ENERGY AND GREENHOUSE GAS COMBUSTION EMISSIONS PROFILES

2.1 U.S. MANUFACTURING (NAICS 31–33)

2.1.1. Overview of U.S. Manufacturing

U.S. manufacturing is highly diverse, using thousands of processes to manufacture countless different products. Manufacturing is a complex composite of many sectors—some convert raw materials into intermediate and final products, while other sectors form, forge, fabricate, and assemble final products.

There are integral links between the "heavy industry" sectors (e.g., chemicals, steel, pulp and paper) that convert raw materials and the sectors that create finished products. For example, steel mills produce intermediate steel products that are sent to forgers and fabricators and supplied to the transportation industry where they become automotive components. Similarly, changes in energy use patterns in the heavy industries can ripple through the sectors they supply goods to, affecting not just product costs, but the life cycle energy embodied in the final product.

This section looks at the energy and emissions profiles for all of U.S. manufacturing, which includes NAICS codes 31 through 33. More in-depth profiles of the top five energy consuming sectors are also detailed later in this chapter. In this section the 15 manufacturing sectors are ranked in the areas of: primary energy use, onsite energy use, energy type, energy end use, applied energy, and GHG emissions.

2.1.2. Energy Use Profile for U.S. Manufacturing and Sector Rankings

A snapshot of total energy use for U.S. manufacturing is shown in Table 2.1-1, along with total and onsite combustions emissions. 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.

Table 2.1-1. Snapshot of energy use and loss within U.S. manufacturing

Category	Energy (TBtu)
Total primary energy	21,972
Offsite losses	6,479
Onsite energy	15,494
Onsite losses	7,974
Steam generation and distribution	2,292
Electricity generation	227
Process energy	4,807
Nonprocess energy	647
Feedstock energy	6,962
Total primary and feedstock energy[a]	27,568
GHG combustion emissions	**MMT CO_2e**
Total	1,261
Onsite	643

[a] 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

Although outside of the scope of the footprint analysis, it is worth noting that a substantial amount of energy is consumed as non-fuel feedstock in manufacturing. As shown in Fig. 2.1-1, U.S. manufacturing consumed nearly 7 quads of feedstock energy in 2006. Liquefied petroleum gas (LPG) and natural gas liquid (NGL) fuels comprise about one-third of feedstock energy consumption, while other feedstocks make up the majority of feedstock energy consumption. The petroleum refining sector (NAICS 324110, feedstock energy consumption equal to 3.4 quads)[3] and the chemicals sector (NAICS 325, feedstock energy consumption equal to 2.8 quads) are the top feedstock energy consuming sectors. In this report, feedstock energy composition is discussed separately at the beginning of each sector's respective chapter.

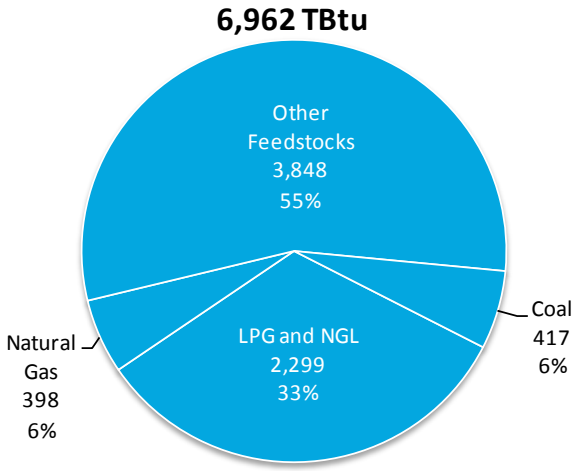
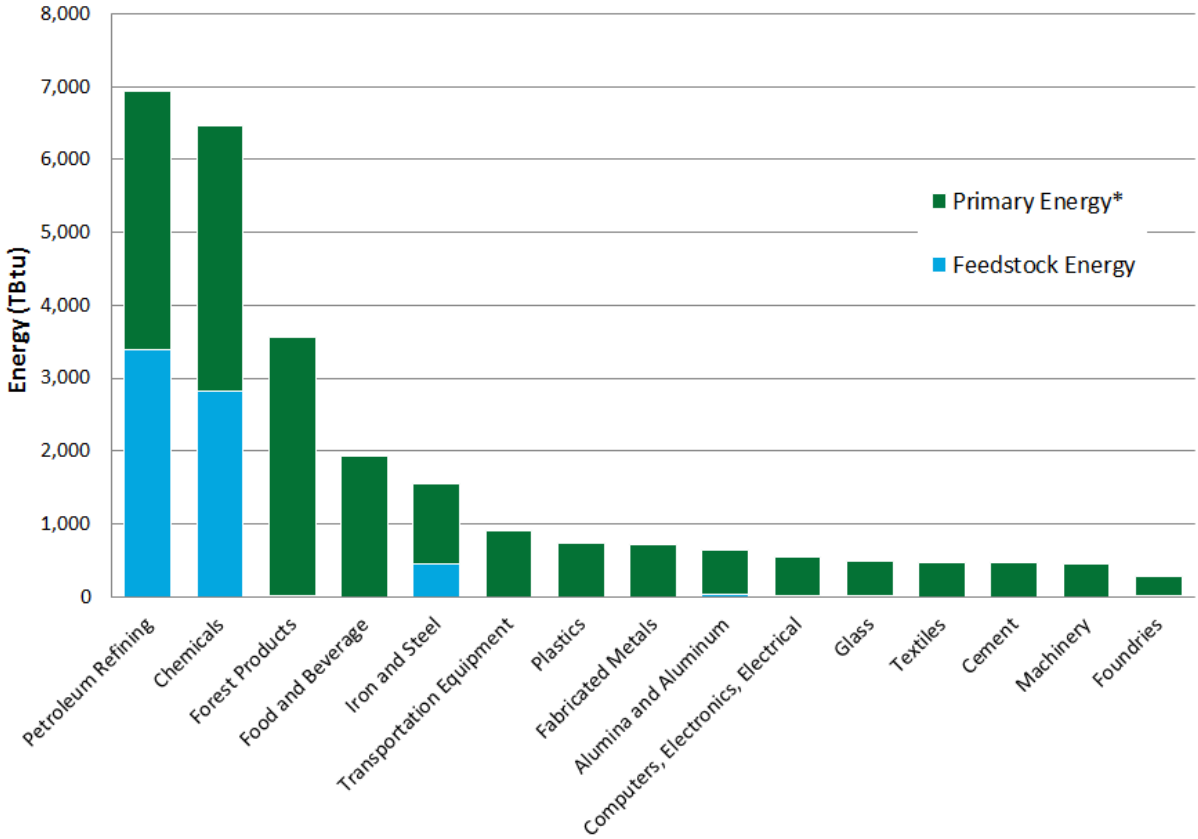


Fig. 2.1-1. Feedstock energy use in U.S. manufacturing

Total energy consumption, by sector, including primary and feedstock energy is shown in Fig. 2.1-2. The primary and feedstock energy profile is the most complete picture of energy consumption in U.S. manufacturing. The combined energy consumption for the fifteen manufacturing sectors considered in Fig. 2.1-2 is 26.1 quads. The total primary and feedstock energy for all U.S. manufacturing (NAICS 31-33) sectors is 27.6 quads.

[3] The reported petroleum feedstock value does not include energy feedstocks that are converted to energy products (e.g., crude oil converted to fuel oil). The actual petroleum feedstock value would be much greater than the value reported by EIA.



*Primary energy use has been adjusted to exclude the energy value of byproduct fuels derived from feedstock energy sources (e.g., waste gas from LPG feedstock in the chemicals sector); this exclusion avoids double counting feedstock energy. In the case of the petroleum refining sector, the feedstock energy includes energy feedstock used for the production of non-energy products (such as asphalt), it does not include energy feedstock that is converted to other energy products. Therefore, for petroleum refining only, there is no adjustment to the primary energy use for byproducts derived from feedstock energy sources.

Fig. 2.1-2. U.S. manufacturing total primary and feedstock energy

For the purposes of this report, primary energy use and onsite energy use in the manufacturing sector are of the most interest in the evaluation of energy use, loss and energy saving opportunities. Thus, the focus of the analysis that follows excludes feedstock energy use.

2.1.2.1. Energy and carbon footprint

The U.S. manufacturing sector footprint is shown in Fig. 2.1-3 and Fig. 2.1-4. The footprint serves 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. Data is presented in two levels of detail. The first page (Fig. 2.1-3) provides a primary energy perspective including offsite and onsite energy flow, while the second page (Fig. 2.1-4) shows detail for the onsite generation and end use of energy. Chapter 1 presents a more detailed walkthrough of the footprints.

