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Energy Efficiency Improvement in the Petroleum Refining Industry

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ABSTRACT

Information has proven to be an important barrier in industrial energy efficiency improvement. Voluntary government programs aim to assist industry to improve energy efficiency by supplying information on opportunities. ENERGY STAR® supports the development of strong strategic corporate energy management programs, by providing energy management information tools and strategies. This paper summarizes ENERGY STAR research conducted to develop an Energy Guide for the Petroleum Refining industry. Petroleum refining in the United States is the largest in the world, providing inputs to virtually every economic sector, including the transport sector and the chemical industry. Refineries spend typically 50% of the cash operating costs (e.g. excluding capital costs and depreciation) on energy, making energy a major cost factor and also an important opportunity for cost reduction. The petroleum refining industry consumes about 3.1 Quads of primary energy, making it the single largest industrial energy user in the United States. Typically, refineries can economically improve energy efficiency by 20%. The findings suggest that given available resources and technology, there are substantial opportunities to reduce energy consumption cost-effectively in the petroleum refining industry while maintaining the quality of the products manufactured.

Introduction

As U.S. manufacturers face an increasingly competitive global business environment, they seek out opportunities to reduce production costs without negatively affecting the yield or the quality of the product. Increasing and increasingly uncertain energy prices in today's marketplace negatively affect predictable earnings. Successful, cost-effective investment into energy efficient technologies and practices meets the challenge of maintaining the output of high quality product with reduced production costs. This is especially important, as energy efficient technologies often include additional benefits, such as increasing the productivity of the company further. Finally, energy efficiency is an important component of a company's environmental strategy. End-of-pipe solutions are often expensive and inefficient while energy efficiency can be the cheapest opportunity to reduce pollutant emissions.

Voluntary government programs aim to assist industry to improve competitiveness through increased energy efficiency and reduced environmental impact. ENERGY STAR, a voluntary program operated by the U.S. Environmental Protection Agency (EPA), stresses the need for strong and strategic corporate energy management programs. ENERGY STAR provides energy management tools and strategies for successful programs. ENERGY STAR works directly with a set of "focus" industries to improve their energy performance. Additional tools are developed and provided to the industry such as benchmarks/measures of efficient plant energy performance and an Energy Guide for energy and plant managers in specific industries. The current paper reports on the research we conducted to support the U.S. EPA and its work with the petroleum refining industry in developing its Energy Guide. The Energy Guide is currently available online (Worrell and Galitsky, 2005). This paper provides information on potential energy efficiency opportunities for petroleum refineries. ENERGY STAR can be contacted (www.energystar.gov) for additional energy management tools that facilitate stronger corporate energy management practices in U.S. industry.

