2.4 PETROLEUM REFINING SECTOR (NAICS 324110)

2.4.1. Overview of the Petroleum Refining Manufacturing Sector

Petroleum refining is a complex industry that generates a diverse slate of fuel products and petrochemicals, from gasoline to asphalt. Refining requires a range of processing steps, including distillation, cracking, reforming, and treating. Most of these processes are highly reliant on process heating and steam energy.

Petroleum refineries are an essential part of the U.S. economy. Crude oil and refined petroleum products have become some of the most highly scrutinized trading commodities in the world. The energy profile of this manufacturing sector is unique compared to other manufacturing sectors in that feedstock and many of the manufactured products are energy commodities that are often measured in terms of energy content, separate from the energy content of purchased fuels and electricity. Most other manufacturing sectors are highly dependent on refined petroleum products.

2.4.2. Energy Use Profile for the Petroleum Refining Sector

The petroleum refining sector is the largest consumer of fuel in U.S. manufacturing, when considering the inclusion of feedstocks or without feedstocks. Close to 90% of onsite fuel use in refining is applied toward process heating, 65% directly and an additional 23% for the generation of steam used in process heating.[12] The petroleum refining sector has the largest process heating energy demand of all manufacturing sectors, and correspondingly is also the largest generator of onsite GHG combustion emissions.

A snapshot of how the petroleum refining sector ranks in terms of energy use and losses within manufacturing is shown in Table 2.4-1. Energy losses are shown in red font. All values are based on the most currently available complete set of manufacturing energy use statistics, representing annual energy use and loss values for calendar year 2006. The petroleum refining sector ranks first in onsite energy use. Since petroleum refineries use proportionally less electricity than fuel compared to other manufacturing sectors the sector falls to third in rank for total primary energy use (accounting for offsite electricity generation and transmission losses). In addition, a large portion of electricity is produced onsite (34% of process and nonprocess electricity demand is produced onsite, compared to 15% for all of manufacturing). The sector ranks first in process applied energy due to the high process heating fuel demand.

Table 2.4-1. Snapshot of the petroleum refining sector: Energy use and rank within U.S. manufacturing

Category	Rank	Energy (TBtu)
Total primary energy	3	3,546
Offsite losses	8	315
Onsite energy	1	3,231
Onsite losses	3	1,052
Steam generation and distribution	3	350
Electricity generation	3	40
Process energy	3	641
Nonprocess energy	11	20
Feedstock energy	1	3,399
Total primary and feedstock energy*	1	6,944
GHG combustion emissions		**MMT CO_2e**
Total	2	244
Onsite	1	210

*When total primary energy and feedstock energy are summed, the energy value of byproduct fuels derived from feedstock energy sources is excluded to avoid double counting of feedstock energy

[12] The end use of steam is not provided in the EIA MECS source data. For the petroleum refining sector, it is assumed that 66% of steam production is used in for process heating, 16% for machine driven processes, 2% for process cooling and refrigeration, 10% for other process uses, 4% for facility HVAC, and 2% other nonprocess applications. More detail is available in Appendix D.

Although it is outside the scope of the footprint analysis, it is worth noting that a significant amount of energy is consumed as non-fuel feedstock in the production of refined petroleum products. As reported in the MECS data, and shown in Fig. 2.4-1, the total feedstock energy consumed in this sector is 3,399 TBtu, which equates to about half of all reported feedstock energy consumed in all of U.S. manufacturing. When feedstock and fuel energy are combined, total primary fuel and feedstock energy used in petroleum refining is about 6.9 quads. This is more than any other manufacturing sector and approximately 25% of all fuel and feedstock energy use in manufacturing.

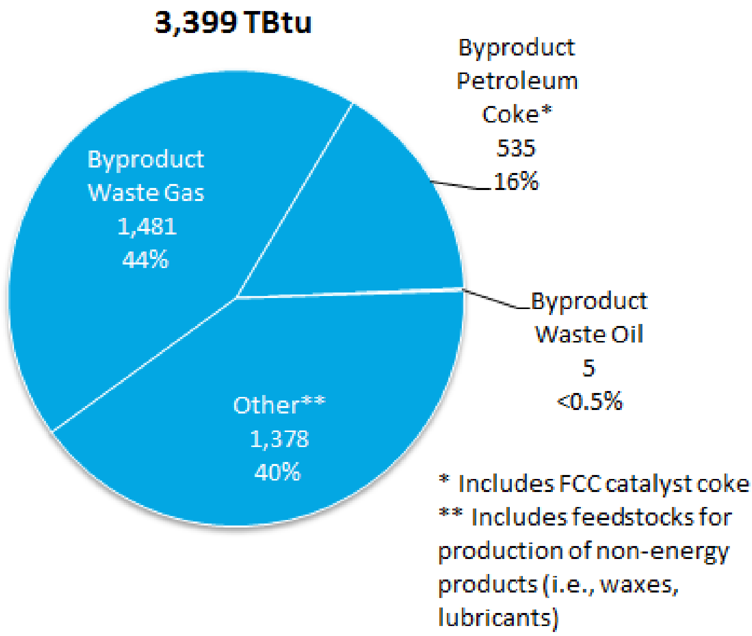

Fig. 2.4-1. Feedstock energy use in the petroleum refining sector

There is limited clarity regarding the composition of "other fuels" used as feedstock energy in this sector. In the MECS source data, feedstock energy for petroleum refining falls into the category of "Other Fuel" and is defined as follows:[13]

'Other' includes energy that respondents indicated was used as feedstock/raw material inputs.

For the petroleum refining sector only (NAICS 324110), the feedstocks and raw material inputs for the production of nonenergy products (i.e., asphalt, waxes, lubricants, and solvents) and feedstock consumption at adjoining petrochemical plants are included in the 'Other' column, regardless of type of energy. Those inputs and feedstocks that were converted to other energy products (e.g., crude oil converted to residual and distillate fuel oils) are excluded.

The total feedstock energy consumed in petroleum refining is significantly greater than 3.4 quads when accounting for feedstock energy that is converted to energy products, such as the conversion of crude oil into gasoline. Many of these energy products are subsequently used as purchased fuels.

The focus of the energy use and loss analysis that follows excludes all feedstock energy use.

[13] This definition can be found on the following website, http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html, in Table 2.2, under the definition of Other Fuel.

2.4.2.1. Energy and carbon footprint

The *Manufacturing Energy and Carbon Footprint* for the petroleum refining sector is shown in Fig. 2.4-2 and Fig. 2.4-3. The footprints serve as the basis for characterizing the offsite and onsite flow of energy, as well as carbon emissions, from generation through end use in the sector.