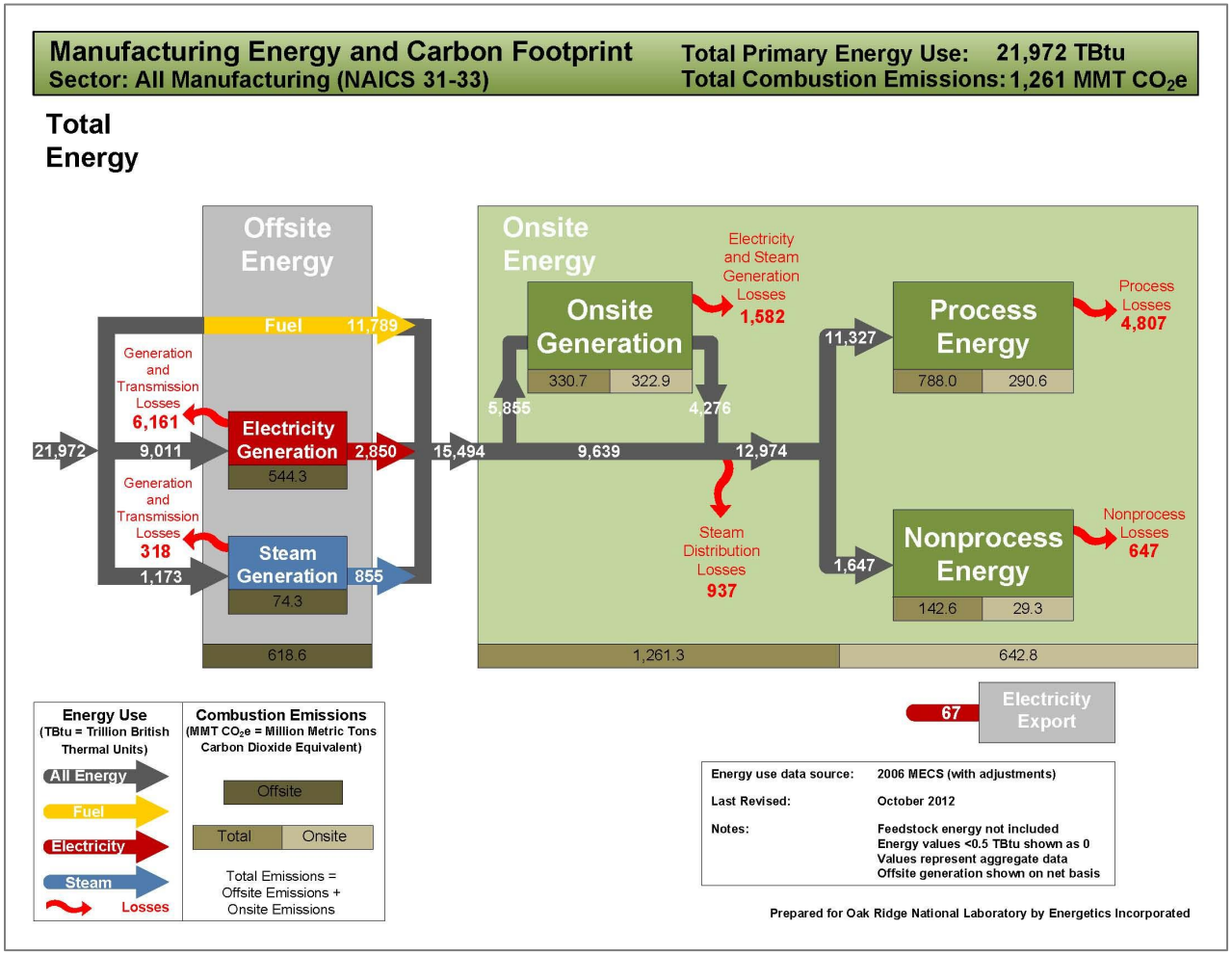


Fig. 2.1-3. Total energy and carbon footprint for U.S. manufacturing

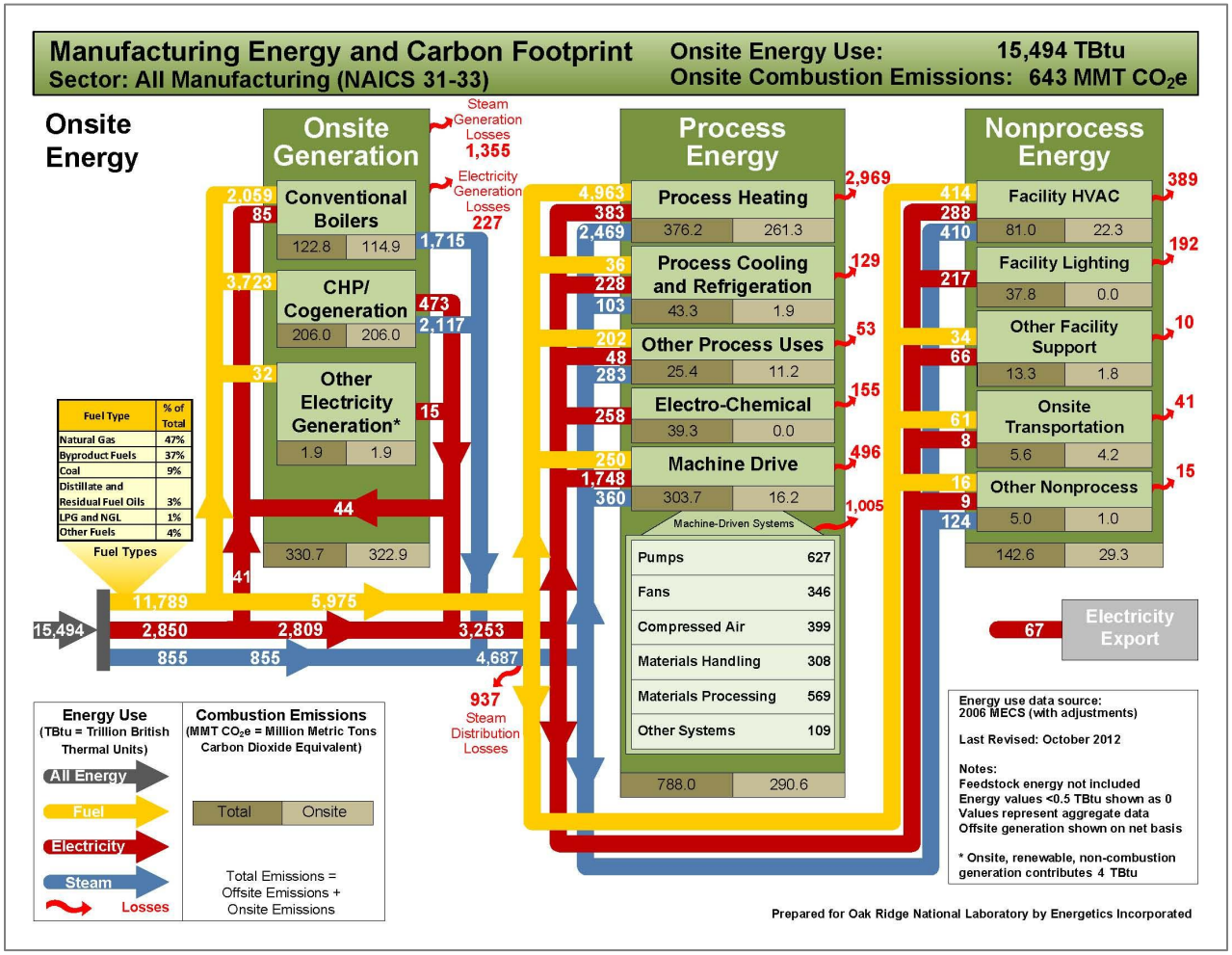


Fig. 2.1-4. Onsite energy and carbon footprint for U.S. manufacturing

2.1.2.2. Primary energy

Primary energy use includes fuels, electricity, and steam consumed, *both external and internal to the plant boundary*. This does not include feedstock energy. Primary energy use is depicted in Fig. 2.1-5, where energy use and loss is shown separately by energy type (steam, electricity, and fuel). Consistent with the footprints, the color blue represents steam energy, red represents electric energy, and yellow represents fuel energy. This same energy coloring scheme is used throughout this report.

The U.S. manufacturing sector consumed 21,972 TBtu of primary energy in 2006. Energy used to generate electricity is the largest category of primary energy use—comprising 9,638 TBtu (44%) of primary energy. Over 93% of primary electricity energy use is attributable to offsite generation and associated losses. The electricity generated offsite that is not lost during generation or transmission accounts for 2,809 TBtu,[4] while onsite electricity generation accounts for 441 TBtu. Overall, manufacturing primary electricity generation is 34% efficient, with 64% of primary energy lost in offsite generation and 2% lost in onsite generation.

[4] The offsite electricity generation value (2,809 TBtu) is slightly lower than the total onsite electricity value (2,850 TBtu) entering the plant boundary in the energy footprint. This difference is due to the 41 TBtu of offsite electricity that is used in onsite generation.

Energy used to generate steam is the next largest category of primary energy use, consuming 6,360 TBtu (29%) of total primary energy. Unlike electricity, the majority, 84%, of primary steam energy use is from onsite generation and associated losses, and only 16% is attributed to offsite steam. Onsite generation of steam is estimated to be 3,066 TBtu[5]; this estimate is dependent on the boiler efficiency assumption explained in Appendix D.

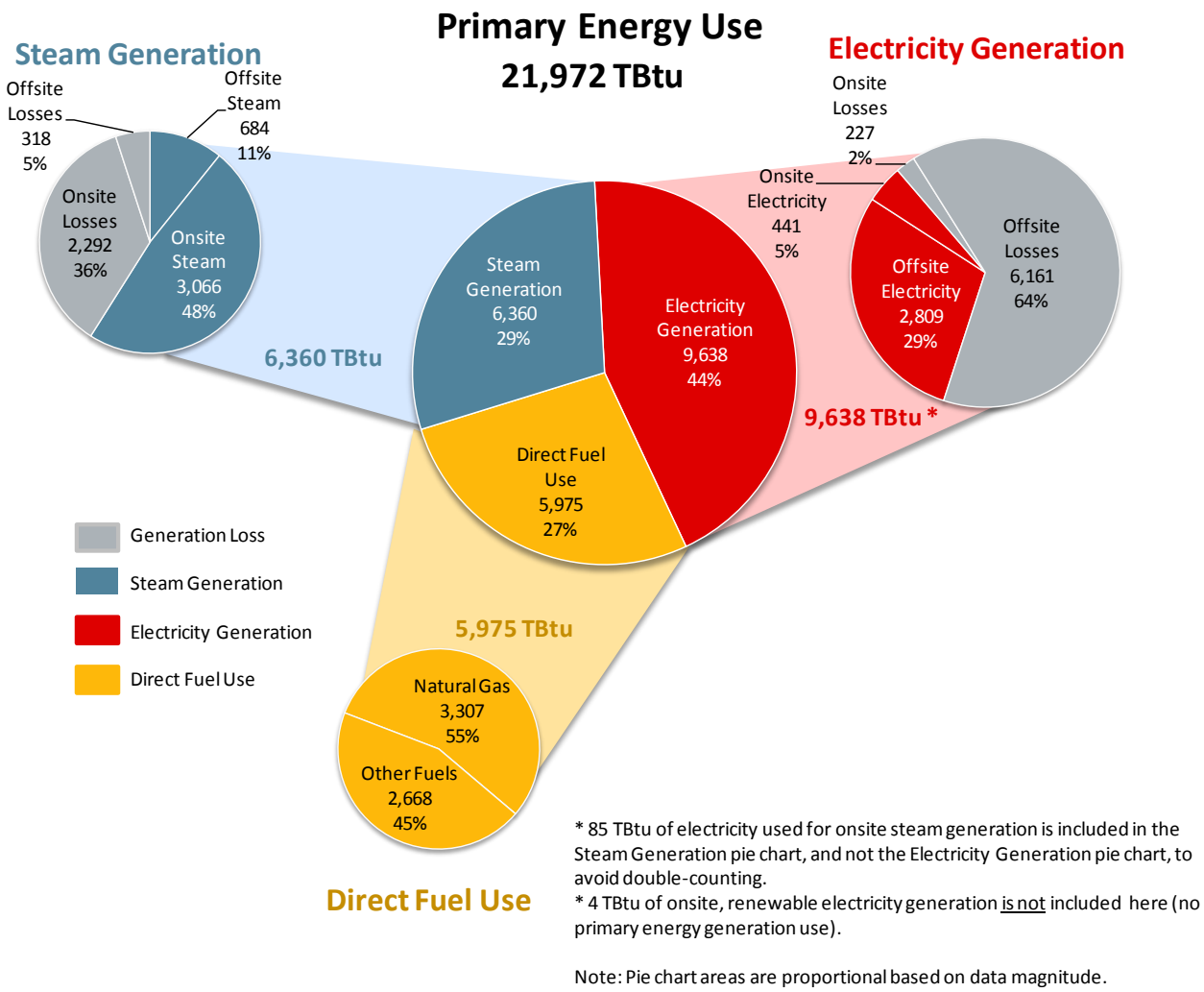


Fig. 2.1-5. Primary energy use by energy type for U.S. manufacturing

Fuel that is directly used by process or nonprocess uses (i.e., not including fuel used to generate electricity or steam onsite) totals 5,975 TBtu, or 27% of total primary energy consumption. Natural gas accounts for over half of direct fuel consumption at 3,307 TBtu, while other fuels—coal, fuel oils, byproduct fuels, and other petroleum-based fuels—account for the remaining 2,668 TBtu of direct fuel energy.

Primary energy use breakdown figures, similar to Fig. 2.1-5, are provided for five of the most energy-intensive manufacturing sectors later in this chapter. It is important to note that in these figures the small amount of electrical energy used for steam generation is included only in the steam generation pie chart to avoid double-counting when both steam and electricity are shown together. The primary energy use for electricity generation increases to 9,727 TBtu when the electrical energy for onsite steam generation is included. Another note to point out is that the onsite electricity generation value includes 4 TBtu of

[5] The onsite steam generation value (1,694 TBtu from CHP and 1,372 TBtu from boilers) includes 20% distribution losses. These values do not match the steam output values shown in the footprint (2,117 from CHP and 1,715 from boilers), as the steam distribution losses are shown further downstream in the footprint.

renewable, non-combustion electricity generation. The forest products sector contributes the majority (3 TBtu) of this renewable electricity generation.

In Table 2.1-2**,** manufacturing sectors are ranked by primary energy use. When offsite and onsite energy generation is considered, the chemicals sector is clearly the greatest user of primary energy, followed closely by the forest products and petroleum refining sectors. Other large energy consuming sectors, with primary energy use over one quad per year, include the food and beverage sector and the iron and steel sector. Transportation equipment manufacturing consumes close to one quad of primary energy, at 904 TBtu, but has a substantially lower share of onsite energy use than the five aforementioned sectors that each consume more than one quad of energy.

