Energy Use and Carbon Emissions in U.S. Manufacturing: Sector Analysis of Energy Supply, End Use, Loss, and Greenhouse Gas Emissions

Caroline Dollinger, Kenta Shimizu, & Sabine Brueske, Energetics
Joe Cresko, U.S. Department of Energy

ABSTRACT

Meeting industrial decarbonization goals requires an understanding of the current energy consumption, energy loss, and emissions within the overall manufacturing sector and individual subsectors. The U.S. Department of Energy's (DOE's) Industrial Efficiency & Decarbonization Office (IEDO)[1] has developed data-rich graphical representations – Manufacturing Energy and Carbon Footprints – that map the flow of energy supply, demand, and losses as well as greenhouse gas (GHG) emissions in diverse U.S. manufacturing sectors. In 2018, the U.S. manufacturing sector[2] consumed 24 quadrillion British thermal units (Btus) of total energy, accounting for 24% of total U.S. energy consumption, and emitted 1,165 million metric tons of carbon dioxide equivalent (MMT CO_2e) (DOE 2021).

The footprints visualize onsite and offsite energy use and loss in manufacturing and associated combustion and process GHG emissions. Each footprint shows the flow of energy (fuel, electricity, and steam) to major end uses (boilers, combined heat and power, process heating, process cooling, machine-driven equipment, and others) and resulting onsite/offsite combustion and onsite process GHG emissions.

Footprints are available for 15 manufacturing sectors (representing 95% of manufacturing primary energy use and 94% of manufacturing GHG emissions) and U.S. manufacturing overall (DOE 2021). The newest footprints, published in December 2021, follow previous versions with notable improvements: expansion of GHG emissions analysis to include process emissions, addition of a carbon footprint, footprints for five additional subsectors; and updated process heating loss assumptions. The footprints can play a key role in decarbonization planning by providing a baseline to assess areas of improvement (such as electrification).

Introduction

The U.S. manufacturing sector consumed 24.4 quadrillion British thermal units (Btus) of total energy in 2018, accounting for approximately 74% of total U.S. industrial primary energy consumption and 24% of total U.S. primary energy as shown in Figure 1. The U.S. industrial sector is comprised of manufacturing and non-manufacturing (construction, agriculture, and mining) sectors. The Manufacturing Energy and Carbon Footprints, updated in 2021, along with other reference materials such as the *Manufacturing Energy Bandwidth Studies*[3], the DOE

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[1] Previously known as the Advanced Manufacturing Office (AMO). In October 2022, AMO was split into the Advanced Materials & Manufacturing Technologies Office (AMMTO) and the Industrial Efficiency & Decarbonization Office (IEDO).

[2] For the purposes of the footprints and in alignment with the U.S. Energy Information Administration (EIA), the U.S. industrial sector is defined as the manufacturing and non-manufacturing (construction, agriculture, and mining) sectors.

[3] The *Manufacturing Energy Bandwidth Studies*, published between 2015 and 2017, are available for eight manufacturing sectors, manufacturing of six lightweight materials, and seawater desalination. In 2023, IEDO is updating a selection of the bandwidth studies.

Industrial Decarbonization Roadmap[4], and the *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis* report[5], provide foundational and detailed information on energy consumption, energy loss, and GHG emissions for the U.S. manufacturing sector. These resources can be used by federal agencies, industry, academia, and others as a basis to assess the opportunity space for energy and GHG emissions improvements. The footprints provide the data to help assess the scale of decarbonization opportunities (such as electrification) within and across the most energy- and carbon-intensive manufacturing sectors.

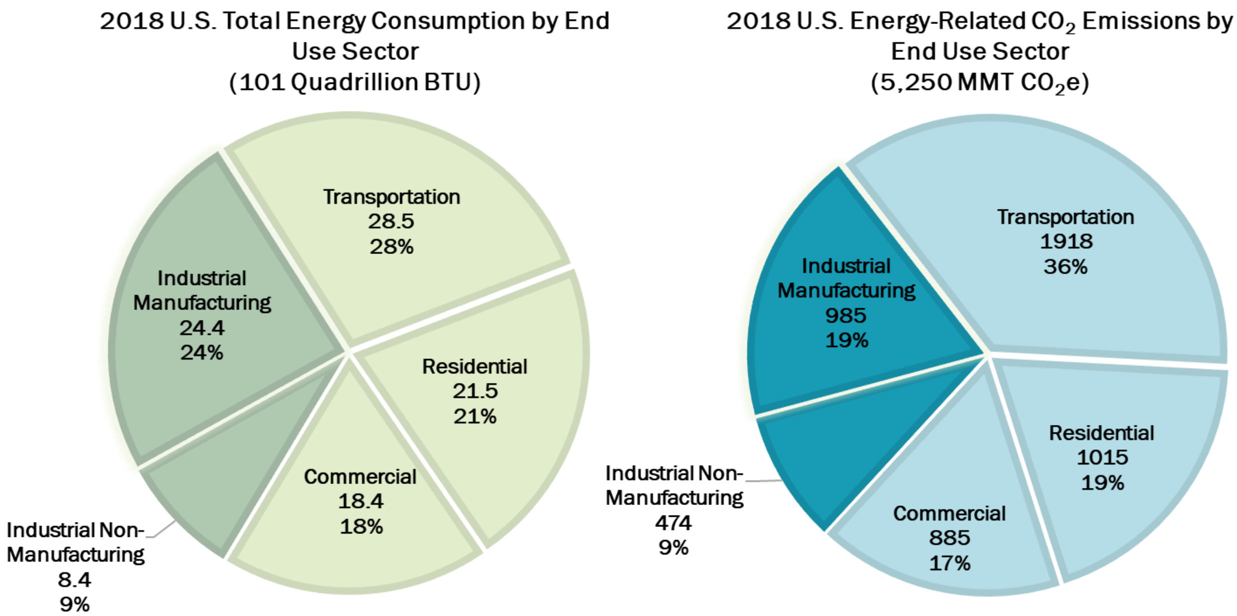

Figure 1. U.S. primary energy consumption (left) and energy-related CO_2 emissions (right), 2018. *Sources*: DOE 2021, EIA 2021b, EIA 2021c Table 2.1.