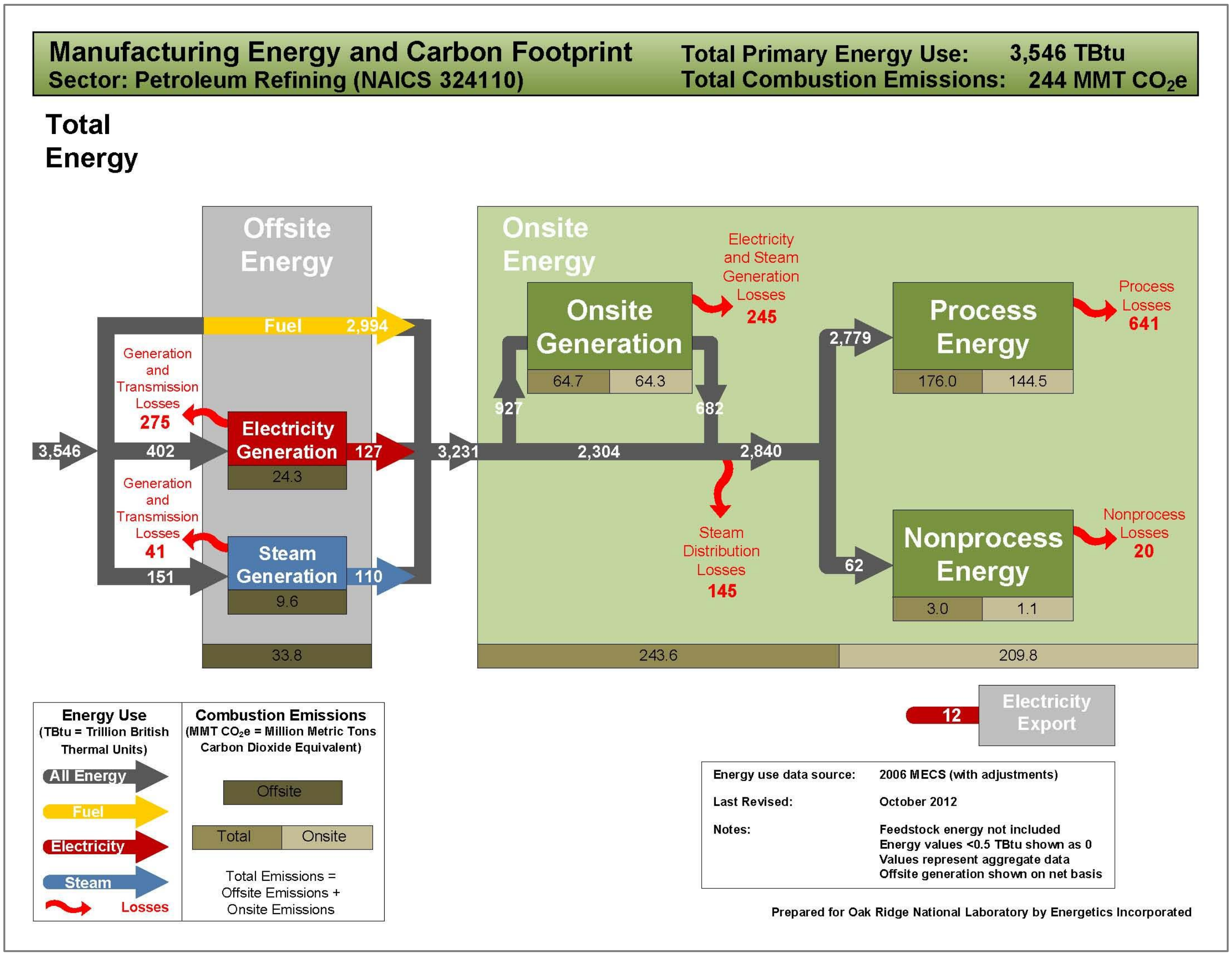

Fig. 2.4-2. Total energy and carbon footprint for the petroleum refining sector

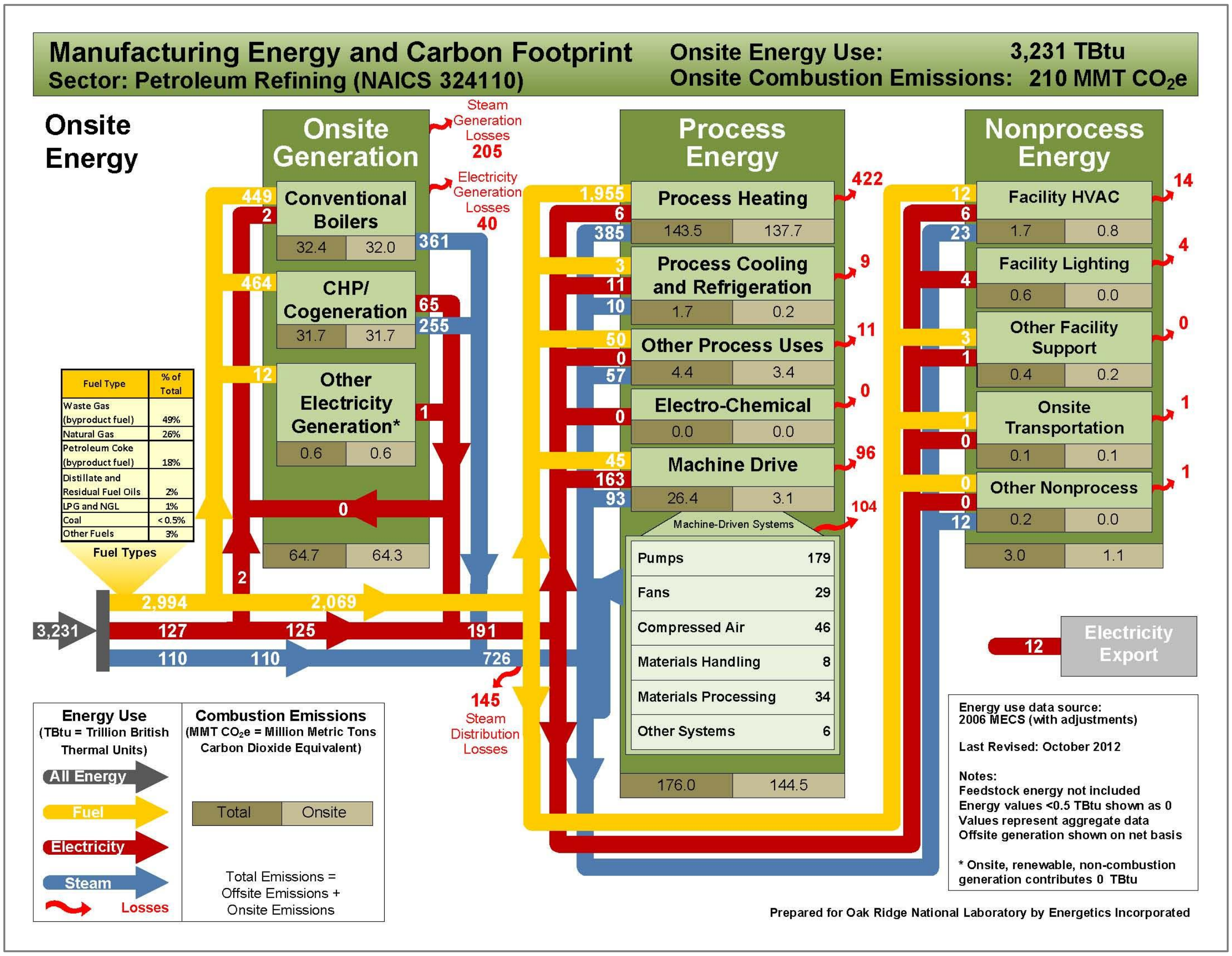

Fig. 2.4-3. Onsite energy and carbon footprint for the petroleum refining sector

2.4.2.2. Primary energy

Primary energy includes fuels, electricity, and steam from both onsite and offsite sources, including generation and distribution losses. In essence, primary energy provides the full picture of total fuel energy use from all sources from generation to end use. In 2006, the petroleum refining sector used 3,546 TBtu of primary energy.

There are three main primary offsite energy generation areas: steam generation, electricity generation, and direct fuel use. In Fig. 2.4-4, it can be seen that the majority of primary energy use, 58%, is attributed to direct fuel use. Steam generation is the next largest contributor at 28%, with the remaining 14% comprising electricity generation. Consistent with the footprints, blue represents steam energy, red represents electric energy, and yellow represents fuel energy.