Table 2.1-2. U.S. manufacturing sector rank by primary energy use

Sector	Primary energy use (TBtu)	Rank	Percent of primary energy consumed onsite	Percent of primary energy consumed offsite
Chemicals	4,513	1	71%	29%
Forest products	3,559	2	79%	21%
Petroleum refining	3,546	3	91%	9%
Food and beverage	1,934	4	67%	33%
Iron and steel	1,481	5	70%	30%
Transportation equipment	904	6	53%	47%
Plastics	729	7	46%	54%
Fabricated metals	708	8	56%	44%
Alumina and aluminum	603	9	45%	55%
Computers, electronics, and electrical equipment	527	10	43%	57%
Textiles	472	11	56%	44%
Cement	471	12	81%	19%
Glass	466	13	71%	29%
Machinery	444	14	46%	54%
Foundries	281	15	56%	44%
All manufacturing	21,972	N/A	71%	29%

The top three sectors share several characteristics that contribute to their high energy consumption. First, the core processes used to convert raw materials in these industries operate at high temperatures and pressures. Second, each consumes vast amounts of steam energy. Third, the energy efficiency of some core processes is below optimal, for a variety of reasons. In the chemicals and petroleum refining industries, for example, distillation columns play a key role in producing chemicals and fuels. The thermal efficiency of these energy-intensive columns is typically low (approximately 10%[6]). To some degree, these same characteristics—high temperatures and pressures, steam intensity, and "thermal inefficiency"—elevate energy use in all energy-intensive industries.

2.1.2.3. Onsite energy

Onsite energy differs from primary energy in that only the fuel energy consumed *within the plant boundary*, or *onsite*, is reported. This includes both purchases and transfers-in of energy, and energy generated onsite; it does not include losses incurred at offsite utilities. Differentiating between inside or

[6] ITP (Industrial Technologies Program), EERE (Energy Efficiency and Renewable Energy). 2009. *Heat Integrated Distillation through Use of Microchannel Technology*. U.S. Department of Energy. http://www1.eere.energy.gov/industry/chemicals/pdfs/heat_distillation.pdf

outside the plant boundary is important when evaluating technology options for improving energy efficiency. Within the plant boundary, a plant has control over its energy consumption. Outside the plant boundary, where energy is generated by or provided by utilities, a plant has little or no control over technology efficiency. However, a plant can reduce energy losses associated with external energy supply by adopting technologies that allow it to generate more energy onsite, more efficiently than the utility (e.g., cogeneration). The end uses of onsite energy are further described herein as either indirect or direct end use. The distinction stems from the inclusion or exclusion of energy used for onsite generation.

Onsite energy use for all of U.S. manufacturing totaled 15,494 TBtu in 2006. This onsite energy use enters the plant boundary in the form of three offsite energy types: fuel, steam, and electricity. A large portion of this fuel is consumed onsite in order to generate additional steam and electricity. Fig. 2.1-6 shows a breakdown of total fuel, electricity, and steam supply from offsite sources; the yellow fuel use portion of the pie chart is further divided by fuel type. Offsite electricity accounts for 18% of this total, while natural gas accounts for 5,512 TBtu, or 36% of this energy. Offsite steam comprises only 855 TBtu, or 5% of total offsite energy supply; the majority of direct steam use is produced onsite. Byproducts fuels (mostly derived from non-fuel feedstock) including byproduct waste gases (still gas, blast furnace gas, or coke oven gas), waste oils, petroleum coke, wood chips/bark, agricultural waste, and pulping/black liquor contribute almost a third (4,385 TBtu) of total offsite energy supply. The remaining 876 TBtu of offsite energy supply consists of other fuels including coke and breeze and other miscellaneous fuels.

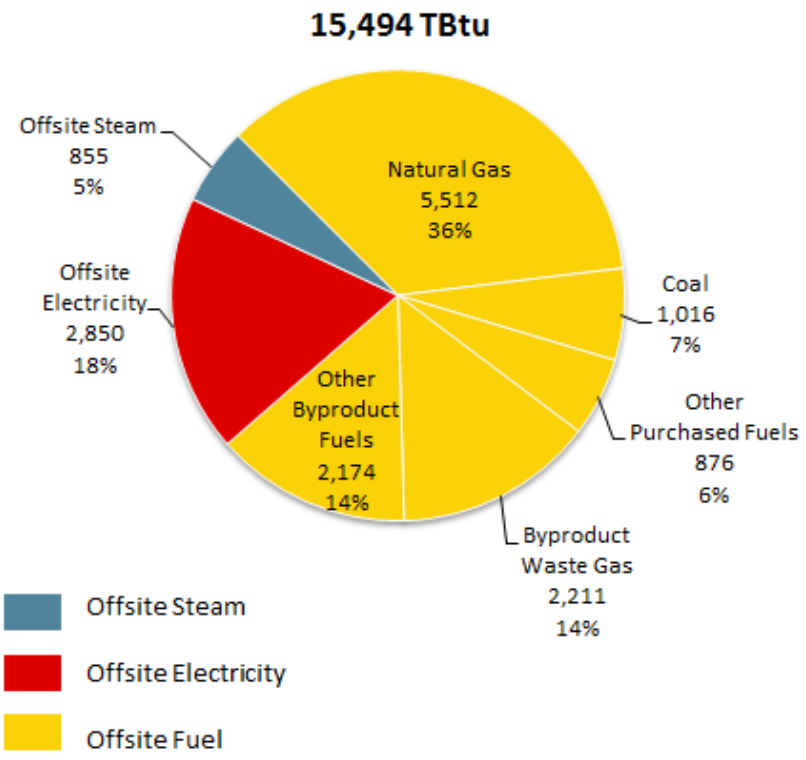


Fig. 2.1-6. Offsite energy supply for U.S. manufacturing

U.S. manufacturers create a diversity of products with many different production processes and technologies, so energy use patterns vary across sectors. A breakdown of offsite fuel, electricity, and steam supply by sector is shown in Fig. 2.1-7, and ranked by order of magnitude from left to right. The fuel category includes byproduct fuels generated at the plant site, as well as the onsite use of renewable sources such as solar, wind, or geothermal energy. Coinciding with the sectors of focus in this report, the top consumers of purchased fuel, electricity, and steam by sector are petroleum refining, chemicals, forest products, food and beverage, and iron and steel.

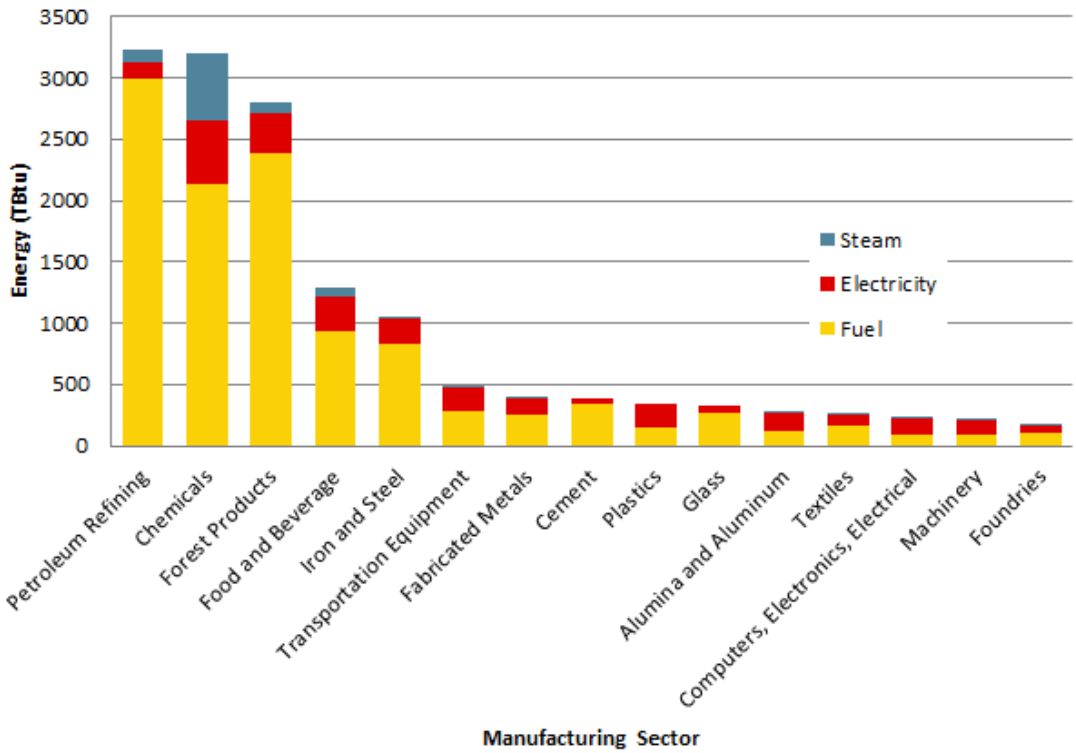


Fig. 2.1-7. Offsite fuel, electricity, and steam supply by manufacturing sector

Similar to Fig. 2.1-7, Table 2.1-3 and Table 2.1-4 compare and rank the offsite supply of fuel, electricity, and steam among the different manufacturing sectors. This comparison provides a means of identifying those sectors that are highly dependent on purchased fuel and electricity. It also helps to identify those sectors that could benefit from the use (or increased use) of efficient onsite cogeneration technology.

Table 2.1-3. Offsite energy supply by U.S. manufacturing sector

Sector	Total		Fuel		Electricity		Steam	
	TBtu	Rank	TBtu	Rank	TBtu	Rank	TBtu	Rank
Petroleum refining	3,231	1	2,994	1	127	10	110	2
Chemicals	3,195	2	2,138	3	517	1	540	1
Forest products	2,799	3	2,381	2	338	2	80	4
Food and beverage	1,295	4	928	4	281	3	86	3
Iron and steel	1,043	5	831	5	201	4	11	5
Transportation equipment	480	6	278	7	195	5	7	7
Fabricated metals	397	7	248	9	143	8	6	8
Cement	382	8	341	6	41	15	0	-
Plastics	336	9	154	11	182	6	0	-
Glass	330	10	267	8	63	13	0	-
Alumina and aluminum	273	11	118	12	152	7	3	9
Textiles	265	12	162	10	94	12	9	6
Computers, electronics, and electrical equipment	228	13	89	15	138	9	1	10
Machinery	204	14	92	14	111	11	1	11
Foundries	158	15	101	13	57	14	0	-
All manufacturing	15,494	N/A	11,789	N/A	2,850	N/A	855	N/A

Table 2.1-4. Offsite energy supply distribution

Sector	Percent fuel	Percent electricity	Percent steam
Petroleum refining	93%	4%	3%
Cement	89%	11%	0%
Forest products	85%	12%	3%
Glass	81%	19%	0%
Iron and steel	80%	19%	1%
Food and beverage	72%	22%	7%
Chemicals	67%	16%	17%
Fabricated metals	62%	36%	2%
Foundries	64%	36%	0%
Textiles	61%	35%	3%
Transportation equipment	58%	41%	1%
Plastics	46%	54%	0%
Machinery	45%	54%	0%
Alumina and aluminum	43%	56%	1%
Computers, electronics, and electrical equipment	39%	61%	0%
All manufacturing	76%	18%	6%

Understanding the relative reliance on purchased fuels, electricity, and steam for each sector is important when assessing the vulnerability of individual sectors to volatility for energy price or supply. A majority of manufacturing sectors do not purchase steam (notwithstanding the chemicals sector, which imports steam to supply 17% of its primary energy use). Rather, most sectors produce steam onsite, consuming fuel in the process. The tables identify five sectors that are most heavily reliant on electricity: computers, electronics and electrical equipment, alumina and aluminum, machinery, plastics, and transportation equipment. Electricity accounts for 41% or more of energy requirements in these sectors.

