Estimation of Energy Efficiencies of U.S. Petroleum Refineries

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Background

Evaluation of life-cycle (or well-to-wheels, WTW) energy and emission impacts of vehicle/fuel systems requires energy use (or energy efficiencies) of energy processing or conversion activities. In most such studies, petroleum fuels are included. Thus, determination of energy efficiencies of petroleum refineries becomes a necessary step for life-cycle analyses of vehicle/fuel systems. Petroleum refinery energy efficiencies can then be used to determine the total amount of process energy use for refinery operation. Furthermore, since refineries produce multiple products, allocation of energy use and emissions associated with petroleum refineries to various petroleum products is needed for WTW analysis of individual fuels such as gasoline and diesel.

In particular, GREET, the life-cycle model developed at Argonne National Laboratory with DOE sponsorship, compares energy use and emissions of various transportation fuels including gasoline and diesel. Energy use in petroleum refineries is key components of well-to-pump (WTP) energy use and emissions of gasoline and diesel. In GREET, petroleum refinery overall energy efficiencies are used to determine petroleum product specific energy efficiencies.

The petroleum refinery energy efficiencies in the GREET model are from Argonne's processing of inputs and outputs of three petroleum refining linear programming (LP) studies that MathPro conducted for California Energy Commission, Engine Manufacturers Association, and Alliance of Automotive Manufacturers, separately. Argonne concluded an average petroleum refinery efficiency of 88%. See the table below for detailed energy efficiencies for petroleum refineries that were configured to produce gasoline with different specifications.

Table 1. Overall Energy Efficiencies of U.S. Petroleum Refineries

Refinery for Producing	Refinery Overall Energy Efficiency (%)	
	Low	High
340 ppm S conventional gasoline	88.4	88.4
150 ppm S reformulated gasoline with MTBE	87.7	87.9
5-30 ppm S reformulated gasoline with MTBE	87.7	89.5
5-30 ppm S reformulated gasoline with ethanol	87.4	88.9
5-30 ppm reformulated gasoline with no oxygenate	87.6	87.8

Source: GM et al. (2001), p.13.

In summer of 2006, ExxonMobil examined the input and output data from Energy Information Administration's (EIA's) publications on U.S. refineries and brought to Argonne's attention that petroleum refinery energy efficiencies in GREET may need to be revised. Since then, Argonne has interacted with ExxonMobil, MathPro, DOE, and EIA to examine available data for petroleum refining efficiency revision. This report summarizes results of this effort so far.

Update of Petroleum Refinery Energy Efficiencies with EIA Survey Data

EIA conducts annual and monthly petroleum refinery surveys among U.S. refiners. The annual survey (Form EIA-820) asks refiners to provide purchased natural gas, coal, electricity, and steam as process fuels for refinery operation. The survey results are summarized in EIA's Annual Refinery Capacity Report (EIA, 2007a). By law, all refineries are required to respond to EIA surveys. In this regard, the coverage of petroleum refineries by the EIA survey should be complete.

However, in the annual survey, EIA specifically asks refiners not to include natural gas use for hydrogen production. EIA does not ask MTBE and ethanol inputs either. On the other hand, EIA asks in its monthly survey (Form EIA-810) inputs of hydrogen, MTBE, ethanol, and other items to refineries. But monthly survey data regarding these inputs has not been summarized in any EIA publications.

Argonne has summarized process fuel use by petroleum refineries in each of the U.S. Petroleum Administration for Defense Districts (PADD). The figure below shows the five U.S. PADDs. Table 2 presents process fuel use from EIA's annual survey in 2006.

