AN ASSESSMENT OF CARBON REDUCTION TECHNOLOGY OPPORTUNITIES
IN THE PETROLEUM REFINING INDUSTRY*

by

Dr. Michael Petrick
Argonne National Laboratory
Energy Systems Division/Bldg. 362
9700 S. Cass Ave.
Argonne, IL 60439-4815

and

Ms. Joan Pellegrino
Energetics, Inc.
7164 Gateway Drive
Columbia, MD 21046

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Dr. Michael Petrick
Argonne National Laboratory
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INTRODUCTION

Petroleum refining is the most energy-intensive industry in the U.S.; the industry accounted for $\approx 7\%$ of total energy consumed in the U.S. in 1994.[1] The amount of energy used in refining petroleum crude oil depends upon many factors and therefore has varied over time. The key factors that have impacted energy use are (1) the cost and quality of crude processed; (2) the cost and availability of fuel and other forms of energy; (3) product slate produced to meet market demand; (4) refinery configuration (complexity and size); (5) capital availability; and (6) environmental regulations (product specifications). Over the past three decades these factors have forced the refining industry to change dramatically; these changes in turn have impacted energy utilization. Over the time period of 1969 to 1974 energy used/bbl processed declined at a rate of 0.8%/yr.[2] In 1975, energy use was about 3.2 Quads. The oil supply disruptions and high price of oil in the 70s motivated the industry to continue efforts to minimize energy usage. By 1983, energy utilization had dropped to 2.6 Quads.[3] Since 1985, refineries have become more complex as the quality of the crude slate processed has declined. The deteriorating crude quality and the market pressures to produce more "white products" per barrel processed motivated refiners to add more advanced processing capability, thus increasing refining complexity and energy utilization per unit of output. By 1990 energy usage had again risen to a level of about 3.0 Quads. Since 1990, energy usage has remained relatively constant; in 1996 the industry utilized 3.258 Quads.[4]

CO₂ Emissions

In 1996, the U.S. refining industry generated an estimated 60.4 MMTCE (million metric tons of carbon equivalent) which is 12% of the total emanating from the industrial sector; this corresponds to 221 MMT (million metric tons) of CO₂, see Table 1. The CO₂ was generated from the combustion of a variety of fuels to produce process heat, steam, and electrical energy. The amount of carbon released from combustion of the fossil fuels is dependent on the carbon content, density, and gross heat of combustion. The carbon emission factor (lbsCO₂/10⁶ Btu) from the fuels typically consumed are presented in Table 1. The principal process sources of CO₂ emissions in refining and estimates of annual (1996) emissions from them are provided in Table 2.

POTENTIAL FOR FUTURE REDUCTIONS IN ENERGY UTILIZATION AND CO₂ EMISSIONS

In order to achieve reductions in the critical greenhouse gas CO₂, the energy efficiency of the key (highest energy consuming) refining processes and energy supply systems must be improved. Efficiency improvements can be achieved via various steps, e.g., (1) introduction of more efficient equipment; (2) reducing process activation energies (through improved catalysts); (3) improving equipment integration to recover more heat; and (4) adopting improved process controls, etc. A number of studies have identified processes and technology innovations/modifications that have the potential to substantially reduce energy consumption.[2][3] As indicated in Table 2, the most energy intensive processes in a refinery considering both specific energy use and percentage of total energy used in the refining process are: distillation; catalytic hydrocracking, reforming and hydrotreating; alkylation; and hydrogen production. While the aforementioned studies cite numerous technology options that could improve the processes energy utilization efficiency, the issues of the economic viability and risk involved in retrofitting these modifications/components into the spectrum of plant configurations that exist in the industry today were not addressed. It is clear that the cost/benefit and payback for incorporating the candidate technologies/processes are highly site specific and are very sensitive to future market and governmental dictates. While refiners can make improvements/modifications to improve energy utilization, they may also be forced to modify refinery processes/configurations to be able to refine crudes of lower quality and comply with environmental dictates. Such changes could have undesirable impacts on energy usage and/or emissions. A clear example of this is given in ref. [6], wherein a major \$2.2 billion revamp of a 400,000 bbl/day refinery is under way to accommodate expected changes in crude supply and to meet current and future product volume and quality demands is described. The refinery crude supply is expected to shift to a higher proportion of Middle East crude, increasing the sulfur intake (to the refinery) by about 45%. Changes in refinery output that result from the extensive modifications include a 10% increase in the white product make and a decrease of 40% in fuel oil production.