In terms of fuel, five sectors are most reliant on fuel use: petroleum refining, cement, forest products, glass, and iron and steel. Fuel use accounts for about 80% or more of energy use in these sectors. Natural gas is of particular interest, since it comprises the largest share of purchased fuel use. Other relatively heavy fuel users include food and beverage, chemicals, fabricated metals, foundries, and textiles.

Equally as important as onsite energy use is onsite energy loss. Onsite losses take various forms; many onsite losses are typical across all sectors, such as those incurred in steam systems, cogeneration units, energy distribution lines, motors, pumps, compressors, and other commonly used equipment. In other cases, onsite losses are highly specific to the manufacturing processes employed. This report provides a macro view of sector-wide energy use and loss, and for this reason average loss estimates are applied (e.g., 20% conventional boiler loss). Average system area loss estimates are provided in Table 1.2-2 and explained in Appendix D. Specific process loss detail (e.g., mechanical pulping efficiency, cement kiln efficiency) is not included in the energy footprint model.

2.1.2.4. Fuel energy

Table 2.1-5 presents the sector ranking for onsite fuel use, while Fig. 2.1-8 illustrates the breakdown of types of fuels used by each sector. As shown, the top five sectors collectively consumed over 9 quads of energy as fuel, with petroleum refining, forest products, and chemicals each reaching over 2 quads. Natural gas is the most commonly used fuel type for most industries, with coal serving as a large fuel source in cement. Byproduct fuels such as waste gases, black liquor, and petroleum coke are also commonly used manufacturing fuels; these are discussed in further detail in the corresponding sector profiles.

Table 2.1-5. U.S. manufacturing sectors ranked by fuel use (*indirect* and *direct end use*)

Sector	Fuel use (TBtu)	Rank	Percent of fuel for *direct* end use	Percent of fuel for *indirect* end use
Petroleum refining	2,994	1	69%	31%
Forest products	2,381	2	13%	87%
Chemicals	2,138	3	30%	70%
Food and beverage	928	4	34%	66%
Iron and steel	831	5	75%	25%
Cement	341	6	89%	11%
Transportation equipment	278	7	77%	23%
Glass	267	8	91%	9%
Fabricated metals	248	9	84%	16%
Textiles	162	10	40%	60%
Plastics	154	11	48%	52%
Alumina and aluminum	118	12	84%	16%
Foundries	101	13	97%	3%
Machinery	92	14	73%	27%
Computers, electronics, and electrical equipment	89	15	69%	31%
All manufacturing	11,789	N/A	51%	49%

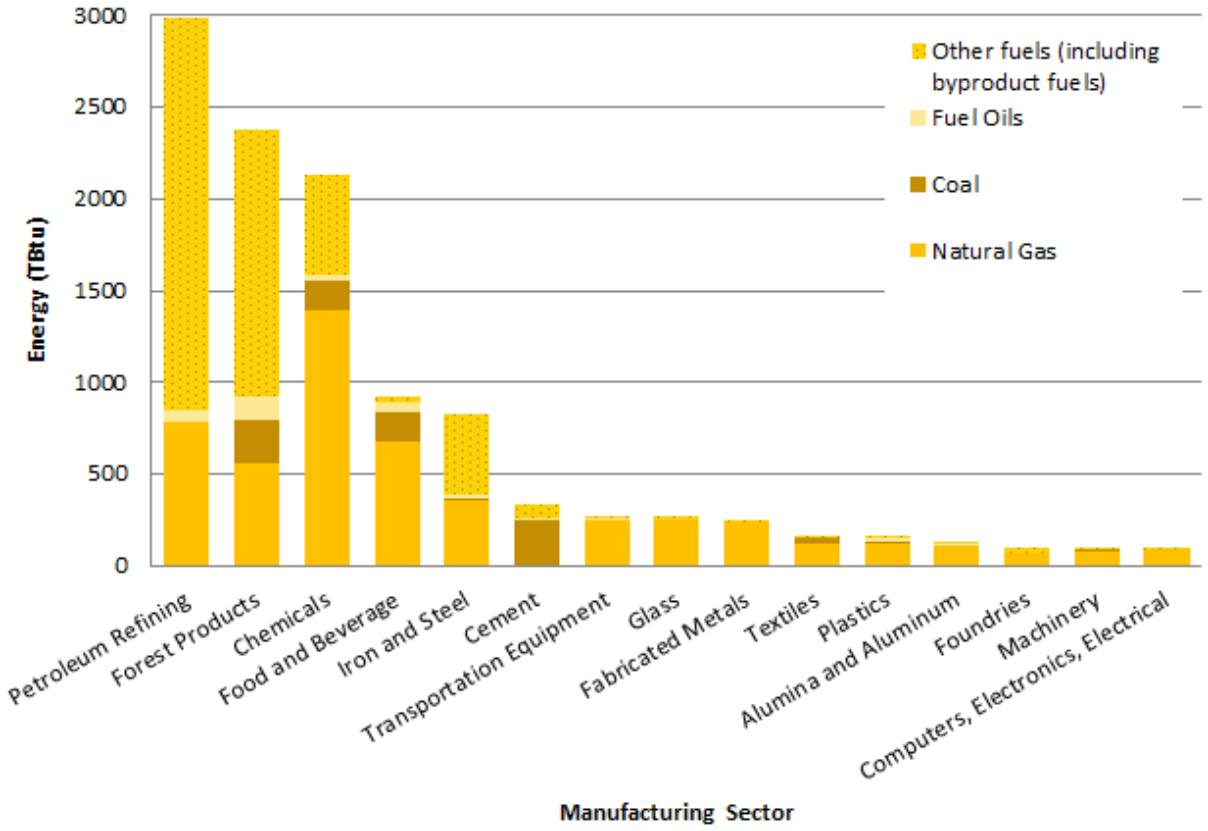


Fig. 2.1-8. Fuel use and type by manufacturing sector

The onsite fuel use totals in Table 2.1-5 and Fig. 2.1-8 include indirect and direct fuel use. The proportion of indirect versus direct fuel use varies widely by sector depending on specific process energy needs and onsite generation capabilities. In Table 2.1-5, the percent of fuel that is used by direct end uses is shown to vary from 13% in Forest Products (where a great deal of fuel is used in CHP systems) to 97% in Foundries (where there is minimal onsite generation).

2.1.2.5. Electrical energy

Onsite electricity demand has two components: offsite electricity and electricity generated onsite. As was shown in Fig. 2.1-5, electricity use accounts for the largest portion of primary energy use across U.S. manufacturing at about 44%. Some of the sectors that are most dependent on electricity (i.e., greater than 40% of primary energy use) rely almost entirely on purchased electricity. As was shown in Table 2.1-4, these industries include computers, electronics and electrical equipment, alumina and aluminum, machinery, plastics, and transportation equipment.

Figure 2.1-9 shows that a large portion of the primary energy consumed for electricity use is associated with generation, transmission and distribution (T&D) losses, taking place mostly offsite. The efficiency of offsite utility power generation, transmission, and distribution is assumed to be 31.6% on average [EIA 2010b], generating 6,161 TBtu of energy losses in order to produce 2,809 TBtu of electricity that is used in U.S. manufacturing.[7] The overall efficiency of electricity generation and transmission, including onsite generation, is 34%. The onsite energy pie chart shows how generated electricity is used by various direct end uses.

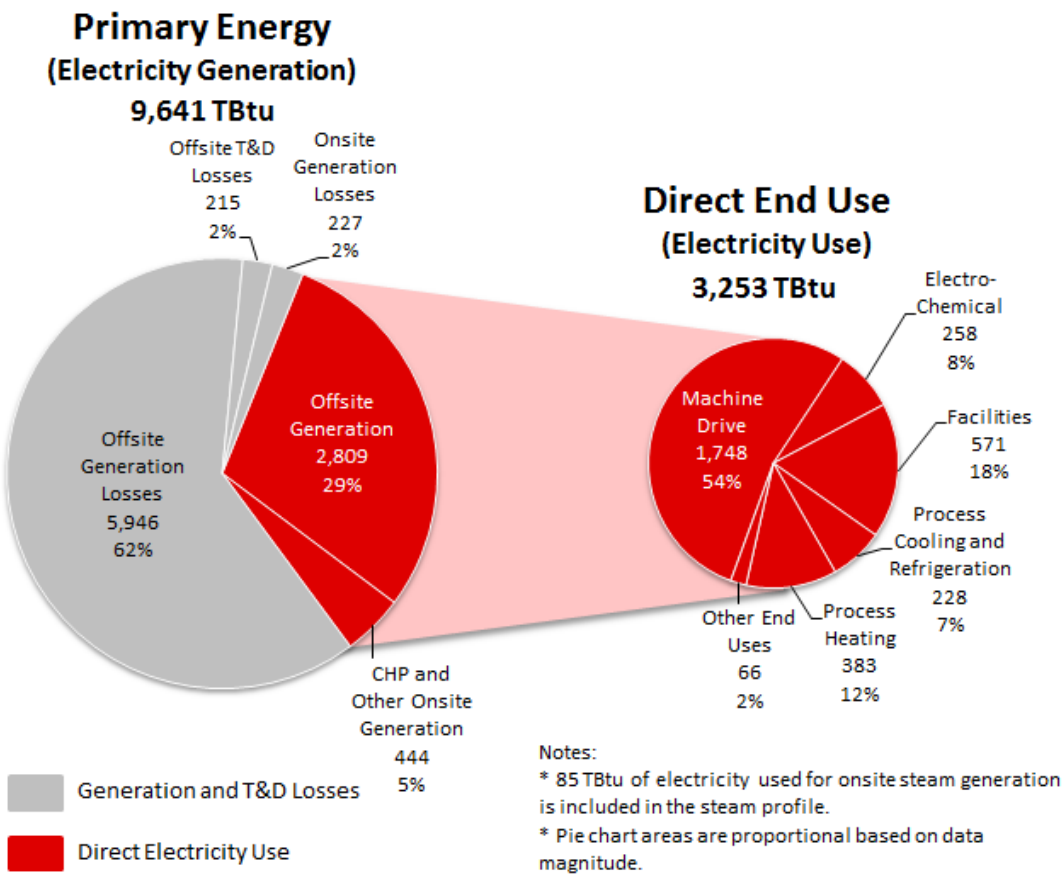


Fig. 2.1-9. Electricity generation and *direct* end use in U.S. manufacturing

[7] Offsite electricity generation (2,809 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 U.S. manufacturing (2,850 TBtu). This difference is due to the small portion of offsite electricity (41 TBtu) that is used by conventional boilers to generate steam.

Manufacturers do meet a moderate portion of their electricity demand through onsite generation. Approximately 444 TBtu of direct electricity use is produced from onsite generation. Most of the electricity produced onsite comes from cogeneration, or CHP units, with only a small percentage of onsite generation originating from other generation methods such as the use of generators running on combustible energy sources or electricity from renewable resources. Renewable energy generation itself contributes about 4 TBtu to onsite electricity generation in U.S. manufacturing.

Approximately 54% of the electricity use in manufacturing is consumed by machine-driven systems such as pumps, conveyors, compressors, fans, mixers, grinders, and other materials handling or processing equipment. Facility energy use, such as HVAC and lighting, is the next largest category, encompassing 17% of electricity use. Process heating follows at 12% of electricity use. The remaining 17% of electricity use is consumed by other process uses such as electrochemical processes and process cooling and refrigeration.

Onsite electricity end use is shown by sector in Table 2.1-6, along with the percent of this electricity end use that is generated onsite. The electricity values listed in Table 2.1-6 are direct electricity use, which includes onsite generated electricity. Total offsite electricity supply, shown in Table 2.1-3, is slightly lower for most sectors given that electricity generated onsite is not included.