Manufacturing Energy and Carbon Footprints

The Manufacturing Energy and Carbon Footprints quantitatively portray manufacturing energy use and loss and greenhouse gas emissions (GHG) in an easy-to-understand fashion. Three energy types – fuel, electricity, and steam – are presented in trillion British Thermal Units (TBtu). Emissions are presented in million metric tons (MMT) carbon dioxide equivalent (CO_2e). In the latest update, footprints are available for U.S. manufacturing overall and for the 15 sectors and five subsectors listed in Table 1. The 15 sectors combined account for 95% of U.S. manufacturing primary energy use and 94% of U.S. manufacturing GHG emissions. New for this version[6] of the footprints is the inclusion of five manufacturing subsectors: petrochemicals; plastics material and resins; semiconductors; automobile and light duty motor

[4] DOE's *Industrial Decarbonization Roadmap* was published in September 2022 and provides decarbonization pathways for five emissions-intensive manufacturing sectors (petroleum refining, chemicals, iron and steel, cement, and food and beverage) based on input from a series of industry workshops and modeling analysis.
[5] The *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis* report (ORNL 2012) was published in 2012, utilizing MECS data for 2006 (latest available at the time). This paper contains a few figures featured in that report with updated 2018 data. IEDO plans to update this full report in the future.
[6] Footprints are available online for data years 2006, 2010, 2014, and 2018.

vehicle; and aerospace product and parts. The subsectors fall under the sectors in the same table cell (e.g., the petrochemicals subsector is a subset of the chemicals sector).

Table 1. U.S. manufacturing sectors and subsectors included in footprints analysis by NAICS codes[7]

Sector/subsector	NAICS code
All manufacturing	31-33
Alumina and aluminum	3313
Cement	327310
Chemicals	325
Petrochemicals	325110
Plastics Material and Resins	325211
Computers, electronics, and electrical equipment	334, 335
Semiconductors	334413
Fabricated metals	332
Food and beverage	311, 312
Forest products	321, 322
Foundries	3315
Glass and glass products	3272, 327993
Iron and steel	331110, 3312
Machinery	333
Petroleum refining	324110
Plastics and rubber products	326
Textiles	313, 314, 315, 316
Transportation equipment	336
Automobile and light duty motor vehicle	336112
Aerospace product and parts	3364

The footprints provide data at three levels of detail: a high-level overview of primary (source) energy and emissions for onsite and offsite heat and power (Figure 2), energy and emissions distribution by onsite end uses (Figure 3), and GHG emissions from energy generation, end use, and non-combustion sources (i.e., process emissions) (Figure 4).[8] The onsite end uses are categorized as generation (conventional boilers; combined heat and power (CHP); and other electricity generation), process (process heating; process cooling and refrigeration; electro-chemical; machine drive; and other process uses), or nonprocess (facility heating, ventilation, and air conditioning (HVAC); facility lighting; onsite transportation; other facility support; and other nonprocess).[9]

[7] North American Industry Classification System (NAICS) codes are used to establish definitions and coverage of each sector and subsector. Details on the sector/subsectors can be found in the supporting document Manufacturing Energy and Carbon Footprints: Scope.
[8] For more information see the supporting document Understanding the 2018 Manufacturing Energy and Carbon Footprints.
[9] End uses are fully defined in the supporting document 2018 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions.

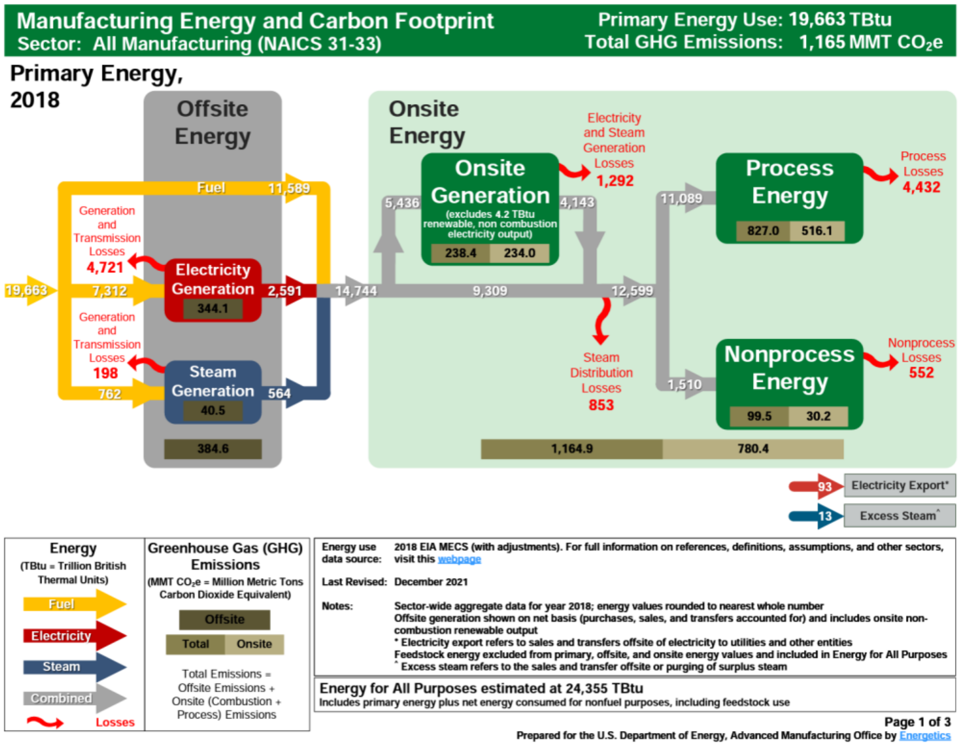

Figure 2. Page 1 of the All Manufacturing energy and carbon footprint, showing primary energy and emissions for 2018. *Source*: DOE 2021.

