Updated Estimation of Energy Efficiencies of U.S. Petroleum Refineries

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December, 2010

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.

Argonne has developed petroleum refining efficiencies from LP simulations of petroleum refineries and EIA survey data of petroleum refineries up to 2006 (see Wang, 2008). This memo documents Argonne's most recent update of petroleum refining efficiencies.

Update of Petroleum Refinery Energy Efficiencies with EIA Survey Data

Argonne has used new data from the 2009 EIA Annual Refinery Capacity report (EIA, 2009a) and the 2008 EIA Petroleum Supply Annual Report (EIA, 2009b) to update the process fuel use in U.S. refineries and the U.S. petroleum refinery input and output tables.

Table 1. Process Fuel Use in U.S. Refineries in 2008 (in 1,000 barrels/year, excepted as noted (EIA, 2009a))

	PADD					U.S.
	I	**II**	**III**	**IV**	**V**	**Total**
Liquefied Petroleum Gas	52	804	516	49	1,509	2,930
Distillate Fuel Oil	29	44	107	0	292	472
Residual Fuel Oil	399	194	3	49	745	1,390
Still Gas	21,328	48,882	114,447	9,121	43,383	237,161
Marketable Petroleum Coke	0	0	27	234	103	364
Catalyst Petroleum Coke	12,198	15,005	39,346	2,641	12,257	81,447
Natural Gas (million cubic feet)	27,872	138,894	381,022	22,762	139,950	710,500
Coal (thousand short tons)	31	12	0	0	0	43
Purchased Electricity (million kWh)	4,192	10,804	20,675	1,886	5,125	42,682
Purchased Steam (million lbs)	5,204	11,022	63,756	1,010	17,777	98,769
Other Products	29	18	1,698	68	2,027	3,840

Argonne also obtained updated hydrogen use data from the Chemical Economics Handbook (CEH). It reports that in 2006 U.S. refineries used 1,470.4 billion standard cubic feet (SCF) of captive hydrogen and 497 billion SCF of merchant hydrogen. CEH classifies captive hydrogen as the hydrogen produced by refineries for use in the same refinery, and excludes hydrogen generated as a by-product of other refinery operations (e.g., catalytic reforming or FCC.) Not including the hydrogen generated as a by-product of other refinery operations does not affect the refinery efficiency (the producing fuels are accounted for already), but it does artificially lower the calculated CO_2 emissions. Merchant hydrogen is defined as that supplied by industrial gas companies for “small-volume intermittent uses, requirements in excess of captive production or large quantities on a short-term basis when the usual supply source is down” (CEH, 2007). Argonne decided to add hydrogen as a separate refinery process fuel instead of converting it to the equivalent NG necessary for its production.

The latest Annual EIA Refinery Capacity Report (EIA, 2009a) has added a new entry for “natural gas used as feedstock for hydrogen production”. The reported amount, 188 billion SCF of NG, is much lower than the numbers from the CEH (815 billion SCF of NG). Argonne decided not to use the EIA reported number as it understands that the new entry in the EIA annual survey (Form EIA-820) must include only a subset of refinery produced hydrogen.

Table 2. 2008 U.S. Petroleum Refinery Inputs and Outputs (in 1,000 barrels/year (EIA, 2009b))