Table 2.1-6. U.S. manufacturing sectors ranked by electricity use *(direct end use)*

Sector	Electricity use (TBtu)	Rank	Percent generated onsite
Chemicals	676	1	28%
Forest products	484	2	37%
Food and beverage	292	3	6%
Iron and steel	214	4	7%
Transportation equipment	195	5	1%
Petroleum refining	191	6	35%
Plastics	181	7	0%
Alumina and aluminum	153	8	1%
Fabricated metals	143	9	1%
Computers, electronics, and electrical equipment	137	10	0%
Machinery	111	11	1%
Textiles	96	12	3%
Glass	63	13	0%
Foundries	57	14	0%
Cement	46	15	10%
All manufacturing	3,253	N/A	15%

The chemicals and forest product sectors have the largest onsite electricity demand. These sectors also are among the largest indirect generators of electricity. The petroleum refining sector is also a large onsite generator (35% of direct electricity demand is generated onsite), but it is ranked lower because overall electricity demand is much lower for the sector.

2.1.2.6. Steam energy

A profile of onsite steam demand from generation and associated losses to end uses is shown in Fig. 2.1-10. About 40% of primary energy inputs are assumed to be lost due to system inefficiencies in steam generation and transmission, both offsite and onsite; see Appendix D for explanation of steam generation

and distribution loss assumptions. CHP generation serves as a principal source of steam energy in the manufacturing sector, comprising over a quarter (27%, 1,694 TBtu) of steam generated. Conventional boilers are the next largest source of steam, providing about 22% (1,372 TBtu) of primary energy for end use, followed by steam generated offsite at 11% (684 TBtu).[8]

Of the 6,360 TBtu of primary energy used for steam, 3,750 TBtu of energy is applied to process and nonprocess end uses. Steam end use is not reported in the EIA MECS data, so the direct end use of steam was estimated based results from a peer review effort described in Appendix E. For all manufacturing, it was determined that 66% of steam energy is applied towards process heating (2,469 TBtu), 11% to facility HVAC (410 TBtu), 10% to machine drive (360 TBtu), 8% to other process uses (283 TBtu), 3% to other nonprocess uses (124 TBtu), and the remaining 3% to process cooling and refrigeration (103 TBtu)

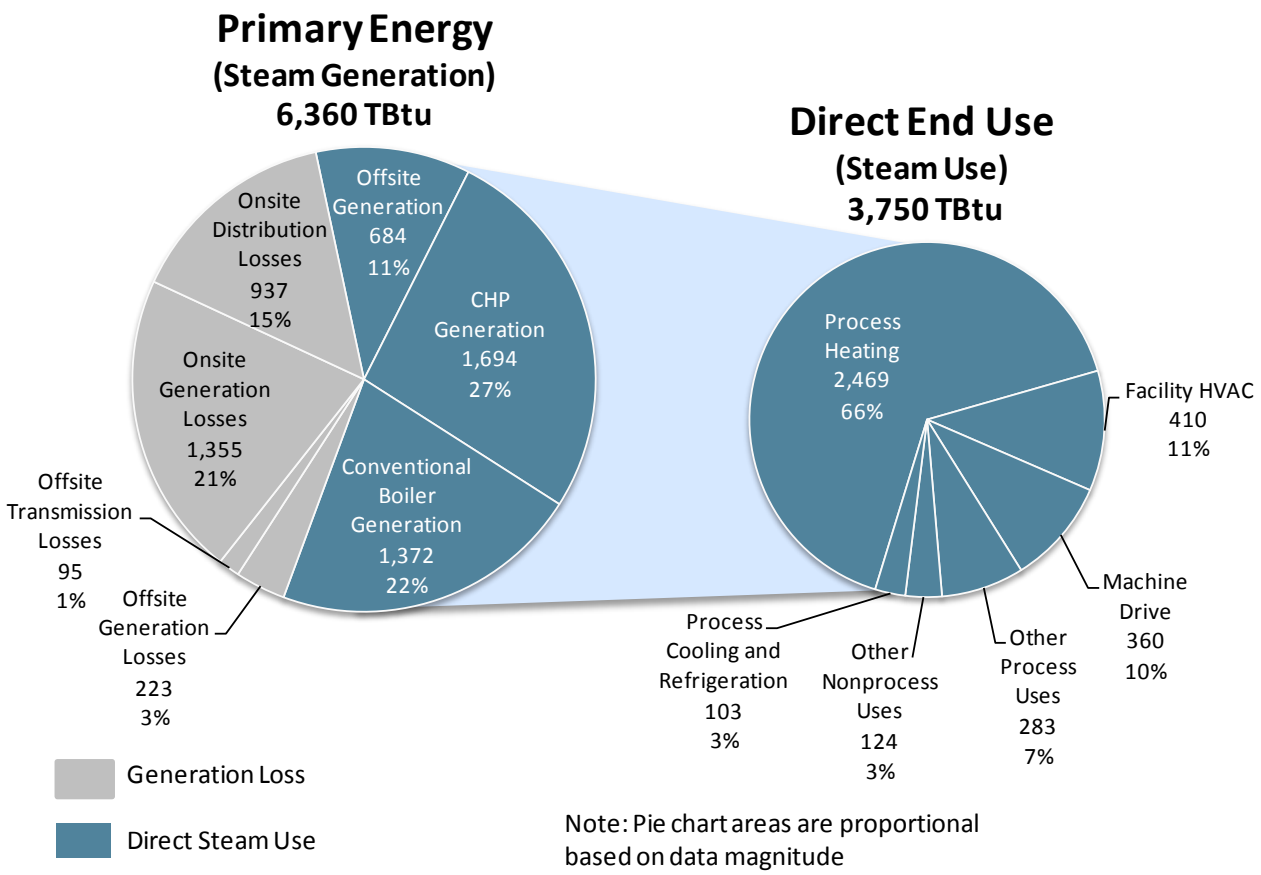


Fig. 2.1-10. Steam generation and *direct* end use in U.S. manufacturing

Manufacturing sector steam use is shown in Table 2.1-7, with sectors ranked by magnitude. The top five sectors—forest products, chemicals, petroleum refining, food and beverage, and iron and steel—all consume over 100 TBtu of steam. The energy conversion component of steam systems (e.g., heat exchangers, injectors, mechanical drives) varies substantially among industries and is generally process- and site-specific. The chemicals sector, for example, uses steam mostly for fluid heating (steam stripping, steam reforming). Other sectors may use steam for direct heating of parts or components, for cleaning, or for other process heating (e.g., sterilization). Common steam direct and indirect end uses in select energy-intensive industries are listed in Table 2.1-8 and described in more detail in the 2012 DOE AMO publication, *Improving Steam System Performance: A Sourcebook for Industry* [AMO EERE 2012b].

[8] The onsite steam generation values (1,679 TBtu from CHP and 1,372 TBtu from boilers) include 20% distribution losses. These values do not match the steam output values shown in the footprint (2,099 TBtu from CHP and 1,715 TBtu from boilers), as the steam distribution losses are shown further downstream in the footprint.

Table 2.1-7. U.S. manufacturing sectors ranked by steam use *(direct end use)*

Sector	Steam use (TBtu)	Rank	Percent generated onsite
Forest products	1,202	1	95%
Chemicals	1,130	2	62%
Petroleum refining	581	3	85%
Food and beverage	443	4	84%
Iron and steel	118	5	92%
Textiles	66	6	89%
Plastics	52	7	100%
Transportation equipment	45	8	88%
Fabricated metals	30	9	84%
Computers, electronics, and electrical equipment	19	10	98%
Cement	17	11	100%
Glass	16	12	100%
Machinery	15	13	97%
Alumina and aluminum	12	14	80%
Foundries	2	15	96%
All manufacturing	3,750	N/A	82%

The steam values listed in Table 2.1-7 encompass all of onsite steam use which includes onsite generated steam and steam from offsite sources. For all sectors, a majority of steam is generated onsite through CHP and conventional boiler systems.

Table 2.1-8. Steam end use equipment in energy-intensive industries [AMO EERE 2012b]

Equipment	Process application	Industry
Condenser	Steam turbine operation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Distillation tower	Distillation, fractionation	Chemicals, petroleum refining
Dryer	Drying	Forest products
Evaporator	Evaporation/concentration	Chemicals, forest products, petroleum refining
Process heat exchanger	Alkylation, process air heating, process water heating, gas recovery/light ends distillation, isomerization, storage tank heating, visbreaking/coking	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Reboiler	Fractionation	Petroleum refining
Reformer	Hydrogen generation	Chemicals, petroleum refining
Separator	Component separation	Chemicals, forest products, petroleum refining
Steam ejector	Condenser operation, vacuum distillation	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Steam injector	Agitation/blending, heating	Chemicals, forest products, petroleum refining
Steam turbine	Power generation, compressor mechanical drive, hydrocracking, naphtha reforming, pump mechanical drive, feed pump mechanical drive	Aluminum, chemicals, forest products, glass, metal casting, petroleum refining, steel
Stripper	Distillation (crude and vacuum units), catalytic cracking, asphalt processing, catalytic reforming, component removal, component separation, fractionation, hydrogen treatment lube oil processing	Chemicals, petroleum refining
Thermo-compressor	Drying, steam pressure amplification	Forest products

2.1.2.7. Onsite generation/CHP energy

Onsite electricity and steam generation is a significant provider of end use energy in U.S. manufacturing; approximately a third of all process and nonprocess energy is generated onsite and over 80% of steam is generated onsite. The (indirect) energy used for onsite generation is primarily fuel (99%), with only 1% of energy in the form of electricity for boilers. Approximately half of all purchased fuel (Table 2.1-5, 49%) is used indirectly for onsite generation (5,814 TBtu). Direct process and nonprocess end uses are shown in more detail in Fig. 2.1-13.

Sector rankings for onsite generation of steam and electricity are presented in Table 2.1-9. The forest products, chemicals, and petroleum refining sectors generate the most onsite steam. In the forest products sector, almost all of the steam is generated in CHP units with black liquor as a contributing fuel source. In the chemicals and petroleum refining sectors, the split between CHP and boiler steam generation is closer to 50/50.

Table 2.1-9. U.S. manufacturing sectors ranked by onsite steam and electricity generation, TBtu

Sector	Onsite steam generation				Onsite electricity generation			
	CHP	Boilers	Total steam	Rank	CHP	Other	Total electricity	Rank
Forest products	1,250	173	1,422	1	174	6	180	2
Chemicals	416	457	873	2	188	1	189	1
Petroleum refining	255	361	616	3	65	1	66	3
Food and beverage	105	363	468	4	17	1	18	4
Iron and steel	71	66	137	5	12	2	14	5
Textiles	10	64	74	6	3	0	3	7
Plastics	0	65	65	7	0	0	0	-
Transportation equipment	10	39	49	8	2	0	2	8
Fabricated metals	2	30	32	9	1	0	1	11
Computers, electronics, electrical	0	23	23	10	0	0	0	-
Cement	22	0	22	11	5	0	5	6
Machinery	4	15	19	12	1	0	1	10
Glass	0	19	19	13	0	0	0	-
Alumina and aluminum	9	3	12	14	1	0	1	9
Foundries	0	3	3	15	0	0	0	-
All manufacturing	2,117	1,715	3,832	N/A	473	15	488	N/A

Onsite electricity generation takes place primarily in CHP units; only 3% of onsite electricity is generated from other electricity generation sources, including renewable sources. Three sectors make up the bulk of onsite electricity generation: chemicals (39%), forest products (37%), and petroleum refining (14%). The proportion of CHP generated electricity vs. steam is higher in the chemicals sector than other sectors as dictated by demand, so although the forest products industry used twice as much fuel for CHP, electricity generation output for the forest products industry is still less than that of the chemicals sector.