The U.S. Petroleum Refining Industry

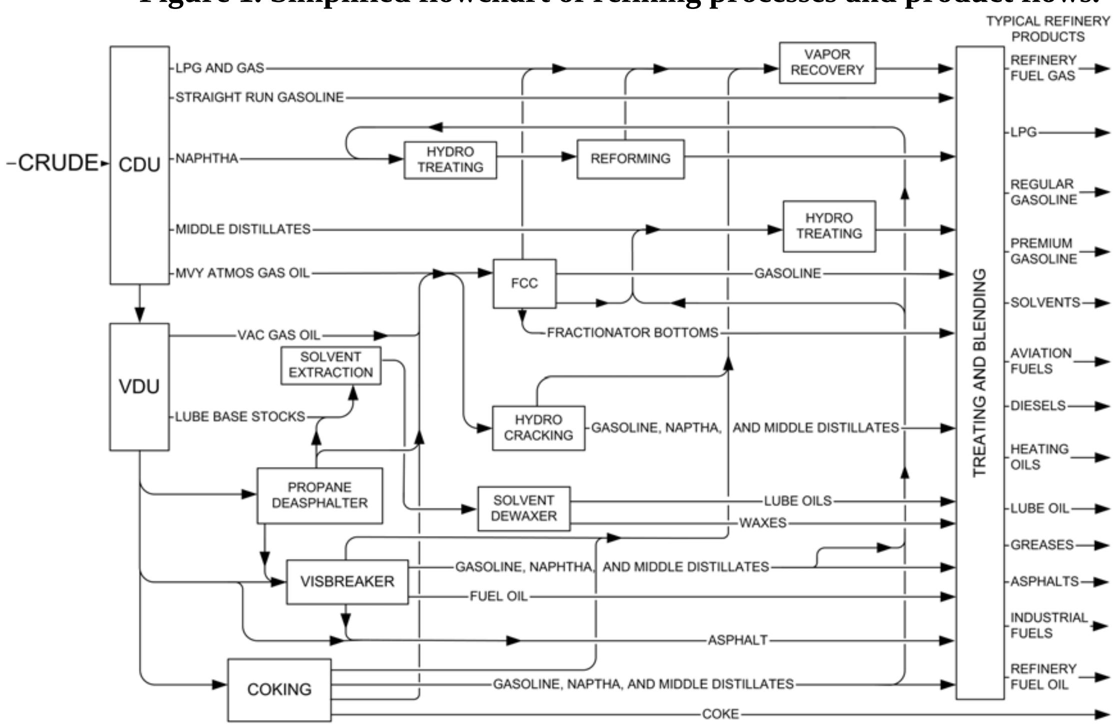
The U.S. has the world's largest refining capacity, processing just less than a quarter of all crude oil in the world. The petroleum refining sector has grown over the past 50 years by about 2%/year on average. Until the second oil price shock refining capacity grew rapidly, but production already started to level off in the mid to late 1970's. This was a period where the industry started to re-organize. It was not until after the mid-1980's that refinery production started to grow again. Since 1985, output has been growing at a rate of 1.4%/year.

Since 1990 the number of refineries has declined from 205 in 1990 to 147 in 2003. Petroleum refineries can be found in 32 states, but heavily concentrated in a few states due to historic resource location and easy access to imported supplies (i.e. close to harbors). Hence, the largest number of refineries can be found on the Gulf coast, followed by California. Although there are a relatively large number of independent companies in the U.S. refining industry, the majority of the refining capacity is operated by a small number of multi-national or national oil processing companies. The largest companies (as of January 2003) are: ConocoPhilips (13% of crude capacity), ExxonMobil (11%), BP (9%), Valero (8%), ChevronTexaco (6%), Marathon Ashland (6%), and Shell (6%), which combined represent 59% of crude distillation (CDU) capacity.

U.S. refineries process various types of crude oil types from different sources. Over the past years, there has been an overall trend towards more heavy crudes and higher sulfur content. This trend is likely to continue, and will affect the product mix, processing needs and energy use of refineries. This trend will result in a further expansion of conversion capacity at U.S. refineries. While the type of processed crude oil is becoming increasingly heavier and higher in sulfur, the demand for oil products, and hence the product mix of the refineries, is changing towards an increased share of lighter products. Started in California, increased air quality demands in many parts of the United States will result in an increased demand for low-sulfur automotive fuels. With limited markets for the hydroskimming refineries, a further concentration of refineries is likely to take place over the next few years. At the same time, the petroleum industry faces other challenges and directions. Increased needs to reduce air pollutant emissions from refinery operations as well as increased safety demands will drive technology choice and investments for future process technology.

A modern refinery is a highly complex and integrated system separating and transforming crude oil into a wide variety of products, e.g. transportation fuels, residual fuel oils, lubricants, and many other products (see Fig. 1). The simplest refinery type is a facility in which the crude oil is separated into lighter and heavier fractions through distillations. Modern refineries have developed much more complex and integrated systems in which hydrocarbon compounds are not only distilled but are also converted and blended into a wider array of products. In all refineries, including small less complex refineries, the crude oil is first distilled. This is followed by conversion in more complex refineries. The most important distillation processes are the crude or atmospheric distillation, and vacuum distillation. Different conversion processes are available using thermal or catalytic processes, e.g. catalytic reformer, where the heavy naphtha, produced in the crude distillation unit, is converted to gasoline, and the Fluid Catalytic Cracker where the distillate of the vacuum distillation unit is converted to gasoline. Newer processes, such as hydrocrackers, are used to produce more light products from the heavy bottom products. Finally, all products may be treated to upgrade product quality (e.g. sulfur removal using a hydrotreater). Side processes that are used to condition inputs, produce hydrogen or by-products include crude conditioning (e.g. desalting), hydrogen production, power and steam production, and asphalt production. Lubricants and other specialized products may be produced at special locations.