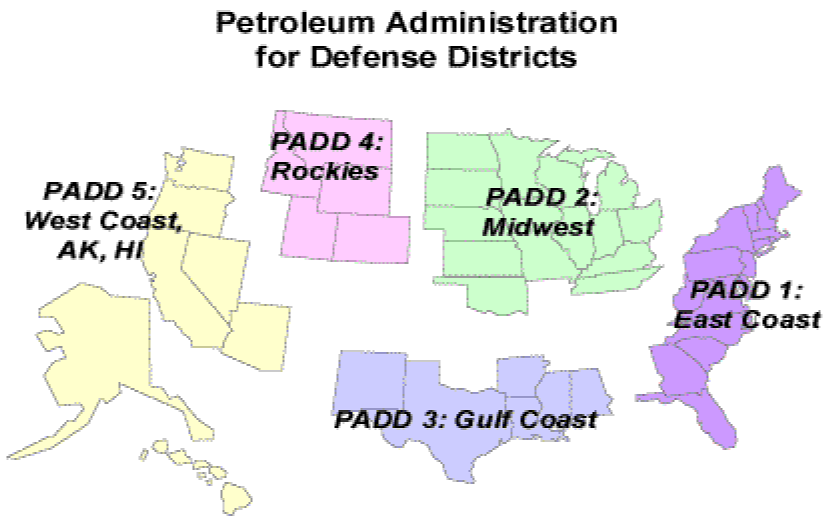

Figure 1. U.S. PADD Map

(Source: EIA, http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/oil_market_basics/paddmap.htm, accessed Oct. 26, 2007)

Table 2. Process Fuel Use in U.S. Refineries in 2006 (1000 barrels/year, excepted as noted, EIA (2007a))

	PADD					U.S.
	I	II	III	IV	V	Total
Crude Oil	0	0	0	0	0	0
Liquefied Petroleum Gas	329	567	277	15	1,468	2,656
Distillate Fuel Oil	23	45	111	0	255	434
Residual Fuel Oil	920	206	1	121	770	2,018
Still Gas	21,232	49,585	125,046	8,496	44,999	249,358
Marketable Petroleum Coke	0	0	194	154	110	458
Catalyst Petroleum Coke	11,033	16,502	45,395	2,664	14,440	90,034
Natural Gas (million cubic feet)	36,225	114,721	395,627	24,830	126,190	697,593
Coal (thousand short tons)	31	3	0	0	0	34
Purchased Electricity (million kWh)	3,576	10,488	18,612	1,704	4,973	39,353
Purchased Steam (million lbs)	5,716	7,298	38,999	757	17,999	70,769
Other Products	54	1,961	1,971	142	2,199	6,327

A large amount of hydrogen is used in refineries. The required hydrogen may be produced captively in refineries or purchased from hydrogen production facilities. ExxonMobil stated that while PADD I refineries may produced most of their hydrogen captively, PADD III refineries rely primarily on purchased hydrogen. Table 2 does not include hydrogen use or natural gas use for captive hydrogen production.

The exclusion of hydrogen use or natural gas use for captive hydrogen production from the EIA survey needs to be remedied. Argonne obtained data of hydrogen use by US refineries from the Chemical Economics Handbook. Since GREET takes into account natural gas, not hydrogen, as a fuel input for refinery simulations, Argonne estimated the amount of natural gas needed for producing the amount of hydrogen used in refineries. The estimated amount of natural gas was then added to the amount of natural gas as process fuel in refineries (which is already contained in EIA survey data).

The Chemical Economics Handbook presents that in 2003 (the most recent year that data is available from it) U.S. refineries used 1,323 billion standard cubic feet (SCF) of captive hydrogen and 370 billion SCF of merchant hydrogen. Taking into account energy content of the used hydrogen and conversion efficiencies from natural gas (NG) to hydrogen, Argonne estimated that this is equivalent to 701 billion SCF of NG. This amount of NG for hydrogen production was added later by Argonne to EIA survey results (as presented in Table 2).

Argonne obtained data on crude inputs and petroleum product outputs for each PADD from EIA's Petroleum Supply Annual (EIA, 2007b). Argonne used this data (Table 3), together with the process fuel use data in Table 2, to estimate petroleum refinery energy efficiencies with a spreadsheet file (which is available on request).

