 598 TBtu of steam generated onsite (150 TBtu of purchased and generated steam is lost through distribution to end uses) (DOE 2014).

Figure 2-7 shows the breakdown of 589 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 petroleum refining include machine driven equipment (i.e., steam turbines), other process end uses, 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.

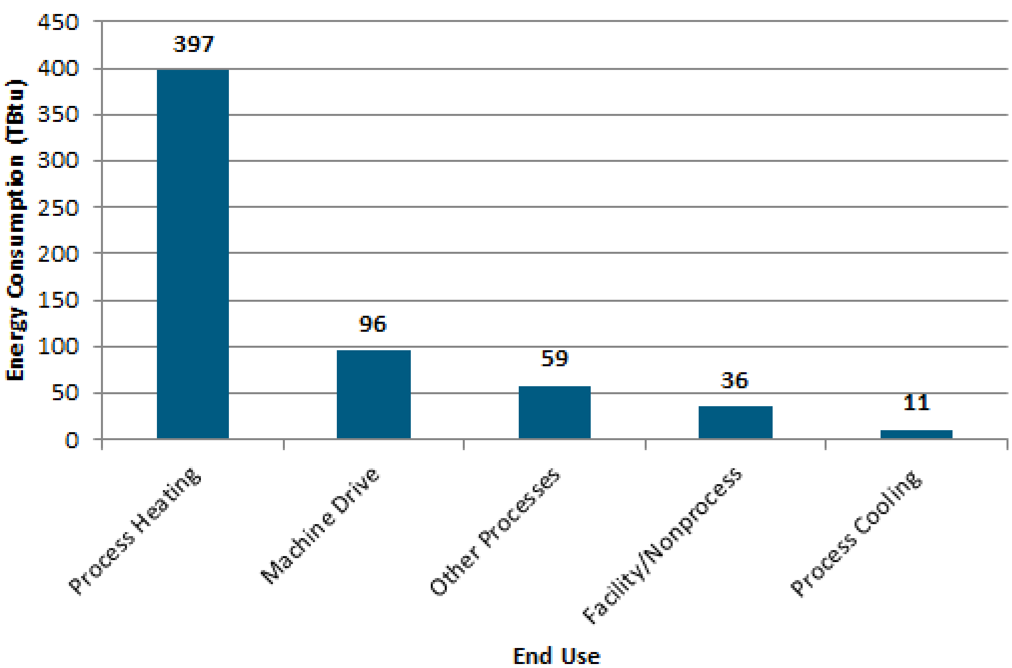


Figure 2-7. Steam Consumption in the Petroleum Refining Sector by End Use, 2010 *(DOE 2014)*

3. Throughputs and Production in U.S. Petroleum Refining

In this bandwidth study, nine petroleum refining processes were selected for individual analysis. For petroleum refining, process data is often reported in terms of capacity, throughput, or production. Capacity is the maximum amount of feed that a petroleum refining process unit is able to process. Throughput is the amount of feed that is actually processed, and is the value used for energy consumption calculations for seven of the processes in this study. Two of the processes (alkylation and isomerization) instead use production values of the process product(s). Table 3-1 presents the U.S. relevant capacity and throughput or production data for the nine processes for the year 2010.

Table 3-1. U.S. Petroleum Refining Process Capacities and Throughputs/Production for the Nine Processes Studied in 2010

Process	**2010 Capacity** (Million barrels/year)	**2010 Throughput or Production*** (Million barrels/year)	Details
Alkylation	423	365**	Based on alkylate production capacity
Atmospheric Crude Distillation	N/A	5,540	Gross input to atmospheric distillation units (considered equivalent to throughput)
Catalytic Hydrocracking	616	532**	Based on downstream charge capacity
Catalytic Reforming	1,221	1,055**	Based on downstream charge capacity
Coking/Visbreaking	892	770**	Based on downstream charge capacity
Fluid Catalytic Cracking	2,115	1,827**	Based on downstream charge capacity
Hydrotreating	5,589	4,829**	Based on downstream charge capacity
Isomerization	235	203**	Based on isobutane, isopentane, and isohexane production capacity
Vacuum Crude Distillation	2,898	2,504**	Based on downstream charge capacity

** Values for alkylation and isomerization are production; all other process values are throughput*

***Capacity factor of 86.4% for 2010 (EIA 2011) applied to capacity determine throughput/production*

Sources: Appendix A2 provides the sources referenced for U.S. capacity and throughput/production data of each process.

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

The year 2010 was used for throughput or production and capacity values to correspond with the latest MECS data, which is also for 2010. In the data provided by EIA, capacity is either listed for the year (2010) or at the start of the following year (January 1, 2011). Production data was gathered from a variety of EIA data sources, including the downstream charge capacities of operable petroleum refineries, production capacities of operable petroleum refineries, and refinery utilization and capacity. Throughput for atmospheric crude distillation was directly available from the data sources, while throughputs or production for the other processes studied were calculated based on the petroleum refinery utilization rate of 86.4% for 2010. A detailed listed of sources can be found in Appendix A2.

The total crude distillation rate of all the refineries in the U.S. was about 15 million barrels per stream day (BPSD) in 2010, versus a capacity of 17.6 million BPSD (EIA 2013c). The crude distillation capacity of individual refineries varies widely from about 3,300 BPSD to 625,000 BPSD (EIA 2012d). The U.S. Small Business Administration classifies refineries with a crude distillation capacity of less than 125,000 barrels per day as small and those with more than 125,000 barrels per day as large (SBA 2012). Although there are more small refineries than large ones, they only account for about 25% of total U.S. refining capacity.

Refinery size has an impact on operating practices and energy efficiency. Typically, small refineries are less complex than medium and large refineries and typically have fewer of the refining process units listed in Figure 2-2. On the other hand, refineries larger than 200,000 barrels per day often have more than one parallel train for the same process units (i.e., two crude distillation towers or two reformers) as a consequence of staged refinery expansions over time (most refineries have a service life of 50-100 years).

4. Current Typical Energy Consumption for U.S. Petroleum Refining

This Chapter presents the energy consumption data for individual petroleum refining processes and sector-wide 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. petroleum refining; they do not represent energy consumption in any specific facility or any particular region in the United States.

4.1. Boundaries of the Petroleum Refining Bandwidth Study

Estimating energy requirements for an industrial process depends on the boundary assumptions; this is especially true in the petroleum refining 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 petroleum refining.

This study does not consider lifecycle energy consumed during raw material extraction (e.g., drilling and exploration), 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. Estimated Energy Intensity for Individual Processes

Energy intensity data are needed to calculate bands of energy consumption in this study. This Section presents the estimated energy intensities of the nine processes studied.

The specific energy needed to process a barrel of feed or produce a barrel of product can vary significantly between processes, 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 feed or output (typically barrels in the petroleum refining industry) and, therefore, reported as Btu per barrel (Btu/bbl). Energy intensity estimates are available for specific equipment performance, process unit performance, or even plant-wide performance. Energy intensity can be estimated by process, both in the United States and other global regions, based on average, representative process and plant performance.

Energy efficiency at petroleum refineries varies depending on regional supply and demand constraints, feedstock characteristics, facility and equipment age, weather conditions, and applicable compliance requirements. Energy efficiency also varies within an individual refinery for many of the same reasons. Swings of 10-15% in energy efficiency are not uncommon whether due to external or internal factors (Kumana & Associates 2013). External factors include variations in feedstock flow, feedstock properties (due to blending), feedstock supply temperature, ambient temperature, and market demand for refined products. Internal factors all stem from either poor design or poor operating practices, the worst of which are usually inefficient heat exchanger network (HEN) design, poor process control due to inadequate instrumentation, failure to reconcile measured data, operating equipment at off-design conditions, unscheduled equipment outages, and sub-optimal heat exchanger cleaning programs (Kumana & Associates 2013).

Appendix A1 presents the CT energy intensities and energy consumption for the nine processes studied in alphabetical order. Table 4-1 presents a summary of the references consulted to identify CT energy intensity by process. Appendix A2 provides the references used for each process.

Because the petroleum refining sector is diverse, covering many products, a range of data sources were considered (see Table 4-1). Current energy intensities for each of the nine petroleum refining processes identified in this study were taken from the *Energy and Environmental Profile of the U.S. Petroleum Refining Industry*, denoted in this report as DOE 2007. Energy intensity values for each of the processes are broken down by electricity and steam/process heat consumption in DOE 2007, resulting in net energy intensity. This study provided the most current representative values for the U.S. petroleum refining industry. Sources for energy intensities in DOE 2007 came from a variety of sources, including Hydrocarbon Processing's *2006 Refining Processes Handbook*. This commonly referenced industry publication provides utility requirements for licensed technologies currently used in petroleum refineries.

Since the publishing of DOE 2007, two additional *Refining Processes Handbooks* (2008 and 2011) have been released. These sources were reviewed and it was determined that they did not provide new information for the nine selected processes. As a result, the energy intensity values are taken directly from DOE 2007. Other sources such as Solomon Associates' Comparative Performance Analysis (well known in the petroleum refining sector for their performance monitoring and benchmarking services) were sought but ultimately unavailable due to confidentiality considerations.

The specific technologies and processes in use at individual petroleum refineries can vary; thus, it is difficult to ascertain an exact amount of energy necessary to complete a process. Consequently, the values for energy intensity provided should be regarded as estimates based on the best available information.

Table 4-1. Published Sources Reviewed to Identify Current Typical Energy Intensities for Processes Studied	
Source	**Description**
DOE 2007	The *Energy and Environmental Profile of the U.S. Petroleum Refining Industry*, published by DOE in 2007 and focused on the U.S., provides a detailed energy breakdown (including total net process energy) for each of the petroleum refining processes that consume a significant amount of energy in the sector and produce numerous products. This was the main source for determining current typical energy intensity.
EIA 2013a	Manufacturing Energy Consumption Survey data released by EIA every four years; this data comes from a survey that is taken by U.S. manufacturers. The most recent year for which MECS data is published is 2010. The data is scaled up to cover the entirety of U.S. manufacturing and for individual manufacturing sectors. For petroleum refining, it provides energy consumption data for the entire sector.
HP 2011, HP 2008a, HP 2006	Hydrocarbon Processing publishes the *Refining Processes Handbook* every few years (including the 2006, 2008, and 2011 versions that were consulted for this bandwidth) which provides utility consumption data (electricity, steam, and fuel) for specific licensed petroleum refining processing technologies. In some cases, multiple technologies are listed for a specific process, allowing for comparison of energy consumption data.

4.3. Calculated Current Typical Energy Consumption for Individual Processes

Table 4-2 presents the calculated onsite CT energy consumption for the nine processes studied. To calculate onsite CT energy consumption, energy intensity for each process (presented initially in Appendix A1) is multiplied by the 2010 throughput or production data (presented initially in Table 3-1 and also in Appendix A1). Feedstock energy is excluded from the consumption values. The CT energy consumption for these nine processes is estimated to account for 2,163 TBtu of onsite energy, or 68% of the 3,176 TBtu of sector-wide onsite energy use in 2010. Appendix A1 presents the onsite CT energy consumption for the nine processes individually in alphabetical order.

Calculated primary CT energy consumption by process is also reported in Table 4-2. 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 sector-wide onsite energy are scaled to account for offsite losses and added to onsite energy (see the footnote in Table 4-2 for details on the scaling method).

Table 4-2. Calculated U.S. Onsite Current Typical Energy Consumption for Processes Studied in 2010 with Calculated Primary Energy Consumption and Offsite Losses					
Process	**Energy Intensity** (Btu/bbl)	**Throughput or Production**[1] (million bbl/year)	**Onsite CT Energy Consumption, Calculated** (TBtu/year)	**Offsite Losses, Calculated** (TBtu/year)[2]	**Primary CT Energy Consumption, Calculated** (TBtu/year)
Alkylation	246,700	365	90	11	101
Atmospheric Crude Distillation	109,100	5,540	604	72	676
Catalytic Hydrocracking	158,900	532	85	10	95
Catalytic Reforming	263,900	1,055	279	33	312
Coking/Visbreaking	147,700	770	114	14	127
Fluid Catalytic Cracking	182,800	1,827	334	40	374
Hydrotreating	80,800	4,829	390	46	437
Isomerization	216,000	203	44	5	49
Vacuum Crude Distillation	89,100	2,504	222	27	250
Total for Processes Studied			**2,163**	**257**	**2,420**

Current typical (CT)

[1] Values for alkylation and isomerization are production; all other process values are throughput

[2] 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 throughput or production data and energy intensity data are provided by process in Appendix A2. The other values are calculated as explained in the text.

4.4. CURRENT TYPICAL ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

In this Section, the CT energy consumption estimates for nine processes studied are provided.

Table 4-3 presents the onsite CT energy consumption by process and sector-wide for U.S. petroleum refining. The nine processes studied account for 68% of all onsite energy consumption by the U.S. petroleum refining sector in 2010. As shown in the last column of Table 4-3, the percentage of coverage of the processes studied is calculated. This indicates how well the processes studied represent total sector-wide MECS-reported energy. The overall percentage of coverage for the processes studied (68%) is used later in this study to determine the extrapolated total sector-wide SOA, PM, and TM energy consumptions.

Table 4-3 also presents CT primary energy consumption by process. Primary energy is calculated from onsite CT energy consumption databased on an analysis of MECS data (DOE 2014), with scaling to include offsite electricity and steam generation and transmission losses (DOE 2014).

Table 4-3. Onsite and Primary Current Typical Energy Consumption for the Nine Processes Studied and Sector-Wide in 2010, with Percent of Sector Coverage			
Process	**Onsite CT Energy Consumption, calculated** (TBtu/year)	**Primary CT Energy Consumption, calculated*** (TBtu/year)	**Percent Coverage** (Onsite CT as a % of Sector-wide Total)**
Alkylation	90	101	19%
Atmospheric Crude Distillation	604	676	7%
Catalytic Hydrocracking	85	95	9%
Catalytic Reforming	279	312	12%
Coking/ Visbreaking	114	127	3%
Fluid Catalytic Cracking	334	374	11%
Hydrotreating	390	437	4%
Isomerization	44	49	3%
Vacuum Crude Distillation	223	250	1%
Total for Processes Studied	2,163	2,420	68%
All Other Processes	1,104	1,135	32%
Total for Petroleum Refining Sector-wide	3,176***	3,555***	100%

Current typical (CT)

** 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).*

*** Calculated by dividing the onsite CT energy consumption for the processes studied by sector-wide onsite CT energy consumption (3,176 TBtu).*

**** Source for sector-wide values is DOE 2014.*

5. State of the Art Energy Consumption for U.S. Petroleum Refining

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. petroleum refineries. Petroleum refineries will output a wide range of refined products using a different series of processes and types of feedstocks, and will therefore vary widely in size, age, efficiency, and energy consumption. Modern petroleum refineries can benefit from more energy-efficient technologies and practices.