	PADD					U.S.
	I	**II**	**III**	**IV**	**V**	**Total**
Refinery and Blender Net Inputs						
Crude	**520,217**	**1,178,861**	**2,525,101**	**196,293**	**940,815**	**5,361,287**
Natural Gas Liquids	**6,998**	**39,044**	**102,279**	**6,537**	**22,701**	**177,559**
Pentanes Plus	0	13,167	32,834	1,952	7,544	55,497
Liquefied Petroleum Gases	6,998	25,877	69,445	4,585	15,157	122,062
Ethane/Ethylene	0	0	0	0	0	0
Propane/Propylene	0	0	0	0	0	0
Normal Butane/Butylene	1,688	9,379	28,565	2,344	8,048	50,024
Isobutane/Isobutylene	5,310	16,498	40,880	2,241	7,109	72,038
Other Liquids	**521,976**	**110,842**	**9,718**	**7,676**	**88,835**	**739,047**
Other Hydrocarbons/Oxygenates	69,617	69,536	47,595	6,322	46,189	239,259
Unfinished Oils	67,913	24,057	177,174	-1,677	18,769	286,236
Motor Gasoline Blend. Comp.	384,446	17,258	-215,079	3,031	23,877	213,533
Reformulated	154,997	21,781	-125,378	0	19,908	71,308
Conventional	229,449	-4,523	-89,701	3,031	3,969	142,225
Aviation Gasoline Blending Component	0	-9	28	0	0	0
Refinery and Blender Net Production						
Natural Gas Liquids	**19,167**	**42,321**	**138,736**	**3,205**	**27,002**	**230,431**
Pentanes Plus	0	0	0	0	0	0
Liquefied Petroleum Gases	19,167	42,321	138,736	3,205	27,002	230,431
Ethane/Ethylene	183	3	6,485	0	0	6,671
Propane/Propylene	18,065	36,728	113,374	3,348	18,505	190,020
Normal Butane/Butylene	-167	5,984	16,871	77	8,122	30,887
Isobutane/Isobutylene	1,086	-394	2,006	-220	375	2,853
Finished Motor Gasoline	**723,212**	**708,794**	**1,057,734**	**108,169**	**530,764**	**3,128,673**
Reformulated	443,226	133,169	136,252	0	387,311	1,099,958
Conventional	279,986	575,625	921,482	108,169	143,453	2,028,715
Finished Aviation Gasoline	**0**	**1,112**	**3,596**	**146**	**652**	**5,506**
Kerosene-Type Jet Fuel	**33,634**	**76,064**	**259,833**	**9,405**	**167,474**	**546,410**
Kerosene	**3,599**	**423**	**1,330**	**427**	**17**	**5,796**
Distillate Fuel Oil	**174,230**	**361,420**	**767,038**	**61,546**	**207,305**	**1,571,539**
15 ppm Sulfur and Under	95,841	319,734	511,203	53,455	174,713	1,154,946
15 to 500 ppm Sulfur	11,279	26,264	171,597	7,981	14,415	231,536
Greater than 500 ppm Sulfur	67,110	15,422	84,238	110	18,177	185,057
Residual Fuel Oil	**41,504**	**19,191**	**108,768**	**4,188**	**53,216**	**226,867**
0.31 percent Sulfur and Under	16,517	1	9,430	793	1,802	28,543
0.31 to 1.00 Percent Sulfur	13,404	3,561	12,136	724	17,699	47,524
Greater than 1.00 Percent Sulfur	11,583	15,629	87,202	2,671	33,715	150,800
Petrochemical Feedstocks	**6,185**	**12,449**	**102,984**	**0**	**883**	**122,501**
Naphtha for Petrochemical Use	6,185	9,577	41,212	0	25	56,999
Other Oils for Petrochemical Use	0	2,872	61,772	0	858	65,502
Special Naphthas	**245**	**1,173**	**13,042**	**1**	**399**	**14,860**
Lubricants	**6,211**	**4,242**	**45,040**	**0**	**7,719**	**63,212**
Waxes	**298**	**767**	**2,584**	**-2**	**0**	**3,647**
Petroleum Coke	**19,336**	**51,784**	**161,039**	**9,036**	**58,058**	**299,253**
Marketable	7,138	36,779	121,691	6,395	45,801	217,804

Catalyst	12,198	15,005	39,348	2,641	12,257	81,449
Asphalt and Road Oil	**30,097**	**63,914**	**31,010**	**11,889**	**13,100**	**150,010**
Still Gas	**22,143**	**47,641**	**117,639**	**9,026**	**48,601**	**245,050**
Miscellaneous Products	**1,010**	**4,663**	**15,986**	**903**	**4,976**	**27,538**

With the new 2008 data, Argonne has updated the overall petroleum refining overall efficiency to 90.8% vs. 90.1% using 2006 data.

Update of Shares of Process Fuels

Argonne created Table 3 with data from Table 1 for use in GREET modeling.

Table 3. Shares of Process Fuels in U.S. Petroleum Refineries (based on 2008 refinery data)

	PADD					U.S. Total
Process Fuel	**I**	**II**	**III**	**IV**	**V**	
LPG	0.1%	0.5%	0.1%	0.2%	1.0%	0.3%
Distillate Fuel Oil	0.1%	0.0%	0.0%	0.0%	0.3%	0.1%
Residual Fuel Oil	1.0%	0.2%	0.0%	0.3%	0.8%	0.2%
Still Gas	49.6%	49.8%	45.2%	52.3%	47.0%	38.7%
Petroleum Coke[a]	28.5%	15.3%	15.6%	15.2%	13.4%	13.5%
Natural Gas	11.1%	24.3%	25.8%	22.4%	26.0%	19.9%
Hydrogen						17.7%
Coal	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%
Purchased Electricity	5.5%	6.3%	4.6%	6.1%	3.2%	4.0%
Purchased Steam	3.8%	3.5%	7.9%	1.8%	6.0%	5.1%
Other Products	0.1%	0.0%	0.6%	0.4%	2.1%	0.6%

[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.