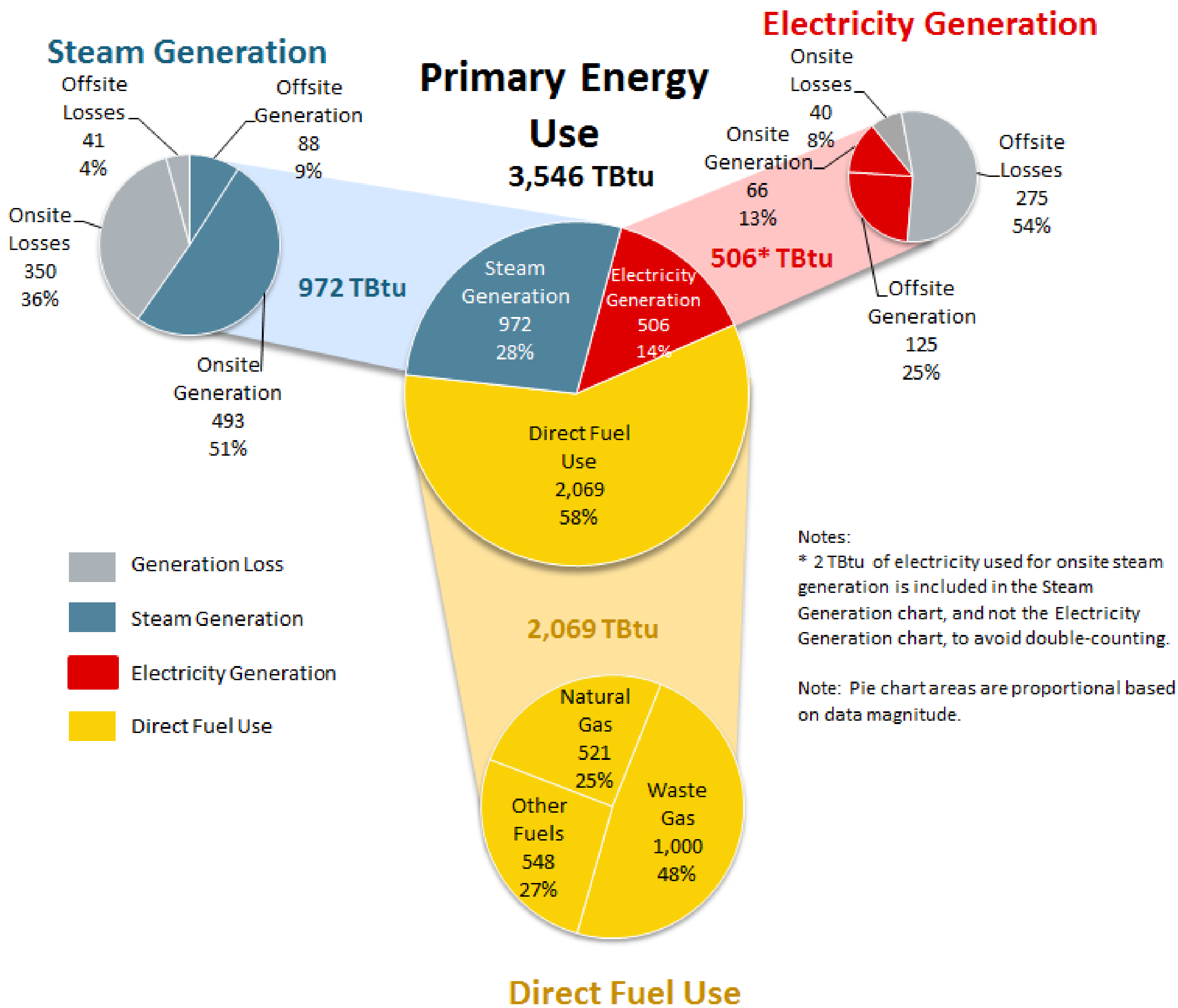

Fig. 2.4-4. Primary energy by energy type in the petroleum refining sector

Approximately 20% of the primary energy used in petroleum refining manufacturing is lost during utility production (encompassing generation, transmission, and distribution), with 9% associated with electricity production and the remaining 11% with steam production. The percentage of utility production loss is lower for petroleum refining than other sectors given that the majority of primary energy is direct fuel use where there is no significant generation losses accounted for. In contrast, over half of the primary energy for electricity generation is lost to generation and transmission losses; this is attributed mostly to offsite losses where the efficiency of electricity supplied from the grid is estimated to be only 31.6%.

The primary energy use values in Fig. 2.4-4 are not directly apparent on the energy and carbon footprints as the footprint is presented in terms of offsite and onsite energy end use, not primary energy end use. The primary energy values in Fig. 2.4-4 are obtained from the footprint model and can be derived from the footprints by summing offsite and onsite generation and loss values. The primary direct fuel use, 2,069 TBtu, is the amount of fuel directed to process and nonprocess end uses after the subtraction of fuel for onsite generation. Almost half of this primary fuel use is waste gas, or what is referred to in refining as refinery fuel gas, consisting primarily of hydrogen, methane, and other light-end gases.

2.4.2.3. Onsite energy

About 3.2 quads, or 91% of primary energy, were consumed onsite by the petroleum refining sector in 2006. This onsite energy enters the plant boundary in the form of three offsite energy types: fuel, steam, and electricity. As shown in Fig. 2.4-5 this energy is primarily fuel, with only a small amount of offsite energy supply in the form of steam and electricity (3% and 4% respectively). Byproduct fuels such as refinery gas and petroleum coke are derived from feedstock in the production process. These byproduct fuels are relied upon heavily for fuel energy in this sector and contribute over 60% of the fuel energy supply. Natural gas makes up most of the remainder of offsite energy supply.

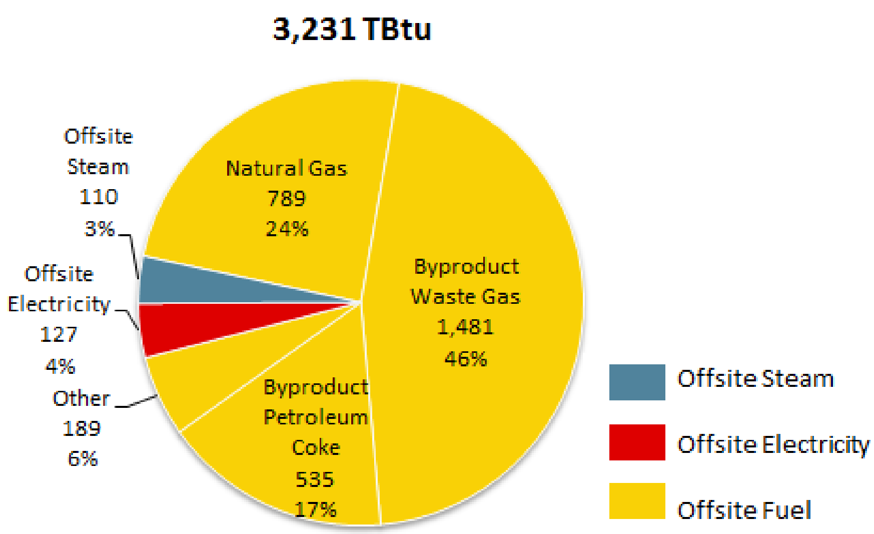

Fig. 2.4-5. Offsite energy supply in the petroleum refining sector

2.4.2.4. Fuel energy

The petroleum refining sector consumed 2,994 TBtu of fuel energy in 2006. Direct fuel use accounts for 58% of primary energy use, and indirect fuel use accounts for an additional 26% of primary energy use. Close to 93% of offsite energy supply in the petroleum refining sector is in the form of purchased or byproduct fuels, which does not include feedstock energy. Approximately 65% of petroleum refining fuel use (excluding feedstock energy) is consumed in process heating end uses, primarily for process unit feed preheaters and distillation reboilers. Furthermore, an additional 30% of fuel use is consumed by boilers and CHP units to generate steam that is used predominantly for process heating uses.