Table 3. 2006 U.S. Petroleum Refinery Inputs and Outputs (1000 barrels/year, EIA (2007b))

	PADD					U.S.
	I	II	III	IV	V	Total
Refinery and Blender Net Inputs						
Crude	**551,850**	**1,203,238**	**2,649,813**	**201,862**	**956,591**	**5,563,354**
Natural Gas Liquids	**4,938**	**49,121**	**97,950**	**6,628**	**24,287**	**182,924**
Pentanes Plus	0	21,709	35,997	1,978	7,628	67,312
Liquefied Petroleum Gases	4,938	27,412	61,953	4,650	16,659	115,612
Ethane/Ethylene	0	0	0	0	0	0
Propane/Propylene	0	0	0	0	0	0
Normal Butane/Butylene	948	11,284	26,351	2,386	8,231	49,200
Isobutane/Isobutylene	3,990	16,128	35,602	2,264	8,428	66,412
Other Liquids	**326,944**	**-9,898**	**49,992**	**3,686**	**81,100**	**451,824**
Other Hydrocarbons/Oxygenates	40,592	45,200	34,926	2,986	38,289	161,993
Unfinished Oils	53,198	17,658	147,945	-674	23,254	241,381
Motor Gasoline Blend. Comp.	233,154	-72,782	-132,887	1,374	19,557	48,416
Reformulated	129,255	22,675	-138,840	0	25,216	38,306
Conventional	103,899	-95,457	5,953	1,374	-5,659	10,110
Aviation Gasoline Blending Component	0	26	8	0	0	34
Refinery and Blender Net Production						
Natural Gas Liquids	**15,691**	**48,409**	**134,434**	**2,697**	**27,729**	**228,960**
Pentanes Plus	0	0	0	0	0	0
Liquefied Petroleum Gases	15,691	48,409	134,434	2,697	27,729	228,960
Ethane/Ethylene	76	0	6,699	0	0	6,775
Propane/Propylene	16,364	38,971	120,442	2,958	19,455	198,190
Normal Butane/Butylene	-1,079	8,197	9,419	-19	7,789	24,307
Isobutane/Isobutylene	330	1,241	-2,126	-242	485	-312
Finished Motor Gasoline	**555,698**	**624,691**	**1,218,029**	**104,419**	**549,917**	**3,052,754**
Reformulated	381,852	131,530	147,322	0	408,225	1,068,929
Conventional	173,846	493,161	1,070,707	104,419	141,692	1,983,825
Finished Aviation Gasoline	**0**	**1,289**	**4,305**	**145**	**839**	**6,578**
Kerosene-Type Jet Fuel	**31,123**	**75,766**	**272,742**	**10,604**	**150,321**	**540,556**
Kerosene	**2,313**	**4,271**	**10,033**	**788**	**-99**	**17,306**
Distillate Fuel Oil	**176,753**	**333,483**	**703,716**	**61,635**	**199,154**	**1,474,741**
15 ppm Sulfur and Under	49,951	146,599	217,000	32,201	109,773	555,524
15 to 500 ppm Sulfur	47,383	140,465	308,176	22,946	56,738	575,708
Greater than 500 ppm Sulfur	79,419	46,419	178,540	6,488	32,643	343,509
Residual Fuel Oil	**42,908**	**20,204**	**106,657**	**5,667**	**56,452**	**231,888**
0.31 percent Sulfur and Under	17,099	3	10,596	660	2,302	30,660
0.31 to 1.00 Percent Sulfur	21,397	2,041	11,781	1,341	18,088	54,648
Greater than 1.00 Percent Sulfur	4,412	18,160	84,280	3,666	36,062	146,580
Petrochemical Feedstocks	**6,948**	**13,210**	**119,945**	**165**	**3,591**	**143,859**
Naphtha for Petrochemical Use	6,948	10,921	53,646	0	33	71,548
Other Oils for Petrochemical Use	0	2,289	66,299	165	3,558	72,311
Special Naphthas	**329**	**2,017**	**10,326**	**-1**	**559**	**13,230**
Lubricants	**6,491**	**5,688**	**47,757**	**0**	**6,863**	**66,799**
Waxes	**161**	**970**	**3,652**	**604**	**0**	**5,387**
Petroleum Coke	**18,009**	**53,156**	**173,251**	**6,592**	**58,423**	**309,431**
Marketable	6,976	36,654	127,859	3,928	43,981	219,398
Catalyst	11,033	16,502	45,392	2,664	14,442	90,033