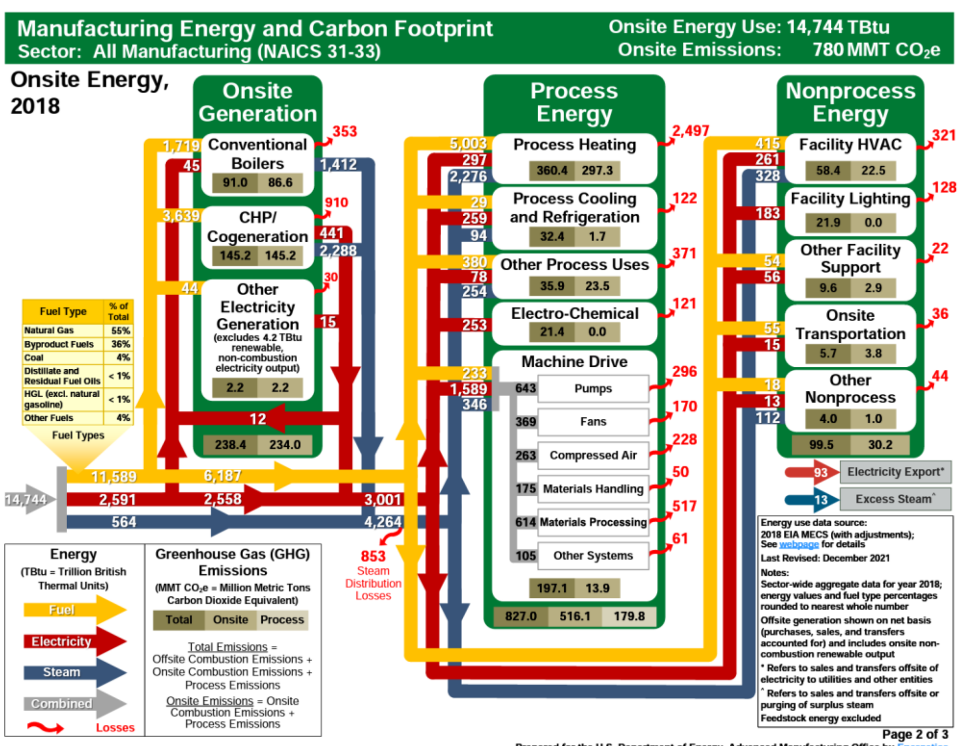

Figure 3. Page 2 of the All Manufacturing energy and carbon footprint, showing onsite energy and emissions by end use for 2018. *Source*: DOE 2021.

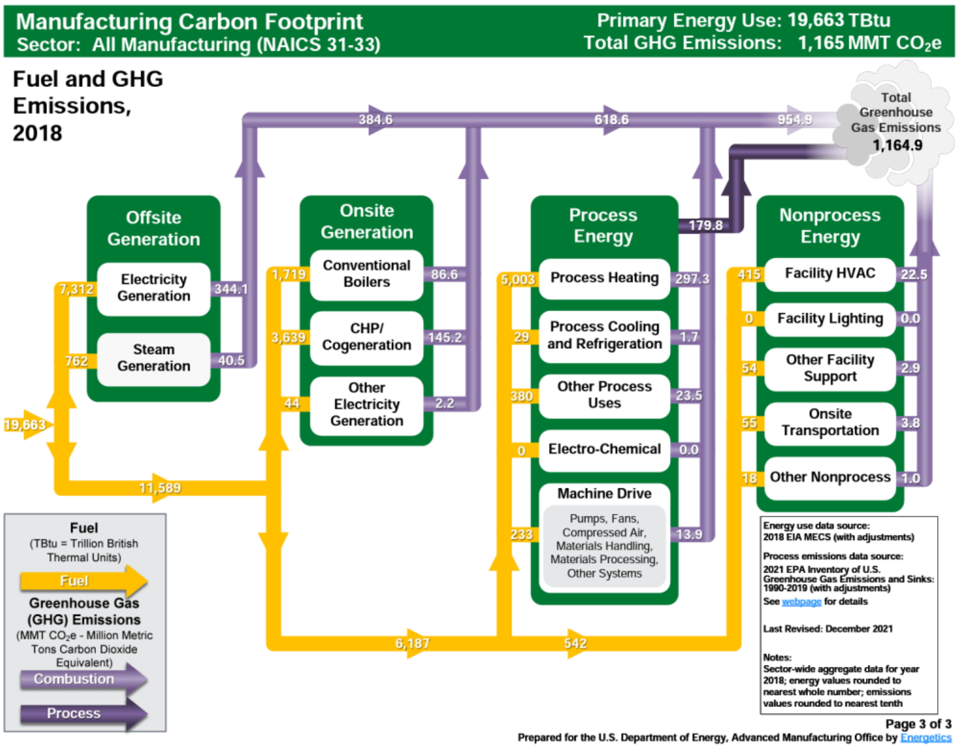

Figure 4. Page 3 of the All Manufacturing energy and carbon footprint, showing GHG emissions for 2018. *Source:* DOE 2021.

The footprints are based on the energy consumption data reported in the U.S. Energy Information Administration's (EIA's) Manufacturing Energy Consumption Survey (MECS) (EIA 2021a). The emissions values are based on both EIA (2021a) and the U.S. Environmental Protection Agency's *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA 2021). The latest year for which MECS data is currently available is 2018. Additional literature sources and industry and subject matter expert opinion are referenced to account for energy loss and emission factors.[10]

Footprints Energy Consumption Results

Data and information from the footprints provide useful ways of summarizing U.S. manufacturing energy consumption and emissions data and determining where industrial decarbonization opportunities may lie by providing the scale of energy use and loss for specific end uses and the sources of emissions. Additionally, since the MECS results are from plant-level data gathered by Census[11] and published every four years, this provides a benchmark to observe trends within manufacturing sectors and overall (DOE 2022c).

Figure 5 and Figure 6 show the same overall U.S. manufacturing 2018 primary energy use (steam, electricity, and fuel) from different perspectives. As shown in the smaller pies in

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[10] Full listing of definitions, assumptions, and references can be found in the supporting document [2018 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions](#).

[11] MECS is sponsored by EIA and administered by the U.S. Census Bureau. For more information visit: www.census.gov/programs-surveys/mecs/about/faq.html.

Figure 5, of the 5,578 TBtu of steam, 39% is lost (35% onsite and 4% offsite), while 62% of the 7,898 TBtu of electricity generation is lost. Natural gas dominates U.S. manufacturing direct fuel consumption, accounting for 61%. The remainder of direct fuel use includes 18% still/waste gas[12], 4% coal, 1% each of natural gas liquids and distillate fuel oil, 0.1% residual fuel oil, and the remainder including other types of fuel (biomass, petroleum coke, blast furnace/coke oven gases, etc.). While the natural gas portion of fuel consumption has increased by 8%, overall U.S. manufacturing fuel consumption has fallen by about 10% between 2002 and 2018 (DOE 2022e).