A modern refinery is designed for flexibility in the type and amount of feedstock that is available as well as the desired outputs. The energy consumption necessary to produce a higher quality product often depends on the amount and type of processing the feedstock crude oil must undergo. Often, refineries will elect to process the most readily available or economical feedstock to maximize productivity. Energy consumption often may be a secondary consideration as refineries choose modifications to increase output and thus profit. Instead of performing costly equipment replacement that may interrupt operations, refineries may be more inclined to seek ways to optimize current operations, investing in improvements to existing equipment, taking advantage of heat or power recovery, or adopt an energy management system.

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

5.1. Calculated State of the Art Energy Consumption for Individual Processes

Appendix A1 presents the onsite SOA energy intensity and consumption for the nine processes considered in this bandwidth study in alphabetical order. The SOA energy consumption for each petroleum refining process is calculated by multiplying the SOA energy intensity for each process by the relevant throughput or production (all relevant data are presented in Appendix A1).

The onsite SOA energy consumption values are the net energy consumed in the process using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a 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. 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 5-1. Published Sources Referenced to Identify State of the Art Energy Intensities for Nine Select Processes

Source Abbreviation	Description
DOE 2013	Compiled results from the 14 DOE Energy Saving Assessments that were conducted at petroleum refineries during 2006-2011 by DOE and Oak Ridge National Laboratory to determine average onsite energy savings.
ExxonMobil 2011	Compiled results from the 14 DOE Energy Saving Assessments that were conducted at petroleum refineries during 2006-2011 by DOE and Oak Ridge National Laboratory to determine average onsite energy savings.
Kumana & Associates 2013	The data represent results from 22 case studies for seven types of process units, both existing and new. The studies were conducted on nine refineries in the U.S., China, and the Middle East between 2003 and 2013.
LBNL 2005a	This 2005 study reviews energy efficiency opportunities available for petroleum refineries.
McKinsey 2009	This report discusses methods to reduce greenhouse gas emissions and energy consumption for 10 different sectors, including petroleum refining.
SEP 2013	The Superior Energy Performance (SEP) Program is currently being demonstrated in numerous manufacturing facilities, 13 of which have achieved certification with various levels of realized percent energy savings. Achieving SEP involves a rigorous certification including adopting an energy management system and measurement and verification of continuous energy improvement.

Other various articles and reports; see Appendix A2 for full references for each process

An important and reliable source of actual field data for SOA energy intensity was from 22 energy efficiency studies completed between 2003 and 2013 at nine different refineries located in China, the Middle East, and the U.S.[3] Energy efficiency improvements were identified for multiple refining processes (integrated atmospheric and vacuum distillation, reforming, hydrotreating, delayed coking, hydrocracking, and isomerization). Significant savings potential was found, ranging from 10-33% at typical simple paybacks of less than five years (see Table 5-2). The primary technique employed was heat recovery optimization using pinch analysis, but included some equipment upgrades (e.g., variable frequency drives for selected large motors), minor process modifications, operational best practices such as load management, and optimizing the design and operation of the site CHP systems. Although most of the efficiency improvements involved retrofitting existing process units, significant savings were also identified in licensor design offerings for completely new units. All the savings projects were identified through application of pinch analysis for optimized heat recovery.

---

[3] Jimmy Kumana, a well-respected petroleum refining industry consultant and energy efficiency course instructor, agreed to serve as a peer reviewer of this petroleum refining bandwidth study and to share the results of case study findings from petroleum refining energy audits conducted in the U.S., China, and the Middle East. The energy savings data provided by his company was consolidated and findings were reported by year and process units only. Information linking their findings with specific refineries has been deliberately omitted.

Table 5-2. Consulted Petroleum Refining SOA Case Studies Breakdown and Details		
Process Unit	**Number of Units**	**% Savings Identified**
Integrated Atmospheric and Vacuum Crude Distillation	6	17%
Coking/Visbreaking	2	15%
Hydrocracking	2	20%
Hydrotreating	6	33%
Isomerization	2	10%
Reforming	4	15%

Source: Kumana & Associates 2013

These savings can be considered to correspond to SOA designs, using existing catalysts and distillation conditions, and taking into account constraints of safety, operability, and layout. The savings potential generally ranged from 10% to 20%, but was over 30% for hydrotreating. Achieving greater savings would likely only be possible by switching to newer and better (more expensive) catalysts that can deliver higher yields, faster kinetics, and greater resistance to activity loss over time. In the crude distillation unit (CDU), improved heat recovery is often limited because of accelerated asphaltene fouling rates at higher temperatures. The solution is to employ a multi-pronged strategy that includes optimized feedstock blending, raising desalter and flash drum temperatures, mechanical modifications to the heat exchanger to ensure adequate fluid velocities and shear rates, and optimized heat exchanger cleaning strategies.

Although all the identified projects in the case studies were both technically and economically feasible, not all were implemented for a variety of reasons including a strategic decision to withhold investment in an urban refinery where a shutdown was being considered, competition for limited capital from higher priority projects (e.g., capacity, safety, environmental), disputes with the licensor over intellectual property rights for the improved design, and inability to incorporate design revisions into the engineering, procurement, and construction (EPC) schedule.

Another important source of data was a comprehensive report on ways for petroleum refineries to increase their energy efficiency by Lawrence Berkeley National Laboratory (LBNL) is *Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries* (LBNL 2005a). This report provides a detailed and valuable overview of energy efficiency opportunities for specific process units as well as in general for petroleum refineries.

The availability of an estimate of energy savings for each measure varies, and it is important to note that all the improvement opportunities will likely not be able to be adopted by an individual refinery due to savings overlap. The authors of this report chose a combination of savings estimates, including adoption of process control, steam distribution savings from improvements, process integration, and the use of power recovery. A general listing of energy efficiency opportunity areas for specific process units as outlined by LBNL 2005a is included in Table 5-3 below.

Table 5-3. Specific Petroleum Refining Process Unit Energy Efficiency Opportunities*	
Process Unit	**Opportunity Areas**
Alkylation	Process controls, process integration (pinch analysis), optimization distillation
Atmospheric Crude Distillation	Process controls, high-temperature combined heat and power (CHP), process integration (pinch analysis), furnace controls, air preheating, progressive crude distillation, optimization distillation
Coking/Visbreaking	Process integration (pinch analysis), furnace controls, air preheating, optimization distillation
Fluid Catalytic Cracking	Process controls, power recovery, process integration (pinch analysis),furnace controls, air preheating, optimization distillation, process flow changes
Hydrocracking	Power recovery, process integration (pinch analysis),furnace controls, air preheating, optimization distillation
Hydrotreating	Process controls, process integration (pinch analysis), optimization distillation, new hydrotreater designs
Reforming	Process integration (pinch analysis), furnace controls, air preheating, optimization distillation
Vacuum Crude Distillation	Process controls, process integration (pinch analysis), furnace controls, air preheating, optimization distillation

** Adapted from LBNL 2005a*

Other valuable sources provided estimates of general savings for SOA, including actual plant assessments returned from the DOE's Energy Savings Assessment (ESA) program and ExxonMobil's GEMS (Global Energy Management System) studies. The ESA program identified an aggregate onsite energy savings of about 3.4% for 14 which were surveyed between 2006 and 2011. These ESA analyses identified a number of energy savings opportunities. Generally, most of the opportunities were related to management of steam systems or process heating. The targeted steam system improvements related to reducing leaks, adjusting the boilers, improving insulation and improving steam traps. The other large source of 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 with unreasonable capital investment and short payback periods (less than 2 years). However, the ESA savings are comparatively small compared to other savings estimates (potentially even insignificant when considering the variability and typical swings in plant energy consumption).

ExxonMobil's GEMS studies identified savings of about 9% in their petroleum refining operations due to improvements made between 2002 and 2011 (ExxonMobil 2011). These savings were applied to each of the nine process units selected for this study[4]. The McKinsey & Company report *Pathways to a Low-Carbon Economy* also estimated that the entire petroleum refining industry could reduce its energy consumption by 13% over CA by 2020 if it adopted currently available best practice technologies (McKinsey 2009). The improvements identified by

[4] Savings were applied to 2010 energy consumption, even though ExxonMobil findings considered 2002 as the base year. Nine percent savings were determined to be in line with other SOA sources.

McKinsey 2009 include waste-heat recovery through heat integration, replacing boilers, heaters, turbines, and motors, and adopting increased cogeneration.

5.2. State of the Art Energy Consumption By Process and Sector-wide

Table 5-4 presents the onsite SOA energy consumption for the nine U.S. petroleum refining processes studied. In this table, the SOA energy consumptions for the processes studied are summed and extrapolated to provide a sector-wide onsite SOA energy consumption. Table 5-4 also presents the onsite SOA energy savings, or the *current opportunity*. The SOA energy savings is also 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 process. The pie chart in Figure 5-2 captures the blue portions of the bar chart shown in Figure 5-1. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is vacuum crude distillation at 23% energy savings; the greatest *current opportunity* in terms of TBtu savings is atmospheric crude distillation at 82 TBtu per year savings.

To extrapolate the sector-wide data presented in Table 5-4 and Figure 5-1, the SOA energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire subsector (68%, as shown in Table 4-3). Percent coverage is the ratio of the sum of all the CT energy consumption for the individual processes studied to the CT energy consumption for the subsector provided by MECS (see Table 4-3). The extrapolated number is the estimated SOA energy consumption for the entire subsector. The SOA energy consumption for the remainder of the sector (i.e., all processes that are not included in the nine processes studied) was calculated by subtracting the total for the processes studied from the sector-wide total. These additional processes are together referred to as All Other Processes in Table 5-4).

Table 5-4 also presents the SOA energy savings percent. 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 petroleum refining processes is a negative value. When comparing energy savings percent from one process 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 Processes Studied and Sector-Wide				
Process	**Onsite CT Energy Consumption** (TBtu/year)	**Onsite SOA Energy Consumption** (TBtu/year)	**SOA Energy Savings**† (CT-SOA) (TBtu/year)	**SOA Energy Savings Percent** (CT-SOA)/ (CT-TM)*
Alkylation	90	80	10	9%
Atmospheric Crude Distillation	604	522	82	20%
Catalytic Hydrocracking	85	74	11	9%
Catalytic Reforming	279	246	33	17%
Coking/ Visbreaking	114	101	12	11%
Fluid Catalytic Cracking	334	289	45	17%
Hydrotreating	390	333	57	9%
Isomerization	44	39	5	11%
Vacuum Crude Distillation	223	192	32	23%
Total for Processes Studied	2,163	1,877	286	14%
All Other Processes	1,013	879	134	14%
Total for Petroleum Refining Sector-wide	3,176	2,756**	420	14%

Current typical (CT), State of the art (SOA)

† SOA energy savings is also called Current Opportunity.

** SOA energy savings percent is the SOA energy savings opportunity from transforming petroleum refining processes. 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)*

*** The sector-wide SOA energy consumption was an extrapolated value, calculated by dividing the total onsite SOA energy consumption for the processes studied by the overall percent coverage from Table 4-3 (68%).*

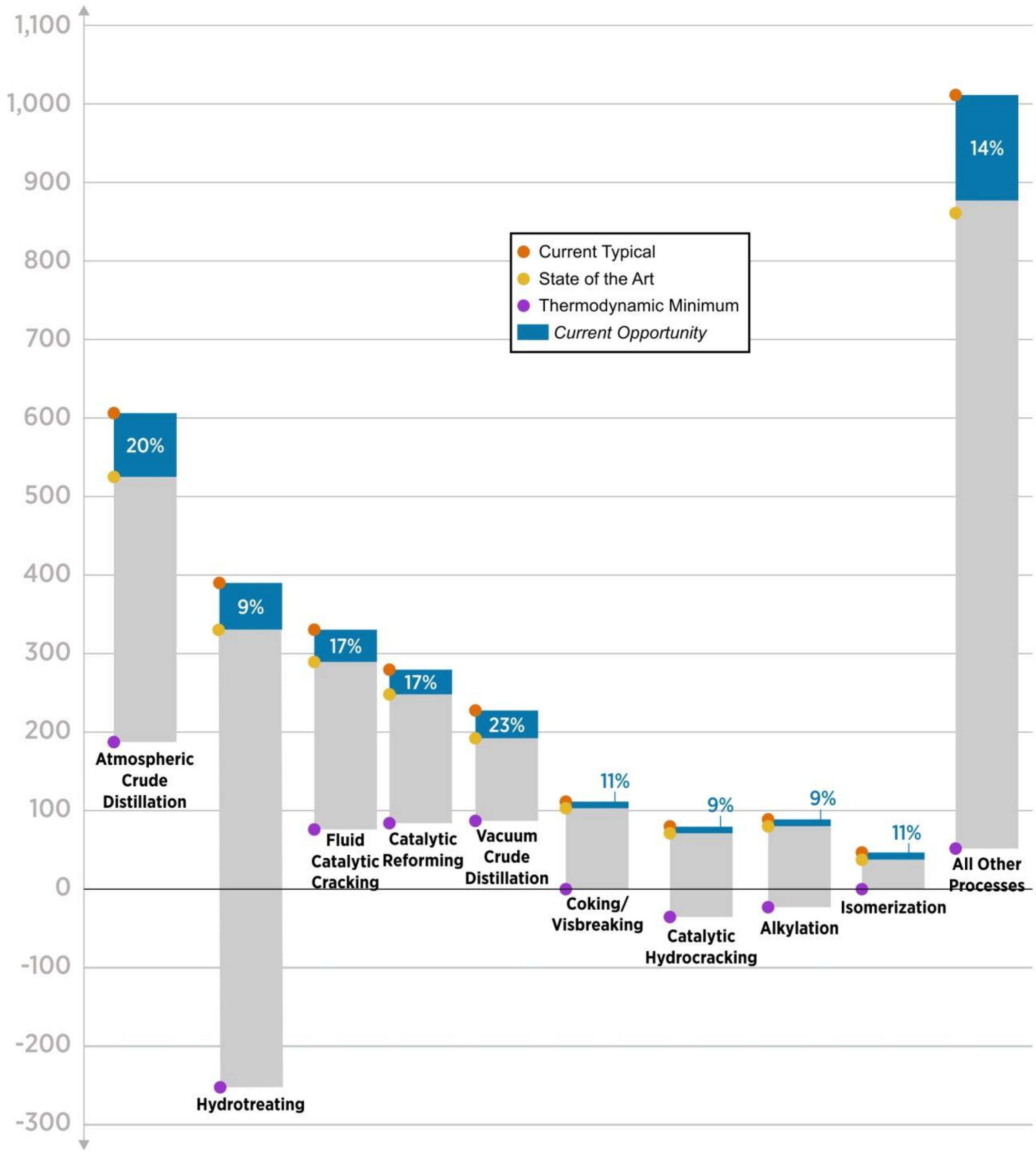


Figure 5-1. Current Opportunity Energy Savings Bandwidths for Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