With regard to environmental emissions, SO₂ and NO_x emissions are expected to be reduced by 35 and 45%, respectively, due primarily to reduced residual oil firing; also, particulate matter emissions will be halved. However, CO₂ emissions from the refining site are expected to rise substantially – by about 22% – because of the use of greater amounts of hydrogen in the refining process. The global emission CO₂ impact resulting from the changes in refining and the combustion of the products produced, however, is expected to remain essentially constant, because of the higher hydrogen content of the refinery's products.

This example serves to underscore the complexity/uncertainties in generating projections relative to levels of energy efficiency improvements and the magnitude of emission reductions that can be achieved. Nevertheless, it seems

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clear that there are a number of steps and/or technology options that, if implemented, could reduce energy usage and help reduce CO₂ emissions. The implementation of refining process/configuration modifications to reduce energy usage will require that the industry provide strong environmental stewardship and that an appropriate investment climate exist. Examples of process/technology/operating improvements that could potentially generate substantial improvements in energy utilization efficiency are outlined in the following sections; they are broken down into three categories, namely: (1) near-term, straightforward improvement opportunities; (2) process/equipment modifications; and (3) long-range opportunities requiring further R&D. Promising options are briefly discussed and a few that may be applicable to a broader spectrum of refineries of varying complexity and are being subjected to more in-depth evaluation are highlighted. Many of the opportunities cited undoubtedly have already been or are being incorporated into the more efficient refineries operating today.

TECHNOLOGY OPPORTUNITIES FOR REDUCING CO₂ EMISSIONS

Near-Term Opportunities

There are a number of equipment, maintenance, and operational improvements that can be considered relatively straight forward that can be made to improve overall system energy utilization efficiency. Such improvements generally have longer pay-backs than current industry standards and thus likely to be difficult to justify under prevailing economic conditions. Nevertheless, with appropriate investment incentives their implementation could produce substantial energy savings and CO₂ reductions.

Monitoring Overall Energy Performance

Every refinery could promote energy efficiency stewardship by rigorously pursuing a program to monitor equipment/process/overall refinery energy performance to identify (as early as possible) deviations from nominal (design) operating conditions and initiating corrective actions. Estimates of energy savings that can be realized through such action range from 1-4%.[7][8]

Utility System Improvements

The principal utility systems in a refinery, the cooling, steam, power, and fuel-gas systems, are integrated with virtually every process subsystem and thus can significantly impact overall refinery operations. The potential for achieving energy savings and CO₂ reductions by improving their function and operation is substantial.

Cooling Water – Perhaps the most overlooked opportunity for saving energy lies in generating improvements in the cooling water system and/or providing supplemental low-temperature cooling. Lower temperature water can substantially lower the light ends emanating from towers, and in turn decrease the reboiler duty (for a constant separation). Similarly, lowering the temperature of operation of absorbers would reduce the amount of light hydrocarbons lost to fuel gas and increase recovery of valuable products. Cooling the feed to the suction of compressor can knock out additional liquid (product) and reduce energy consumption; lowering the suction and intercooler temperatures will also improve efficiency even if no additional liquid is removed. Numerous other opportunities exist that would derive from the availability of enhanced cooling.