A large portion of the process heating fuel demand is supplied by byproduct fuels derived from feedstock in the production process. As shown in Fig. 2.4-5, 63% of offsite energy supply to petroleum refineries is in the form of byproduct fuels. Waste gas, also called refinery fuel gas, is the most commonly used byproduct fuel and constitutes almost half (46%) of offsite energy supply. Refinery fuel gas is an essential byproduct fuel in petroleum refineries; the hydrogen content in the fuel improves the enthalpy of combustion which allows for greater transfer of heat into the process, as compared to purchased natural gas. A second byproduct fuel category, petroleum coke, contributes 18% of onsite fuel use, or 17% of offsite energy supply. Review of the definition provided by EIA for "petroleum coke"[14] confirms that the byproduct petroleum coke is primarily consumed in the fluid catalytic cracking (FCC) process unit, where coke deposited on the catalyst is combusted, or burned off, during catalyst regeneration. The combustion of this coke is internal to the process operation and provides the process heat energy necessary to raise the FCC

[14] EIA definition of "coke (petroleum)," http://www.eia.gov/glossary/index.cfm?id=C: A residue high in carbon content and low in hydrogen that is the final product of thermal decomposition in the condensation process in cracking. This product is reported as marketable coke or catalyst coke. The conversion is 5 barrels (of 42 U.S. gallons each) per short ton. Coke from petroleum has a heating value of 6.024 million Btu per barrel.

reactor to reaction temperature. Likely there are other, less significant, forms of byproduct fuel used in petroleum refining that are not categorized in the MECS byproduct fuel data.

Natural gas is the second largest fuel type used in petroleum refining. Natural gas is purchased from outside suppliers to supplement the available refinery fuel gas supply. Natural gas contributes 26% of offsite energy supply, or 24% of all imported energy. Most process heaters, boilers, and turbines are fueled by a combination of fuel gas and natural gas, often times the two are blended and supplied from a central fuel gas drum. Other fuel sources not detailed in Fig. 2.4-5 include fuel oils, LPG, coal, and feedstocks for the production on nonenergy products (e.g., asphalt, wax) and petrochemical products.

2.4.2.5. Electrical energy

In 2006, the petroleum refining sector used 191 TBtu of electricity for direct[15] process uses. By comparison, the chemicals sector used 676 TBtu for direct process uses. Electricity accounts for 14% of primary energy use (see Fig. 2.4-4), but only 6% of direct end use energy (see Fig. 2.4-9). This difference can be explained by the relative inefficiency of offsite electricity generation, transmission, and distribution (T&D) as compared to direct fuel use.

Figure 2.4-6 shows that 65% of sector electricity used for process and nonprocess end uses is produced offsite, while the remaining 34% of electricity is produced onsite. This proportion of onsite generation is higher than most other sectors; for example, in the iron and steel sector, only 7% of electricity is from onsite generation. Onsite electricity is primarily generated in CHP systems. In the petroleum refining sector, CHP units are 69% efficient, over twice as efficient as the efficiency of electricity supplied from the grid (31.6%). The majority of electricity use (85%) is to run machine-driven equipment. Process cooling and facility energy use (including HVAC and lighting) each consume 6% of generated electricity.

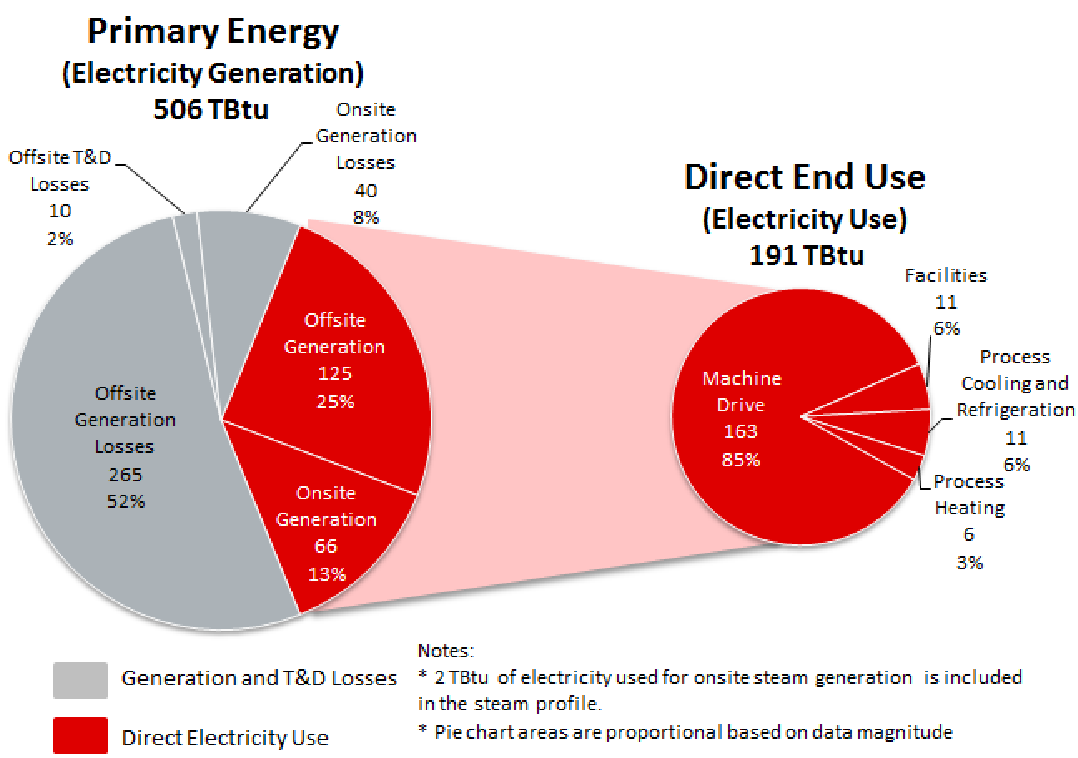

Fig. 2.4-6. Electricity generation and *direct* end use in the petroleum refining sector

[15] Offsite electricity generation (125 TBtu) shown in this chart is lower than the value of offsite energy entering the plant boundary shown in the energy and carbon footprint for this sector (127 TBtu). This difference is due to the small portion of offsite electricity (2 TBtu) that is used by conventional boilers to generate steam.

2.4.2.6. Steam energy

The petroleum refining sector uses 581 TBtu of steam energy, half as much as the forest products and chemicals manufacturing sectors and approximately five times as much as the iron and steel manufacturing sector. Fig. 2.4-7 shows the losses that occur in steam production (left pie chart) and the end uses of steam (right pie chart). Approximately 85% of steam is produced onsite in either CHP units or conventional steam boilers, while 15% of steam demand from offsite sources including transfers in from other facilities. Conventional boilers contribute a relatively large portion of onsite steam, nearly 60%, as compared to steam from CHP generation.