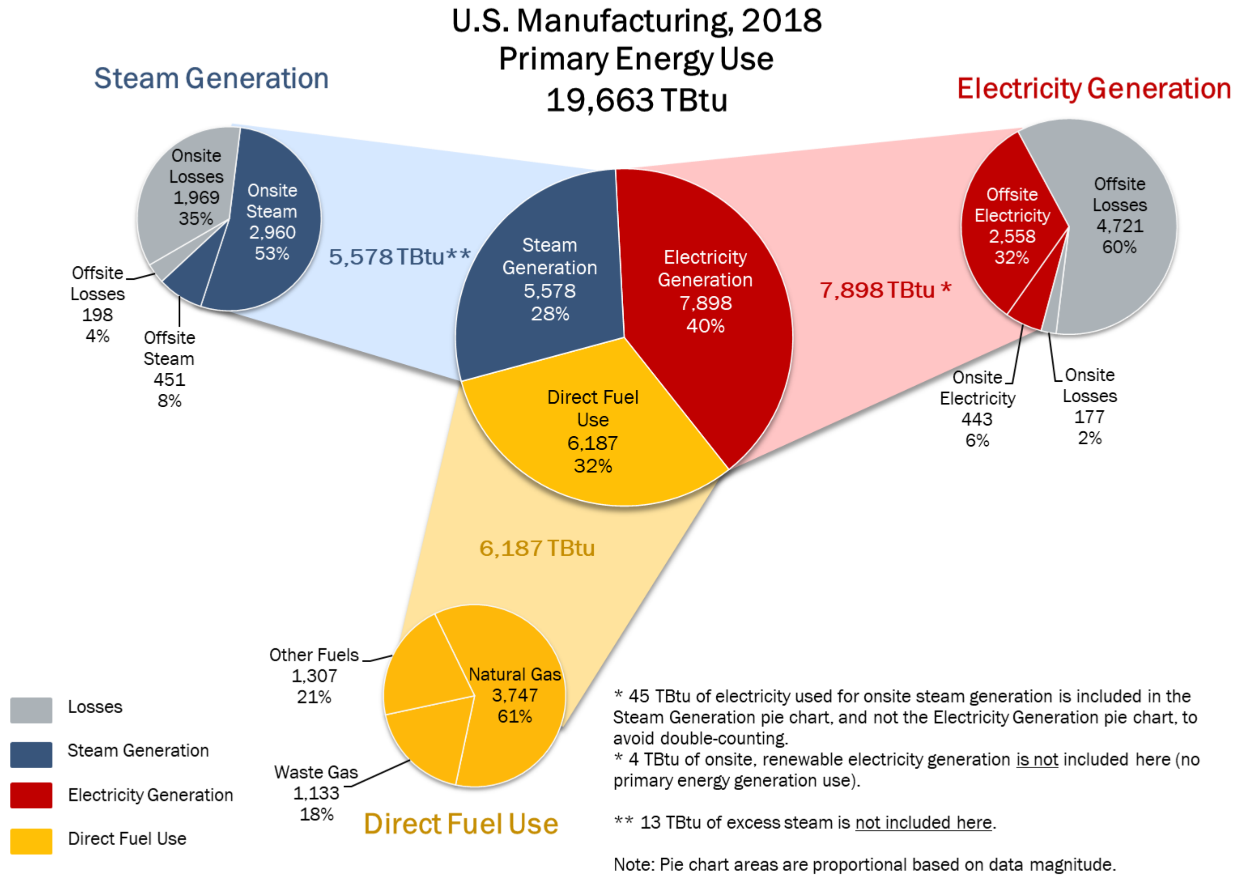

Figure 5. U.S. manufacturing primary energy use by energy type, 2018. *Source:* DOE 2021

Figure 6 presents the same base data of overall U.S. manufacturing 2018 primary energy use (steam, electricity, and fuel) broken down by applied and lost energy. Applied energy[13] refers to the portion of energy consumed by the end uses after accounting for generation, transmission, distribution, and end use losses. For electricity, steam, and fuel, applied energy accounts for 19%, 39%, and 64% respectively. Overall, about 39% of the 19,663 TBtu of primary energy consumption for U.S. manufacturing is applied while losses account for the

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[12] Waste gas is produced as a byproduct during manufacturing processes from petroleum/coal products. In petroleum refining, the waste gas is specifically referred to as still gas (a mix of refined hydrocarbons). Blast furnace and coke oven gases in iron and steel manufacturing is accounted for separately.

[13] The term "applied energy" in this context was coined by the Manufacturing Energy and Carbon Footprint analysis team at Energetics.

remaining 61%. Identifying and estimating specific losses within a sector's end uses helps to begin identifying areas of opportunity for increasing efficiency.