The traditional approach to lower cooling water temperatures is to revamp cooling towers using modern fill material to get a closer approach to the wet bulb temperature. Specific limits are encountered with this approach that vary with the ambient conditions. Additional/enhanced cooling capability, however, can be achieved by judicious use of a new generation of waste heat-driven absorption chiller systems to either further reduce the temperature of cooling water streams or to cool process streams directly. Such systems also provide an opportunity to utilize low-grade heat that is in excess in various parts of the refinery. Table 3 provides examples of typical stack gas waste heat streams from various refinery process units that could be used to drive efficient advanced absorption refrigeration units to provide enhanced cooling. As indicated, these streams contain approximately one-half of a Quad (10^{15} Btu).

The WHAARP System – The application of a waste heat driven ammonia absorption refrigeration plant (WHAARP) was recently demonstrated at a 30,000 bbl/day refinery of the (then) Colorado Refinery Company in Commerce City, Colorado. The installation of the unit was supported by a DOE grant from the ClimateWise Demonstration Program. The WHAARP, which began operation in August, 1997, provides 85 tons of refrigeration at -30°F to cool the net gas/treat gas stream from the reformers; 65,000 barrels per year of LPG which previously was flared or burned as fuel is recovered. The plant is powered by the 290°F waste heat effluent stream from the reformer reactor. The WHAARP also produces 180 tons of refrigeration at 26°F that is available for other applications such as cooling the FCC main column overhead wet gas streams to debottleneck the compressors and the unsaturated gas plant sponge absorbing light cycle oil streams. The high grade product recovery translates into a reduction in CO₂ emissions of ≈10,000 tons/yr. The simple payback for this first-of-a-kind demonstration installation was 1.5 years [9].

Distillation – The distillation process, which utilizes ≈25% of the process energy consumed in a refinery complex [3], is a prime target for effecting reductions in energy use. A promising approach to increase efficiency is to lower the cooling water temperatures to the reflux condenser. Preliminary analyses of a typical distillation tower was carried out with the aid of the computer simulation ASPEN Plus[®]. ASPEN models the tower as a fairly typical crude fractionator having two pumparound loops for interstage cooling and three sidestrippers for removal of products, namely, kerosene, diesel and atmospheric gas oil (AGO). The overhead product is heavy naphtha, while the bottoms product is residual crude (RED-CRD). The crude feed entering the tower after being heated in a furnace having a duty of 200 million Btu/hr for the base case (this duty is a dependent variable calculated to satisfy the energy requirements of the tower).

For a 5% increase in the cooling duty (2.75 million Btu) on this tower, the furnace duty may be reduced by 12.2 million Btu/hr without changing the product rates. The reduction in furnace duty is 4.4 times the value of the increased cooling duty. A rough economic analysis based on the assumptions of (1) COE of an advanced absorption refrigeration unit of 0.8; (2) refrigeration unit costs of \$1500/ton; and (3) energy savings equivalent to crude price of \$15/bbl

indicated a payback period of 1.0-2.0 years, which is consistent with the experience at the Denver refinery cited earlier. The judicious application of enhanced cooling to distillation towers can thus have substantive impacts on energy use by not only direct improvement of process/equipment efficiency but also indirectly by opening up opportunities for improved heat integration across the refinery complex.

Steam Systems – Steam is used for a number of purposes throughout the refinery and accounts for about 20% of energy use. It is used as a stripping agent, in vacuum jets, as a heating medium, and in powering turbines and pumps. A number of opportunities exist to increase steam (energy) utilization efficiency. Letdown valves can be replaced with back-pressure turbines to reduce pressures to the desired intermediate levels and in so doing produce electrical power supplanting purchased power. Steam-driven ejector systems and condensing turbines that drive pumps, blowers, etc. can be replaced by the new generation of more efficient electrical motors thus generating a net reduction in energy usage. More vigorous maintenance of steam traps, valves, and rapid repair of other steam leaks can also generate significant steam savings. Finally, controlled reduction of stripping steam not only reduces direct energy consumption but also makes the fractionation more efficient in the top of the tower and thus reduces the reflux or pumparound requirements to meet separation specifications. Reducing stripping steam in turn reduces energy required in the sour water stripper.