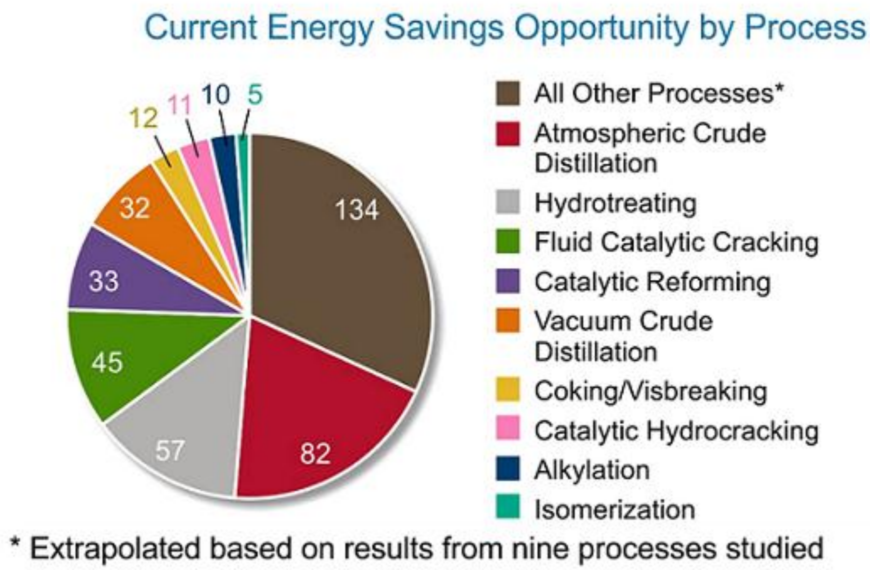


Figure 5-2. Current Energy Savings Opportunity by Petroleum Refining Process Studied *(Energy Savings Per Year in TBtu)*

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

If all U.S. petroleum refineries were able to attain onsite SOA energy intensities, it is estimated that 286 TBtu per year of energy could be saved from the nine processes alone, corresponding to a 14% energy savings sector-wide. 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 petroleum refining processes have relatively large available energy savings opportunities. In the following Sections, several processes are highlighted and the nature of the onsite SOA energy savings is discussed. Appendix A1 provides detailed data for each individual process.

5.2.1.1. Atmospheric Crude Distillation

As the first step of the petroleum refining process, atmospheric distillation plays an important role and is the largest energy consuming process. About 82 TBtu per year or 29% of the total SOA energy savings for the sector can be attributed to atmospheric crude distillation. The crude oil is preheated in a series of heat exchangers in order to preheat and vaporize the crude oil feed before entering the atmospheric distillation tower. Retrofitting the crude oil preheat train to reach the highest possible furnace inlet temperature is the main method to reduce the process's overall energy use. As mentioned in Section 4.2, higher temperatures can lead to accelerated fouling, which reduces the effectiveness of the HEN revamp. To maintain good efficiency, an active heat exchanger cleaning program may have to be undertaken.

5.2.1.2. Fluid Catalytic Cracking

Fluid catalytic cracking (FCC) accounts for 45 TBtu per year or 16% of the total SOA energy savings for petroleum refining. While the FCC unit can generally be considered as a net energy producer from a utility standpoint, a large source of the surplus energy comes from the catalyst regeneration step during which coke is burned off. This energy can be recovered and used for heating purposes and to provide the endothermic heat of reaction; the catalytic cracking is typically performed at a high temperature, between 900°F and 1000°F. Power recovery is another example of an opportunity to improve energy efficiency in FCCs.

5.2.1.3. Catalytic Reforming

Of the total petroleum refining SOA energy savings, 33 TBtu per year or about 12% comes from catalytic reforming. Catalytic reforming involves four major reactions in the presence of a metal catalyst, three of which are endothermic (dehydrogenation, dehydrocyclization, and isomerization) while the other is exothermic (hydrocracking). The temperature of the hydrocarbon feed stream is typically maintained at about 950°F. The significant amount of process energy being used as fuel for process heaters is an area to improve energy efficiency.

5.2.1.4. Vacuum Crude Distillation

Of the 286 TBtu per year of available sector-wide SOA energy savings, vacuum crude distillation accounts for 32 TBtu per year or 11%. Vacuum distillation processes the heavy crude residue, or bottoms product, from atmospheric crude distillation. The components of this residue have boiling points above 750°F, resulting in very high temperatures in the equipment and cause the formation of coke deposits. Operating the distillation tower in a vacuum lowers the temperature necessary to separate the components and reduce some of the negative effects of the residue itself on the process.

6. Practical Minimum Energy Consumption for U.S. Petroleum Refining

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway that can be used to make petroleum refining products in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. petroleum refining. In this Chapter, the R&D energy savings made possible through R&D advancements in petroleum refining 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 Petroleum Refining Industry

As a matter of business strategy, the major U.S. refining companies have been steadily reducing their R&D budgets for over 40 years, choosing instead to rely on third parties to perform most of the new technology development. The dissemination of new techniques is then shared through forums such as technical literature (e.g., publications such as Hydrocarbon Processing, Oil & Gas Journal, etc.) or industrial seminars or conferences (IPPC 2012).

A 2004 energy efficiency roadmap for California's petroleum refineries notes that the top priority areas for R&D in refining in order of significance are: new process technology, improved process operations, conserving and generating electricity, energy systems/ management, and treatment and sulfur removal (CEC 2004). Because oil refining technology is fairly standard across the world, these targeted areas of improvement are likely to apply to all refineries, whether located in the U.S. or elsewhere in the world.

In general, oil and gas companies are very reliant on technology royalties. Research in this sector is very tightly protected due to the competitive nature of the industry. For the most part, R&D information is kept confidential until the technology has been developed, piloted, and successfully licensed. An attempt was made in this study, to solicit research savings estimates from leading petroleum refining companies. All operating companies declined to cooperate due to concerns of confidentiality. Only UOP, whose sole business is process development and technology licensing as a vendor to the oil refining industry, provided a summary of research savings areas by process unit with corresponding energy savings estimates. Other sources of savings estimates were consulted and a full list can be found in Section 6.3 below.

It is also worth noting that there are cultural barriers in most oil refining companies towards adopting innovative new technology, because over the years the industry has become a commodity business with very thin profit margins. Refinery managers are generally rewarded for maintaining target production throughput and yield, with minimal downtime. The penalty for unscheduled production outages (a possible consequence of pursuing of cost savings) far outweighs any potential benefits. The reality is that despite accounting for 60% of a refinery's controllable costs, energy efficiency is usually a secondary priority at best (Kumana & Associates 2013).

6.2. Description of a Future Refinery

Current trends in the petroleum refining industry suggest that the refinery of the future will have the following characteristics (Kumana & Associates 2013):

- Greater capacity; at least 200,000 barrels per day and as much as 600,000 barrels per day
- Utilization of multiple feedstock sources; there are only a handful of giant oil fields in the world capable of supplying all of the crude oil requirements of such large refineries
- More complex, with the ability to process heavier (i.e., American Petroleum Institute (API) gravity less than 20) and higher sulfur crudes; this will require investment in more hydrotreating and other advanced technologies
- Campaign-style operation for the crude distillation/vacuum distillation units (i.e., running different feedstock blends depending upon crude oil feedstock availability, each one for only a few days at a time). Some of the larger refineries in India receive crude oil from over 50 different sources. Tank farm operations and optimized blending strategies will become increasingly important.
- Located at or near major sea-ports, pipeline hubs, or major production fields
- Co-located with a petrochemicals complex (e.g., 10 large grass-roots refineries built in the past decade largely fit this profile)

The larger existing refineries will likely continue to expand in production capacity to meet demand requirements. Energy efficiency will remain a significant concern for refineries as the price of feedstocks, operations, and compliance increase. Process modifications will be needed for refineries to operate flexibly and be able to handle feedstocks of varying composition and quality. Also, refineries will need to be able to produce higher quality and range of products, including new alternative or more environmentally friendly fuels, from these lower quality feedstocks in order to keep up with increasing demand.

Refineries will have to comply with any future environmental regulations, whether it is through emissions allowances or fuel quality requirements. The establishment of different, non-traditional refineries that take advantage of alternative feedstocks (e.g., biomass, coal, and crude shale oil) and processes may become more widespread, including biorefineries, coal liquid refineries, shale oil refineries, and gasification refineries.

Table 6-1 below, adapted from *The Refinery of the Future* by James G. Speight, provides some predictions of likely process changes and technology developments that in the nine process units that are the focus of this bandwidth analysis. Other general cross-cutting development areas include catalyst innovations and adaptation to new feedstocks.

Table 6-1. Examples of Future Refining Technology and Process Developments*	
Process	**Details**
Atmospheric and vacuum crude distillation	**Short-term developments**: improved heat recovery and integrating atmospheric and vacuum distillation **Long-term developments:** integration of different distillation columns into one reactor or alternative process routes that allow for combined conversion/distillation **Alternative processes:** membranes or freeze concentration
Catalytic Hydrocracking	Will take central position in integration of refineries and petrochemical plants due to flexibility; development of innovative fixed bed designs that allow better catalyst utilization or online catalyst removal in order to handle increased heavy feedstocks
Coking/visbreaking	**Coking:** changes to reactor internals and nature of catalysts, but likely to remain as a commonly used refinery process **Visbreaking:** may be increasingly used as pretreatment process
Hydrotreating	**Advanced hydrotreating developments:** new catalysts, catalytic distillation, and processing at mild conditions, hydrodesulfurization development will continue for cleaner transportation fuel production **Upgrading approaches:** higher activity and more resilient catalysts, replacement of reactor internals for increased efficiency, adding reactor capacity, specialized process design and hardware **Long-term developments:** new desulfurization technologies or evolution of the older technologies that will reduce the need for hydrogen

** Adapted from Speight 2011*

6.3. Calculated Practical Minimum Energy Consumption for Individual Processes

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific petroleum refining 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 petroleum refining industry was conducted. This research turned up a very limited range of promising new technologies for consideration.

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 A1 presents the onsite PM energy consumption for the nine processes considered in this bandwidth study in alphabetical order. The PM energy consumption for each process is calculated by multiplying the estimated PM energy intensity for each process by the process's 2010 throughput or production volume (the energy intensity and throughput or production data are also presented in Appendix A1).These values exclude feedstock energy. The lower limit for onsite PM energy intensity and onsite PM energy consumption are presented in Appendix A1.The upper limit of the PM range is assumed to be the SOA energy consumption. The PM energy consumption for each process is expressed as a range because the energy savings impacts are speculative and based on unproven technologies.

Table 6-2 presents the key sources consulted to identify PM energy intensities in petroleum refining. 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 6-2. Key Published Sources Reviewed to Identify Practical Minimum Energy Intensities for Select Processes

Reference Abbreviation	Source
ANL 1999	The Potential for Reducing Energy Utilization in the Refining Industry, Argonne National Laboratory, Petrick, M. and Pellegrino, J, 1999.
HP 2008b	"Improved crude oil fractionation by distributed distillation", Hydrocarbon Processing (HP), Haddad, H.N. and Manley, D.B., 2008.
LBNL 2000	Emerging Energy-Efficient Industrial Technologies, Lawrence Berkeley National Laboratory (LBNL), Martin, N., Worrell, E., Ruth, M., Price, L., Elliott, R.N., Shipley, A.M., Thorne, J, 2000.
Szklo & Schaeffer 2007	"Fuel specification, energy consumption, and CO2 emissions in oil refineries," Energy 32: 1075-1092, Szklo, A. and Schaeffer, R., 2007.
UOP 2013	Industrial contact estimates

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 A3.

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 the nine processes. In Appendix A3, technologies are aligned with the most representative process. Some of the technologies have applicability to more than one process (e.g., both atmospheric and vacuum distillation).

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. 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 process, the technology that resulted in the lowest energy intensity was conservatively selected for the PM energy intensity.

R&D in some process areas is more broadly applicable, such as utility/power generation improvements and crosscutting technologies. 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 utility and crosscutting improvements were assumed to be applicable to all nine processes studied. To calculate PM energy consumption, the CT energy intensity and TM energy intensity were multiplied by the combined estimated savings for utility and crosscutting improvements (27%-39%) and subtracted from the CT energy consumption.

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, refinery-wide energy savings, process energy savings, or energy-type savings. In each case, the reported energy savings were adjusted to determine PM energy intensity.

6.3.1. 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 specific processes (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.

6.4. Practical Minimum Energy Consumption By Process and Sector-wide

Table 6-3 presents the onsite PM energy consumption for the nine processes studied and petroleum refining sector-wide. 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.