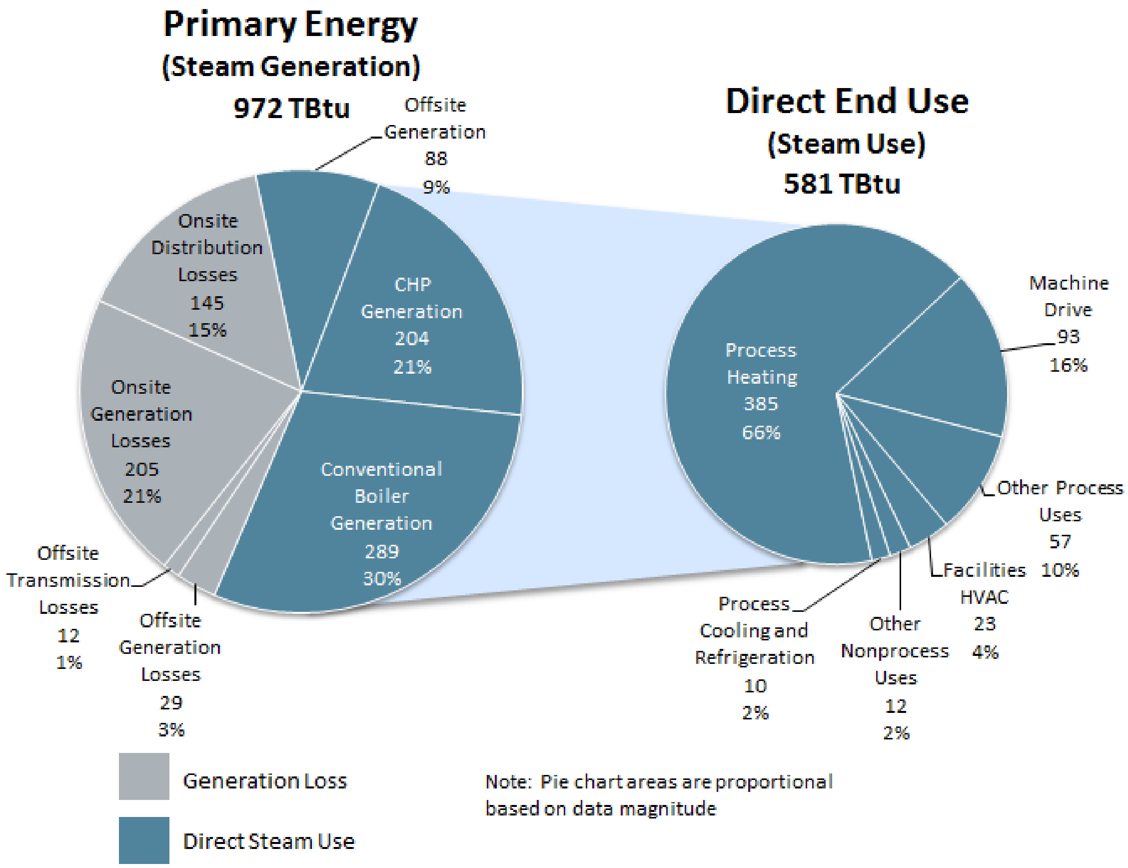

Fig. 2.4-7. Steam generation and *direct* end use in the petroleum refining sector

2.4.2.7. Combined heat and power energy

The petroleum refining sector meets a large amount of steam and electricity demand through onsite generation. CHP units contribute a large portion of this onsite generation, 41% of onsite steam and 98% of onsite electricity. One of the key reasons CHP generation is readily applied in petroleum refining is the availability of large quantities of byproduct waste gas. As with process heating and conventional boiler fuel use, the byproduct gas is blended with natural gas to fuel CHP systems. As shown in Fig. 2.4-8, 65% of CHP fuel use is in the form of byproduct gas.

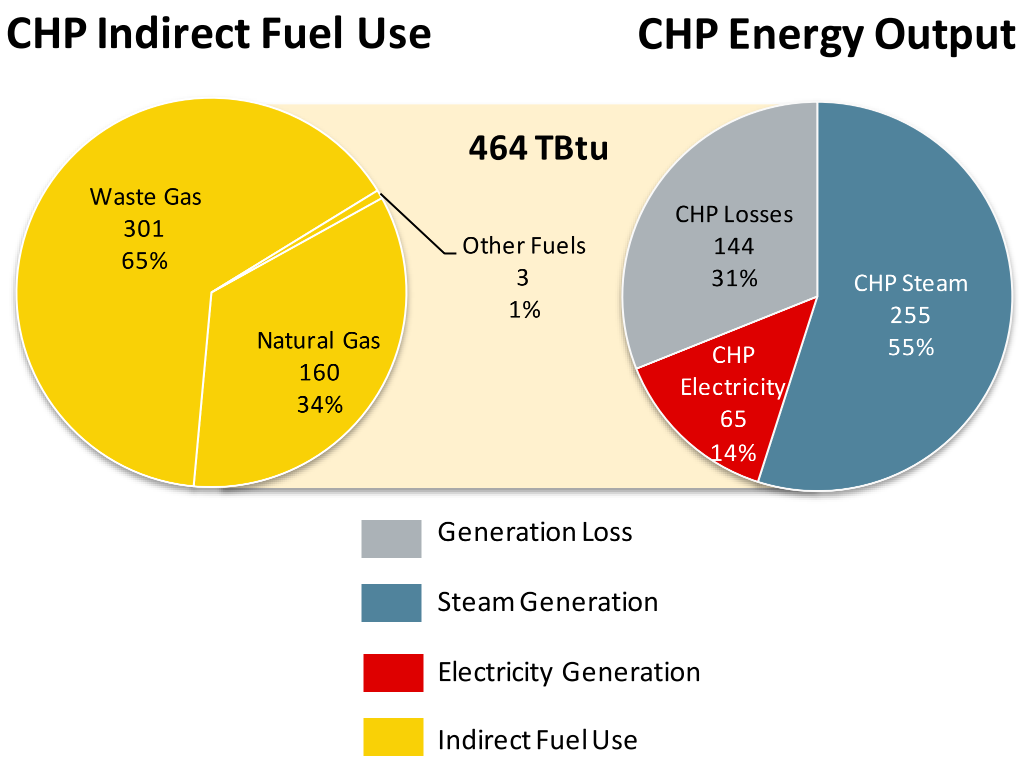

Fig. 2.4-8. CHP fuel consumption and energy output in the petroleum refining sector

2.4.2.8. Direct end use energy

Fig. 2.4-9 shows the breakdown of primary energy by type at its direct end use. Direct fuel use is the most significant share of primary energy, at 58%, followed by steam at 16% and electricity at 6%. Generation losses account for the remaining 20% of primary energy use.

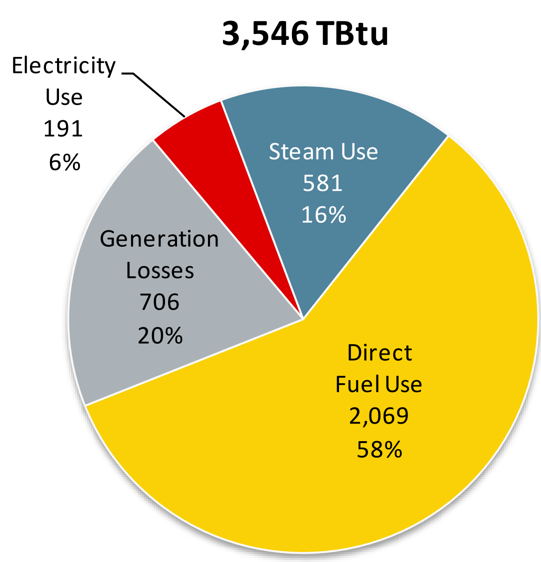

Fig. 2.4-9. Primary energy by type at *direct* end use in the petroleum refining sector

A more detailed view of primary energy use is detailed in Fig. 2.4-10, where it can be seen that the great majority of primary energy is used for process end uses (78%, 2,779 TBtu), largely process heating. Energy lost during the generation of electricity and steam is also significant (20%, 706 TBtu).Nonprocess end uses account for only 2% of primary direct end use energy.