Equipment Maintenance – Aggressive maintenance programs to keep equipment operating in optimal condition can reduce energy consumption substantially. A major opportunity exists with regard to controlling heat exchanger fouling, since the overall energy efficiency of refineries is heavily dependent on the feed/effluent heat exchangers that recover thermal energy from high temperature processes. Foulant buildup impedes heat transfer, which must be compensated for by burning additional gas or liquid fuels in furnaces, thus, reducing energy efficiency. The resulting economic and energy costs for the US refineries are well known: 0.2 Quads of energy (about 6.5% of the total energy consumed in refining) and more than \$2 billion per year [10]. The total worldwide energy and cost penalties are believed to be in the range of 5 to 8 times that of the US refineries. The fouling problem will become exacerbated as the quality of the crude state processed in the future deteriorates.

Opportunities for achieving significant fouling mitigation in the near term include adjusting refinery process operational parameters (where possible) to below threshold fouling conditions derived from laboratory experiments; incorporating various mitigation measures (e.g., enhanced surface tubes, tube inserts and chemical additives) in the existing heat exchange equipment; and pursuing more rigorous maintenance procedures, e.g., increased frequency of heat exchanger cleaning. The long-term solution of the refinery fouling problem will require the development of prediction models and comprehensive data bases. An aggressive effort to control fouling will facilitate additional heat integration of process equipment, thereby further increasing overall energy efficiency. A major factor impeding the pursuit of aggressive programs to minimize fouling however is the economic justification; costs can easily exceed energy savings.

Mid-Term Opportunities – Process/Equipment Modifications

Major opportunities to reduce energy usage in the mid-term also exist through retrofitting and/or replacement of existing equipment nearing the end of its useful life and during major refinery revamps that are periodically undertaken to meet market/environmental dictates. Examples of process/equipment modification opportunities are as follows.

Fired (Process) Heaters/Boilers – As indicated previously, over 60% of the energy used in refineries is obtained from burning gaseous fuels in refinery heaters/furnaces. Approaches that seek to alter furnace designs and control and achieve greater heat recovery can be used to improve process heater efficiency. Heat transfer can be enhanced through improved luminosity. Efficiency gains in the 5 to 10% range appear realizable. A variety of luminosity enhancing techniques have been tried with varying degrees of success. Also, the use of oscillating (pulsed) combustion, where the fuel flow is oscillated while the air flow remains constant, a technique now being evaluated, indicates potential efficiency gains of 5 to 10% in process heater applications. Re-radiation plates have been reported to produce similar gains. The use of recuperators to recover energy, e.g., air preheat, is possible, especially for higher temperature processes; cost and an increase in NO_x emissions tends to constrain the use of this approach. A promising route for improving boiler/furnace efficiency is through incorporation of improved sensors and controls. For example, balancing the burners in a multi-burner installation and reducing excess air can cut fuel use by 10 to 25%. Reducing excess air in single-burner boilers can lead to similar gains. The technology to automate excess air firing is available.

Distillation – Because distillation is the most energy-intensive process in refining, it is not surprising that numerous studies have been undertaken to identify opportunities to reduce energy usage in the distillation system. As an example, an energy analysis [11] identified where, within the overall distillation system, the highest potential exists to reduce energy consumption. Not surprisingly, the equipment/subsystems with the highest improvement potential identified were the fired heater, condensate reflux system, the crude preheating train, and the effluent cooling train. The use of enhanced cooling (the WHAARP system) to reduce condensate reflux cited earlier is an example of the steps that can be taken with respect to the reflux conditions. The opportunities identified further underscore the importance of enhancing combustion efficiency and improving waste heat recovery as discussed earlier. The most frequently recommended modifications to the distillation processes, summarized in [11-13] include (1) improving the fired heater combustion efficiency; (2) incorporating staged crude preheat; (3) replacement of steam ejector vacuum pumps with efficient electrically-driven mechanical vacuum pumps; (4) improving heat recovery and integration between the crude and vacuum distillation units (estimates of reduction of distillation energy usage range from 10-20%) [9]; and (5) substitution of reboilers heated by the main column bottom for the stripping steam in the stripping columns.