Figure 1. Simplified flowchart of refining processes and product flows.

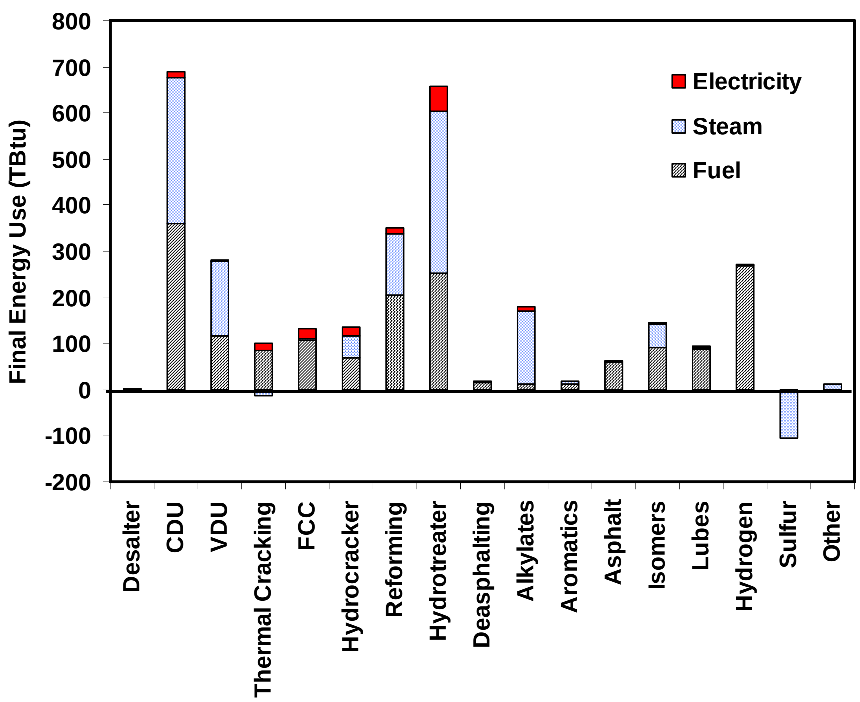


Energy Use in Petroleum Refining

The petroleum refining industry is one of the largest energy consuming industries in the United States and in many states. Energy use in a refinery varies over time due to changes in the type of crude processed, the product mix (and complexity of refinery), as well as the sulfur content of the final products. Furthermore, operational factors like capacity utilization, maintenance practices, as well as age of the equipment affect energy use in a refinery from year to year. In recent years, energy consumption in refineries peaked in 1998, and has since then slightly declined. In 2001, the latest year for which data was available at the time of study, total final energy consumption is estimated at 3025 TBtu. Primary energy consumption is estimated at 3369 TBtu. The difference between primary and final electricity consumption is relatively low due to the small share of electricity consumption in the refinery and relatively large amount of self-produced electric the main fuels used in the refinery are refinery gas, natural gas and coke. The refinery gas and coke are by-products of the different processes. The coke is mainly produced in the crackers, while the refinery gas is the lightest fraction from the distillation and cracking processes. Natural gas and electricity represents the largest purchased fuels in the refineries. Natural gas is used for the production of hydrogen, fuel for co-generation of heat and power (CHP) and as supplementary fuel in furnaces. In 1998 cogeneration within the refining industry represented almost 13% of all industrial cogenerated electricity (EIA, 2001). In 2001 the petroleum refining industry generated about 13.2 TWh, representing 26% of all power consumed onsite (EIA, 2002).

A number of key processes are the major energy consumers in a typical refinery, i.e. crude distillation, hydrotreating, reforming, vacuum distillation and catalytic cracking. Hydrocracking and hydrogen production are growing energy consumers in the refining industry. Figure 2 depicts an energy balance for refineries for 2001 that is based on publicly available data on process throughput (EIA, 2002), specific energy consumption (Gary and Handwerk, 1994; U.S. DOE-OIT, 1998; U.S. DOE-OIT, 2002) and energy consumption data (EIA, 2001; EIA, 2002). The energy balance is an estimate based on publicly available data, and is based on many assumptions on process efficiencies and throughputs.

