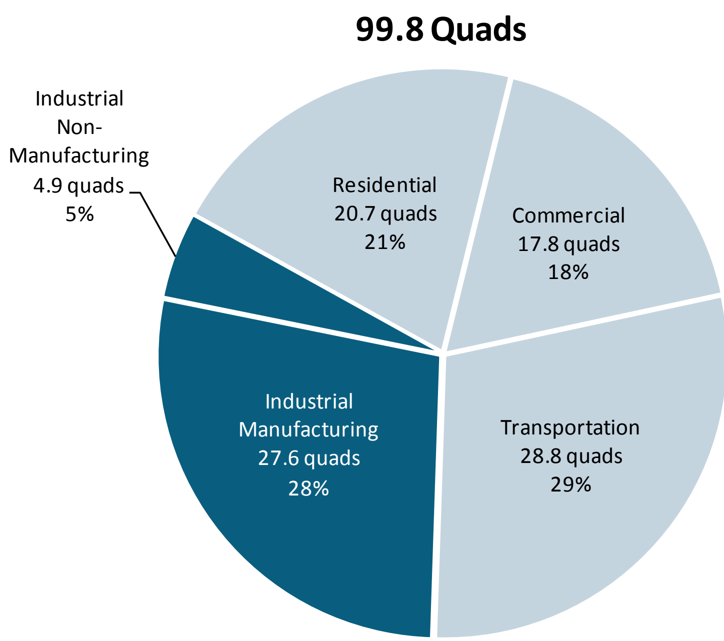
INTRODUCTION

1.1 BACKGROUND

1.1.1. The Importance of Energy Efficiency in U.S. Manufacturing

The United States (U.S.) manufacturing sector uses significant amounts of energy to convert raw materials into usable products. As shown in Fig. 1.1-1, the U.S. manufacturing sector is estimated to consume over one quarter of all U.S. energy use.



Note: The manufacturing energy consumption value shown in this figure is based on analysis presented in this report, while all other energy consumption values in this figure utilize data collected from the EIA Annual Energy Review 2009 [EIA 2010a].

Fig. 1.1-1. 2006 U.S. energy consumption [EIA 2010a]

According to manufacturing energy use statistics from the U.S. Department of Energy's Energy Information Administration (EIA), the U.S. manufacturing sector consumed 21.1 quadrillion Btu (quads) of fuel and feedstock energy [EIA 2009] in 2006. When the estimated electricity and steam losses outside the plant (offsite) are included in this total, the primary and feedstock energy consumed by U.S. manufacturing increases to 27.6 quads. Total U.S. energy consumption for all sectors in 2006 was 99.8 quads [EIA 2010a]. Of this total, the industrial sector consumed 32.5 quads, or 33%. Of this 33%, manufacturing consumed approximately 28%, while non-manufacturing sectors (including agriculture, mining, and construction) consumed the remaining 5% of industrial energy.

The efficiency of energy use, as well as the cost and availability of energy, have a substantial impact on the competitiveness and economic health of U.S. manufacturers. More efficient use of energy lowers production costs, conserves limited energy resources, and increases productivity. More efficient energy use also improves the environment by reducing emissions of greenhouse gases and air pollutants.

Energy efficiency measures the effectiveness with which energy is converted into usable work or heat. *Efficiency* is a term commonly used to measure the performance of energy conversion equipment, such as process heaters, boilers, and power generators; it is defined as the ratio of useful heat and/or electricity output to the heat content of the fuel consumed. The physical parameters of a process, as well as equipment design, age, and operating and maintenance practices, can lead to real-world performance that is well below the ideal efficiency. Less-than-optimal energy efficiency means that some of the input energy is lost either mechanically or as waste heat. Energy losses cost U.S. manufacturers billions of dollars each year and generate millions of metric tons of greenhouse gas emissions.

Increasing the efficiency of energy use could substantially benefit U.S. manufacturers and the nation, but the thousands of complex manufacturing processes make this a daunting task. However, significant opportunities to address energy efficiency exist in the common energy systems used across manufacturing sectors, such as boilers, onsite power systems, fired heaters, heat exchangers, compressors, motors, pumps, and others. A first step in realizing these opportunities is to identify how manufacturers are using energy. Where does this energy come from? What form is it in? Where is it used? How much is lost? This report is intended to help answer these questions for the U.S. manufacturing sector.

1.1.2. Focus and Goals of this Report

The U.S. Department of Energy's Advanced Manufacturing Office (DOE/AMO) conducts research, development, and deployment (RD&D) to accelerate the development and implementation of energy-efficient and environmentally sound industrial technologies and manufacturing practices. This analysis is designed to help DOE/AMO focus R&D efforts on the most significant opportunities for reducing energy consumption.