A more limited opportunity exists to improve the efficiency of the distillation process itself, for example, by optimizing the number of trays, using more efficient packings, etc. The greatest potential for improving distillation efficiency would require major revamps of towers to essentially alter the distillation process by increasing the number of internal heat-integrated and condensing steps, thus reducing the loads on the fired heater and main condenser.

Fluid Catalytic Cracker (FCC) – Substantive reductions in energy usage and hence CO₂, can be achieved through modification of key refining processes to increase efficiency and/or increase product yields per barrel processed to meet market demand. Such an approach not only reduces energy usage and emissions but also improves competitiveness. The FCC presents an especially attractive opportunity because it is now and is likely to continue to be the key process for meeting future demand for “white products”. The product slate yields from the FCC can be adjusted through modification of operating parameters in the riser reactor, e.g., residence time, and/or equipment such as feed nozzles, injection locations, etc., and by utilizing improved catalysts as discussed in a following section. Advanced computational fluid dynamics (CFD) models are being developed to provide a tool for designing changes in FCC operation to achieve the changes desired.[14-15] Recent experimental and FCC simulation studies suggest that it may be possible to increase desired product yields from 3–7% per barrel of crude processed with appropriate modifications of equipment and operating conditions. An analysis of increasing FCC white product yield by 7% indicated that if this were done across the U.S. refining industry the energy savings could reach 36×10^{12} Btu/year and CO₂ emissions could be reduced by 0.9 MMTCE annually. The expected shift to lower quality (lower API gravity and higher sulfur) crudes expected to occur in the future will turn the FCC into an exporter of energy. This will require installation of additional heat recovery equipment such as catalyst coolers, CO boilers, etc., which can be used for generation of additional steam, air preheat, etc. or for production of electric power, thus reducing consumption of other fuels such as gas and electricity purchased from utilities.

Coke/Residue Gasification/Advanced Cogeneration for the Production of Steam, Electricity and H₂ – The gasification technology that exists today provides refiners with a unique opportunity, albeit perhaps a costly one, to simultaneously improve energy utilization, reduce emissions, and add value to the bottom of the barrel by converting the coke and waste residues to a synthesis gas that can be used for producing electricity, process steam and H₂. The integration of a coke/residue gasifier with a cogeneration plant and H₂ production system can provide refiners with an enhanced capability to process the lower quality petroleum feeds (expected in the future), to meet changing market product demand and environmentally mandated specifications. The technology would also allow the refiner to become an exporter of energy and provide an inherent capability to dispose of various problem liquid/solid carbonaceous residues. The gasifier converts the various residues into a clean syngas composed of H₂ and CO which can then be split into several streams that can be fed to a cogeneration plant to produce electricity and steam at desired pressure levels and to a H₂ plant. Any excess electrical power generated in the cogeneration plant can be fed into the utility grid stream. Incorporation of a cogeneration plant also provides the capability to optimize the steam utility system. The syngas generated from the low-value residual waste thus supplants natural gas normally needed to augment the refinery's fuel gas supply and that used for the production of H₂. The technology is already being introduced into various refineries.[6][17] Specific gains in energy use efficiency (CO₂ reduction) achievable through the introduction of tri-generation systems are site specific and thus cannot be generalized. Estimates however can be made of the impact of the introduction of advanced cogeneration technologies under development such as advanced turbine systems and fuel cells. Developments to date indicate that the advanced turbines have the potential to increase overall efficiency by as much as 13 percentage points (30 to 43%) and the fuel cells by 24 percentage points. Market penetration studies [18] of the two technologies indicate that carbon emissions from the industry would be reduced by ≈ 1 MMTCE by the year 2020 resulting from an energy savings of 58×10^{12} Btus.