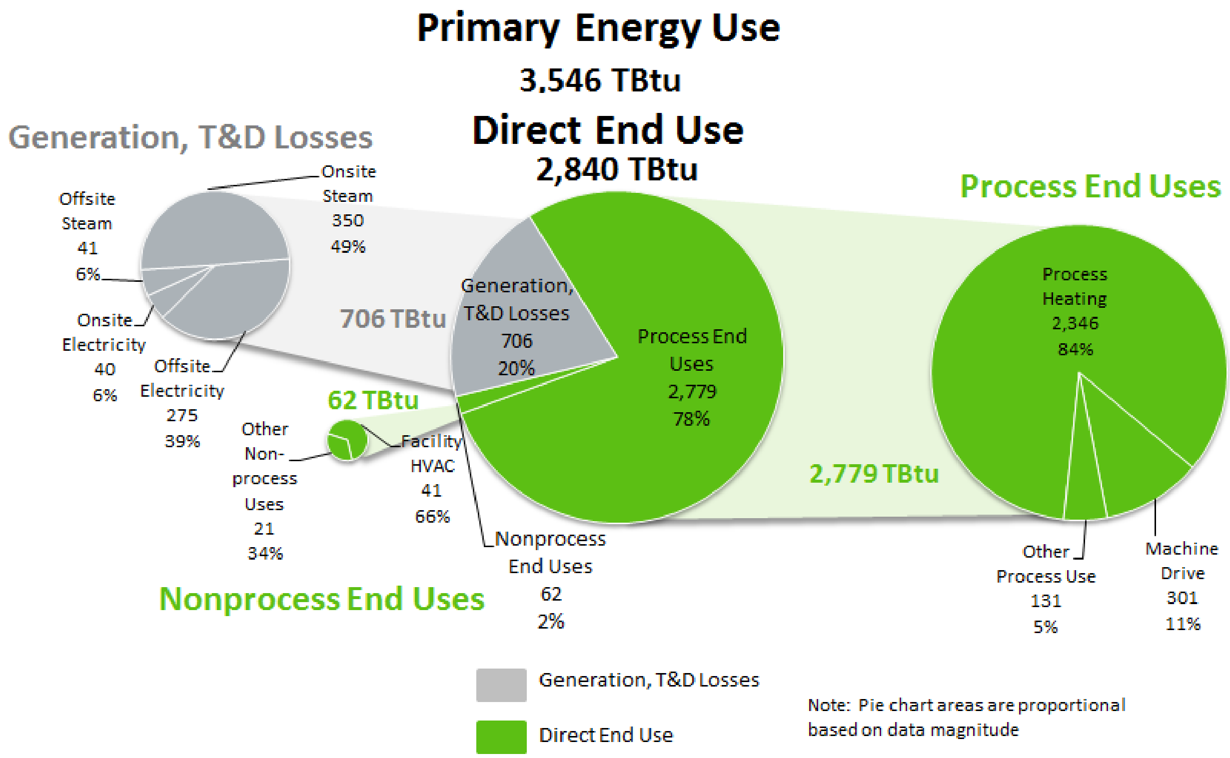

Fig. 2.4-10. Primary energy by *direct* end use in the petroleum refining sector

Compared to other U.S. manufacturing sectors, petroleum refining sector consumes the most energy for process heating systems, and is the third-greatest consumer of energy for machine-driven systems. Process heating systems consume 2,346 TBtu out of the 2,779 TBtu total (84%) delivered to process end uses. These process heating systems include steam and fired systems such as furnaces and reboilers. Machine-driven systems are the next largest use of process energy in the sector at 301 TBtu (11%). As shown in Fig. 2.4-7, the majority of steam is used for process heating systems, while electricity is the main source of energy for machine-driven systems.

Onsite steam losses are 350 TBtu, which equals nearly 50% of sector generation losses. Offsite electricity losses are the next-largest category of generation losses, equal to 275 TBtu (39%). Facility HVAC is the largest user of nonprocess energy. Other nonprocess energy uses include facility lighting, onsite transportation, and other facility support.

2.4.2.9. Applied end use energy

In addition to the energy generation losses identified above, direct end use losses have also been calculated in the energy footprint model. When both generation and end use losses are accounted for, the energy that remains is the *applied energy*. Applied energy can be illustrated by re-examining Fig. 2.4-4, which shows primary energy by energy type for the petroleum refining sector. Each of the energy types (i.e., fuel, electricity, or steam) shown in this figure have associated onsite and offsite generation losses (shown with onsite and offsite losses combined in light gray) that are incurred during energy generation and transmission and distribution). While the majority of electricity generation losses take place offsite (as shown in Fig. 2.4-6), the majority of steam generation losses are onsite (as shown in Fig. 2.4-7), and direct fuel use is assumed to have no associated generation losses. After taking into account these generation losses, a further portion of the remaining energy is lost at direct end uses, due to process and nonprocess system and equipment inefficiencies, shown in dark gray. The remaining energy is applied to end uses, shown in light green as "Applied Energy" in Fig. 2.4-11.

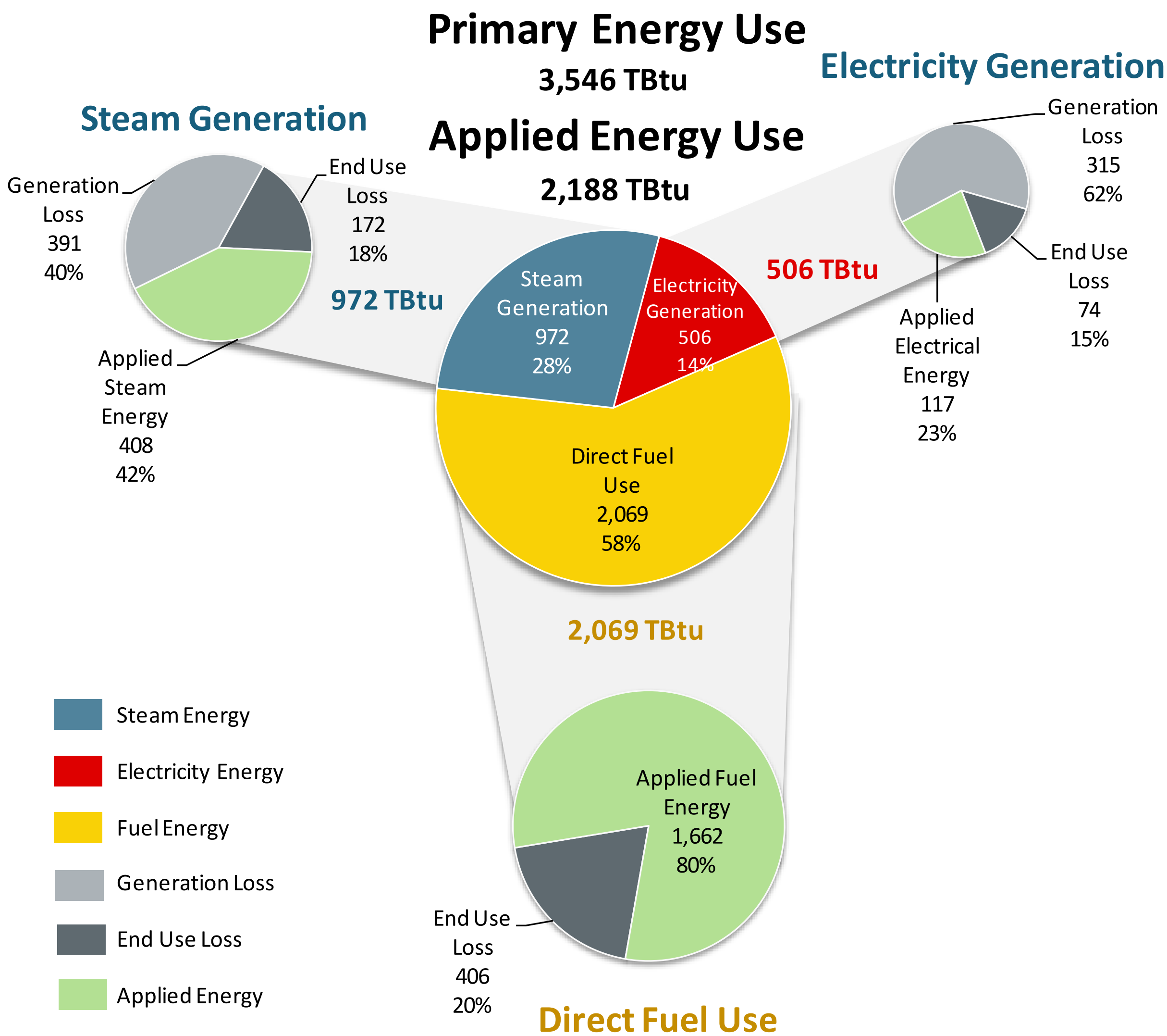

Fig. 2.4-11. Primary energy and applied energy by energy type in the petroleum refining sector