Figure 2. Estimated energy use by petroleum refining process. Energy use is expressed as primary energy consumption. Electricity generation efficiency is assumed to be 32% (incl. transmission and distribution losses). Boilers have an efficiency of 77%.



For the energy balance, similar capacity utilization is assumed for all installed processes, based on the average national capacity utilization. In reality the load of the different processes may vary, which may lead to a somewhat different distribution. In cracking the severity and in hydrotreating the treated feed may affect energy use. An average severity is assumed for both factors.

Although the vast majority of greenhouse gas (GHG) emissions in the petroleum fuel cycle occur at the final consumer of the petroleum products, refineries are still a substantial source of GHG emissions. The report summarized in this paper focuses on CO_2 emissions due to the combustion of fossil fuels, although process emissions may occur at refineries. The CO_2 emissions in 2001 are estimated at 222 Million tonnes of CO_2 (equivalent to 60.5 MtCE). This is equivalent to nearly 12% of industrial CO_2 emissions in the United States.

Energy Management Opportunities

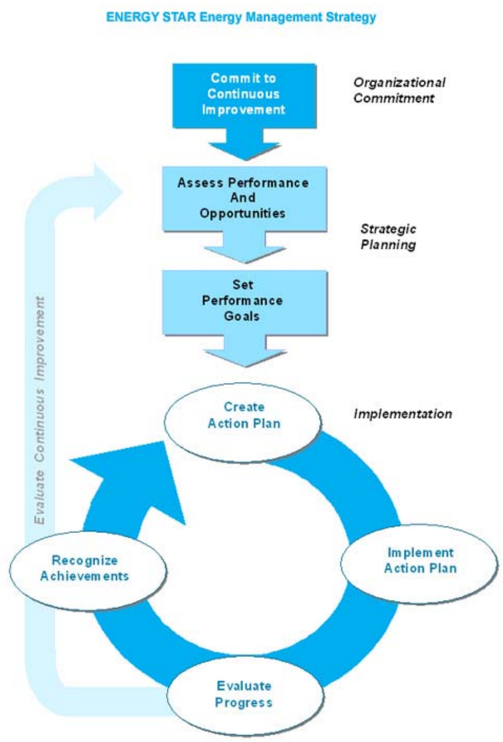
A large variety of opportunities exist within petroleum refineries to reduce energy consumption while maintaining or enhancing the productivity of the plant. Studies by several companies in the petroleum refining and petrochemical industries have demonstrated the existence of a substantial potential for energy efficiency improvement in almost all facilities. Major areas for energy-efficiency improvement are utilities (30%), fired heaters (20%), process optimization (15%), heat exchangers (15%), motor and motor applications (10%), and other areas (10%). Of these areas, optimization of utilities, heat exchangers and fired heaters offer the most low-investment opportunities, whereas in other areas low-cost opportunities will exist, but additional opportunities may require investments. Experiences of various companies have shown that most investments are relatively modest. However, all projects require operating costs as well as engineering resources to develop and implement the project. Project savings and costs will be different for every refinery. Based on each unique situation the most favorable selection of energy-efficiency opportunities should be made.

Although technological changes in equipment conserve energy, changes in staff behavior and attitude can have a great impact; staff should be trained in both skills and in implementing the company's general approach to energy efficiency in their day-to-day practices. Improving energy efficiency in refineries should be approached from several directions. A strong, corporate-wide energy management program is essential. Crosscutting equipment and technologies such as boilers, compressors and pumps, all common to most plants and manufacturing industries including petroleum refining, present well-documented opportunities for improvement. Equally important, the production process can be fine-tuned to produce additional savings.