Update of Energy Efficiencies for Producing Individual Petroleum Products

Argonne has decided to modify the methodology used for the allocation of energy efficiencies between individual refinery products. A new paper by Bredeson et al. (2010) presents a modified allocation method that utilizes a hydrogen-energy equivalency to better allocate emissions consistently with refinery behavior. The simple energy allocation method fails to properly account for emissions associated with hydrogen production. Hydrogen is generated in a refinery's catalytic reformer in order to boost gasoline's octane rating. This same hydrogen is used in the refinery to hydro-process distillate material into commercial diesel and jet fuel. From this perspective catalytic reforming transfers energy from gasoline to distillate products. The paper's conclusions show that the energy efficiencies of LPG, gasoline, and distillate (diesel and jet) products should be considered equal. Furthermore, the energy efficiency of the heavier cuts (vacuum residue) will depend on the refinery's configuration (residue upgrading capacity) and type of crude being processed (heavy or light).

Argonne conducted an analysis of available residue upgrading units in U.S. refineries using the 2009 EIA Annual Refinery Capacity Report (EIA, 2009a). Roughly 67% of crude is processed by refineries that include residue upgrading units (mostly delayed coker units, but also a few visbreakers and others). Residue upgrading units are large energy consumers and produce hydrogen-deficient intermediate products that need to be further upgraded into commercial products, thus using more hydrogen.

Argonne decided to classify refinery products in two categories in order to calculate their energy efficiencies: LPG/gasoline/distillate as one group, and the remaining products (residual oil and naphtha, mostly) as another group. In 2008 the first group accounted for 84.6% of the energy content of all petroleum products from U.S. refineries, while the other group carried the 14.5% remaining. Using Figures 2 and 3 from Bredeson et al. (2010), Argonne estimated a ratio of 2.6 between the LPG/gasoline/distillate and residual energy intensities, using a weighted average between coker and residual oil #6 cases with the 67%/33% split above.

Assigning an energy efficiency of 89.9% for the LPG/gasoline/distillate group (0.9% lower than the 90.8% overall refining) equals to a relative energy intensity of 1.11 and an energy allocation of 93.5% for this group. This corresponds to a 6.5% energy allocation for the residual group, and thus a relative energy intensity of 0.42 and an energy efficiency of 95.9%.The calculated ratio between the two groups' energy intensities is 2.6, the same as calculated from the Bredeson paper. In Table 4 we present these final product-specific energy efficiencies.

Table 4. Refining Energy Efficiencies for Individual Petroleum Products

	Allocated % of Total Refining Fuel Use	% of Total Refinery Products Energy Content	Relative Energy Intensity	Overall Petroleum Refinery Efficiency	
				90.8% (with all products included)	**87.6%** (with less desirable products excluded)
LPG Gasoline Distillate	93.5%	84.6%	1.11	**89.9%**	**86.5%**
Other (residue, naphtha)	6.5%	15.4%	0.42	**95.9%**	**94.4%**

Outstanding Issues

Energy Efficiencies of Refinery By-Products (LPG, residual oil)

Allocating energy efficiencies to refinery products is a difficult task. Refineries operate to produce transportation fuels (gasoline, jet fuel, diesel, etc.) as best suited to current economic conditions, but they also produce other less commercially important by-products such as LPG and residual oil. The energy efficiency of residual oil (and of other heavier products) can be calculated from data from refineries without residue upgrading capacity, as explained in Bredeson et al. (2010.) The case of LPG (a lighter product) is a bit different, as its production in refineries stays fairly constant only depending on the type of crude being processed and the refinery configuration. Depending on those two factors the actual LPG energy efficiency can be calculated from somewhat higher to somewhat lower from the gasoline/distillate group. Argonne has decided to fix the LPG energy efficiency to that of the gasoline/diesel group of products.

Energy Efficiencies of Refineries Processing Heavy Crudes

Refineries consume more energy when processing heavier crudes. Heavier crudes have a larger vacuum residue fraction that needs to be upgraded in order to maintain a commercially viable product slate. Residue upgrading consumes large amounts of energy (i.e. delayed coker units with high CO_2 emissions) and hydrogen. Residue upgrading units produce hydrogen deficient intermediate products that need to be further hydro-processed into commercial refinery products (gasoline/jet fuel/diesel.) Argonne may eventually consider introducing a dependency on the crude heaviness (API gravity and/or distillation curve points) for future calculations of refinery energy efficiencies.

Oil Sands

Currently Argonne's methodology pushes all the burden of oil sands processing to the upstream recovery steps. In the currently used methodology processing oil sand-derived crudes (syn-crudes) does not impact the energy efficiencies of refineries. Argonne will evaluate the existing arguments for separating the extra energy burdens of processing syn-crudes between the oil sands recovery steps and the refinery processing.

Hydrogen

Argonne will work to reconcile the hydrogen consumption numbers coming from the EIA and those from the Chemical Economics Handbook. One possible explanation is that the EIA number only includes hydrogen generation from steam methane reforming (SMR), while the CEH captive production figure would include both the hydrogen amounts from SMR of natural gas but also from other fuels such as naphtha.

References

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