This report documents the energy pathway, from supply through demand, for several of the most energy-intensive manufacturing sectors. It captures step-by-step energy use and losses from offsite sources, onsite generation, and process and nonprocess end uses. A key output of this analysis is the "footprint" that graphically displays energy use and associated greenhouse gas (GHG) combustion emissions across U.S. manufacturing process and nonprocess end uses. Areas of high energy losses and GHG emissions represent central targets of opportunity for more advanced, efficient energy systems.

The methodology and approach used in conducting this analysis is described below. The report is organized into individual profiles of the largest energy-consuming industries (chemicals, forest products, petroleum refining, food and beverage, and iron and steel) and an aggregated energy profile for U.S. manufacturing as a whole.

1.2 METHODOLOGY

1.2.1. Scope of Footprint Analysis

This analysis examines a large subset of U.S. manufacturing to capture the bulk of energy consumption and GHG emissions. Table 1.2-1 lists the 15 manufacturing sectors selected for analysis, which together represent about 94% of U.S. manufacturing energy consumption. A footprint is created for each of the sectors selected for analysis and the U.S. manufacturing sector is also analyzed as a whole and shown in a sixteenth footprint.

Manufacturing sectors were selected on the basis of their relative energy intensities, contributions to the economy, and pertinence to existing energy efficiency programs. As shown in Table 1.2-1, the 15 manufacturing sectors are comprised of a combination of subsectors defined by their respective North American Industry Classification System (NAICS) codes. The scope of these 15 sectors is explained in Appendix B. A complete set of the two-page footprint diagrams for all sectors, including the All Manufacturing footprint, can be found in Appendix C. The footprints are also available at the DOE/AMO website,[1] along with documents outlining assumptions, definition of terms, and references.

[1] AMO footprints website: http://www1.eere.energy.gov/manufacturing/resources/footprints.html

Table 1.2-1. Manufacturing sectors selected for analysis

Food and beverage NAICS 311 Food NAICS 312 Beverage and tobacco products	**Iron and steel** NAICS 3311 Iron and steel mills and ferroalloys NAICS 3312 Steel products
Textiles NAICS 313 Textile mills NAICS 314 Textile product mills NAICS 315 Apparel NAICS 316 Leather and allied products	**Alumina and aluminum** NAICS 3313
Forest products NAICS 321 Wood products NAICS 322 Paper	**Foundries** NAICS 3315
Petroleum refining NAICS 324110	**Fabricated metals** NAICS 332
Chemicals NAICS 325	**Machinery** NAICS 333
Plastics and rubber products NAICS 326	**Computers, electronics, and electrical equipment** NAICS 334 Computer and electronic products NAICS 335 Electrical equipment, appliances, and components
Glass and glass products NAICS 3272 Glass and glass products NAICS 327993 Mineral wool	**Transportation equipment** NAICS 336
Cement NAICS 327310	

1.2.2. Source Data and Adjustments

The analytical model for detailing sector-specific energy use and loss and associated GHG emissions reflects the latest energy-use statistics, relevant emissions guidelines, and input from industry experts. Energy-use statistics were obtained from the most recent DOE/EIA-published *Manufacturing Energy Consumption Survey* (MECS) results for survey year 2006 [EIA 2009]. The MECS data tables were adjusted to account for withheld data or to avoid double-counting. In addition, some assumptions were introduced when estimating energy losses and steam allocation; these are discussed later in this section. The adjustments and assumptions applied to the MECS data are outlined in Appendix D, Footprint Data Adjustments and Assumptions. Steam allocation assumptions are outlined in Appendix E, Allocation of Steam to Process and Nonprocess End Uses. Process heating loss assumptions are outlined in Appendix F, Estimation of Process Heating Energy Loss. ***As a result of these adjustments, the energy use and loss values in the footprints do not directly represent MECS data, and should not be cited as MECS output.***

The electrical end use distribution to machine driven systems was obtained from the 2002 Oak Ridge National Laboratory study, *U.S. Industrial Electric Motor Systems Market Opportunities Assessment* [OIT EERE 2002b]. In this 2002 study, motor populations from 265 industrial facilities across the country were inventoried, which resulted in a motor size and motor application database by manufacturing sector. Motor applications were grouped into six system areas – pumps, fans, compressed air, materials handling, materials processing, and other systems. Machine driven system energy for refrigeration was not included as a motor application system area in the footprint analysis because it is already accounted for in MECS reported process cooling and refrigeration end use. Machine drive system allocation and assumptions are outlined in Appendix D.