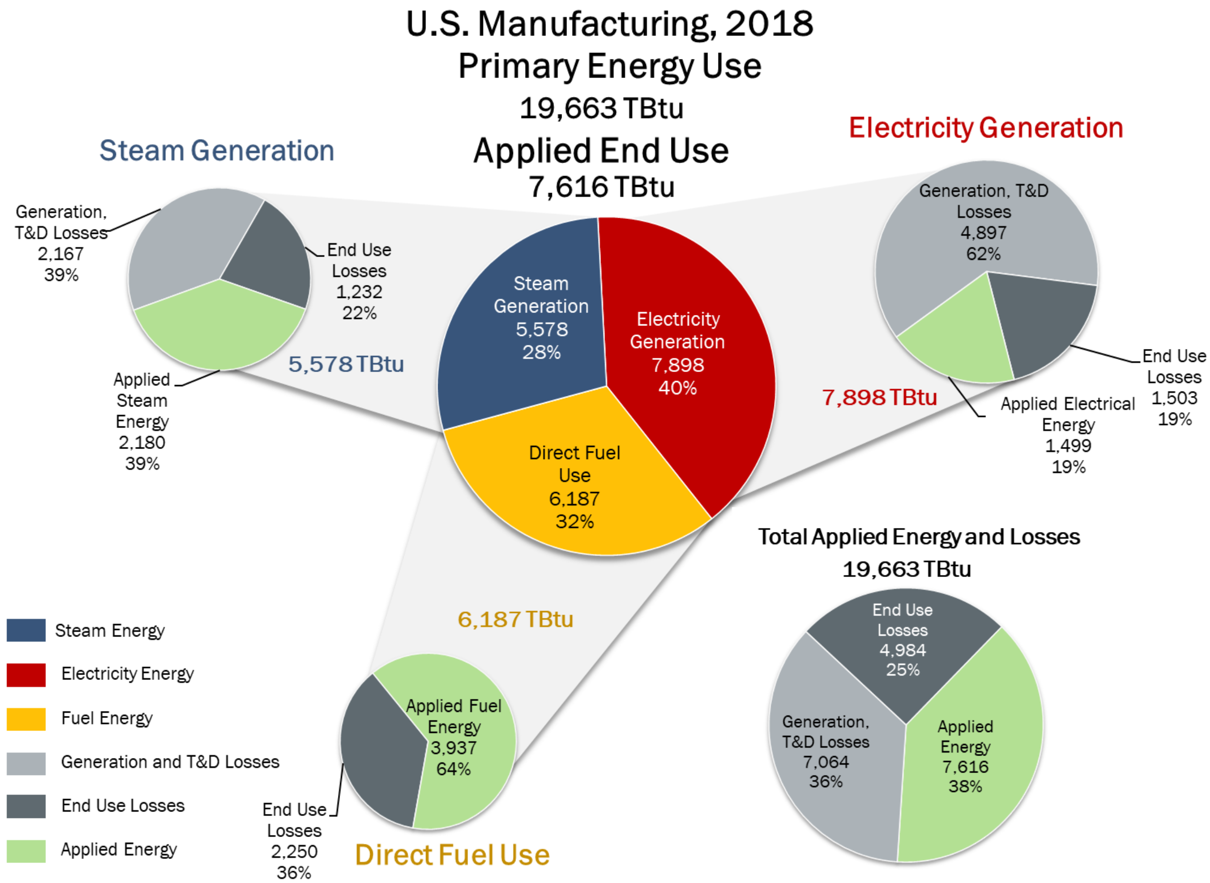

Figure 6. U.S. manufacturing primary and applied energy consumption and losses by energy type, 2018. *Source:* DOE 2021

Primary energy, losses (generation, transmission, distribution, and direct end use loss), and applied energy are presented in Table 2 for the 15 sectors studied in the footprints and U.S. manufacturing overall (listed in order of highest to lowest applied energy). While the chemicals sector has a higher primary energy consumption than the petroleum refining sector, a higher percentage of that primary energy is lost, resulting in refining having the highest applied energy value. Total losses in 2018 for the various sectors range from 39% (petroleum refining) to 78% (plastics), with an overall weighted average of 61% for U.S. manufacturing.

Table 2. U.S. manufacturing primary energy, applied energy, and energy loss by sector, 2018

Sector	Primary energy use (TBtu)	Generation, transmission, and distribution loss		Direct end use loss		Overall % of primary energy lost	Applied energy (TBtu)
		TBtu	% of primary energy	TBtu	% of primary energy		
Petroleum Refining	3,728	734	20%	709	19%	39%	2,284
Chemicals	4,842	1,686	35%	1,169	24%	59%	1,987

Forest Products	2,883	1,206	42%	932	32%	74%	745
Food and Beverages	1,935	876	45%	513	27%	72%	546
Iron and Steel	1,469	454	31%	470	32%	63%	545
Transportation Equipment	659	327	50%	146	22%	72%	186
Fabricated Metals	479	231	48%	106	22%	70%	142
Cement	367	71	19%	154	42%	61%	142
Plastics	562	318	56%	106	19%	75%	139
Computers, Electronics and Electrical Equipment	393	216	55%	64	16%	71%	113
Aluminum	372	170	46%	103	28%	73%	100
Glass	272	88	32%	103	38%	70%	81
Machinery	299	158	53%	66	22%	75%	75
Foundries	160	68	43%	46	29%	71%	46
Textiles	183	99	54%	43	23%	78%	41
All Manufacturing	19,663	7,064	36%	4,984	25%	61%	7,615

Figure 7 and Table 3 present a summary of U.S. manufacturing's direct energy use and loss for 2018 using the footprints data. Direct fuel, electricity, and steam use combine to account for 64% of U.S. manufacturing primary energy use in 2018, while losses account for the remaining 36%.

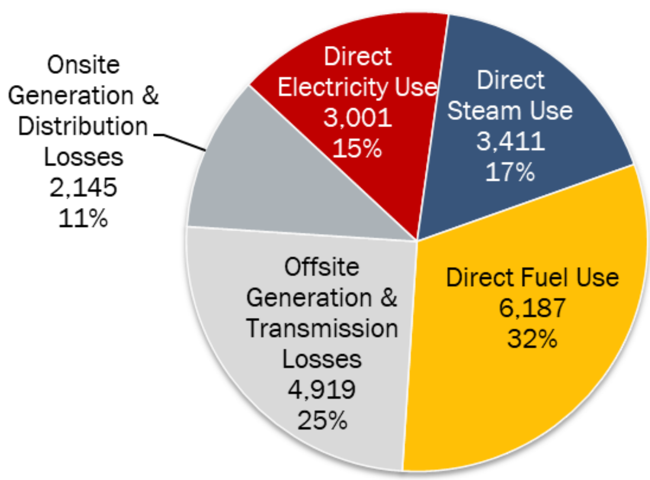

Figure 7. U.S. manufacturing direct energy use and loss, 2018. *Source:* DOE 2021

Table 3. U.S. manufacturing energy consumption summary, 2018

Category	Energy (TBtu)
Total primary energy	19,663
Offsite losses	4,919
Onsite energy	14,744

Onsite losses	7,130
Steam generation and distribution	1,969
Electricity generation	177
Process energy	4,433
Nonprocess energy	552
Energy for all purposes*	24,355

*Energy for all purposes is defined as the total first use of energy onsite plus offsite generation and transmission losses.

Footprints Emissions Results

U.S. manufacturing facilities emitted 1,165 million metric tons of CO_2 equivalent (MMT CO_2e) in 2018 (DOE 2021). The footprints provide details on the breakdown of offsite and onsite combustion emissions and process emissions overall and by end use. Figure 8 displays the breakdown of the emission types and emissions by energy type. As shown in the left chart, onsite combustion accounted for over half of total emissions, followed by one-third from offsite combustion, and 15% from onsite process (non-combustion) emissions. Overall, Scope 1 emissions (onsite combustion and process) account for 67% and Scope 2 emissions (offsite combustion) account for 33%.