Long-Range Opportunities Requiring Further R&D

For the longer term there are a number of research directions in regard to novel refinery process development/improvement that have the potential to produce breakthroughs in regard to refinery efficiency and reductions of emissions. It seems clear that new approaches to refining will need to be developed to counteract the pressure of increasing refinery complexity and energy utilization to process lower quality crudes. Major incentives exist to eliminate or reduce the levels of metals, sulfur, and nitrogen as early as possible in the refining process because of their adverse effect on catalyst performance (re product yields and energy utilization) in key processes such as FCC, hydrocracking, and hydrotreating. Also as discussed previously, an incentive exists to reduce energy usage in the crude and vacuum towers, the major consumers of energy in the refining process. An example of a potentially attractive process modification that has been explored [19-20] is to input the crude directly into a controlled (millisecond range) thermal cracking unit bypassing the atmospheric and vacuum towers and subsequently hydrotreating/hydrocracking the streams to achieve the product slate desired. The product streams from the thermal cracker would contain 30-50% less sulfur, 50-80% less nitrogen, and 95% less asphaltenes and metals. In addition, up to 80% of the energy released in the coke combustor could be recovered as usable energy in the form of steam.

Replacement of the atmospheric and vacuum columns with controlled thermal cracking of crude could yield a substantial reduction in combustion of fuels, along with a reduction in carbon emissions. An estimate was made of the specific energy and carbon impacts by comparing a refinery using atmospheric and vacuum distillation and delayed coking with a refinery using thermal cracking in combination with mild hydrocracking of heavy distillates and hydrotreating of light distillates. Both scenarios are based on case studies and field test data provided in [19-20]. Each refinery upgrades Arabian crude (API 28) containing relatively high sulfur and nitrogen; both produce the same amount of coke (12 wt.% of crude) and use it to generate steam. The replacement of the crude distillation scheme with a thermal cracking process results in a net energy savings of about 63,300 Btu per barrel of oil processed or $\approx 10\%$ of the energy used in refining. A similar reduction in carbon emissions is projected based on the CO₂ factors shown in Table 1.

Other long-term promising R&D directions that could result in major improvement in energy use and reduction in CO₂ include (1) development of new generation of catalysts with lower energies of activation that can be used in and selectively increase product yields for hydroprocessing, catalytic cracking, and alkylation and (2) biodesulfurization of the crude and other process streams.

A Showcase Demonstration Refinery Efficiency Improvement Program

In 1996, the DOE Office of Industrial Technology (OIT), in collaboration with a consortium of small refining service providers headed by Planetec, and Argonne National Laboratory entered into an agreement with the management of the Colorado Refinery Company to undertake a study to define a comprehensive package of process efficiency improvements as a showcase demonstration program to show the economic and environmental benefits that could occur from implementing a package of technologies that would reduce energy use and in turn gaseous emissions such as GHGs as well as other criteria pollutants. Initially, a utility system and energy/mass balance was completed to establish a baseline. Thereafter a wide spectrum of efficiency improvement studies were undertaken to identify the most promising opportunities, e.g.s., process integration of fuel/gas systems; energy management of electrical/chemical fuel sources; steam system analyses; waste heat driven, high-lift heat pump applications; cooling enhancements; high efficiency motors; product yield improvements; cogeneration system impacts, etc. Thirty-three (33) utility and efficiency improvement measures, many of which were described above, were identified and integrated into a four-phase master plan that could be implemented over a period of 3-5 years. Thirteen relatively low-cost, efficiency improvement measures, e.g.s., installation of inserts in selected heat exchanger tubes to improve heat transfer (thermal efficiency); installation of a vacuum crude unit heater, installation of enhanced insulation in selected components, etc. were completed in Phase I. These improvements had a payback of 0.66 years.