1.2.3. Carbon Footprint Analysis

Both the Environmental Protection Agency's (EPA) *Mandatory Greenhouse Gas Reporting Rule* [EPA 2009b] and the EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks* [EPA 2010] were referenced in formulating the methodology and emission factors used for calculating greenhouse gas (GHG) emissions in this report. The carbon footprint calculations in this analysis conform to EPA GHG mandatory reporting requirements, referencing the same emissions calculations and fuel-specific emission factors. Unique emission factors were used for each sector based on fuel type breakdown. Emissions are reported as CO_2-equivalent (CO_2e), as per the GHG reporting requirements. CO_2e emissions in this report consist of combustion-related emissions of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Process emissions are excluded from the analysis, as these are not directly related to the use of energy as fuel.

All quoted carbon emissions in this report are carbon dioxide-equivalent (CO_2e) GHG emissions, unless explicitly identified otherwise. Effectively, "carbon emissions" will be used interchangeably with "GHG combustion emissions" throughout this report.

1.2.4. A Walkthrough of the Footprints

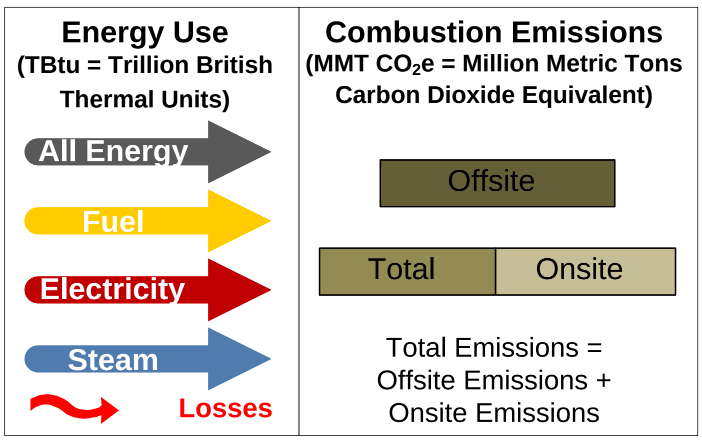


Fig. 1.2-1. Footprint legend

The output from the footprint model is presented in the form of graphical "footprints" that map the flow of energy supply, demand, and loss for selected U.S. manufacturing industries. The model and footprints can be adapted to other sectors and subsectors as needed. Fig. 1.2-1 previews the color legend used throughout this report. The chemicals sector energy and carbon footprint is provided as an example in Fig. 1.2-2 and Fig. 1.2-3. Each footprint consists of two figures; the first figure offers an overview of the sector's total **primary energy** flow including offsite energy and losses, while the second figure presents a more detailed breakdown of the **onsite energy** flow. (Note: All footprints do not include feedstock energy, which is discussed separately in section 2.1.2.). The term "Total" in the footprints refers to the total sum of offsite and onsite values. In energy terms, this is often referred to as *total primary energy*.

Energy use is shown as input and output flow lines to the various pathway stages; energy values appear in white font within the flow arrows. Energy use is broken down by energy type and distinguished by color (as shown in Fig. 1.2-1): dark gray = all energy, yellow = fuel, dark red = electricity, and blue = steam. Energy losses are represented as wavy red arrows. GHG emissions are shown in the boxes along the bottom of each pathway stage. Offsite, onsite, and total GHG emissions are distinguished by color as shown in the legend: dark brown = offsite emissions, light brown = onsite emissions, and medium brown = total emissions (offsite + onsite).

The footprint pathway captures both energy supply and demand. On the supply side, the footprints provide details on energy purchases and transfers in to a plant site (including fuels derived from byproducts), and onsite generation of steam and electricity. On the demand side, the footprints illustrate the end use of energy within a given sector, from process energy uses such as heaters and motors, to nonprocess uses such as heating, ventilation, and air conditioning (HVAC) and lighting. Fuel and electricity end use allocations in each sector are based on MECS data, while sector-specific steam end use allocations are summarized in Table 1.2-3 and detailed in Appendix E. The footprints also identify where energy is lost due to generation and distribution losses and system inefficiencies, both inside and outside the plant boundary. Losses are critical, as they represent immediate opportunities to improve efficiency and reduce energy consumption through best energy management practices and technologies.

The energy footprint shown in Fig. 1.2-2 shows primary energy, beginning with the fuel, electricity, and steam supplied to the plant boundary from offsite sources (power plants, fuel and gas distributors, etc.). Many industries generate byproduct fuels that are also part of the energy supply. Notable examples include black liquor and wood byproducts used in pulp and paper mills and waste gas from petroleum refineries.