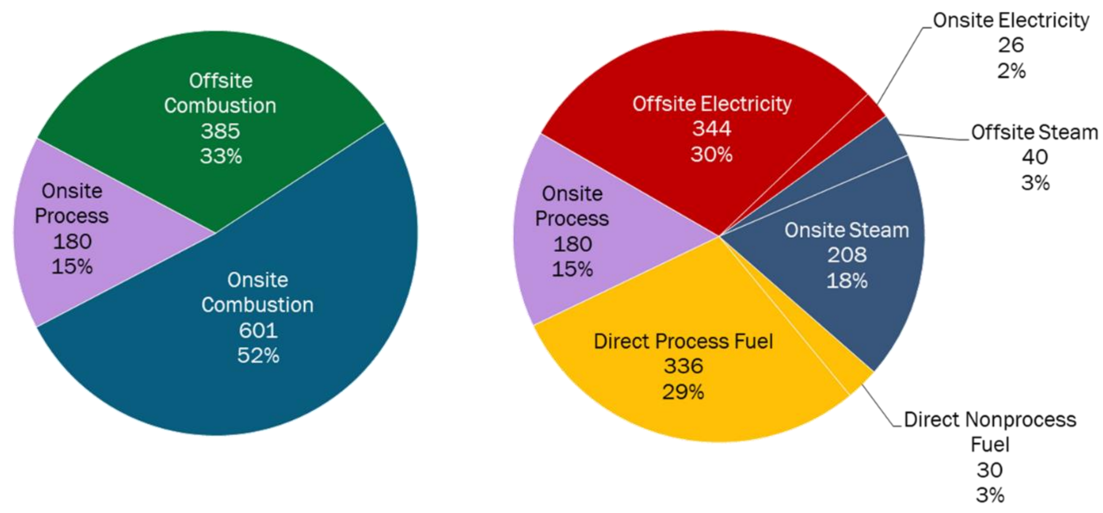

Figure 8. U.S. manufacturing GHG emissions by emission type (left) and energy type (right)

Emissions from onsite non-combustion processes (i.e., process emissions) are those released from physical or chemical transformation of raw materials and process equipment leaks, rather than from fuel combustion.[14] This analysis is the first time that Manufacturing Energy and Carbon Footprints include process emissions; prior footprints analyses (2014 and earlier data) considered only combustion emissions. The process emissions are based on an analysis of data from the Industrial Processes and Product Use chapter of the U.S. Environmental Protection Agency's (EPA's) *Inventory of U.S. Greenhouse Gas Emissions and Sinks* (EPA 2021). Examining detailed process-level data reported by MECS and EPA enables analysts and

[14] An example of process emissions are the emissions released during clinker production process when raw materials are heated in a cement kiln.

policymakers to better understand and visualize energy use and GHG emissions in U.S. manufacturing.

The Footprints analyze and map 15 manufacturing sectors that collectively represent 94% of the total manufacturing sector's GHG emissions. Emissions detail on each sector and overall U.S. manufacturing are provided in Table 4. The five highest emitting sectors account for about 75% of the total U.S. manufacturing GHG emissions, with chemicals and petroleum refining together accounting for approximately half of the total. Process emissions are concentrated in five sectors: chemicals; iron and steel; cement; computers, electronics, and electrical equipment; and alumina and aluminum.

Table 4. U.S. manufacturing emissions by sector, 2018

Sector	**GHG Emissions (million metric tons CO_2e)**				
	Offsite Combustion Emissions	Onsite Combustion Emissions	Total Combustion Emissions	Onsite Process Emissions	Total GHG Emissions
Chemicals	90	171	261	71	332
Petroleum Refining	33	211	244	0	244
Iron and Steel	29	27	56	45	100
Food and Beverage	51	45	96	0	96
Forest Products	35	44	80	0	80
Cement	5	22	27	39	66
Transportation Equipment	23	9	32	0	32
Plastics	22	5	27	0	27
Computers, Electronics, and Electrical Equipment	15	4	19	5	24
Fabricated Metals	17	7	23	0	23
Alumina and Aluminum	12	6	18	3	21
Glass	6	7	14	1	15
Machinery	11	4	14	0	14
Textiles	7	2	9	0	9
Foundries	5	2	7	0	7
All Manufacturing	385	600	985	180	1,165

Cross-Sector Process Heating Opportunities

Process heating is the largest end use of energy in the U.S. manufacturing sector, accounting for 60% of energy as shown in Figure 9 (DOE 2021); the majority of process heating energy (66%) comes from fuels (DOE 2021). Additionally, emissions from industrial process heating amount to 360 MMT CO_2e or about 31% of the manufacturing total. In the *Industrial Decarbonization Roadmap*[15] (DOE 2022d), process heating plays a large role in identified decarbonization opportunities, including through improving energy efficiency, electrifying process heat, and better utilizing of heat resources (e.g., waste heat recovery, heat upgrading/reuse).

[15] The *Industrial Decarbonization Roadmap* identifies decarbonization pathways for five emissions-intensive manufacturing sectors (petroleum refining; chemicals; iron and steel; cement; and food and beverage).

Literature and data on process heating systems energy losses are not readily available for manufacturing overall or specific sectors to help determine where the best improvement opportunities exist. Process heating in manufacturing varies widely in terms of the size and type of equipment used. To address this information gap for the footprints, a 11- member process heating working group (PHWG) of industry experts was convened in June 2021 to estimate process heating energy losses for various manufacturing sectors. The estimates provide a breakdown of process heating energy loss by sector, supporting efforts to evaluate opportunities to promote rapid decarbonization and improve energy efficiency.[16]

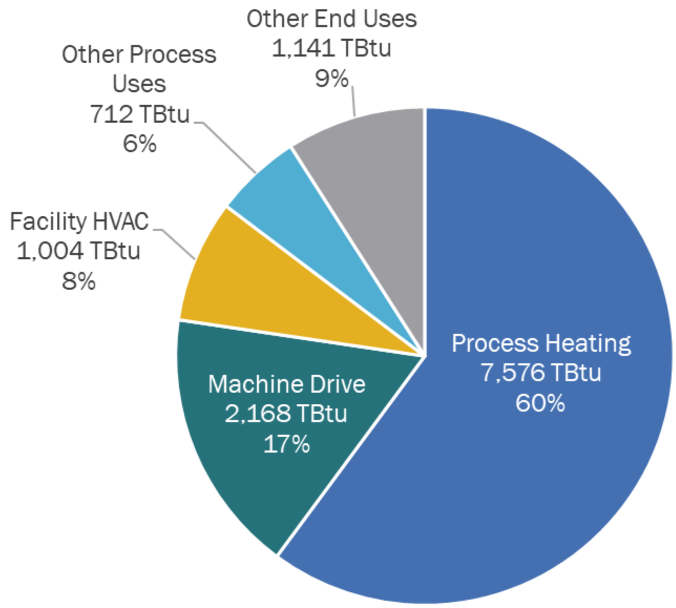

Figure 9. U.S. manufacturing onsite process and nonprocess end use energy consumption, 2018. *Source:* DOE 2021

Process heating loss is defined as the inefficiency (unrecovered heat loss) associated with industrial heating equipment, including furnaces, steam heat exchangers, and electric heaters. Heat loss is defined as any thermal energy generated in the process that is not directly transferred to the material being heated and includes exhaust losses, leaks in the combustion gas to the environment, and radiative heat loss.