Changing how energy is managed by implementing an organization-wide energy management program is one of the most successful and cost-effective ways to bring about energy efficiency improvements. An energy management program creates a foundation for improvement and provides guidance for managing energy throughout an organization. In companies without a clear program in place, opportunities for improvement may be unknown or may not be promoted or implemented because of organizational barriers. These barriers may include a lack of communication among plants, a poor understanding of how to create support for an energy efficiency project, limited finances, poor accountability for measures or perceived change from the status quo. Even when energy is a significant cost for an industry, many companies still lack a strong commitment to improve energy management. EPA, through ENERGY STAR, has worked with many of the leading industrial manufacturers to identify the basic aspects of an effective energy management program. The major elements are depicted in Figure 3. A successful program in energy management begins with a strong commitment to continuous improvement of energy efficiency. This typically involves assigning oversight and management duties to an energy director, establishing an energy policy, and creating a cross-functional energy team. Steps and procedures are then put in place to assess performance, through regular reviews of energy data, technical assessments and benchmarking. From this assessment, an organization is then able to develop a baseline of performance and set goals for improvement.

Performance goals help to shape the development and implementation of an action plan. An important aspect for ensuring the successes of the action plan is involving personnel throughout the organization. Personnel at all levels should be aware of energy use and goals for efficiency. Staff should be trained in both skills and general approaches to energy efficiency in day-to-day practices. In addition, performance results should be regularly evaluated and communicated to all personnel, recognizing high performers.

Figure 3. Main elements of a strategic energy management system.



Evaluating performance involves the regular review of both energy use data and the activities carried out as part of the action plan. Information gathered during the formal review process helps in setting new performance goals and action plans and in revealing best practices. Establishing a strong communications program and seeking recognition for accomplishments are also critical steps. Strong communication and recognition help to build support and momentum for future activities.

Companies like BP have successfully implemented aggressive greenhouse gas (GHG) emission reduction programs at all their facilities worldwide (including both exploration and refining facilities). BP has reduced its global GHG emissions to 10% below 1990 levels within 5 years of the inception of its program; years ahead of its goal, and while decreasing costs. These efforts demonstrate the potential success of a corporate strategy to reduce energy use and associated emissions. ExxonMobil's Global Energy Management System (GEMS) identified over 200 best practices and performance measures for key process units, major equipment, and utility systems. In addition to the strong focus on operation and maintenance of existing equipment, these practices also address energy efficiency in the design of new facilities. GEMS identified opportunities to improve energy efficiency by 15% at ExxonMobil refineries and chemical plants worldwide. Yet, other companies have used participation in voluntary programs to boost energy management programs. Petro-Canada participates in Canada's Climate Change Voluntary Challenge and Registry. In Europe, various countries have voluntary agreements between industry sectors and governments to reduce energy or greenhouse gas emission intensity. For example, all refineries in The Netherlands participated in the Long-Term Agreements between 1989 and 2000. BP, ExxonMobil, Shell, and Texaco all operate refineries in The Netherlands. The refineries combined (processing about 61 Million tons of crude annually) achieved a 17% improvement of energy efficiency. Today, the refineries participate in a new agreement in which the refineries will be among most energy-efficient refineries worldwide by 2010.

The length of this paper does not allow an in-depth discussion of all energy efficiency opportunities in petroleum refineries. For a more detailed discussion the reader is referred to the ENERGY STAR Energy Guide (Worrell and Galitsky, 2005). The Energy Guide includes case studies for U.S. refineries with specific energy and cost savings data when available. For other measures, the Guide includes case study data from refineries around the world. For individual refineries, actual payback period and energy savings for the measures will vary, depending on plant configuration and size, plant location and plant operating characteristics. The energy efficiency improvement opportunities are divided into the following categories energy management, (flare) gas recovery, power recovery, boiler improvements, steam distribution, heat exchangers, process integration, process heaters (furnaces), distillation, hydrogen management, motor systems, pumps, compressed air, fans, lighting, cogeneration, power generation, and miscellaneous opportunities.

Table 1 and 2 summarize the energy efficiency opportunities that have been identified in U.S. petroleum refineries. The opportunities are divided in crosscutting (Table 1) and sector-specific measures (Table 2). Worrell and Galitsky (2005) provide more detailed information on the likely savings and economics of each measure. As an example of the descriptions, we discuss the potential for further process integration.

Table 1. Summary of energy efficiency opportunities for utilities and crosscutting energy uses.