About 60% of onsite electricity and steam generation is from CHP units. As shown in Fig. 2.1-11, CHP systems produce nearly 4 quads of energy output; steam accounts for 57% (2,117 TBtu) and electricity 13% (473 TBtu). The remaining 30% of CHP energy is energy losses (1,133 TBtu); proportionally distributed between steam and electricity based on useful output when needed. Natural gas is the most widely used fuel at 864 TBtu, followed by pulping/black liquor, which consumes 440 TBtu exclusively in the forest products sector. Waste gases and biomass are also significant sources of fuel, followed by coal, and other fuels including residual fuel oil and blast furnace/coke oven gases used in the iron and steel sector.

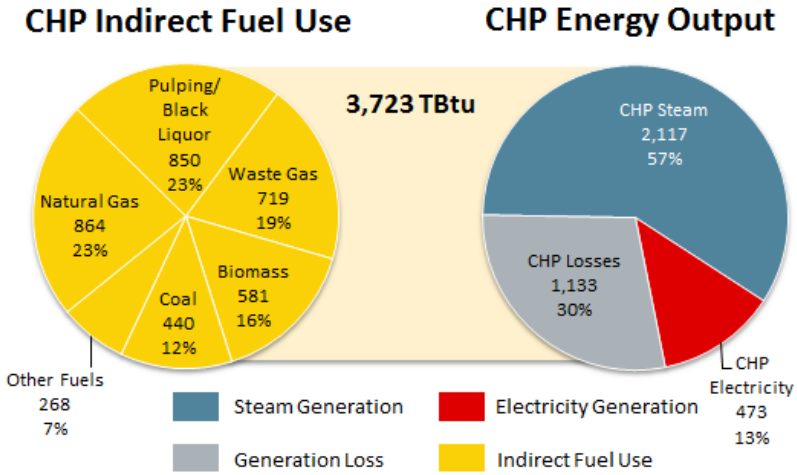


Fig. 2.1-11. CHP fuel consumption and energy output in U.S. manufacturing

Sector rank for CHP output is presented in Table 2.1-10. The forest products sector ranks highest with over twice the output of the chemicals sector, due to heavy use of pulping/black liquor and biomass fuel. Petroleum refining (320 TBtu) and food and beverage (122 TBtu) are also top users of CHP energy. CHP electricity output is derived from 2006 EIA MECS data, while steam output is estimated using CHP efficiency data published by DOE [EIA 2006]. Refer to Appendix D for boiler and CHP efficiency details.

Table 2.1-10. U.S. manufacturing sectors ranked by CHP fuel use and output, TBtu

Sector	Fuel use	Steam output	Electricity output	Total output	Rank
Forest products	1,884	1,250	174	1,424	1
Chemicals	949	416	188	604	2
Petroleum refining	464	255	65	320	3
Food and beverage	163	105	17	122	4
Iron and steel	120	71	12	83	5
Cement	37	22	5	26	6
Textiles	18	10	3	13	7
Transportation equipment	16	10	2	12	8
Alumina and aluminum	14	9	1	10	9
Machinery	7	4	1	5	10
Fabricated metals	4	1	1	3	11
Plastics	1	0	0	0	12
Foundries	0	0	0	0	-
Glass	0	0	0	0	-
Computers, electronics, and electrical equipment	0	0	0	0	-
All manufacturing	3,723	2,117	473	2,590	N/A

2.1.2.8. Direct end use energy

Often analysts are particularly interested in the direct end use of energy, as this is where investment in research and development in new process technology is most prevalent. The direct end use of energy is the best measure of process energy because this includes both offsite and onsite generated energy sources. Further illustration of direct end use is presented in Fig. 2.1-12.

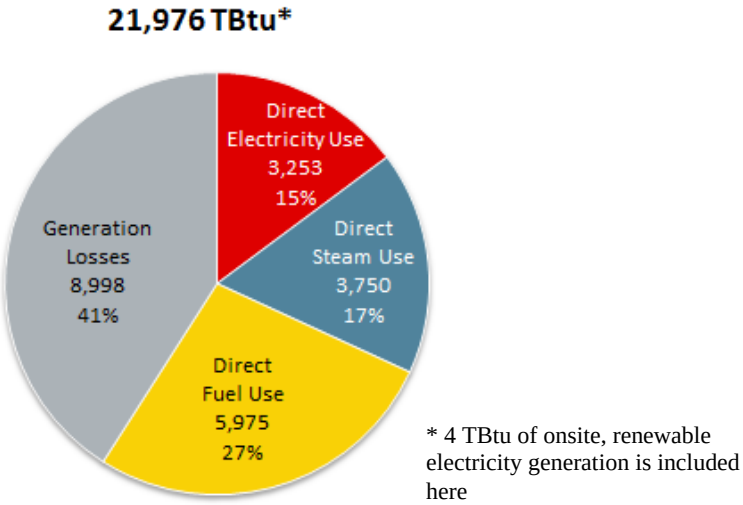


Fig. 2.1-12 Primary energy by type at *direct* end use in U.S. manufacturing

The direct process end use categories are based on the EIA-MECS categories of data and include process heating, process cooling and refrigeration, machine drive, electrochemical, and other process uses. Direct nonprocess end use categories include facility HVAC, facility lighting, other facility, onsite transportation, and other nonprocess uses.

The breakdown of primary energy by type at direct end use is shown in Fig. 2.1-12. When offsite and onsite generation losses are excluded, 12,978 TBtu of onsite electricity, fuel, and steam is used for process and nonprocess end uses. The major end uses of this energy are shown in Fig. 2.1-13. Process heating, machine drive, and facility HVAC combined consume almost 90% of direct end use energy.

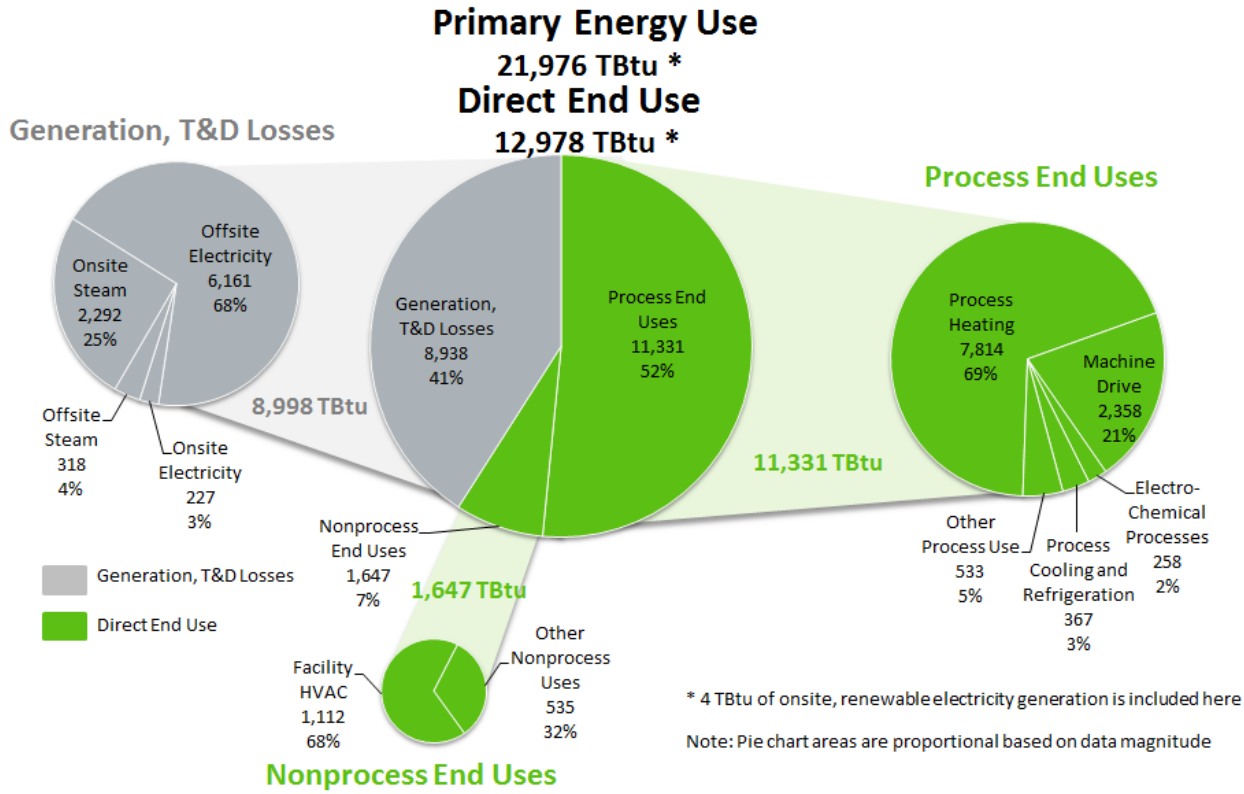


Fig. 2.1-13. Primary energy by *direct* end use in U.S. manufacturing

Fig. 2.1-13 shows primary energy end use equal to 21,976 TBtu, while Fig. 2.1-5 shows primary energy input equal to 21,972 TBtu. The primary end use includes 4 TBtu of onsite renewable electricity that is generated onsite and used in direct end use. Since there is no energy input for this renewable energy source, the primary energy input for electricity generation is 4 TBtu lower.

For the nonprocess end use pie chart, facility lighting, other facility support, onsite transportation, and other nonprocess end uses are combined as “Other Nonprocess Uses” totaling 535 TBtu. The detailed breakdown of this end use is shown in the energy footprints in Appendix C.

Process heating serves as the single largest end use, consuming over 69% of direct end use energy and approximately 36% of all primary energy use. Process heating systems are widely used across many sectors for the direct and indirect heating and cooling of gases, fluids, and solids (e.g., metals). As Table 2.1-11 illustrates, energy use attributed to process heating systems is significant (greater than 1 quad) in three industries (petroleum refining, chemicals, and forest products) and is above 200 TBtu in five other industries. Table 2.1-12 shows that process cooling systems energy use is only above 100 TBtu for the chemicals and food and beverage industries.

Table 2.1-11. U.S. manufacturing sectors ranked by process heating energy

Sector	TBtu	Rank
Petroleum refining	2,346	1
Chemicals	1,268	2
Forest products	1,102	3
Iron and steel	723	4
Food and beverage	555	5
Cement	311	6
Glass	255	7
Fabricated metals	201	8
Transportation equipment	117	9
Foundries	106	10
Plastics	101	11
Alumina and aluminum	100	12
Textiles	100	13
Computers, electronics, and electrical equipment	51	14
Machinery	37	15

Table 2.1-12. U.S. manufacturing sectors ranked by process cooling energy

Sector	TBtu	Rank
Chemicals	107	1
Food and beverage	106	2
Forest products	40	3
Petroleum refining	24	4
Transportation equipment	17	5
Plastics	16	6
Computers, electronics, and electrical equipment	13	7
Textiles	12	8
Fabricated metals	6	9
Machinery	3	10
Alumina and aluminum	3	11
Glass	2	12
Iron and steel	1	13
Foundries	1	14
Cement	0	15

Table 2.1-13 shows the primary energy used for motor-driven equipment, the second largest process end use of energy. Chemicals and forest products are the largest users of machine drive energy, followed by petroleum refining and food and beverage.

Table 2.1-13. U.S. manufacturing sectors ranked by machine drive energy

Sector	TBtu	Rank
Chemicals	586	1
Forest products	524	2
Petroleum refining	301	3
Food and beverage	169	4
Iron and steel	112	5
Plastics	96	6
Transportation equipment	78	7
Fabricated metals	73	8
Machinery	56	9
Textiles	54	10
Cement	39	11
Computers, electronics, and electrical equipment	36	12
Glass	29	13
Alumina and aluminum	22	14
Foundries	19	15

The sector ranking of nonprocess energy use is shown in Table 2.1-14. The forest products, chemicals, transportation equipment, food and beverage, and computers, electronics, and electrical equipment sectors each consume over 100 TBtu for nonprocess energy end uses; primarily due to facility HVAC and lighting, and onsite transportation systems for moving products within the plant boundary and other facility support.