The PHWG estimated process heating losses for 2018 for U.S. manufacturing as a whole and 15 energy-intensive manufacturing sectors representing 95% of manufacturing process heating energy use. Table 5 summarizes the process heating energy consumption, share of total U.S. manufacturing process heating energy use, and losses. The energy used for process heating in 2018 included approximately 5,003 TBtu of fuel, 2,276 TBtu of steam, and 297 TBtu of electricity (DOE 2021). The types of fuels included natural gas, coal, biomass, fuel oils, liquefied gases, and byproduct fuels.

[16] For more information on references used by the PHWG, see Table 4 in the supporting document 2018 Manufacturing Energy and Carbon Footprints: Definitions and Assumptions.

Table 5. U.S. manufacturing sectors ranked by process heating energy consumption in 2018

Sector	Process Heating Energy Consumption, TBtu	Percent of Total U.S. Manufacturing Process Heating Energy Use, %	Process Heating Energy Loss, TBtu	Percent Process Heating Energy Loss, %
Petroleum Refining	2,469	33%	420	17%
Chemicals	1,708	23%	410	24%
Forest Products	943	12%	563	60%
Iron and Steel	746	10%	337	45%
Food and Beverage	465	6%	258	55%
Cement	222	3%	102	46%
Glass	144	2%	84	58%
Fabricated Metals	97	1%	33	34%
Alumina and Aluminum	96	1%	43	45%
Transportation Equipment	85	1%	38	45%
Plastics and Rubber	64	1%	14	23%
Foundries	56	1%	29	51%
Computers and Electronics	37	<1%	13	34%
Textiles	28	<1%	17	59%
Machinery	26	<1%	9	34%
All Manufacturing	7,576	100%	2,496	33%

Roughly half of the 15 sectors have similar process heating loss percentages, in the range of 30–50%. However, a large disparity is observed at the extremes. Process heating loss for the petroleum refining industry is estimated at 17%, while the losses for the forest products and textiles are roughly 60%. This variation is largely attributable to differences in the dominant heating processes within each sector and the impact of high-efficiency technologies, like waste heat recovery.

Thermal drying, which is associated with high exhaust losses, accounts for a significant portion of process heating energy consumption in the forest products, textiles, and food and beverage manufacturing sectors, contributing to their high overall process heating loss. On the other hand, petroleum refining has the lowest process heating loss percentage of all the manufacturing sectors, mostly due to extensive use of waste heat recovery and thermal integration. The recovery process generally yields greater benefits in refining than in other sectors because it is more effective when applied to liquids and gases than to the solid feedstocks and intermediaries used in other sectors. The high operating temperatures and exothermic behavior of some refining and chemical manufacturing processes also improve the opportunity for waste heat recovery and minimizing process heating loss.

Variations in process heating loss may arise due to many combinations of factors, including but not limited to:

- Sophistication of process heating equipment
- Average equipment age
- Process heating temperature
- Usage of heat recovery systems
- Number of process heating steps
- Heat transfer volume

- Equipment specifications/operating conditions
- Materials used in the process heating equipment
- Energy mix of process heating input

By identifying the factors that contribute to process heating loss in different sectors, IEDO and other stakeholders can focus their R&D efforts on energy efficiency and emissions reductions solutions that will have the most impact in industrial process heating. A recent DOE (2023) report considers the energy, emissions, and environmental impacts of two different electrification pathways for cement pyroprocessing through a life cycle assessment. The 2015 Quadrennial Technology Review *Process Heating Technology Assessment* (DOE 2015) and the 2022 report *Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy* (DOE 2022f) provide more information on opportunities for improving industrial process heating efficiency. DOE's Industrial Heat Shot[17] and recently announced Electrified Processes for Industry without Carbon (EPIXC) Institute[18] provide examples of the process heating-focused decarbonization efforts.

Other Manufacturing Energy and Emissions Visualizations

The energy and emissions data from the footprints is also available in a Sankey diagram format, as shown in Figure 10 and Figure 11. Sankey diagrams provide a graphical representation of weighted energy and emissions flows within the manufacturing sector, showing how the energy inputs (on the left) are either transformed to applied energy or losses (Figure 10) or combustion and process emissions (Figure 11) (on the right).

In Figure 10, the primary energy (fuel, electricity, and steam) entering manufacturing facilities is shown on the left. A significant portion of the primary energy is lost during offsite electricity generation, transmission, and distribution to manufacturing (bottom dark grey bar). Further losses (represented by the light gray bars) occur during onsite generation, process energy end use, and nonprocess energy end use (supporting functions). As shown in the bottom right grey box, total losses (offsite and onsite) amount to 12,048 TBtu. Applied energy (top right green box) amounts to 7,615 TBtu. Definitions and energy Sankey diagrams for six different manufacturing sectors (including overall consumption and loss like Figure 10 below, onsite generation, process energy, and nonprocess energy) are available on the DOE website.[19]

This footprint iteration added a new set of carbon Sankey diagrams (Figure 11), showing the GHG emissions generated in U.S. manufacturing in 2018. The left side provides a breakdown of each offsite energy supply type (electricity, fuel (natural gas, liquid petroleum-based fuels, coal, and other fuels), and steam). The diagram shows the distribution of the offsite energy supply to onsite generation, process end uses, and nonprocess end uses, followed by the resulting process (dark purple) and combustion emissions (light purple). Definitions and carbon Sankey diagrams for all manufacturing and six carbon-intensive manufacturing sectors are available on the DOE website.[20]

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[17] For more information on the Industrial Heat Shot, visit www.energy.gov/eere/industrial-heat-shot

[18] The EPIXC Institute was announced by DOE on May 16, 2023. See https://www.energy.gov/eere/articles/doe-selects-arizona-state-university-lead-new-institute-drive-industrial

[19] Energy Sankeys are available for all manufacturing, cement, chemicals, food & beverage, forest products, iron & steel, and petroleum refining at www.energy.gov/eere/iedo/2018-manufacturing-static-energy-sankey-diagrams.