In Table 6-3, data is extrapolated to estimate the total PM subsector opportunity. PM energy consumption for the individual processes studied is summed and the data is extrapolated to estimate sector total. PM subsector energy savings is also expressed as a percent in Table 6-3. 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 6-3. Onsite Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for the Processes Studied and Sector-Wide				
Process	**Onsite CT Energy Consumption** (TBtu/year)	**Onsite PM Energy Consumption** (TBtu/year)	**PM Energy Savings †** (CT-PM) (TBtu/year)	**PM Energy Savings Percent** (CT-PM)/ (CT-TM)*
Alkylation	90	56-80	10-34	9-30%
Atmospheric Crude Distillation	604	314-522	82-290	20-70%
Catalytic Hydrocracking	85	57-74	11-27	9-22%
Catalytic Reforming	279	188-246	33-90	17-46%
Coking/ Visbreaking	114	66-101	12-48	11-42%
Fluid Catalytic Cracking	334	243-289	45-92	17-35%
Hydrotreating	390	252-333	57-138	9-21%
Isomerization	44	25-39	5-19	11-43%
Vacuum Crude Distillation	223	135-192	32-88	23-64%
Total for Processes Studied	2,163	1,336-1,877	286-826	14-40%
All Other Processes	1,013	626-879	134-387	14-40%
Total for Petroleum Refining Sector-wide	3,176	1,963-2,756**	420-1,213	14-40%

Current typical (CT), Practical minimum (PM), Thermodynamic Minimum (TM)

† *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 process. Potential opportunity reflects the difference between CT and TM energy consumption. Calculation: (CT- PM)/(CT- TM).*

** *The sector-wide PM energy consumption was an extrapolated value, calculated by dividing the total onsite SOA energy consumption for the processes studied by the overall percent coverage from Table 4-3 (68%).*

Figure 6-1 presents the *current opportunity* and the *R&D opportunity* for each process; 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. For the processes studied, the greatest *current opportunity* in terms of percent savings is vacuum crude distillation at 23% energy savings; the greatest *R&D opportunity* is atmospheric crude distillation at 70% energy savings. In Figure 6-2, the *current* and *R&D* savings opportunity is shown in terms of TBtu per 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 atmospheric crude distillation at 82 TBtu per year savings; the greatest *R&D opportunity* in terms of TBtu savings is also atmospheric crude distillation at 290 TBtu per year savings. In terms of both percent energy savings and TBtu/year savings, this process shows the greatest overall opportunity.

To extrapolate the data for all other processes that is shown in Table 6-3 and Figure 6-2, the PM energy consumption of each individual process studied is summed, and the sum is divided by the percent coverage for the entire sector (68%, see Table 4-3). The percent coverage of processes studied compared to the total CT energy consumption of the sector is shown in the last column of Table 4-3. Percent coverage is the ratio of the sum of all the CT energy consumption for the individual processes studied to the CT energy consumption for the sector provided by MECS (see Table 4-3). The PM energy consumption for the remainder of the sector (i.e., all processes that are not included in the nine processes studied) was calculated by subtracting the total for the processes studied from the sector-wide total. These additional processes are together referred to as All Other Processes in Table 6-3.

Table 6-3 also presents the PM energy savings percent. 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 process 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:

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

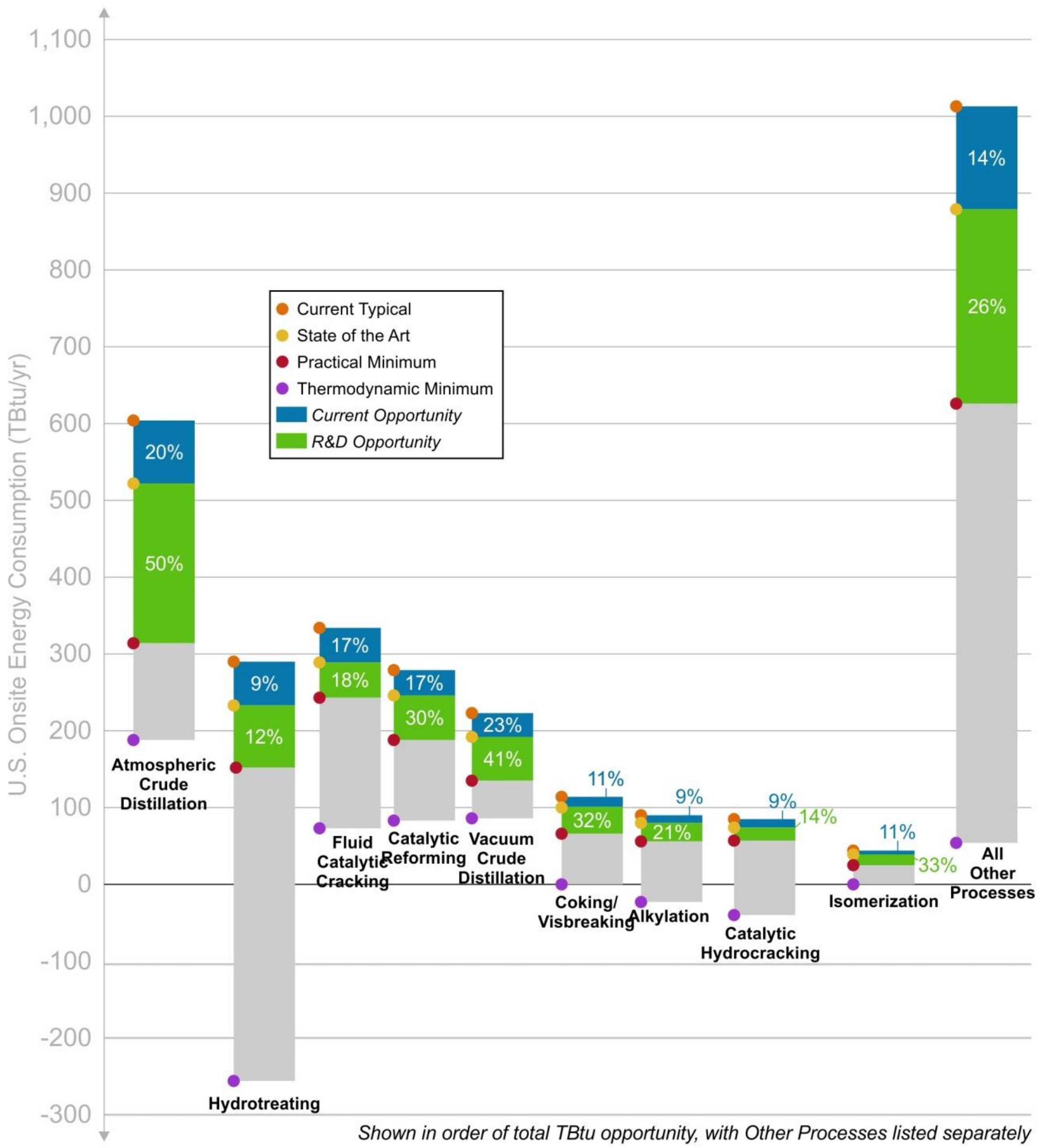


Figure 6-1. Current and R&D Opportunity Energy Savings Bandwidths for the Petroleum Refining Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

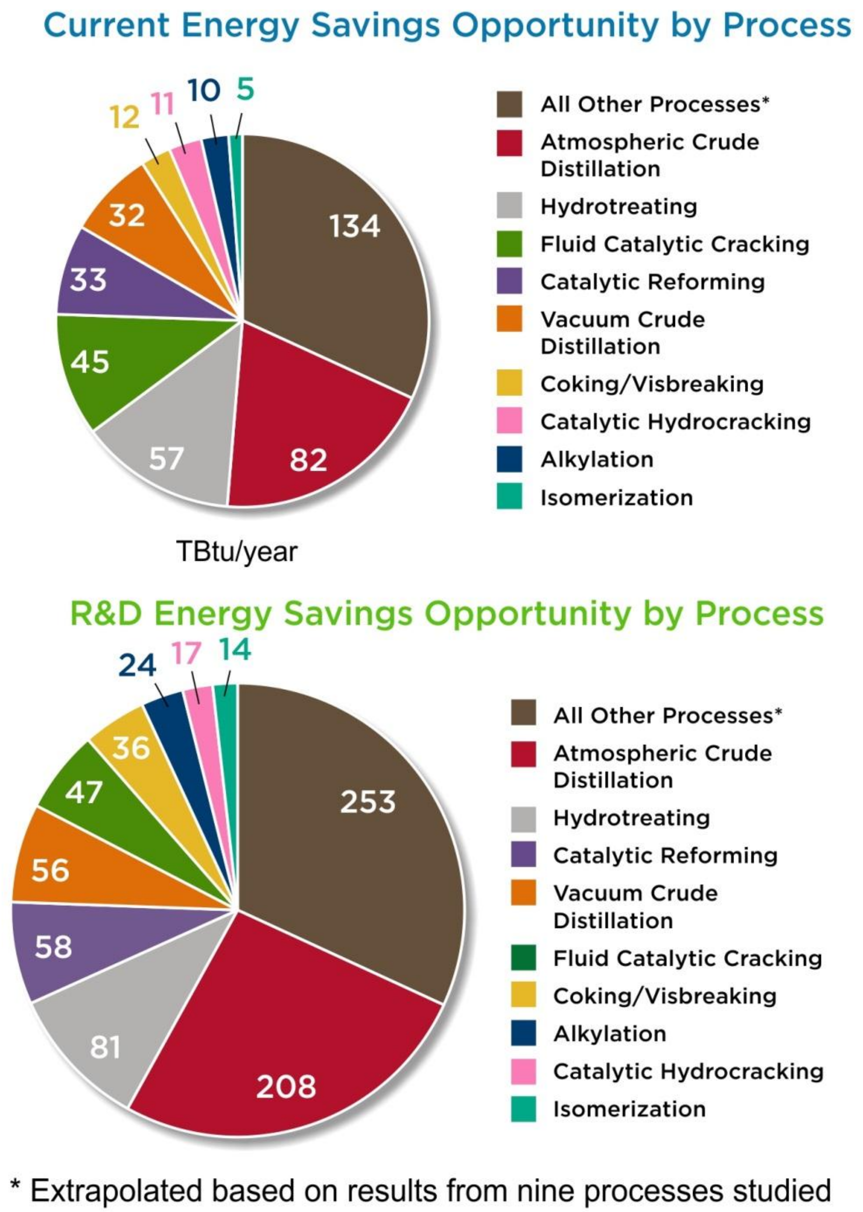


Figure 6-2. Current and R&D Energy Savings Opportunities by Petroleum Refining Process Studied *(Energy Savings Per Year in TBtu)*

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 6-3. 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.

6.4.1. Atmospheric and Vacuum Crude Distillation Practical Minimum Energy Savings

While energy intensity and overall consumption will vary for different refineries, depending upon feedstock composition, capacity, and other factors, there are alternative distillation equipment, processes, and techniques that are being given extensive R&D consideration, especially when compared to the other seven process units. There are numerous ways to reduce the energy consumption of atmospheric and vacuum distillation, and together these two process units offer significant R&D opportunity savings. Thermal cracking is one example of a process that could conceivably replace crude distillation, wherein thermally intensive distillation is replaced by less thermally intensive- cracking. Compared to atmospheric and crude distillation, thermal cracking would consume about 25% less energy (ANL 1999).

As mentioned in Table 6-1, heat recovery and integrating atmospheric and vacuum crude distillation are both examples of developments that can help reduce the energy consumption of these process units. In the example of progressive distillation, two separation processes –gasoline fractionation and a naphtha stabilizer− are integrated, resulting in savings of about 30% in energy. Dividing wall columns are another example of integrating atmospheric and vacuum crude distillation using a vertical partition. Although both of these new types of distillation have been applied to select refineries in a limited fashion, more development is needed to make the technology commercially acceptable. For heat recovery, self-heat recuperation, or where whole-process heat is re-circulated so that no heat needs to be added, is one example of how the energy efficiency of atmospheric distillation could be included (Kansha et al. 2012).

7. Thermodynamic Minimum Energy Consumption for U.S. Petroleum Refining

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

7.1. Thermodynamic Minimum Energy

TM energy consumption is the calculated minimum amount of energy theoretically needed to complete a petroleum refining process, 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 process. Some petroleum refining processes are net producers of energy (i.e., exothermic processes); this created energy was considered in this analysis.

7.2. Calculated Thermodynamic Minimum Energy Consumption for Individual Processes

Appendix A1 presents the onsite TM energy consumption for the nine processes considered in this bandwidth study in alphabetical order. For a given process, the TM energy intensity is multiplied by the annual U.S. production or throughput to determine the total onsite TM energy consumption (the energy intensity and production/throughput data are also presented in Appendix A1). Table 7-1 presents the references for the TM energy intensity values and the applicable process. Appendix A2 also provides the references for the TM energy intensity data for each individual process.

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

Source	Process
DOE 2006	Catalytic reforming, alkylation, and fluid catalytic cracking
Internal calculations based on change in Gibbs free energy at ideal conditions (see Appendix A5 for details)	Atmospheric and vacuum distillation, hydrotreating, catalytic hydrocracking, isomerization, and coking/visbreaking

Petroleum refining can at times result in net energy gain through exothermic processes; this is the case for a few processes studied (e.g., hydrotreating). For exothermic petroleum refining 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 processes requiring an energy intensive transformation (e.g., atmospheric crude distillation), 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.

7.2.1. Calculated Thermodynamic Minimum Energy Intensities

As noted in Table 7-1, the TM energy intensity for six of the nine processes studied was calculated based on the change in Gibbs free energy (ΔG) at ideal conditions. Full assumptions, explanations, and other information on how these TM energy intensities were calculated can be found in Appendix A5.

For atmospheric and vacuum crude distillation, the overall head balance can be described by:

$$Thermodynamic\ Minimum\ Energy\ Intensity = Energy\ Out - Energy\ In$$

The TM energy intensity was calculated as the change in Gibbs free energy, ΔG_{dist}, which was equal to 69,313 Btu per barrel. Catalytic hydrotreating is the process by which hydrogen is added to reduce double bonds and to remove sulfur, nitrogen, oxygen and halogen impurities from the feedstock. To calculate the change in energy, ΔG_{rxn} was calculated for each reaction at the temperature of the reactor, and was summed to determine the overall ΔG or TM energy intensity of -53,000 Btu per barrel. Hydrocracking is an exothermic process, which replaces a carbon-carbon single bond and a hydrogen-hydrogen single bond with two carbon-hydrogen bonds. The TM energy intensity for hydrocracking was calculated to be equal to -71,900 Btu per barrel, although this number varies directly with the amount of hydrogen needed to hydrocrack the incoming feed stream.