Asphalt and Road Oil	**34,012**	**74,796**	**41,021**	**17,002**	**17,880**	**184,711**
Still Gas	**21,778**	**50,344**	**127,445**	**8,397**	**50,929**	**258,893**
Miscellaneous Products	**1,095**	**5,886**	**13,728**	**805**	**4,305**	**25,819**

For GREET simulations, Argonne defines the petroleum refinery efficiency as the following:

Petroleum Refinery Energy Efficiency =
energy in all petroleum products/(energy in crude input, other feedstock inputs, and process fuels)

Petroleum product outputs, crude and other feedstock inputs are presented in Table 3. Process fuel inputs are presented in Table 2. Both tables present inputs and outputs in volumes. Heat content of each input or output is needed to generate inputs and outputs in energy units. Argonne obtained heat contents of most products from EIA. For steam input, Argonne estimated the amount of NG required generating the amount of steam as reported in Table 2 (details are presented in Argonne's spreadsheet file).

The preliminary results from this examination show a petroleum refinery overall efficiency of 90.1% vs. the efficiency of 88% from an early Argonne analysis.

Outstanding Issues Regarding Petroleum Refinery Overall Energy Efficiencies

Energy Contents of Products

Calculation of petroleum refinery efficiencies relies on EIA survey data or results from refinery LP simulations. In both cases, inputs and outputs are presented in volumetric units such as barrels. For energy efficiency calculations, energy contents of the individual input and output items as shown in Tables 2 and 3 are needed so that energy inputs and outputs can be derived from volumetric inputs and outputs.

EIA presents energy contents for most refinery input and output items, which Argonne used. Energy content values for individual items can vary, which can result in different efficiency results. However, without other comprehensive data sources on energy content values, it is not clear how much effects energy contents of petroleum products have on refinery energy efficiency results.

Energy in Less Desirable Refinery Products

In refinery efficiency calculations, Argonne considers energy contents of all refinery products including less desirable products such as asphalts and road oils. If energy contents in these products are excluded or assigned less values, petroleum refinery efficiency would be lowered. For example, if energy in asphalt, road oils, and other miscellaneous products (as shown in Table 3) is excluded from refinery energy output, the U.S. refinery energy efficiency is reduced from 90.1% to 86.4%.

Hydrogen Consumption in Refineries

Both merchant and captive hydrogen (and feedstocks such as NG for hydrogen production) are not included in EIA-820 survey form. While captive hydrogen production is surveyed in EIA-810, this information is not summarized in any EIA publication. To supplement this data gap, for now, Argonne adds hydrogen use that it obtained from the Chemical Economics Handbook to EIA survey results. In the long run, the data gap of hydrogen use in EIA annual survey data may be remedied by EIA and others.

With the current Argonne remedy approach, both merchant and captive hydrogen use by refineries are obtained from the Chemical Economics Handbook. However, captive hydrogen can be produced from natural gas and still gas within refineries. If the amount of still gas use as reported in EIA-820 already includes the amount used for captive hydrogen production, still gas-based captive hydrogen production should be already considered in EIA-820. Efforts will be needed to take into account only merchant hydrogen and natural gas-based captive hydrogen.

On the other hand, a near-term, improved remedy is to summarize captive hydrogen production within refineries from EIA-810 survey data, while merchant hydrogen for refinery use could be obtained from such sources as the Chemical Economics Handbook. Furthermore, captive hydrogen from EIA-810 needs to be separated into still gas- and natural gas-based hydrogen in order to avoid potential double-counting of still gas-based hydrogen production.

In the long run, EIA could expand EIA-820 annual survey form to ask three questions: 1) how much hydrogen is purchased by a refinery? 2) How much hydrogen is produced within the refinery? And 3) of the hydrogen produced in the refinery, how much is produced from still gas and how much from natural gas? This will provide adequate information to estimate hydrogen use in U.S. refineries.

Shares of Process Fuels in Petroleum Refineries

GREET simulations of petroleum refineries require shares of different process fuels for refinery operation. With data in Table 2, Argonne was able to generate updated process fuel shares for GREET modeling. Table 4 presents the shares.