[20] Carbon Sankeys are available for all manufacturing, cement, chemicals, food & beverage, forest products, iron & steel, and petroleum refining at www.energy.gov/eere/iedo/2018-manufacturing-static-carbon-sankey-diagrams.

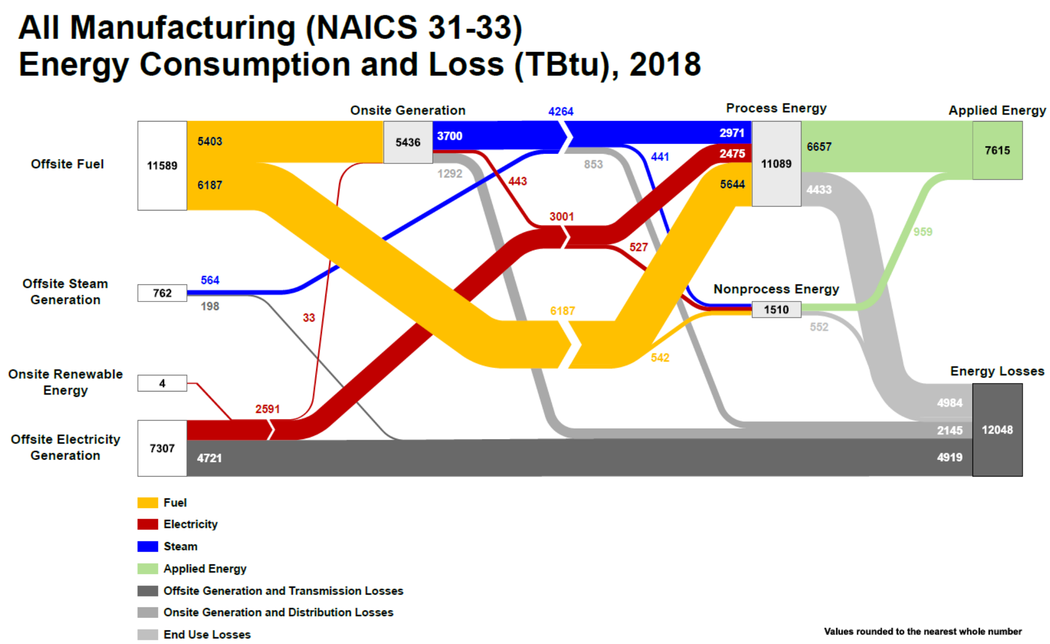

Figure 10. U.S. manufacturing energy consumption and loss Sankey diagram, 2018. Values in TBtu. *Source:* DOE 2022b

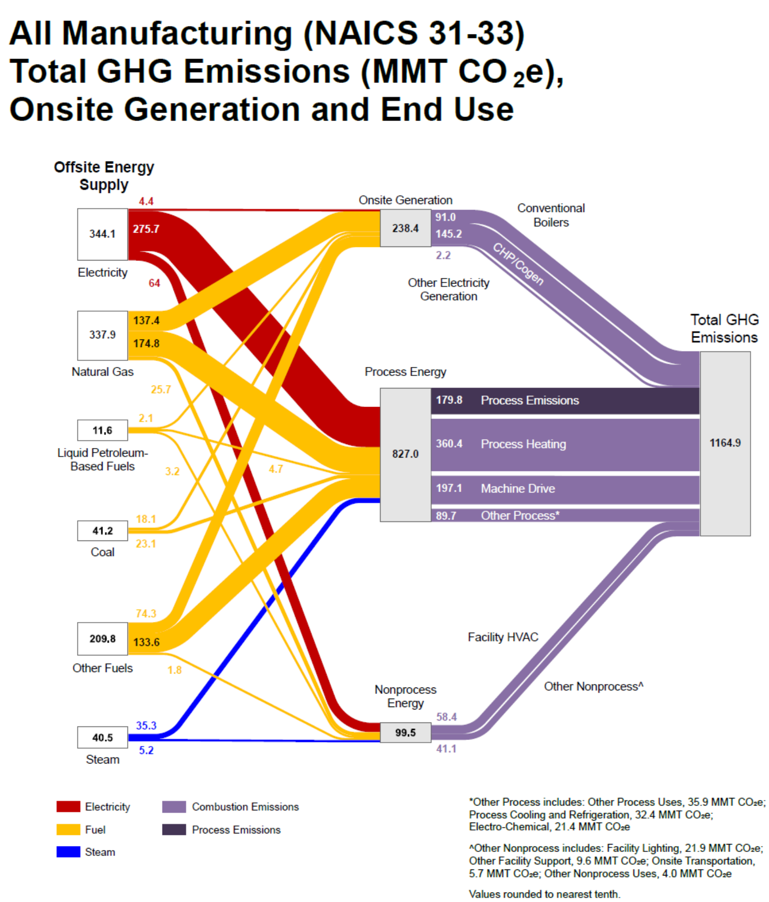

Figure 11. U.S. manufacturing carbon Sankey diagram, 2018. *Source:* DOE 2022a

Conclusions

To reach the ambitious U.S. industrial decarbonization goals, all opportunities to reduce energy and emissions will need to be considered. Through this effort, baseline energy and emissions data is presented in numerous forms, including footprints, Sankey diagrams, and summary figures to provide context on energy use within manufacturing sectors and subsectors. Detail is shown on electricity, fuel, and steam allocated to various end uses, offsite and onsite losses, and resulting combustion and process emissions. An example deep dive using the footprints analysis is provided in this paper on industrial process heating, providing context on the challenges in estimating losses considering the wide range of manufacturing equipment sizes and applications. Identifying where the losses occur can help researchers target what energy or emission reduction technologies would have the greatest impact within and across manufacturing. The manufacturing energy and carbon footprints provide a key reference for industrial decarbonization stakeholders seeking foundational baseline data and a framework for energy and emissions reductions opportunities within manufacturing as a whole or specific sectors.

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