The isomerization process is exoergonic; based on the assumptions of the inputs and output streams (found in Appendix A5), the TM energy intensity was calculated as -4.91 Btu per barrel, though this number is strongly dependent upon which branched alkanes are favored by the catalyst and operating conditions. Finally for coking and visbreaking, the TM energy intensity was assumed to be equal to the TM energy intensity for delayed coking (calculated as 350 Btu per barrel) because it consumes a majority of the energy for the coking/visbreaking process.

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

The minimum baseline of energy consumption for a petroleum refining process is its TM energy consumption. If all the 2010 level of petroleum refining 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 nine processes studied (excluding feedstock energy). In theory, if heat generating processes could be carefully coupled with heat consuming processes, this could greatly offset the energy usage in petroleum refining 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 extrapolated TM energy consumption for the entire sector. The extrapolation for sector-wide TM energy consumption is done with the same methodology as for SOA energy consumption and PM energy consumption (as explained in Section 5.2 and 6.4).

The TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero).

Table 7-2. Thermodynamic Minimum Energy Consumption by Process and Sector-Wide for the Nine Processes Studied and Extrapolated to Sector Total	
Process	**Onsite TM Energy Consumption** (TBtu/year)
Alkylation	-21
Atmospheric Crude Distillation	188
Catalytic Hydrocracking	-38
Catalytic Reforming	83
Coking/ Visbreaking	0
Fluid Catalytic Cracking	73
Hydrotreating	-256
Isomerization	0
Vacuum Crude Distillation	86
Total for Processes Studied	115
All Other Processes	54
Total for Petroleum Refining Sector-wide	169*

Thermodynamic minimum (TM)

† Estimates for the entire sector were extrapolated by dividing the onsite TM energy consumption for the processes studied by the overall percent coverage of 68% (see Table 4-3).

8. U.S. Petroleum Refining Energy Bandwidth Summary

This Chapter presents the energy savings bandwidths for the petroleum refining processes studied and sector-wide based on the analysis and data presented in the previous Chapters and the Appendices. Data is presented for the nine processes studied and extrapolated to estimate the energy savings potential for all of U.S. petroleum refining.

8.1. Petroleum Refining Bandwidth Profile

Table 8-1 presents the *current opportunity* and *R&D opportunity* energy savings for the nine processes studied and extrapolated to estimate the sector total. The process totals are summed to provide a sector-wide estimate. The energy savings data was extrapolated to account for all other processes not included in the nine processes studied, as explained in Section 5.2 (SOA) and 6.4 (PM). Each row in Table 8-1 shows the opportunity bandwidth for a specific petroleum refining process and sector-wide.

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

- *Current Opportunity* – 286 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 540 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 complete all of the U.S. petroleum refining sector processes (based on extrapolated data), the analysis shows the following:

- *Current Opportunity* – 420 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 793 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 petroleum refining processes. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are speculative and based on unproven technologies.

Table 8-1. Current Opportunity and R&D Opportunity Energy Savings for the Nine Processes Studied and Extrapolated to Sector-Wide Total		
Process	**Current Opportunity** (CT-SOA) (TBtu/year)	**R&D Opportunity** (SOA-PM) (TBtu/year)
Alkylation	10	24
Atmospheric Crude Distillation	82	208
Catalytic Hydrocracking	11	17
Catalytic Reforming	33	58
Coking/Visbreaking	12	36
Fluid Catalytic Cracking	45	47
Hydrotreating	57	81
Isomerization	5	14
Vacuum Crude Distillation	32	56
Total for Processes Studied	286	540
All Other Processes	134	253
Total for Petroleum Refining Sector-wide	420	793

Current typical (CT), state of the art (SOA), practical minimum (PM)

From the processes studied, the greatest *current* and *R&D* energy savings opportunity for petroleum refining comes from upgrading production methods in atmospheric crude distillation and hydrotreating.

The *impractical* bandwidth represents the energy savings potential that would require fundamental changes in petroleum refining. 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. The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

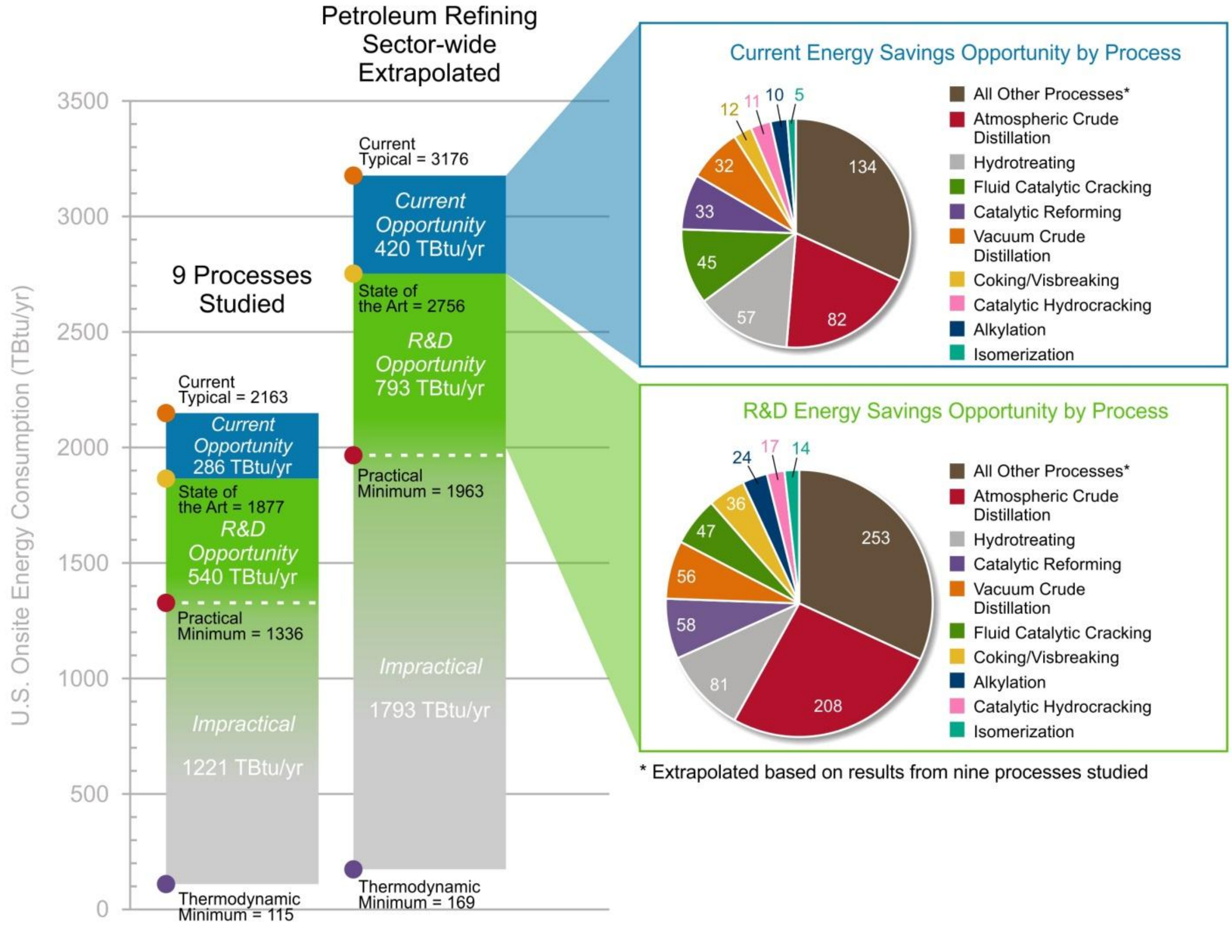


Figure 8-1. Current and R&D Energy Savings Opportunities in U.S. Petroleum Refining for the Processes Studied and for Sector-Wide based on Extrapolated Data

Figure 8-2 shows the bandwidth summaries for the petroleum refining processes presented in order of highest current plus R&D energy savings opportunity. Atmospheric crude distillation is the largest energy consuming process in petroleum refining. If the lower limit of PM energy consumption could be reached, this would save about 290 TBtu/year compared to CT, amounting to 9% of CT energy consumption for the entire petroleum refining sector. Other processes, such as alkylation, catalytic hydrocracking, and isomerization, have a much smaller difference between CT energy consumption and the PM energy consumption. Figure 8-2 shows the relative size of the *current* and *R&D opportunity* energy savings potential for each process.

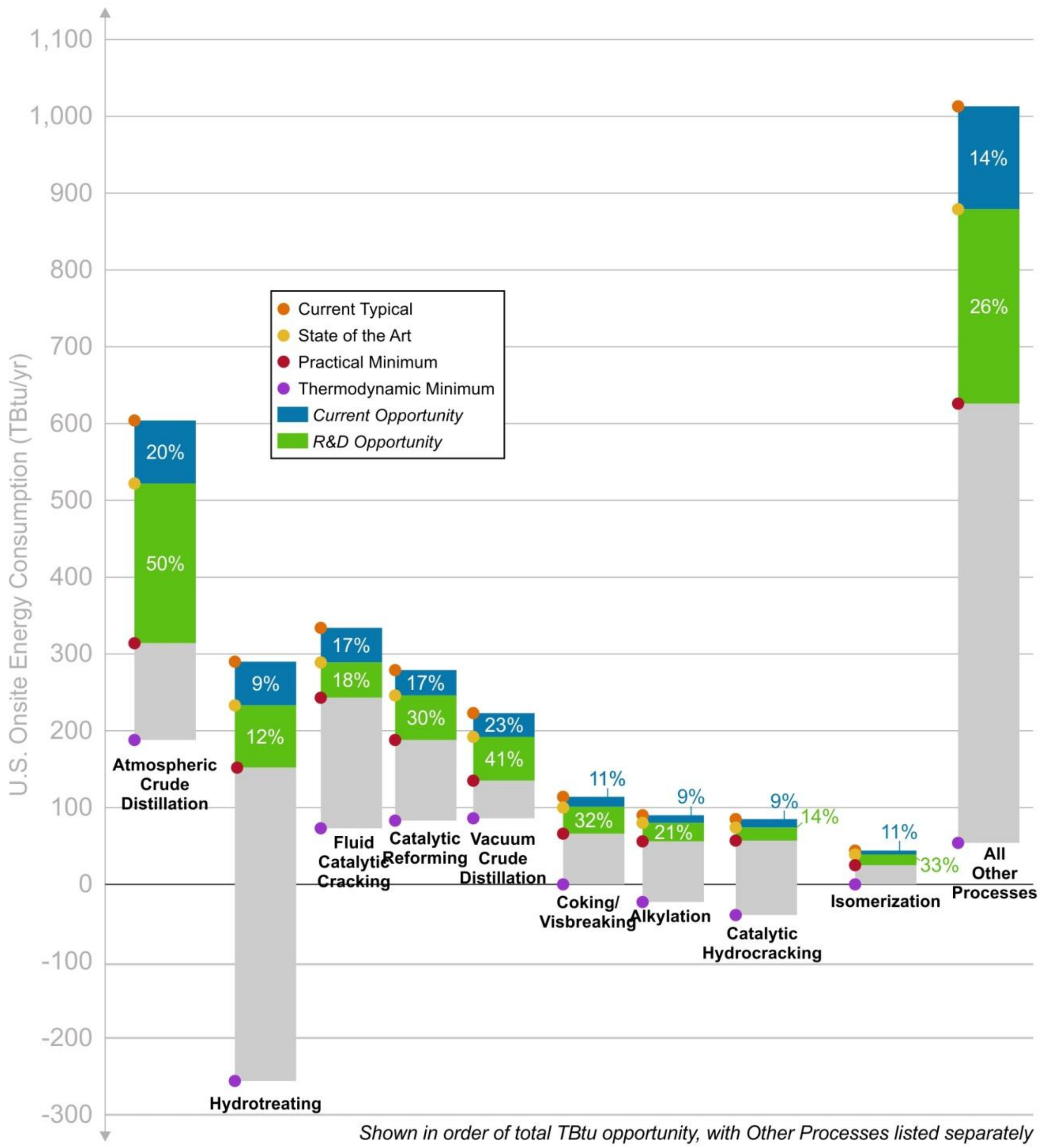


Figure 8-2. Current and R&D Opportunity Energy Savings Bandwidths for the Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

9. References

AIChE 2000	*Refining Overview- Petroleum Process & Products (CD-ROM).* Self, F., Ekholm, E., and Bowers, K. American Institute of Chemical Engineers (AIChE). 2000.
Al-Mutairi 2010	"Optimal Design of Heat Exchanger Network in Oil Refineries." Al-Mutairi, E.M. *Chemical Engineering Transactions* 21(2010): 955-960. 2010.
ANL 1999	*The Potential for Reducing Energy Utilization in the Refining Industry.* Argonne National Laboratory (ANL). Petrick, M. and Pellegrino, J. 1999. www.ipd.anl.gov/anlpubs/1999/10/34061.pdf
Bulasara et al. 2009	"Revamp study of crude distillation unit heat exchanger network: Energy integration potential of delayed coking unit free hot streams." Bulasara, V.K., Uppaluri, R., Ghoshal, A.K. *Applied Thermal Engineering* 29 (2009): 2271-2279. 2009.
CEC 2004	*Energy Efficiency Roadmap for Petroleum Refineries in California*. Prepared by Energetics, Inc. for the California Energy Commission (CEC). 2004. http://energy.gov/sites/prod/files/2013/11/f4/refining_roadmap.pdf
Chang et al. 2012	"Characterization, Physical and Thermodynamic Properties of Oil Fractions." In *Refinery Engineering: Integrated Process Modeling and Optimization*, 1st ed. Chang, A.F., Pashikanti, K., and Y.A. Liu. 2012. Wiley-VCH Verlag GmbH & Co. www.wiley-vch.de/books/sample/3527333576_c01.pdf
ChemEd DL n.d.	"Bond Enthalpies." Chemical Education Digital Library (ChemEd DL). n.d.
Colorado School of Mines n.d.	"Delayed Coking: Chapter 5." Presentation. Colorado School of Mines. n.d.
DOE 1999	"Effective Fouling Minimization Increases the Efficiency and Productivity of Refineries." U.S. Department of Energy, Office of Industrial Technologies. January 1999. www.energy.gov/sites/prod/files/2014/05/f16/foulmitpet.pdf
DOE 2003	"Gasoline Biodesulfurization." U.S. Department of Energy, Industrial Technologies Program. May 2003. http://energy.gov/sites/prod/files/2014/05/f16/gasbiopet_final.pdf
DOE 2006	*Energy Bandwidth for Petroleum Refining Processes.* Prepared by Energetics, Inc. for U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT). 2006. http://energy.gov/sites/prod/files/2013/11/f4/bandwidth.pdf