Management & Control Energy monitoring Site energy control systems	**Process Integration** Total site Pinch analysis Water Pinch analysis
Power Generation CHP (cogeneration) Gas expansion turbines High-Temperature CHP Gasification (Combined Cycle)	**Energy Recovery** Flare gas recovery Power recovery Hydrogen recovery Hydrogen pinch analysis
Boilers Boiler feedwater preparation Improved boiler controls Reduced flue gas volume Reduced excess air Improve insulation Maintenance Flue gas heat recovery Blowdown heat recovery Reduced standby losses	**Steam Distribution** Improved insulation Maintain insulation Improved steam traps Maintain steam traps Automatic monitoring steam traps Leak repair Recover flash steam Return condensate
Heaters and Furnaces Maintenance Draft control Air preheating Fouling control New burner designs	**Distillation** Optimized operation procedures Optimized product purity Seasonal pressure adjustments Reduced reboiler duty Upgraded column internals
Compressed Air Maintenance Monitoring Reduce leaks Reduce inlet air temperature Maximize allowable pressure dewpoint Controls Properly sized regulators Size pipes correctly Adjustable speed drives Heat recovery for water preheating	**Pumps** Operations & maintenance Monitoring More efficient pump designs Correct sizing of pumps Multiple pump use Trimming impeller Controls Adjustable speed drives Avoid throttling valves Correct sizing of pipes Reduce leaks Sealings Dry vacuum pumps
Motors Proper sizing of motors High efficiency motors Power factor control Voltage unbalance Adjustable speed drives Variable voltage controls Replace belt drives	**Fans** Properly sizing Adjustable speed drives High-efficiency belts
Lighting Lighting controls T8 Tubes Metal halides/High-pressure sodium	High-intensity fluorescent (T5) Electronic ballasts Reflectors LED exit signs

Table 2. Summary of process-specific energy efficiency opportunities.

Desalter Multi-stage desalters Combined AC/DC fields	**Hydrocracker** Power recovery Process integration (pinch) Furnace controls Air preheating Optimization distillation
Crude Distillation Unit Process controls High-temperature CHP Process integration (pinch) Furnace controls Air preheating Progressive crude distillation Optimization distillation	**Coking** Process integration (pinch) Furnace controls Air preheating
Vacuum Distillation Unit Process controls Process integration (pinch) Furnace controls Air preheating Optimization distillation	**Visbreaker** Process integration (pinch) Optimization distillation
Hydrotreater Process controls Process integration (pinch) Optimization distillation New hydrotreater designs	**Alkylation** Process controls Process integration (pinch) Optimization distillation
Catalytic Reformer Process integration (pinch) Furnace controls Air preheating Optimization distillation	**Hydrogen Production** Process integration (pinch) Furnace controls Air preheating Adiabatic pre-reformer
Fluid Catalytic Cracker Process controls Power recovery Process integration (pinch) Furnace controls Air preheating Optimization distillation Process flow changes	**Other** Optimize heating storage tanks Optimize flares

Process integration or pinch technology refers to the exploitation of potential synergies that are inherent in any system that consists of multiple components working together. In plants that have multiple heating and cooling demands, the use of process integration techniques may significantly improve efficiencies. Developed in the early 1970's it is now an established methodology for continuous processes (Linnhoff, 1992). The methodology involves the linking of hot and cold streams in a process in a thermodynamic optimal way (i.e. not over the so-called 'pinch'). Process integration is the art of ensuring that the components are well suited and matched in terms of size, function and capability. Pinch Analysis takes a systematic approach to identifying and correcting the performance limiting constraint (or pinch) in any manufacturing process (Kumana, 2000). The pinch approach has been extended to resource conservation in general, whether the resource is capital, time, labor, electrical power, water or a specific chemical species such as hydrogen.

The critical innovation in applying pinch analysis was the development of "composite curves" for heating and cooling, which represent the overall thermal energy demand and availability profiles for the process as a whole. When these two curves are drawn on a temperature-enthalpy graph, they reveal the location of the process pinch (the point of closest temperature approach), and the minimum thermodynamic heating and cooling requirements. These are called the energy targets. The methodology involves first identifying the targets and then following a systematic procedure for designing heat exchanger networks to achieve these targets. The optimum approach temperature at the pinch is determined by balancing the capital-energy tradeoffs to achieve the desired payback. The procedure applies equally well to new designs as well as retrofit of existing plants. The energy savings potential using Pinch Analysis far exceeds that from well-known conventional techniques such as heat recovery from boiler flue gas, insulation and steam trap management.