Table 4. Shares of Process Fuels in U.S. Petroleum Refineries (based on 2006 refinery data)

Process Fuel	PADD I	II	III	IV	V	U.S. Total (w/o H2)	U.S. Total (w/ H2)
LPG	0.5%	0.4%	0.1%	0.1%	0.9%	0.3%	0.3%
Distillate Fuel Oil	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%	0.1%
Residual Fuel Oil	2.2%	0.2%	0.0%	0.7%	0.9%	0.4%	0.3%
Still Gas	48.6%	51.3%	47.4%	49.8%	48.0%	48.4%	39.3%
Petroleum Coke[a]	25.3%	17.2%	17.4%	16.6%	15.6%	17.7%	14.3%
Natural Gas	14.2%	20.4%	25.7%	25.0%	23.1%	23.2%	37.8%[b]
Coal	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Purchased Electricity	4.7%	6.2%	4.0%	5.7%	3.0%	4.3%	3.5%
Purchased Steam	4.1%	2.4%	4.6%	1.4%	6.0%	4.3%	3.5%
Other Products	0.1%	2.0%	0.7%	0.8%	2.3%	1.2%	1.0%

[a] Petroleum coke here includes both marketable and catalyst petroleum coke. Between the two, catalyst petroleum coke accounts for the majority of the petroleum coke share.
[b] Natural gas share for the U.S. total includes natural gas use for hydrogen production. PADD-specific natural gas use for hydrogen production is not available and thus not included in PADD-specific NG shares.

Energy Efficiencies for Producing Individual Petroleum Products

Overall refinery efficiencies, as presented in the above sections, need to be converted into petroleum product-specific refinery efficiencies so that energy and emission effects of individual transportation fuels (e.g., gasoline and diesel) can be evaluated. This conversion can be accomplished by allocating total refinery energy use into individual refinery products at the aggregate refinery level. Allocation methods used so far for petroleum-based fuels (e.g., gasoline, diesel, and liquefied petroleum gas) are based primarily on mass, energy content, or market value shares of individual refinery products from a given refinery. The allocation at the aggregate refinery level is not capable of accounting for the energy use and emission differences associated with producing individual fuels at the next sub-level: individual refining processes within a refinery. Allocation at the refining process level, instead of at the aggregate refinery level, is advocated by the International Standard Organization but requires detailed energy use and emission data for individual refining processes.

Wang et al. (2004) presented means of allocating total refinery energy use among various refinery products at the level of individual refinery processes. Even though allocations at the refining process level generate more reliable results, the difference between refinery aggregate level allocation and the refining process allocation causes very small differences in life-cycle results of individual products. Thus, Argonne uses the refinery aggregate level allocation method here to derive refinery product-specific efficiencies from petroleum refinery overall efficiencies presented above.

Argonne took the following steps for the conversion. Using a rule of thumb for U.S. petroleum refineries, Argonne allocated 60% of total refining process fuel use to gasoline production, 25% to diesel production, and the remaining 15% to other petroleum products. In 2006, of the total production of all petroleum products from U.S. refineries, motor and aviation gasoline accounts for 47.0% by energy content, diesel fuels for 25.7%, and other products for the remaining 27.3%. These shares were derived from U.S. petroleum refinery product outputs as in EIA (2007b, see

Table 3) and energy contents of various petroleum energy products. With the assumed allocations of total refinery fuel use and the calculated product shares, Argonne calculated a relative energy intensity of 1.28 for gasoline production, 0.97 for diesel production, and 0.55 for other products together, all relative to the energy intensity for production of all petroleum products combined. These relative energy intensities were used to adjust relative net process fuel used for each refinery product.

With the above information, Argonne estimated the energy efficiencies of producing gasoline, diesel fuel, and other petroleum products. Table 5 presents our estimated energy efficiencies for individual refinery products. In an above section, we discussed whether less desirable products from refineries should be excluded from petroleum refinery efficiency calculations. In Table 5, we present product-specific energy efficiencies with this case.

Table 5. Refining Energy Efficiencies for Individual Petroleum Products

	Overall Petroleum Refinery Efficiency	
	90.1% (with all products included)	86.4% (with less desirable products excluded)
Gasoline	87.7%	83.3%
Diesel	90.3%	86.7%
LPG	94.3%	92.1%
Residual oil	94.3%	92.1%
Naphtha	94.3%	92.1%

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