DOE 2007	*Energy and Environmental Profile of the U.S. Petroleum Refining Industry*. Prepared by Energetics, Inc. for U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT). 2007. http://energy.gov/sites/prod/files/2013/11/f4/profile.pdf
DOE 2011	*Grand Challenge Portfolio: Driving Innovations in Industrial Energy Efficiency*. U.S. Department of Energy, Industrial Technologies Program. 2011. www1.eere.energy.gov/manufacturing/pdfs/grand_challenges_portfolio.pdf
DOE 2013	"Energy Savings Assessments (ESA)." Conducted by the U.S. Department of Energy (DOE) and Oak Ridge National Laboratory (ORNL) between 2006 and 2011.
DOE 2014	"Manufacturing Energy and Carbon Footprints", U.S. Department of Energy (DOE), Advanced Manufacturing Office (AMO) (formerly Industrial Technologies Program, or ITP), 2014. http://energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2010-mecs
Downing 2011	"Increase Your Boiler Pressure to Decrease You Electric Bill: The True Cost of CHP." Proceedings of the Industrial Energy Technology Conference. Downing, A. May 2011. http://repository.tamu.edu/bitstream/handle/1969.1/94796/ESL-IE-11-05-19.pdf?sequence=1
EIA 2011	"Table 5.9 Refinery Capacity and Utilization, Selected Years, 1949-2011." *Annual Energy Review 2011*. U.S. Energy Information Administration (EIA). 2011. www.eia.gov/totalenergy/data/annual/pdf/sec5_23.pdf
EIA 2012a	"Downstream Charge Capacity of Operable Petroleum Refineries." U.S. Energy Information Administration (EIA). 2012. www.eia.gov/dnav/pet/pet_pnp_capchg_dcu_nus_a.htm
EIA 2012b	"Production Capacity of Operable Petroleum Refineries." U.S. Energy Information Administration (EIA). 2012. www.eia.gov/dnav/pet/pet_pnp_capprod_dcu_nus_a.htm
EIA 2012c	"Table 1: Number and Capacity of Operable Petroleum Refineries by PAD District and State as of January 1, 2012." *Refinery Capacity 2012.* U.S. Energy Information Administration (EIA). 2012. www.eia.gov/petroleum/refinerycapacity/table1.pdf
EIA 2012d	"Capacity of Operable Petroleum Refineries by State and Individual Refinery as of January 1, 2012." *Annual Refinery Report* Form EIA-820. U.S. Energy Information Administration (EIA). 2012. http://www.eia.gov/petroleum/refinerycapacity/archive/2012/refcap2012.cfm

EIA 2012e	"What are the major sources and users of energy in the United States?" U.S. Energy Information Administration (EIA). May 2012. www.eia.gov/energy_in_brief/article/major_energy_sources_and_users.cfm
EIA 2013a	Manufacturing Energy and Consumption Survey 2010. U.S. Energy Information Administration (EIA). 2013. www.eia.gov/consumption/manufacturing/data/2010/
EIA 2013b	"Refinery Net Production." U.S. Energy Information Administration (EIA). 2013. www.eia.gov/dnav/pet/pet_pnp_refp2_dc_nus_mbbl_a.htm
EIA 2013c	"Refinery Utilization and Capacity." U.S. Energy Information Administration (EIA). 2013. www.eia.gov/dnav/pet/pet_pnp_unc_dcu_nus_a.htm
EIA 2013d	"U.S. States: State Profiles and Energy Estimates." U.S. Energy Information Administration (EIA). 2013. www.eia.gov/state/
EIA 2013e	"International Energy Statistics." U.S. Energy Information Administration (EIA). 2013. www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm
EIA 2013f	"Fuel Consumed at Refineries" U.S. Energy Information Administration (EIA). 2013. www.eia.gov/dnav/pet/pet_pnp_capfuel_dcu_nus_a.htm
ExxonMobil 2011	*2011 Corporate Citizenship Report.* ExxonMobil. 2011. www.exxonmobil.com/Corporate/Files/news_pub_ccr2011.pdf
Gary et al. 2007	*Petroleum Refining: Technology and Economics,* 5th edition. Gary, J.H., Handwerk, G.E., and Kaiser, M.J. New York, NY: Marcel Dekker, Inc. 2007.
GTI 2011	*Final Technical Report: Advanced Energy and Water Recovery Technology from Low Grade Waste Heat.* Gas Technology Institute. 2011. www.osti.gov/bridge/servlets/purl/1031483/1031483.pdf
HP 2006	*2006 Refining Processes Handbook.* Hydrocarbon Processing (HP). 2006.
HP 2008a	*2008 Refining Processes Handbook.* Hydrocarbon Processing (HP). 2008.
HP 2008b	"Improved crude oil fractionation by distributed distillation", Hydrocarbon Processing (HP), Haddad, H.N. and Manley, D.B., 2008.
HP 2011	*2011 Refining Processes Handbook.* Hydrocarbon Processing (HP). 2011.
IPPC 2012	*Best Available Techniques (BAT) Reference Document for the Refining of mineral oil and gas. Final Draft.* European Commission. Integrated Pollution Prevention and Control (IPPC) Bureau. 2013. http://eippcb.jrc.ec.europa.eu/reference/BREF/FD_REF_July_2013online.pdf

Kansha et al. 2012	"Application of the self-heat recuperation technology to crude oil distillation." Kansha, Y., Kishimoto, A., and Tsutsumi, A. *Applied Thermal Engineering* 43(2012): 153-157. 2012.
Kumana & Associates 2013	J D Kumana, Kumana & Associates, Houston, Texas. Personal communication. 2013.
LBNL 2000	*Emerging Energy-Efficient Industrial Technologies*. Lawrence Berkeley National Laboratory (LBNL). Martin, N., Worrell, E., Ruth, M., Price, L., Elliott, R.N., Shipley, A.M., Thorne, J. 2000. https://escholarship.org/uc/item/5jr2m969#page-2
LBNL 2005a	*Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries*. Worrell, E. and Galitsky, C. Lawrence Berkeley National Laboratory (LBNL). 2005.
LBNL 2005b	*Assessment of Energy Use and Energy Savings Potential in Selected Industrial Sectors in India.* Sathaye, J., Price, L., de la Rue du Can, S., and Fridley, D. Lawrence Berkeley National Laboratory (LBNL). 2005. http://eetd.lbl.gov/node/49899
McKinsey 2009	*Pathways to a Low-Carbon Economy.* McKinsey & Company. 2009. www.mckinsey.com/client_service/sustainability/latest_thinking/pathways_to_a_low_carbon_economy
Nelson 1958	*Petroleum Refinery Engineering,* 4th ed. Nelson, W.L. New York: McGraw Hill. 1958.
NRC 2004	*Pinch Analysis: For the Efficient Use of Energy, Water & Hydrogen. Oil Refining Industry: Energy Recovery at a Fluid Catalytic Cracking (FCC) Unit*. Natural Resources Canada (NRC). 2004.
NRC 2005	*Pinch Analysis: For the Efficient Use of Energy, Water & Hydrogen. Oil Refining Industry: Energy Recovery at a Delayed Coker Unit*. Natural Resources Canada (NRC). 2005.
Riazi 2007	*Characterization and Properties of Petroleum Fractions*. Riazi, M.R. ASTM Stock Number: MNL 50. USA: ASTM International. 2007.
SBA 2012	"Table of Small Business Size Standards Matched to North American Industry Classification System." U.S. Small Business Administration (SBA). 2012. www.sba.gov/sites/default/files/files/Size_Standards_Table.pdf
SEP 2013	"SEP Certified Facilities." Superior Energy Performance (SEP). 2013. http://energy.gov/eere/amo/certified-facilities

Speight 2011	*The Refinery of the Future*. Speight, J. G. United Kingdom: Gulf Professional Publishing. 2011.
Szklo & Schaeffer 2007	"Fuel specification, energy consumption, and CO_2 emissions in oil refineries." *Energy 32:* 1075-1092. Szklo, A. and Schaeffer, R. 2007.
Tarighaleslami et al. 2011	"An Exergy Analysis on a Crude Oil Atmospheric Distillation Column." Tarighaleslami, A.H., Omidkhah, M.R., and Sinaki, S.Y. *Chemical Engineering Transactions* 25(2011):117-122. 2011.
UOP 2009	*UOP FCC Design Advancements to Reduce Energy Consumption and CO_2 Emissions.* Wolschlag, L.M., Couch, K.A., Zhu, F., and Alves, J. UOP LLC. 2009. www.honeywell-uop.cn/wp-content/uploads/2011/02/UOP-FCC-Energy-Optimization-tech-paper1.pdf.
UOP 2013	UOP, a Honeywell Company. Personal communications. 2013.
USCB 2012a	"North American Industry Classification System." United States Census Bureau (USCB). 2012. www.census.gov/eos/www/naics/index.html
USCB 2012b	"Annual Survey of Manufacturers." United States Census Bureau (USCB). 2012. www.census.gov/manufacturing/asm/index.html
Varga et al. 2010	"Process Simulation for Improve energy efficiency, maximize asset utilization and increase in feed flexibility in a crude oil refinery." Varga, Z., Rabi, I., Stocz, K.K. *Chemical Engineering Transactions* 21(2010): 1453-1458.
Zhang et al. 2012	"Sustaining high energy efficiency in existing processes with advanced process integration technology." Zhang, N., Smith, R., Bulatov, I., and Klemes, J.J. *Applied Energy*. 2012.

Appendix A1: Master Petroleum Refining Table

Table Aa. U.S. Production Volume of Nine Select Petroleum Refining Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	2010 Throughput or Production* (million bbl)	Energy Intensity (Btu/bbl)				Calculated Onsite Energy Consumption (TBtu/year)			
		CT	SOA	PM Lower Limit	TM**	CT	SOA	PM Lower Limit	TM
Alkylation	365	246,700	219,400	154,400	-58,000	90.2	80.2	56.4	-21.2
Atmospheric Crude Distillation	5,540	109,100	94,300	56,700	34,000	604.4	522.4	314.3	188.3
Catalytic Hydrocracking	532	158,900	139,000	107,400	-71,900	84.6	74.0	57.2	-38.3
Catalytic Reforming	1,055	263,900	233,000	178,400	79,000	278.5	245.9	188.3	83.4
Coking/Visbreaking	770	147,700	131,700	85,100	350	113.8	101.4	65.6	0.3
Fluid Catalytic Cracking	1,827	182,800	158,300	132,700	40,000	334.0	289.3	242.5	73.1
Hydrotreating	4,829	80,800	68,900	52,200	-53,000	390.2	332.7	252.0	-255.9
Isomerization	203	216,000	192,500	122,300	-5	43.9	39.1	24.8	0.0
Vacuum Crude Distillation	2,504	89,100	76,500	54,000	34,200	223.1	191.5	135.2	85.6

** Values for alkylation and isomerization are production; all other process values are throughput*

*** Based on previous bandwidth and author calculations*

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. Throughput/Production Data of the 9 Processes 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. Throughput Data of the Nine Petroleum Refining Processes Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands

Process	Throughput/ Production Reference(s)	Throughput/ Production Value Description	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	TM Energy Intensity Reference
Alkylation	EIA 2012b; EIA 2013c	Based on alkylate production capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009	DOE 2006
Atmospheric Crude Distillation	EIA 2013c	Gross input to atmospheric distillation units	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; LBNL 2005b; Tarighaleslami et al. 2011; Zhang et al. 2012; Varga et al. 2010; Bulasara et al. 2009; Kumana & Associates 2013	Internal Calculations
Catalytic Hydrocracking	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007, HP 2011	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; Kumana & Associates 2013	Internal Calculations

Table A2. References for U.S. Throughput Data of the Nine Petroleum Refining Processes Studied and Energy Intensity Data Used to Calculate the Current Typical, State of the Art, and Thermodynamic Minimum Energy Consumption Bands					
Process	**Throughput/ Production Reference(s)**	**Throughput/ Production Value Description**	**CT Energy Intensity Reference(s)**	**SOA Energy Intensity Reference(s)**	**TM Energy Intensity Reference**
Catalytic Reforming	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; Kumana & Associates 2013	DOE 2006
Coking/Visbreaking	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; NRC 2005; Kumana & Associates 2013	Internal Calculations
Fluid Catalytic Cracking	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007, HP 2011	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; NRC 2004; Al-Mutairi 2010; UOP 2009	DOE 2006
Hydrotreating	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; Kumana & Associates 2013	Internal Calculations
Isomerization	EIA 2012b; EIA 2013c	Based on isobutane, isopentane, and isohexane production capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; Kumana & Associates 2013	Internal Calculations
Vacuum Crude Distillation	EIA 2012a; EIA 2013c	Based on downstream charge capacity and 2010 capacity factor of 86.4%	DOE 2007	LBNL 2005a; SEP 2013; DOE 2013; ExxonMobil 2013; McKinsey 2009; LBNL 2005b; Kumana & Associates 2013	Internal Calculations