Table 2.1-14. U.S. manufacturing sectors ranked by nonprocess energy

Sector	TBtu	Rank
Forest products	256	1
Chemicals	253	2
Transportation equipment	196	3
Food and beverage	166	4
Computers, electronics, and electrical equipment	103	5
Machinery	91	6
Fabricated metals	88	7
Plastics	84	8
Iron and steel	82	9
Petroleum refining	62	10
Textiles	52	11
Glass	30	12
Foundries	26	13
Alumina and aluminum	16	14
Cement	14	15

2.1.2.9. Applied end use energy

Up until this point in the analysis, energy losses have only been estimated for offsite and onsite generation of electricity and steam. However, there is another form of energy loss that is important to include in an overall manufacturing energy use balance – direct energy end use losses. Direct end uses refer to process and nonprocess end uses, with energy consumption shown in Fig. 2.1-13.

End use losses are the system and equipment losses that occur in process and nonprocess energy end use, e.g., electric motor shaft losses, or process heating insulation and exhaust losses. End use efficiency has been estimated for each direct end use, as shown by the wavy red arrows in originating from end uses in the manufacturing energy footprints Fig. 2.1-3 and Fig. 2.1-4. The energy that is not lost to system and equipment inefficiencies (end use losses) is ***applied*** to the end use.

When both generation and end use losses are accounted for, the energy that remains is referred to herein as ***applied energy***. Applied energy is best illustrated by re-examining Fig. 2.1-5, which shows primary energy by energy type for U.S. manufacturing. 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. 2.1-9), the majority of steam generation losses are onsite (as shown in Fig. 2.1-10), while 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 in the figure below. The remaining energy is applied to end uses, shown in light green as "Applied Energy" in Fig. 2.1-14 below.

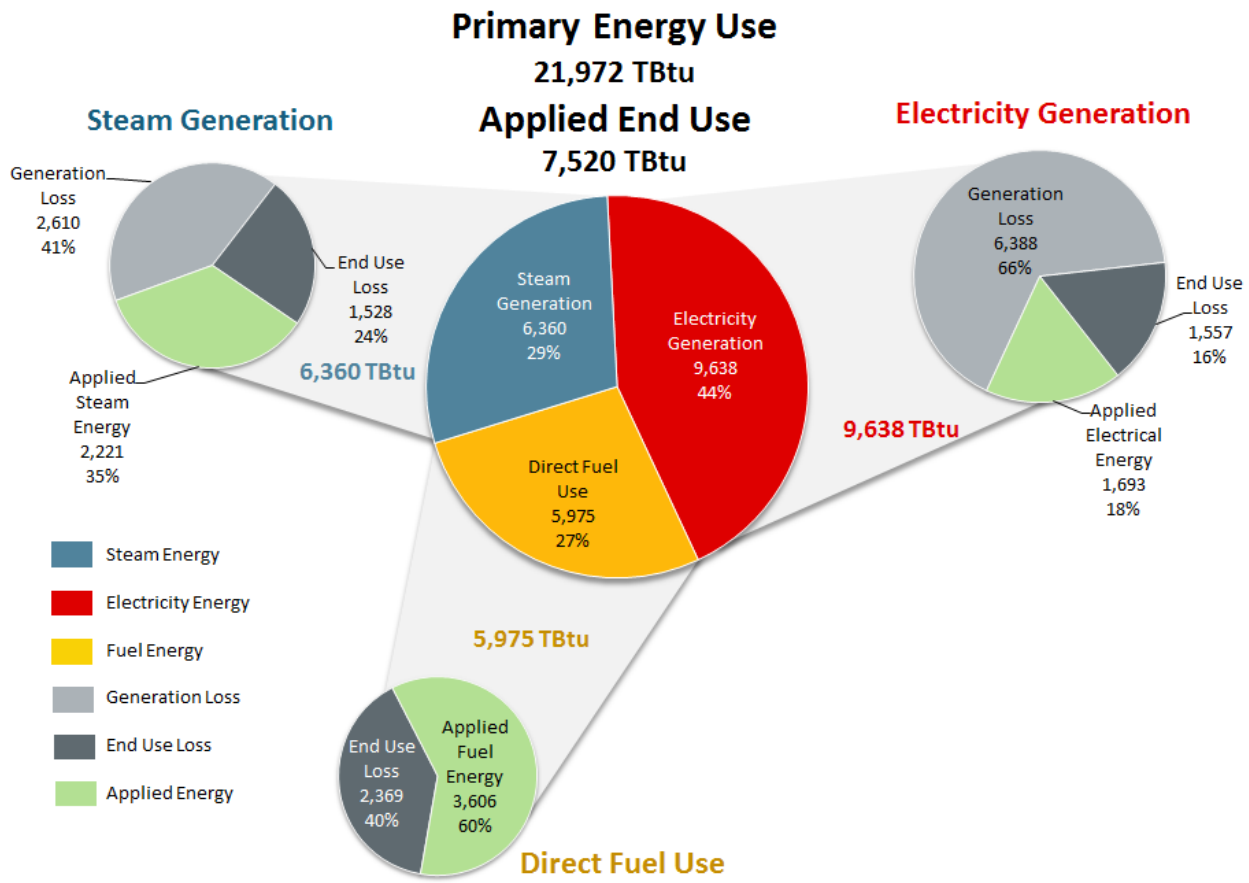
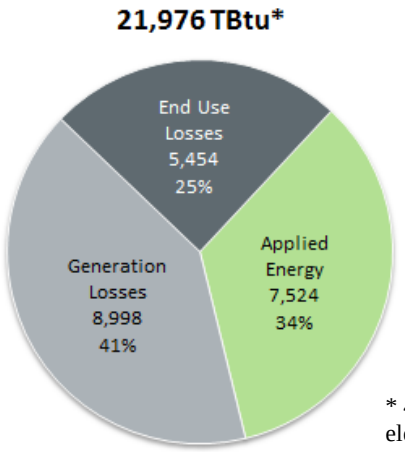


Fig. 2.1-14. Primary energy use and applied energy by energy type for U.S. manufacturing

U.S. manufacturing primary energy generation losses, end uses losses, and applied energy is shown in Fig. 2.1-15, which shows that 34% of all primary energy input is applied to process and nonprocess end uses. Generation losses account for 41% of primary energy input and end use losses account for the remaining 25% of primary energy input.



* 4 TBtu of onsite, renewable electricity generation is included here

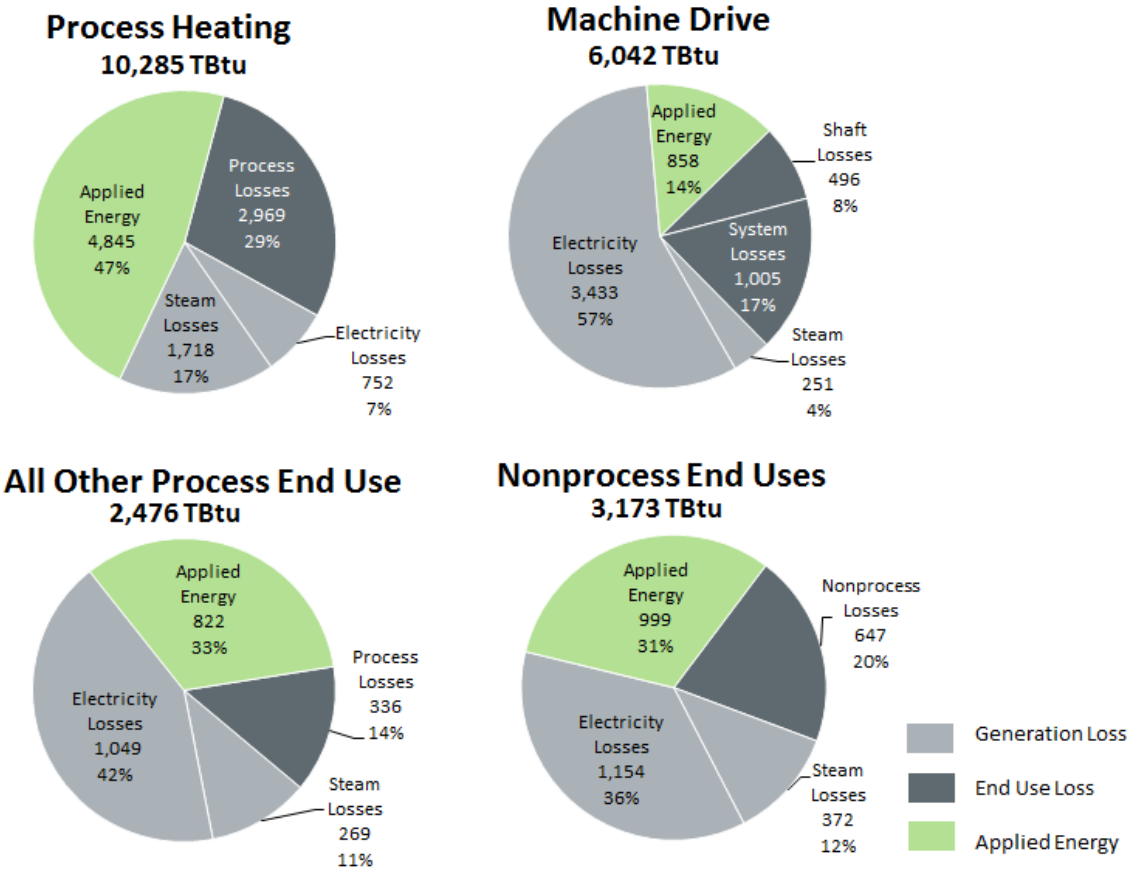
Fig. 2.1-15. Primary energy by loss and applied energy in U.S. manufacturing

Table 2.1-15 provides a sector ranking for applied energy and the percent of the primary energy that is applied to end use. In five of these industries (glass, cement, forest products, iron and steel, food and beverage), direct end use losses are over 30% of primary energy input energy. In seven out of 15 sectors, over 70% of primary energy is lost to generation, transmission, and distribution loss or direct end use loss.

Table 2.1-15. U.S. manufacturing sectors ranked by applied energy

Sector	Primary energy use (TBtu)	Generation, transmission, and distribution loss		Direct end use loss		Overall % of primary energy lost	Applied energy	Rank
		TBtu	% of primary energy	TBtu	% of primary energy			
Petroleum refining	3,546	706	20%	661	19%	39%	2,179	1
Chemicals	4,513	2,062	46%	902	20%	66%	1,550	2
Forest products	3,559	1,005	28%	1,173	33%	61%	1,382	3
Food and beverage	1,934	647	33%	587	30%	64%	700	4
Iron and steel	1,481	525	35%	464	31%	67%	493	5
Transportation equipment	904	450	50%	188	21%	71%	267	6
Fabricated metals	708	328	46%	164	23%	69%	217	7
Cement	471	103	22%	160	34%	56%	208	8
Plastics	729	423	58%	125	17%	75%	181	9
Glass	466	145	31%	174	37%	68%	147	10
Computers, electronics, and electrical equipment	527	309	59%	91	17%	76%	126	11
Alumina and aluminum	603	338	56%	141	23%	79%	124	12
Machinery	444	250	56%	90	20%	77%	104	13
Textiles	472	244	52%	129	27%	79%	98	14
Foundries	281	125	44%	75	27%	71%	81	15
All manufacturing	21,972	8,998	41%	5,454	25%	66%	7,520	N/A

Applied energy can also be calculated for specific end uses, as shown in Fig. 2.1-16. In this figure, generation losses are labeled as either steam or electricity losses. 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.