Pinch analysis, and competing process integration tools, have been developed further in the past years. The most important developments in the energy area are the inclusion of alternative heat recovery processes such as heat pumps and heat transformers, as well as the development of pinch analysis for batch processes (i.e. including time as a factor in the heat integration optimization). Even in new designs, additional opportunities for energy-efficiency improvement can be identified using process integration techniques. Pinch analysis has also been extended to the areas of water recovery and efficiency, and hydrogen recovery (Hydrogen Pinch, see also below). Water used to be seen as a low-cost resource to the refinery, and was used inefficiently. However, as the standards and costs for wastewater treatment and feedwater makeup increase, the industry has become more aware of water costs. In addition, large amounts of energy are used to process and move water through the refinery. Hence, water savings will lead to additional energy savings. Water Pinch can be used to develop targets for minimal water use by reusing water in an efficient manner. No Water Pinch analysis studies specific for the petroleum refining industry were found. Major oil companies, e.g. BP and Exxon, have applied Hydrogen Pinch analysis for selected refineries.

Total Site Pinch Analysis has been applied by over 40 refineries around the world to find optimum site-wide utility levels by integrating heating and cooling demands of various processes, and by allowing the integration of CHP into the analysis. Process integration analysis of existing refineries and processes should be performed regularly, as continuous changes in product mix, mass flows and applied processes can provide new or improved opportunities for energy and resource efficiency.

Major refineries that have applied total site pinch analysis are: Amoco, Agip (Italy), BP, Chevron, Exxon (in The Netherlands and UK), and Shell (several European plants). Typical savings identified in these site-wide analyses are around 20-30%, although the economic potential was found to be limited to 10-15% (Linnhoff-March, 2000). A total-site analysis was performed of an European oil refinery in the late 1990's. The Solomon's Energy Intensity Index of the refinery was within the top quartile. The refinery operates 16 processes including a CDU, VDU, FCC, reformer, coker and hydrotreaters. A study of the opportunities offered by individual process optimization of the CDU, VDU, FCC, coker and two hydrotreaters found a reduction in site EII of 7.5%. A total-site analysis including the cogeneration unit identified a potential reduction of 16% (Linnhoff-March, 2000). Identified opportunities including the conversion of a back-pressure turbine to a condensing turbine, and improved integration of the medium-pressure and low-pressure steam networks. The economically attractive projects would result in savings of approximately 12-13%. Site analyses by chemical producer Solutia identified annual savings of $3.9 Million (of which 2.7 with a low payback) at their Decatur plant, 0.9M$/year at the Anniston site and 3.6 M$/year at the Pensacola site (Dunn and Bush, 2001).

Conclusions

Petroleum refining in the United States is the largest in the world, providing inputs to virtually any economic sector. Energy costs represents one the largest production cost factors in the petroleum refining industry, making energy efficiency improvement an important way to reduce costs and increase predictable earnings and reduce the bottom line.

Competitive benchmarking data indicates that most petroleum refineries can economically improve energy efficiency by 10-20%. This potential for savings amounts to annual costs savings of millions to tens of millions of dollars for a refinery, depending on current efficiency and size. Improved energy efficiency may result in co-benefits that far outweigh the energy cost savings, and may lead to an absolute reduction in emissions.

The paper identified energy efficiency opportunities available for petroleum refineries. Specific energy savings for each energy efficiency measure based on case studies of plants and references to technical literature are provided. The paper draws upon the experiences with energy efficiency measures of petroleum refineries worldwide. The findings suggest that given available resources and technology, there are opportunities to reduce energy consumption cost-effectively in the petroleum refining industry while maintaining the quality of the products manufactured, underling the results of benchmarking studies. Further research on the economics of the measures, as well as the applicability of these to different refineries, is needed to assess the feasibility of implementation of selected technologies at individual plants.

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