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Atmospheric/Vacuum Crude Distillation							
Thermal Cracking	Replacement for crude distillation; alternative to primary separation. Separates crude oil into fractions by cracking large hydrocarbon molecules into smaller ones, thus lowering their boiling points.	Crude distillation	Szklo & Schaeffer 2007, ANL 1999	63,266 Btu/bbl feed (25%)	The replacement of the crude distillation scheme with a thermal cracking process results in a net energy savings of about 63,266 Btu/bbl of oil processed (ANL 1999). Not including electricity losses, hydrogen, and produced energy, the processes would be 199,159 Btu/bbl for crude distillation and 148,407 Btu/bbl for thermal cracking, which would be about a 25% reduction.	Assume a 25% reduction over CT for atmospheric and vacuum distillation. **Applying this technology would result in a PM of 81,800 Btu/bbl for atmospheric distillation and 66,800 Btu/bbl for vacuum distillation.**	81,800 (atmospheric), 66,800 (vacuum)
Progressive Distillation	Integrates atmospheric and vacuum distillation columns; atmospheric distillation, vacuum distillation, gasoline fractionation, and naphtha stabilizer	Only new distillation units (not retrofits)	Szklo & Schaeffer 2007, HP 2008, LBNL 2005	30% savings on total energy use for crude distillation units (Szklo & Schaeffer 2007); 35% reduction in fuel use (LBNL 2005)	Only applicable to distillation units to be constructed or large crude distillation expansion projects	Assume the lower savings of 30% total savings over CT. Applying this technology **would result in a PM of 76,400 Btu/bbl for atmospheric distillation and 62,400 Btu/bbl for vacuum distillation.**	76,400 (atmospheric), 62,400 (vacuum)

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Atmospheric/Vacuum Crude Distillation (continued)							
Self-heat Recuperation	Whole-process heat is recirculated within the process without heat addition, leading to large energy savings	Atmospheric crude distillation	Kansha et al. 2012	48% energy consumption compared to conventional atmospheric distillation	Reduction in energy consumption compared to conventional distillation, requires development of compressors that work at high temperature	Assume a 48% savings when compared to CT for atmospheric distillation (109,100 Btu/bbl). **Applying this technology would result in a PM of 56,700 Btu/bbl for atmospheric distillation.**	56,700
Dividing-wall columns	Integrates two conventional distillation columns into one by inserting a vertical partition in the central section. The column can contain trays or packing and can handle more than three components.	Crude distillation	Szklo & Schaeffer 2007, IPPC 2012	15% saving potential (total fuel consumption) (Szklo & Scheaffer, 2007); Can reduce energy costs by 30%	Dividing-wall columns can save up to 30% in energy costs and reduce total fuel consumption by 15%	Assume a 25% reduction over CT for atmospheric and vacuum distillation. **Applying this technology would result in a PM of 92,700 Btu/bbl for atmospheric distillation and 75,700 Btu/bbl for vacuum distillation.**	92,700 (atmospheric), 75,700 (vacuum)

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Hydrotreating							
Biodesulfurization	Biological removal of sulfur from gasoline that is an alternative to hydrodesulfurization/ hydrotreating. Biodesulfurization utilizes a biological agent (or catalyst) for the removal of sulfur, rather than the conventional cobalt or molybdenum catalysts commonly deployed for hydrodesulfurization. The use of the biological agent results in lower temperatures and atmospheric pressure and eliminates the need for hydrogen as a feed and combustion of fuel gas	Hydro-desulfurization/ hydro-treating (certain fuels)	Szklo & Schaeffer 2007, ANL 1999, DOE 2003	70-80% (Szklo & Schaeffer 2007), 84% (ANL 1999) decrease in energy use	ANL 1999 estimate based upon using BDS process for desulfurization of about 50% of diesel fuel having a sulfur content greater than .05%. (HDS 356,000 Btu/bbl, BDS 56,000 Btu/bbl)	Comparing ANL 1999's CT for hydrotreating of 56,000 Btu/bbl to the CT of 80,800 Btu/bbl, the savings would be 31%. **Applying this technology would result in a PM of 55,800 Btu/bbl.**	55,800

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Utilities - CHP, Boilers, Pumps, etc.							
Microturbines	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 2006 Petroleum Refining Energy Footprint, 320 TBtu of direct end use is from CHP systems, which equates to 10% of plant wide energy use. 14% savings of 10% energy use results in 1.4% average savings in a typical refinery. **Practical minimum specific energy savings of 1.4% over CT applied to all processes.**	1.4% savings over CT for all processes
Crosscutting Technologies							
New High-Temperature, 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.	Could potentially apply when electric or natural gas radiant heaters used in process heating.	DOE 2011	25% reduction in energy for process heat	Potential to reduce energy consumption by 25% for process heat.	Referencing 2006 Petroleum Refining Energy Footprint, 2,346 TBtu of direct end use for process heating. This equates to 83% of direct end use. 25% savings of 83% energy use results in 21% average savings. **Practical minimum specific energy savings of 21% over CT applied to all process units.**	21% savings over CT for all processes

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Crosscutting Technologies (continued)							
Fouling minimization	Predicting fouling threshold and controlling heat exchanger fouling	Heat exchangers	Szklo & Schaeffer 2007, ANL 1999, DOE 1999	2% improvement in overall refinery energy use (ANL 1999, Szklo & Schaeffer 2007)		The 2% improvement applies to all energy use, so assume 2% savings for each process unit. **Practical minimum energy savings would be 2% over CT applied to all process units.**	2% savings over CT for all process units
Advanced Energy and Water Recovery Technology from Low-Grade Waste Heat	Technology involves the recovery of high purity water and energy from low grade heat, high moisture waste streams using nanoporous membranes. Concept will be proven in laboratory and evaluates in "two different types of industrial environments."	Applies to refineries that utilize wet scrubbers	DOE 2011; GTI 2011	Estimated 20-30% greater energy efficiency in recovery from low grade waste heat; 18.9 TBtu/year for the refining industry	An energy efficiency gain of 20-30% could be achieved when a transport membrane condenser is used along with water recovery	There will be an estimated 18.9 TBtu/year energy savings for the refining industry with wet scrubbers. Compared to the overall CT energy consumption of 3,176 TBtu/year, this represents a 1% energy savings. **Practical minimum energy savings of 1% over CT is applied to all process units.**	1% savings over CT for all process units

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 intensity. PM savings estimate.)	**PM Energy Intensity** (Btu/bbl) or % savings
Crosscutting Technologies (continued)							
Higher efficiency motors and lubricants, higher efficiency burners, and better heat integration[1]		All process units	UOP 2013	Range of savings for each process, accounting for 3% electricity, 10% fuel gas, and 20% steam reductions	These technology improvements would enable the following reductions: 3% reduction in electricity (higher efficiency motors and lubricants), 10% reduction in fuel gas (higher efficiency burners), and 20% reduction in steam (better heat integration)	Overall, the total energy savings for all process units would be 12%. **Practical minimum specific energy savings of 12% over CT overall, with savings for the individual process units ranging from 2-18% over CT.**	2-18% for individual process units[1], 12% overall

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

[1] *Savings for individual process units for this technology improvement are as follows: 12% for alkylation, 14% for atmospheric crude distillation, 17% for coking/visbreaking, 2% for fluid catalytic cracking, 7% for catalytic hydrocracking, 10% for hydrotreating, 18% for isomerization, 7% for catalytic reforming, and 15% for vacuum crude distillation.*

REFERENCES FOR TABLE A3

ANL 1999	*The Potential for Reducing Energy Utilization in the Refining Industry*. Argonne National Laboratory. Petrick, M. and Pellegrino, J. 1999. www.ipd.anl.gov/anlpubs/1999/10/34061.pdf
DOE 1999	"Effective Fouling Minimization Increases the Efficiency and Productivity of Refineries." U.S. Department of Energy, Office of Industrial Technologies. January 1999. www.energy.gov/sites/prod/files/2014/05/f16/foulmitpet.pdf
DOE 2003	"Gasoline Biodesulfurization." U.S. Department of Energy, Industrial Technologies Program. May 2003. http://energy.gov/sites/prod/files/2014/05/f16/gasbiopet_final.pdf
DOE 2011	*Grand Challenge Portfolio: Driving Innovations in Industrial Energy Efficiency*. U.S. Department of Energy, Industrial Technologies Program. 2011. www1.eere.energy.gov/manufacturing/pdfs/grand_challenges_portfolio.pdf
GTI 2011	*Final Technical Report: Advanced Energy and Water Recovery Technology from Low Grade Waste Heat.* Gas Technology Institute. 2011. www.osti.gov/bridge/servlets/purl/1031483/1031483.pdf
HP 2008	"Improved crude oil fractionation by distributed distillation", Hydrocarbon Processing (HP), Haddad, H.N. and Manley, D.B. 2008.
IPPC 2012	*Best Available Techniques (BAT) Reference Document for the Refining of mineral oil and gas*. Final Draft. European Commission. Integrated Pollution Prevention and Control (IPPC) Bureau. 2013. http://eippcb.jrc.ec.europa.eu/reference/BREF/FD_REF_July_2013online.pdf
Kansha et al. 2012	"Application of the self-heat recuperation technology to crude oil distillation." Kansha, Y., Kishimoto, A., and Tsutsumi, A. *Applied Thermal Engineering* 43(2012): 153-157. 2012.
LBNL 2000	*Emerging Energy-Efficient Industrial Technologies*. Lawrence Berkeley National Laboratory (LBNL). Martin, N., Worrell, E., Ruth, M., Price, L., Elliott, R.N., Shipley, A.M., Thorne, J. 2000. https://escholarship.org/uc/item/5jr2m969#page-2
LBNL 2005	*Energy Efficiency Improvement and Cost Saving Opportunities for Petroleum Refineries*. Worrell, E. and Galitsky, C. Lawrence Berkeley National Laboratory (LBNL). 2005.
Szklo & Schaeffer 2007	"Fuel specification, energy consumption, and CO_2 emissions in oil refineries." *Energy 32:* 1075-1092. Szklo, A. and Schaeffer, R. 2007.
UOP 2013	Personal communications. 2013.

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 (A) = 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 petroleum refining 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**	
Atmospheric and Vacuum Crude Distillation													
Thermal cracking	L	Engineering judgment	M	Applicable to distillation, but would involve replacement	H	Noted as 'high-cost' to replace all towers	H	Complete replacement of distillation	L	Insufficient information	M	Could remove contaminants (e.g., sulfur) and reduce CO2 emissions	44%
Dividing-wall columns	H	Are some commercial units, 'proven technology'	H	Widely applicable	M	Lower capital costs	M	Technology still needs more development	L	Insufficient information	L	Engineering judgment	67%
Progressive Distillation	H	Applied to 2 refineries (LBNL 2005) -TRL 8	M	Applicable to distillation, but would involve replacement	M	Lower cost	H	Applicable to new refineries only	L	Insufficient information	L	Engineering judgment	56%
Self-heat recuperation	L	Engineering judgment – TRL 1	M	Applicable to distillation, but would involve replacement	NA	Insufficient information	H	More optimization and modification needed	L	Insufficient information	L	Insufficient information	40%

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**	
Hydrotreating													
Biodesulfur-ization	L	Engineering Judgment - TRL 1	L	Applicable depending on sulfur content	M	Lower capital and operating costs	L	Would require significant breakthroug h	L	Insufficient information	M	Improved environment al performance	56%
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%

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)													
Fouling Minimization	M	Engineering Judgment	H	Applicable to all refineries	NA	Insufficient information	L	Small, well understood process change	M	Engineering judgment	L	Engineering judgment	73%
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.

Appendix A5: Thermodynamic Minimum Calculation Details

This Appendix provides details on how the thermodynamic minimum energy intensities for atmospheric and vacuum crude distillation, hydrotreating, catalytic hydrocracking, isomerization, and coking/visbreaking were calculated and assumptions and reference values used. The thermodynamic minimum energy intensities for catalytic reforming, alkylation, and fluid catalytic cracking were taken from the previous bandwidth, DOE 2006.

Atmospheric and Vacuum Crude Distillation Thermodynamic Minimum Energy Intensity

Distillation takes advantage of differences in boiling points to separate crude oil. The overall heat balance is described by:

Thermodynamic Minimum Energy Intensity = Energy Out – Energy In

It is assumed for these TM energy intensity calculations that:

- Crude oil behaves as an “ideal solution”; that is, the properties of the component in solution are equal to the sum properties of the pure component
- The heavier fractions must be distilled under vacuum (10 millimeters mercury (mm Hg)) to prevent the heavy fractions from degrading
- No work is spent establishing or maintaining the vacuum
- Crude fractions enter at room temperature and exit at their respective boiling points, except for residual oil which exits at the temperature of the boiler
- The stream enters and exits as a liquid
- The process is adiabatic meaning that no heat is lost to the environment
- All processes were considered to be completely reversible
- Heat recovery is limited by the processes’ Carnot efficiency.
- Change in entropy (ΔS) was calculated at 842°F (450 °C)
- Heat capacities are those for ideal gases

During the distillation process, the crude oil is heated so that the lighter fractions evaporate, which allows the vapor to rise up through the column until it contacts a tray that is at the vapor component’s boiling point. The component condenses and exits the column as a liquid stream. Therefore, the energy input is the amount of energy required to raise the temperature of each component from the ambient temperature (e.g., 77°F / 25°C) to its boiling point. The energy required to evaporate the crude oil component is cancelled out by the energy released when the component vapor condenses. As an *ideal solution*, the boiling point of the pure substance is used and any effects of intermolecular interactions are ignored.

The TM energy intensity was calculated as the change in Gibbs free energy, ΔG_{dist} (heat of reaction and Gibbs free energy are related as follows: $\Delta G = \Delta H - T\Delta S$, where T is absolute temperature (either Kelvin or Rankine), ΔH is the change in enthalpy, and ΔS is the change in entropy).

The energy consumed by atmospheric distillation includes energy that goes into heating the heavy fractions that must be distilled under vacuum. However, for the TM energy intensity calculation, the energy consumption of atmospheric distillation is limited to the separation energy for the crude fractions that can be distilled at atmospheric pressure, and the work done to establish or maintain a vacuum. In addition, the calculation excludes the energy content of the fuel gas stream generated via atmospheric distillation and excludes the heat recovery that takes place via the crude preheat train.