Note: Pie chart areas are not proportional to magnitude of energy consumption

Fig. 2.1-16. Primary applied energy by *direct* end use in U.S. manufacturing

For process heating applications, 47% of primary energy is applied to the process. 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 fuel or steam. Process heating losses do vary greatly by sector. An explanation of the methodology used in estimating process heating loss is provided in Appendix F, while loss estimates for all end uses are shown in Appendix D.

In machine-driven systems, only 14% of primary energy is applied, primarily because of the inefficiency in electricity generation. Electricity losses are the result of turbine and power system efficiencies which are as low as 25% for older steam-based systems, but as high as 50 – 60%% for state-of-the-art combined cycle gas turbines. On average, this means every kilowatt hour of electricity generated by a utility requires three kilowatt hour equivalents of fuel. Although the manufacturing facility does not incur these losses, including them in the loss analysis provides a total (primary) picture of the energy associated with the use of electricity.

The machine drive, or shaft losses represent the inefficiency of converting fuel (in engines), steam (in turbines), or electricity (in motors) into rotating, kinetic energy. The machine driven system losses represent the inefficiency of applying this kinetic energy as effective work, such as compressing air in a rotary screw compressor. Machine-driven system losses total 1,005 TBtu and shaft losses comprise 499 TBtu, for a combined total of 1,504 TBtu, or 25% of machine driven primary energy use.

2.1.3. Greenhouse Gas Combustion Emissions Profile for U.S. Manufacturing and Sector Rankings

This analysis considers GHG combustion emissions released during the combustion of fuels for energy use, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), since these are the most common greenhouse gases released during the combustion of fuel (further detail on fuel emission factors is provided in Appendix D). The GHG combustion emission profiles shown here are similar to the energy profiles in that emissions are reported either with or without emissions released during offsite energy generation. As labeled in the sector footprints, "Total" emissions include emissions from offsite steam and electricity generation, which is equivalent to primary energy use in the energy profiles. "Onsite" GHG combustion emissions are the result of either indirect (e.g., CHP systems or boilers) or direct (e.g., process or nonprocess end uses) fuel use within the plant boundary. As discussed in Chapter 1, the GHG emissions shown in the energy and carbon footprint represent combustion emissions; process emissions (e.g., CO_2 emissions released during iron and steel production and the calcination reaction during cement manufacturing, perfluorocarbon emissions emitted during aluminum smelting) are not included in this analysis. GHG emissions should not be interpreted as life cycle emissions.

Total U.S. manufacturing GHG combustion emissions were equal to 1,261 million metric ton of CO_2 equivalent (MMT CO_2e) in 2006 as shown in Fig. 2.1-17. Onsite emissions, which result from fuel consumption for all onsite end uses (including onsite steam and electricity generation and process and nonprocess end uses), contribute 51% of total emissions. Offsite emissions, which are produced during the offsite generation of electricity and steam, contribute the remaining 49% of total emissions.

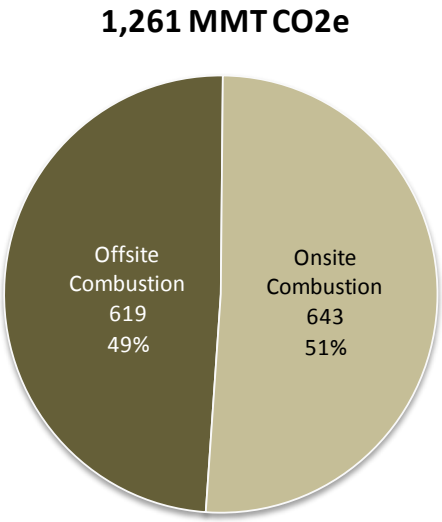


Fig. 2.1-17. Onsite and offsite GHG combustion emissions in U.S. manufacturing

A more detailed breakdown of emissions in shown in Fig. 2.1-18, which shows total emissions by energy type. Onsite consumption of fuels (shown in yellow in the pie chart), including natural gas, fuels derived from byproducts, coal, and other fuels account for 51% of total emissions. Emissions released during the offsite production of electricity account for 43% of emissions, while the remaining 6% of emissions are released during offsite steam production.

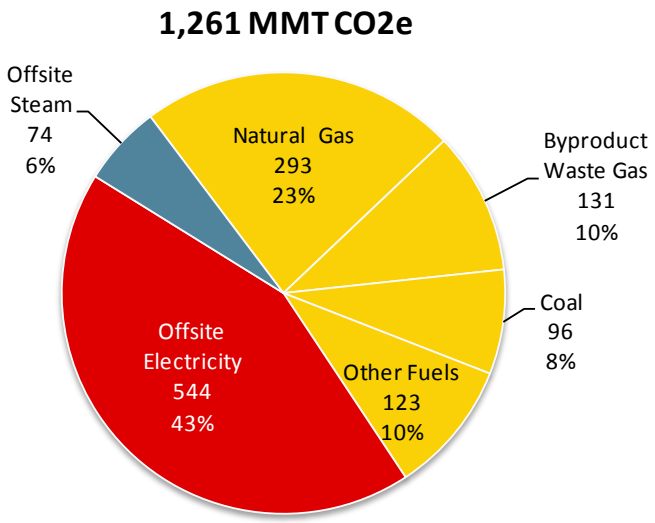


Fig. 2.1-18. Total GHG combustion emissions in U.S. manufacturing (shown by energy supply type)

An alternate view of emissions is shown in Fig. 2.1-19, which also shows 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 during onsite generation of steam in boilers or 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 about 43% of all emissions. Steam generation (offsite or onsite) contributes a further 29% of emissions, while the remaining 25% of emissions are released during fuel combustion for process and nonprocess end uses.

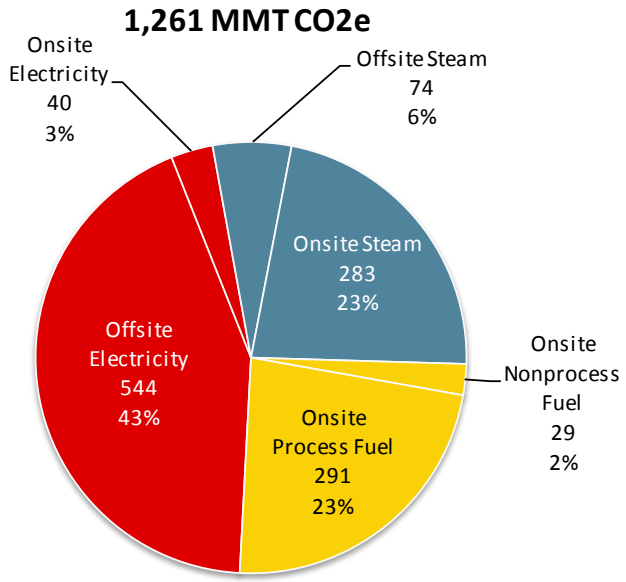


Fig. 2.1-19. Total GHG combustion emissions in U.S. manufacturing (shown by energy end use type)

Emissions can also be attributed to direct end uses, as shown in Fig. 2.1-20. In this figure, the emissions released from both offsite and onsite electricity and steam generation are distributed to direct end uses, along with emissions released when fuel is consumed at direct end uses. This pie chart allows for a direct comparison of the emissions resulting from different process and nonprocess direct end uses. Almost half

of manufacturing sector end use emissions result from process heating applications. The next highest contributor of emissions is machine-driven uses (which include a large proportion of offsite electricity emissions). The emissions associated other process and nonprocess uses are also shown in the figure.

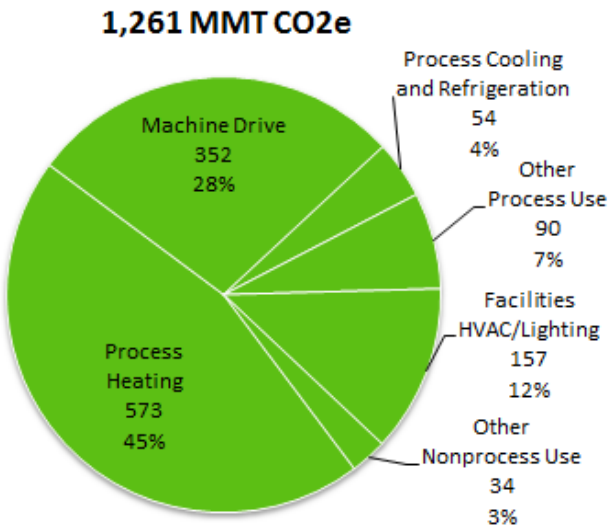


Fig. 2.1-20. Total GHG combustion emissions in U.S. manufacturing (shown by direct energy end use)

Table 2.1-16 shows manufacturing sector rankings by total and onsite emissions, respectively. In terms of total emissions, chemicals, petroleum refining, forest products, and food and beverage produce the highest emissions, each emitting over 100 MMT CO_2e. Focusing on onsite emissions, petroleum refining, with its heavy onsite use of fossil fuels, contributes the most towards emissions at a value of 210 MMT CO_2e, almost double the emissions of the next-largest onsite emitting sector, chemicals. Forest products and food and beverage follow with onsite emissions in each sector totaling over 50 MMT CO_2e.

Table 2.1-16. U.S. manufacturing sectors ranked by total GHG combustion emissions

Sector	Total emissions (MMT CO_2e)	Rank	Onsite emissions (MMT CO_2e)	Rank
Chemicals	275	1	129	2
Petroleum refining	244	2	210	1
Forest products	140	3	68	3
Food and beverage	117	4	56	4
Iron and steel	62	5	23	6
Transportation equipment	53	6	15	7
Plastics	44	7	9	11
Fabricated metals	41	8	13	9
Cement	39	9	31	5
Alumina and aluminum	36	10	6	12
Computers, electronics, electrical equipment	31	11	5	15
Textiles	29	12	10	10
Machinery	26	13	5	14
Glass	26	14	14	8
Foundries	16	15	5	13
All manufacturing	1,261	N/A	643	N/A

Note: CO_2 emissions from biomass fuel combustion (also known as biogenic CO_2) are not included in the total emission factor because the uptake of CO_2 during biomass growth results in zero net emissions over time

2.1.4. Energy and Emissions Profile Summary Table

The energy and emissions profiles for U.S. manufacturing are summarized in Fig. 2.1-17 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 GHG 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 2.1-17. Energy use, loss, and GHG combustion emissions in U.S. manufacturing

U.S. manufacturing			Energy (TBtu)			GHG 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 (11,789 TBtu)	-	-	N/A	-	Distributed to onsite	Distributed to onsite direct
		Electricity generation/transmission	9,011	6,161		544.3		
		Steam generation/transmission	1,173	318		74.3		
		Total offsite (including fuel supply)	**21,972**	**6,479**		**618.6**		
Onsite	Indirect	Conventional boilers	2,143	429	N/A	114.9	122.8	Distributed to onsite direct
		CHP/cogeneration	3,723	1,133		206.0	206.0	
		Other electricity generation[a]	32	20		1.9	1.9	
		Steam distribution	-	937		0.0	0.0	
		Total onsite generation	**5,898**	**2,519**		**322.9**	**330.7**	
	Direct	Process heating	7,814	2,969	4,845	261.3	376.2	572.6
		Process cooling and refrigeration	367	129	239	1.9	43.3	54.1
		Machine drive	2,358	1501	858	16.2	303.7	352.9
		Electro-chemical	258	155	103	0.0	39.3	42.5
		Other process uses	533	53	480	11.2	25.4	48.0
		Nonprocess energy	1,647	647	999	29.3	142.6	191.3
		Total process and nonprocess	**12,978**	**5,454**	**7,524**	**319.9**	**930.6**	**1,261.3**

* 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)
[a] Onsite, renewable, non-combustion generation contributes 4 TBtu