Fig. 2.4-12 shows the breakdown of primary energy by energy loss and applied energy. In this sector, 61% of primary energy input is applied to process and nonprocess end uses, significantly higher than the manufacturing average of 34% and more than any other individual sector. Applied end use energy is larger in this sector than other manufacturing sectors due to the high demand for fuel use and lower associated electricity generation losses.

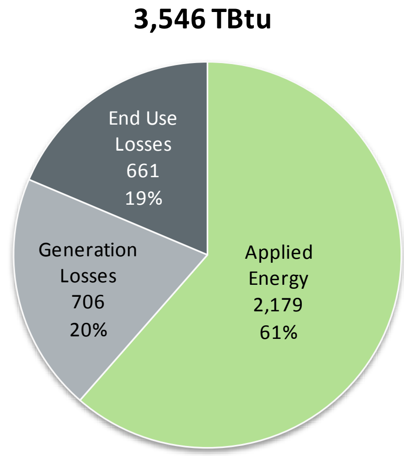

Fig. 2.4-12. Primary energy by loss and applied energy in the petroleum refining sector

Applied energy can also be calculated for specific end uses, as shown in Fig. 2.4-13. End use losses are labeled as process or nonprocess losses; in the case of machine drive end use, process losses are further defined as machine drive, or machine driven system losses. For process heating, 74% of primary energy is applied to the process (detail of the methodology to estimate process heating losses are shown in Appendix F). Process heating applied energy is relatively high compared to other end uses, because the majority of process heating energy is consumed in the form of steam and fuel. In machine-driven systems, only 16% of primary energy is applied to direct end uses, primarily because of the inefficiency in electricity generation.

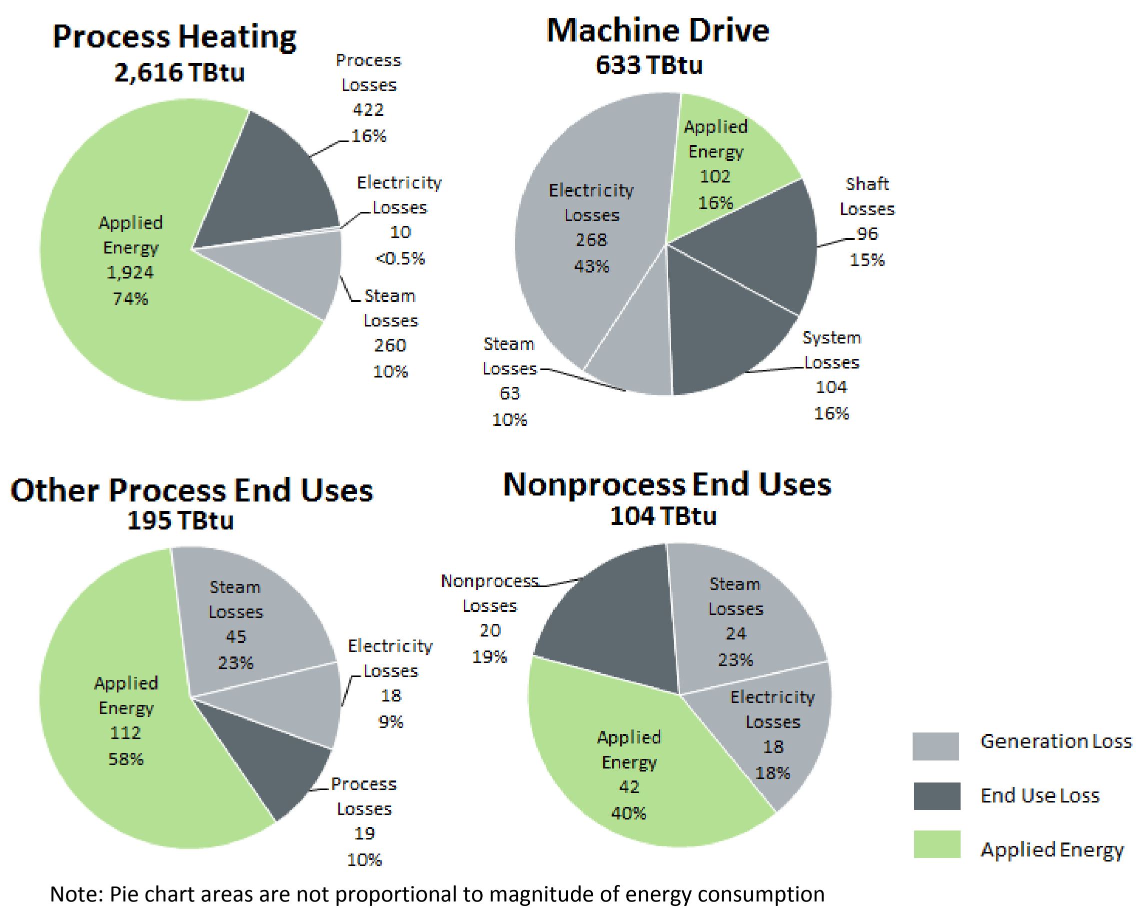

Fig. 2.4-13. Primary applied energy by *direct* end use in the petroleum refining sector

2.4.3. Greenhouse Gas Combustion Emissions Profile for the Petroleum Refining Sector

GHG combustion emissions in the petroleum refining sector totaled 244 MMT CO_2e in 2006, ranking second among manufacturing sectors (fewer emissions than only the chemicals sector). Greenhouse gas emissions by offsite energy supply type are shown in Fig. 2.4-14. This sector releases more onsite emissions than any other manufacturing sector (210 MMT CO_2e), which is reflected in the abundance of yellow colored fuel use in Fig. 2.4-14. Emissions released during offsite electricity and steam generation contribute a relatively small portion of overall sector emissions, with offsite electricity contributing 10% of emissions and offsite steam generation contributing 4% of emissions. The onsite consumption of fuels, including natural gas, byproduct waste gases, byproduct petroleum coke, coal, and other fuels accounts for 86% of total emissions. These fuels are used for both direct (e.g., process or nonprocess) and indirect (e.g., fuel for CHP units or boilers) end uses. Table D.5 shows fuel GHG combustion emission factors associated with fuel combustion, as well as electricity and steam generation