The WHAARP unit, which was cost shared by DOE, was installed in Phase II. The partial use of the system has led to the recovery of ~180 bbls of petroleum products/day since initiation of operation in August, 1997. Phase III and IV each comprise nine (9) efficiency improvement measures; if and when they are implemented, they would have simple paybacks of 2.58 and 2.04 years, respectively. The overall payback for the four-phase master plan is 2.3 years. The impact of the complete implementation of the first three phases of the master plan on the refinery's energy intensive index (EII), energy consumed per barrel of oil produced, and emissions are substantial as shown in Fig. 1 and Table 4, respectively. As indicated in Fig. 1, the EII (normalized to the year 1994), will drop by ~25%. The improved energy use efficiency that would be achieved during the three phases could reduce on and off site refinery emissions by 30,100 tons/year. The dramatic improvements realizable need to be placed in perspective; the refinery is of moderate complexity (complexity index = 6.75) and had a relatively high EII. Numerous opportunities for improving efficiency that existed in the refinery may not be available in a large heat-integrated complex refinery. Each refinery is unique and therefore the opportunities in each will differ.

CONCLUSIONS

The refining industry is a major source of CO₂ emissions in the industrial sector and therefore in the future can expect to face increasing pressures to reduce emission levels. The energy used in refining is impacted by market dictates, crude quality, and environmental regulations. While the industry is technologically advanced and relatively efficient, opportunities nevertheless exist to reduce energy usage and CO₂ emissions. The opportunities will vary from refinery to refinery and will necessarily have to be economically viable and compatible with each refiner's strategic plans. Recognizing the many factors involved, a target of 15-20% reduction in CO₂ emissions from the refining sector does not appear to be unreasonable, assuming a favorable investment climate.

Table 1. Carbon Emissions from Combustion of Fossil Fuels in Petroleum Refineries - 1996

Fuel Type	Carbon Emission Factor* (lbs CO ₂ /million Btu)	1996 Energy Use in Refining (Trillion Btu)	Carbon Emissions (MMTCE)
Crude Oil	163.9	0.01	0.0002
LPG	138.6	26.7	0.46
Distillate Fuel	161.2	4.3	0.09
Residual Fuel	173.6	54.9	1.18
Refinery Gas	141.5	1,435.0	25.14
Petroleum Coke	224.98	524.0	14.60
Natural Gas	116.9	797.6	11.53
Coal	207.5	3.1	0.08
Electricity	133.4	337.0	5.57
Purchased Steam	207.5	40.1	1.03
Unfinished Oils	163.3	35.7	0.72
TOTALS		3258.41	60.39

*Carbon Emission Factors[5][18]

Table 2. Estimated Carbon Emissions from Selected Refining Processes

Process	Average Energy Use ^a (10 ³ Btu/bbl)	1997 Capacity (10 ⁶ bbl/cday)	Annual Carbon Emissions (MMTCE)
Atmospheric Distillation ^b	113.8	15.45	11.87
Vacuum Distillation	91.5	7.15	4.43
Delayed Coking	166	1.671	2.07
Fluid Catalytic Cracking	100 (97.7) ^c	5.2	-0.06
Catalytic Hydrocracking	240 (71.8) ^c	1.3	1.31
Catalytic Hydrotreating	120 (31.1) ^c	10.7	5.98
Catalytic Reforming	284 (15.4) ^c	3.6	6.55

a Includes losses from generation and transmission of electricity (electricity conversion factor of 10,500 Btu/kWh). Does not include H₂ or O₂.

b Includes energy consumed for desalting of crude.

c Net steam export is shown in parentheses.

Table 3. Sources of Waste Heat in the Refinery Complex
(based on 1997 U.S. crude capacity, 93% utilization) [18]

Heater and Boiler Stack Gas Source	Temp. Range of Stack Gas (°F)	Waste Heat Content (10 ³ Btu/ bbl feed)	Annual Energy Value (Trillion Btu)
Atmospheric Distillation	700-900	13.8	74.4
Vacuum Distillation	700-900	3.7	19.7
Fluid Catalytic Cracking	800-900	8.5	46.0
Catalytic Hydrocracking	700-900	3.0	16.9
Catalytic Reforming	700-950	13.1	70.6
Cokers	800-1000	1.2	6.6
Alkylation	650-700	6.3	33.8
Visbreaking	700-800	2.4	12.6
Hydrotreating	700-900	3.4	34.7
Lube Oil Manufacture	700-900	2.0	10.5
Asphalt Processing	550-600	0.8	4.4
Electricity Generation	550-600	2.1	11.7
Central Boilers	400-500	26.7	143.7
TOTAL		87.0	485.6