The vacuum distillation process is also simplified to calculate the TM energy intensity. Similar to atmospheric distillation, it is assumed that all energy consumed by the vacuum distilled fractions as they are heated from ambient temperature to their boiling points is included in the vacuum distillation TM energy intensity. In reality, the heavy components are heated from ambient conditions to a higher temperature as they pass through the atmospheric distillation tower. In addition, it is assumed that the residue stream produced is processed further in coking units, rather than used to generate heat for the vacuum distillation tower. Table A5 shows the physical and chemical properties of the crude oil fractions.

Table A5. Sample Product Fractions from Barrel of Crude Oil Feedstock, Used in Calculating Distillation Thermodynamic Minimum Energy Intensity									
	Product	**Temperature Cut**	**Volume % of Crude**	**Specific Gravity**	**Volume Average boiling point (°F)**	**Watson Factor (K_w)**	**C_p (Btu/ °F*lb)**	**$\Delta H_{heating}$ (Btu/bbl)**
Atmospheric Distillation	LPG	<=C4	1.57	0.57	37	NA	0.19	0
	Light Straight Run	C5-165 °F (C5-74 °C)	8.26	0.67	98	12.3	0.54	245
	Heavy Straight Run	165-331 °F (74-166 °C)	20.96	0.76	248	11.7	0.54	5,015
	Light Middle Distillate	331-896 °F (166-480 °C)	17.11	0.81	479	12	0.59	11,454
	Heavy Middle Distillate	896-480 °F (480-249 °C)	17.52	0.85	529	11.8	0.58	14,193
	Total		**65.42%**					**30,907**
Vacuum Distillation	Vacuum Gas Oil	480-999 °F (249-537 °C)	24.71	0.90	791	12.0	0.64	13,526
	Residual	≥999 °F (≥537 °C)	9.87	0.99	999	11.7	0.64	20,468
	Total		**34.58%**					**33,394**
Distillation Total			**100%**	**0.83**	**490**			**64,897**

Sources: Riazi 2007; Chang et al. 2012; Nelson 1958

Notes: "C" refers to number of carbon atoms in the hydrocarbon; rounding errors present.

The energy required to raise the temperature of each fraction to its boiling point (bp) is calculated by:

$$\Delta H_{fraction} = mC_p\Delta T = mass_{crude\ fraction} * C_p * (T_{bp} - 77°F)$$

Where m is mass, C_p is specific heat capacity, and T_{bp} is the boiling point temperature. The ΔS is calculated by the following equation:

$$\Delta S = \sum_{\forall i} x_i ln x_i$$

Where x_i is the mole fraction of a given species.

This equation yields a value of ΔS=-9.85 Btu/K for the sample barrel depicted in Table A5. This value is negative because there is a decrease in entropy (disorder) in the system. The separation of a mixture, even an ideal one, typically requires an input of energy.

Thus the ΔG_{dist} is calculated as follows

$$\Delta G_{dist} = \Delta H - T\Delta S = 64,897 - 842*(-9.85) = 69,312 \text{ Btu/bbl of crude oil}$$

This value is the least possible energy that must be spent to heat all of the fractions to their boiling point and to separate the incoming feed stream to its components. However, there are energy losses which can be systemically accounted for because of Carnot inefficiencies. The energy used to boil the component is not completely recovered upon condensation in a distillation process. Only a fraction of the ΔH_{vap} can be recovered according to the equation:

$$q_{loss} = q_{input}\left(\frac{T_b - T_c}{T_b * T_c}\right)$$

where $q_{input} = \Delta H_{vap}$, T_b is the boiler temperature, and T_c is the condenser temperature on an absolute scale.

Assuming a boiler operating at 660°F (atmospheric) or 1063°F (vacuum) and the condenser operating at the average boiling point of each fraction gives a total energy loss of 1.4 Btu/bbl for the distillation process. Accounting for this known limit to distillation leads to theoretical process minimum, which accounts for the previously calculated TM energy intensity and the limits of the distillation process resulting in ΔG_{dist}=69,313 Btu/bbl.

Hydrotreating Thermodynamic Minimum Energy Intensity

Catalytic hydrotreating is the process by which hydrogen is added to reduce double bonds and to remove sulfur, nitrogen, oxygen and halogen impurities from the feedstock. It is assumed for the TM calculation that:

- The entire hydrotreater process occurs at 570 °F
- 300 standard cubic feet (scf) of H_2 is consumed per barrel
- All streams consist of ideal gases
- Sample barrel characteristics:
    - Sulfur: 0.3675 weight percent (wt%)
    - Mercaptan 25 parts per million (ppm)
    - Nitrogen 970 ppm
    - No halogens or oxygen
    - 75% of remainder H_2 goes to reduce molecules with 1 double bond
    - 25% of remainder H_2 goes to reduce molecules with 2 double bonds

Hydrotreaters are run between 300 and 400 °C (assumed 570 °F for entropy calculations) which is insufficient to permit cracking.

To calculate the change in energy, ΔG_{rxn} was calculated for each reaction at the temperature of the reactor. Temperature only impacts entropy which was assumed to be the change in moles of ideal gas. No change in the temperature of the feed stream was assumed through the length of the reactor. For the sample barrel: sulfur was 0.3675 wt% (evenly divided between sulfide, disulfide and thiophene), nitrogen was 970 ppm and mercaptan sulfur was 25 ppm. The balance of the hydrogen consumed was assumed to go to saturating olefins.

Table A6. Change in Gibbs Free Energy for Hydrotreating Reactions			
Reaction	**ΔG_{rxn}** (Btu/scf)	**Cubic Feet of H_2**[a]	**ΔG_{rxn}** (Btu/bbl)
Hydrogenation of one double bond	-180.64	215.06	-38,849
Hydrogenation of two double bonds	-181.46	71.70	-13,007
Desulfurization of sulfide	-64.77	1.81	-117
Desulfurization of mercaptan	-65.90	0.02	-2
Desulfurization of disulfide	-56.72	2.71	-154
Desulfurization of thiophene	-123.94	3.62	-448
Denitrogenation of pyrrole	-142.51	2.30	-328
Denitrogenation of pyridine	-32.08	2.88	-92
Deoxidation of phenol	-133.01	0	0
Deoxidation of peroxides	-383.30	0	0
Dehalogenation (chlorine)	-100.65	0	0
Hydrocracking	-47.93	0	0
Total		**300**	**-53,000**

[a] *Volume at standard temperature and pressure (25°C and 1 atmospheric pressure)*

Source: Chang et al. 2012 and ChemEd DL n.d.

The energy consumed by a hydrotreater is strongly related to the degree of saturation of the feed stream and the amount of impurities in a barrel of oil. Given a set ratio of impurities, the majority of H_2 is consumed in reducing C-C double bonds. For these calculations 75% of unsaturated molecules were assumed to have one double bond and 25% to have two double bonds. The small difference between the two free energies of reaction is the result of entropy differences in the two reactions. With 300 scf of H_2 consumed in the feed stream, the ΔG or final TM energy intensity value is equal to -53,000 Btu/bbl. A typical hydrocracker consumes between 200 and 800 scf H_2/bbl. This corresponds to the range ΔG between -35,000 and -143,000 Btu/bbl. Thus the degree of unsaturation plays a large role in determining the TM of a hydrocracker. While all reactions at this temperature are exoergonic, there is nearly six-fold greater energy released from the hydrogenation of a double bond as opposed to the denitrogenation of pyridine. With greater saturated feedstocks the concentration of impurities plays a larger role in determining the TM energy intensity.

Catalytic Hydrocracking Thermodynamic Minimum Energy Intensity

Hydrocracking is an exothermic process, which replaces a carbon-carbon single bond and a hydrogen-hydrogen single bond with two carbon-hydrogen bonds. This reduces the chain lengths of hydrocarbons to create more valuable molecules. It is assumed for the hydrocracking TM energy intensity calculation that:

- The entire hydrocracking process occurs at 572°F (300 °C)

- 1,500 scf of H_2 is consumed per barrel
- All streams consist of ideal gases
- No processes other than cracking occur in the hydrocracker
- Entropy is dominated by the change in moles of gas

As in Table A6, for each cubic foot of H_2 consumed -47.93 Btu of energy are released in the hydrocracking of a molecule. The sample barrel used (see Table A5) consumes 1,500 scf of H_2. Thus the TM for hydrocracking is equal to -71,900 Btu/bbl, although this number varies directly with the amount of hydrogen needed to hydrocrack the incoming feed stream.

Isomerization Thermodynamic Minimum Energy Intensity

In the model for the isomerization process, the following incoming and outgoing streams were assumed as follows in Table A7:

Table A7. Isomerization Process Stream Assumptions

Chemical	Input (wt%)	Output (wt%)	ΔG_f (Btu/mol)	ΔG (Btu/bbl)
Isopentane	22	41	-146	-38.66
n-Pentane	33	12	-139	40.86
2,2-Dimethylbutane	1	15	-176	-28.86
2,3-Dimethylbutane	2	5	-169	-5.92
2-Methylpentane	12	15	-166	-5.81
3-Methylpentane	10	7	-163	5.72
n-Hexane	20	5	-158	27.76
Total	100	100		-4.91

Source: Gary et al. 2007

It is also assumed for this TM energy intensity calculation that:

- The change in volume is negligible
- No dehydrogenation or cracking occurs
- Only five and six carbon molecules rearrange
- The feed and exit stream is fully characterized by Table A7
- Streams enter and exit the process at the same temperature
- No change in entropy since the number of molecules remains the same

The thermodynamic minimum is the change in free energy that occurs between the input and output streams. Branched alkanes are energetically more stable, thus this process is exoergonic. For a barrel consisting of these inputs and outputs the ΔG is -4.91 Btu/bbl. This number is strongly dependent upon which branched alkanes are favored by the catalyst and operating conditions.

Coking/Visbreaking (Delayed Coking) Thermodynamic Minimum Energy Intensity

Because delayed coking consumes a majority of the energy for the coking/visbreaking process unit, the TM energy intensity for delayed coking was assumed to also be the TM energy intensity for all coking/visbreaking. The calculation of the TM for delayed coking is described in this section. For coking, the change in entropy is proportional to the natural log of the ratio of the number of moles after and before coking. With a temperature of 600 °F, the ΔS= -3.7 Btu/bbl. Combined with the ΔH from the sample barrel, the ΔG or TM for the delayed coking process is 345.0 Btu/bbl. Coking is an endoergonic process meaning it requires energy to proceed. A list of assumptions and calculations can be found in Table A8 and Table A9 below.

It is also assumed for this TM energy intensity calculation that:

- Entropy is dominated by the change in moles; for every molecule that enters, about 2.1 exit
- Coking proceeds at 600 °F
- No chlorine, nitrogen, oxygen or metals are in the feed stream
- 15% unsaturation in gasoline and 20% unsaturation in gas oil for the exit stream
- No saturation in residual crude feed or coke stream
- LPG unsaturation is as noted in Table A5
- Sample delayed coker input/output is based on crude oil from North Slope, Alaska in Gary et al. 2007
- Production volumes are based upon 100,000 BPCD
- Conradson Carbon = 19%

Table A8. Coking Process Assumptions and Calculations									
	Component	**Stream Make-up** (vol%)	**Production Rate** (lb/hour)	**Sulfur Content** (wt%)	**C/H ratio**	**Avg. C length**	**Degree of Unsaturation**	**Total ΔH in Bonds** (Btu/bbl)
Input	1000°F+ Residual Crude	100%	345,080	2.30	1.3	30.0	15%	-9,919
Output	Gas	10.5 wt%	36,230	6.50	see Table A9 below			771
	Gasoline	23.3%	61,420	0.65	2.3	8.0	15%	2,373
	Gas Oil	45.2%	142,530	1.95	1.8	18.0	20%	4,889
	Coke	30.4 wt%	104,900	2.27	0.5	50.0	30%	2,234
Total		100.0%	345,080					349
ΔG = 345.0 Btu/bbl								

Source: Gary et al. 2007, Colorado School of Mines n.d., AIChE 2000; Bond enthalpies are from ChemEd DL n.d.

Table A9. Calculations Used to Determine Coking Entropy		
Component	**Production Rate** (lb/hour)	**Total ΔH in Bonds** (Btu/bbl)
Methane	12,580	270.4
Ethylene	640	13.8
Ethane	7,300	163.2
Propylene	1,990	44.1
Propane	5,520	125.1
Butylene	2,060	46.2
i-butane	890	20.3
n-butane	2,310	52.7
H_2	270	25.6
CO_2	140	1.5
H_2S	2,530	8.3
Total	**36,230**	**771.2**

THERMODYNAMIC MINIMUM ENERGY INTENSITY REFERENCES

AIChE 2000	*Refining Overview- Petroleum Process & Products (CD-ROM).* Self, F., Ekholm, E., and Bowers, K. American Institute of Chemical Engineers (AIChE). 2000.
Chang et al. 2012	"Characterization, Physical and Thermodynamic Properties of Oil Fractions." In *Refinery Engineering: Integrated Process Modeling and Optimization*, 1st ed. Chang, A.F., Pashikanti, K., and Y.A. Liu. 2012. Wiley-VCH Verlag GmbH & Co. www.wiley-vch.de/books/sample/3527333576_c01.pdf
ChemEd DL n.d.	"Bond Enthalpies." Chemical Education Digital Library (ChemEd DL). n.d.
Colorado School of Mines n.d.	"Delayed Coking: Chapter 5." Presentation. Colorado School of Mines. n.d.
DOE 2006	*Energy Bandwidth for Petroleum Refining Processes.* Prepared by Energetics, Inc. for U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT). 2006. http://energy.gov/sites/prod/files/2013/11/f4/bandwidth.pdf
Gary et al. 2007	*Petroleum Refining: Technology and Economics*, 5th edition. Gary, J.H., Handwerk, G.E., and Kaiser, M.J. New York, NY: Marcel Dekker, Inc. 2007.
Nelson 1958	*Petroleum Refinery Engineering*, 4th ed. Nelson, W.L. New York: McGraw Hill. 1958.
Riazi 2007	*Characterization and Properties of Petroleum Fractions*. Riazi, M.R. ASTM Stock Number: MNL 50. USA: ASTM International. 2007.

ENERGETICS
A Subsidiary of VSE Corporation

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

For more information, visit: manufacturing.energy.gov

DOE/EE-1230 • June 2015