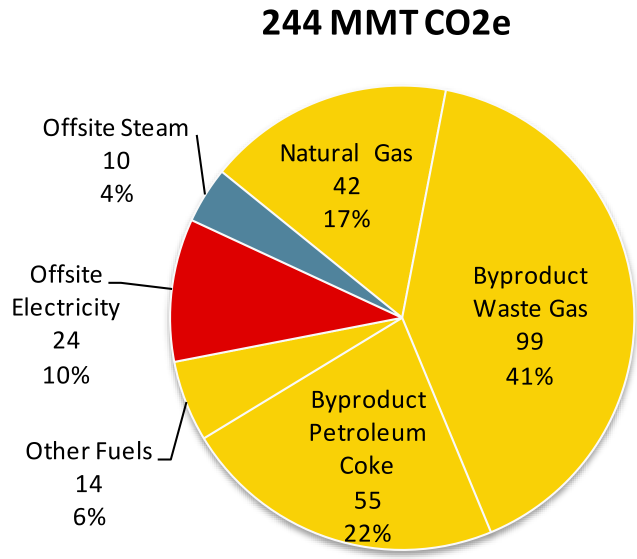

Fig. 2.4-14. Total GHG combustion emissions in the petroleum refining sector (shown by energy supply type)

An alternative view of emissions is shown in Fig. 2.4-15, which also shows total emissions by energy type, but this figure assigns emissions to onsite electricity and steam production (as opposed to assigning emissions strictly to offsite supplied fuels). All emissions associated with electricity production are shown in red, including emissions released during offsite electricity generation and emissions released during onsite generation of electricity. All emissions associated with steam production are shown in blue, including emissions released during offsite steam generation and emissions released to generate steam onsite in boilers and CHP systems. Lastly, all emissions associated with fuel combustion at process and nonprocess end uses are shown in yellow. Electricity generation (offsite and onsite) contributes only 13% of all emissions. Steam generation (offsite or onsite) contributes a further 28% of emissions, while the majority of emissions, 59% (145 MMT), are released during the combustion of fuel for process or nonprocess end uses.

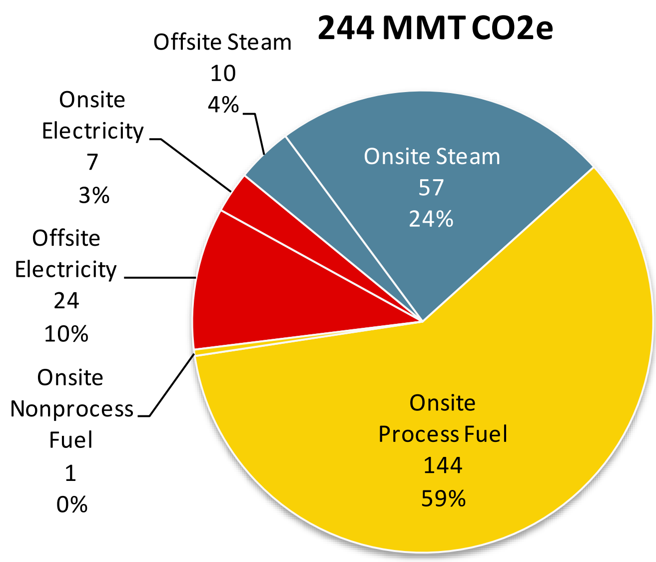

Fig. 2.4-15. Total GHG combustion emissions in the petroleum refining sector (shown by energy end use type)

Emissions can also be associated by the direct end uses of energy, as is shown in Fig. 2.4-16. In this figure, the emissions released from offsite both offsite and onsite electricity and steam generation are distributed to direct end uses, along with emissions resulting from fuel consumed at the direct end uses. This pie chart allows for a direct comparison of the emissions resulting from individual direct process and nonprocess end uses. Process heating accounts for 75% of emissions, while machine driven end uses account for 17% of total emissions.

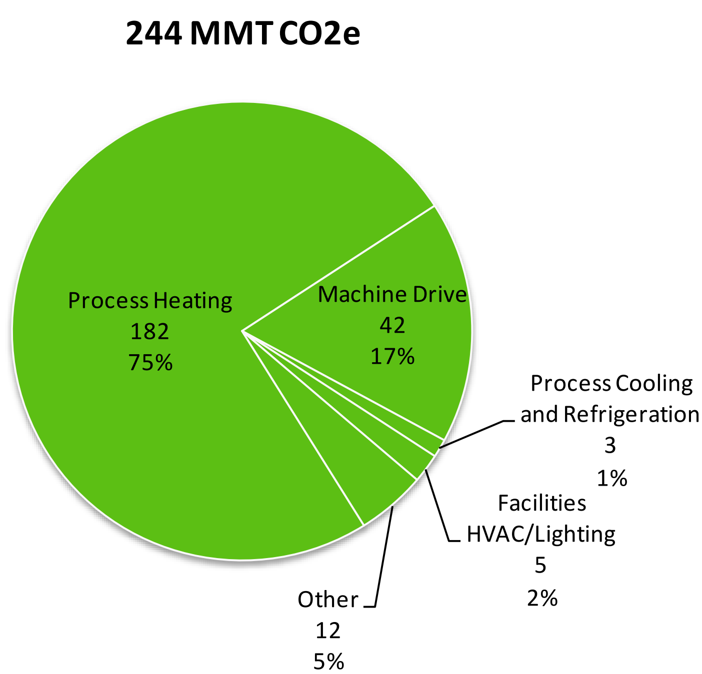

Fig. 2.4-16. Total GHG combustion emissions in the petroleum refining sector (shown by direct energy end use)

2.4.4. Energy and Emissions Profile Summary Table

The energy and emissions profiles for the petroleum refining sector are summarized in Table 2.4-2 below. Offsite and onsite contributions to energy supply, use and loss are shown separately in this table, along with GHG combustion emissions. "Applied energy" is calculated for each direct energy use area by subtracting associated offsite and onsite energy losses. For GHG combustion emissions, emissions from the point of use, whether offsite or onsite, are depicted in the first emissions column; offsite emissions are combined with onsite emissions in the total emissions columns. The values in this table correspond to the energy and carbon footprints, which show two carbon values associated with each onsite end use: at point of use and the total based on onsite use.

Table 2.4-2. Energy use, loss, and GHG combustion emissions in the petroleum refining sector

Petroleum refining			Energy (TBtu)			GHG combustion emissions (MMT CO_2e)		
			Energy use	Energy loss	Applied energy	At point of use	Total based on onsite use*	Total based on direct end use**
Offsite		Fuel supply (2,994 TBtu)	-	-	N/A	-	Distributed to onsite	Distributed to onsite direct
		Electricity generation/transmission	402	275		24.3		
		Steam generation/transmission	151	41		9.6		
		Total offsite (including fuel supply)	**3,546**	**315**		**33.8**		
Onsite	Indirect	Conventional boilers	451	90	N/A	32.0	32.4	Distributed to onsite direct
		CHP/cogeneration	464	144		31.7	31.7	
		Other electricity generation	12	11		0.6	0.6	
		Steam distribution	-	145		0.0	0.0	
		Total onsite generation	**927**	**391**		**64.3**	**64.7**	
	Direct	Process heating	2,346	422	1,924	137.7	143.5	182.0
		Process cooling and refrigeration	24	8	16	0.2	1.7	3.1
		Machine drive	301	200	102	3.1	26.4	41.7
		Electro-chemical	0	0	0	0.0	0.0	0.0
		Other process uses	107	11	96	3.4	4.3	10.0
		Nonprocess energy	62	20	42	1.1	3.0	6.9
		Total process and nonprocess	**2,840**	**661**	**2,179**	**145.5**	**178.9**	**243.6**

* These values are referenced as "Total" emissions in the footprints, Total emissions = onsite emissions + offsite emissions (i.e., emissions associated with offsite generation are distributed to indirect and direct onsite end uses)
** These values represent direct end use carbon emissions only (i.e., emissions associated with offsite and onsite generation are distributed to direct (and final) end use)