Table 4. Total Reduced Emissions
Master Plan — Phases I-III

CO	-16.2
NOx	-53.4
SO ₂	-12.0
PM10	-6.5
VOC	-253.0
CO ₂	-29,754.0

Fig. 1: Projected Energy Intensity For Denver Refinery

REFERENCES

- [1] *Monthly Energy Review*, DOE/EIA-0035, April 1998.
- [2] V. O. Haynes, "Energy Use in Petroleum Refineries," ORNL/TM-5433, September 1976.
- [3] "Industry Profiles - Final Report: Energy Profiles for US Industry," US Department of Energy, Office of Industrial Technologies, 1990, Washington, DC; US Government Printing Office.
- [4] "Annual Energy Outlook 1997 with Projections to 2015," DOE/EIA, 0383 (1997).
- [5] Energetics, Inc., "Energy and Environmental Profile of U.S. Petroleum Refining Industry," Draft Report for U.S. DOE, July 1998.
- [6] P. Ladeur and H. Bijwaard, "Shell Plans \$2.2 Billion Renovation of Dutch Refinery," *Oil & Gas Journal*, April 1993.
- [7] J. Robertson, Potential Energy Improvements-Emphasis on Refining, Personal Communication to ANL, March 1997.
- [8] "Ongoing Study of Energy Efficiency Improvements at a Low Complexity Refinery," Internal Technical Memoranda/ANL, 1977.
- [9] B. Brant, S. Brueske, D. Erikson, and K. Papar, "New Waste-Heat Refrigeration Unit Cuts Flaring, Reduces Pollution," *Oil & Gas Journal*, May 18, 1998.
- [10] S. H. Leach and J. L. Holuska, "Fouling of Refinery Heat Transfer Equipment," Hemisphere Publishing Co., Washington DC, pp. 619-643, 1981.
- [11] R. Rivero, et al., Energy Analysis of a Crude Oil Atmospheric Distillation Unit, Proceedings of the International Symposium on Thermodynamic Analysis and Improvement of Energy Systems TAIES '89, International Academy Publishers, Beijing 1989, pp. 506-510.
- [12] M. D. Levine et al., Efficient Use of Energy Utilizing High Technology-Assessment of Energy Use in Industry and Buildings, World Energy Council Report, September 1995, London, Kogan Page Ltd.
- [13] T. J. Mix et al., Energy Conservation in Distillation, CEP, April 1978.
- [14] S. L. Chang, et al., "Interactions of Multiphase Hydrodynamics, Droplet Evaporation, and Chemical Kinetics in FCC Riser Reactors," HTD-Vol. 357, Proc. of the ASME Heat Transfer Division 1:261-269, the 7th AIAA/ASME Joint Thermophysics and Heat Transfer Conference, Albuquerque, NM (June 1998).
- [15] S. L. Chang, et al., "A Hybrid Technique for Coupling Chemical Kinetics and Hydrodynamics Computations in Multiphase Reacting Flow Systems," HTD-352, Proc. of the ASME Heat Transfer Division 2:149-158, the 1997 Intl. Mechanical Engineering Congress and Exposition, Dallas, TX (November, 1997).
- [16] J. L. Robertson, *Energy and the Environment in the 21st Century*, MIT Press, Cambridge, MA 1990.
- [17] M. Quintana et al., *The Gasification Solution-Heavy End Optimization*
- [18] "Assessment of Carbon Reduction Technologies in the Petroleum Refining Industry," Draft Report, prepared by Energetics, Inc./Argonne National Laboratory, March, 1998.
- [19] D. B. Bartholis et al., *Petroleum Refinery of the Future*, Japan Petroleum Institute, Tokyo, Oct. 27, 1986.
- [20] F. N. Dawson et al., *Heavy Crude Oil Processing Via Fluidized Bed Cracking and Hydrogeneration -Final Report*, CRADA No. C/ANL-9301001, September 1995.