The energy footprint shown in Fig. 1.2-3 shows onsite energy demand by energy type and end use. The onsite energy that reaches the plant boundary is used either indirectly for onsite generation or directly for process and nonprocess end uses. Onsite energy generation, consisting of conventional boilers, combined heat and power (CHP)/cogeneration systems controlled by a manufacturing establishment, and other electricity generation such as renewable energy sources, contributes to the electricity and steam demands of process and nonprocess end uses. A percentage breakdown of energy use by fuel type, including fuels derived from byproducts, is presented as a yellow call out box at the beginning of the onsite fuel pathway.

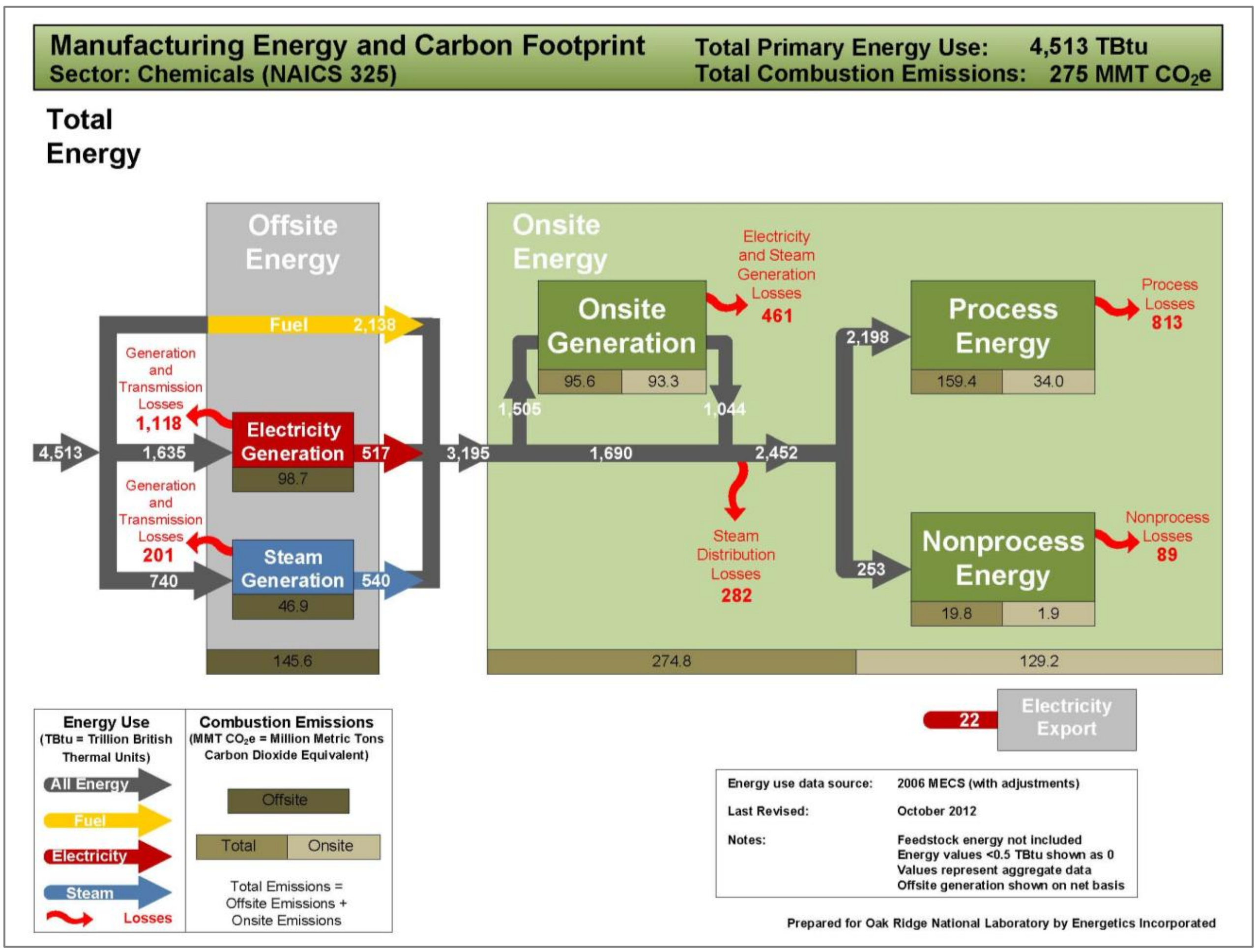


Fig. 1.2-2 Total primary energy use and GHG combustion emissions for the chemicals sector

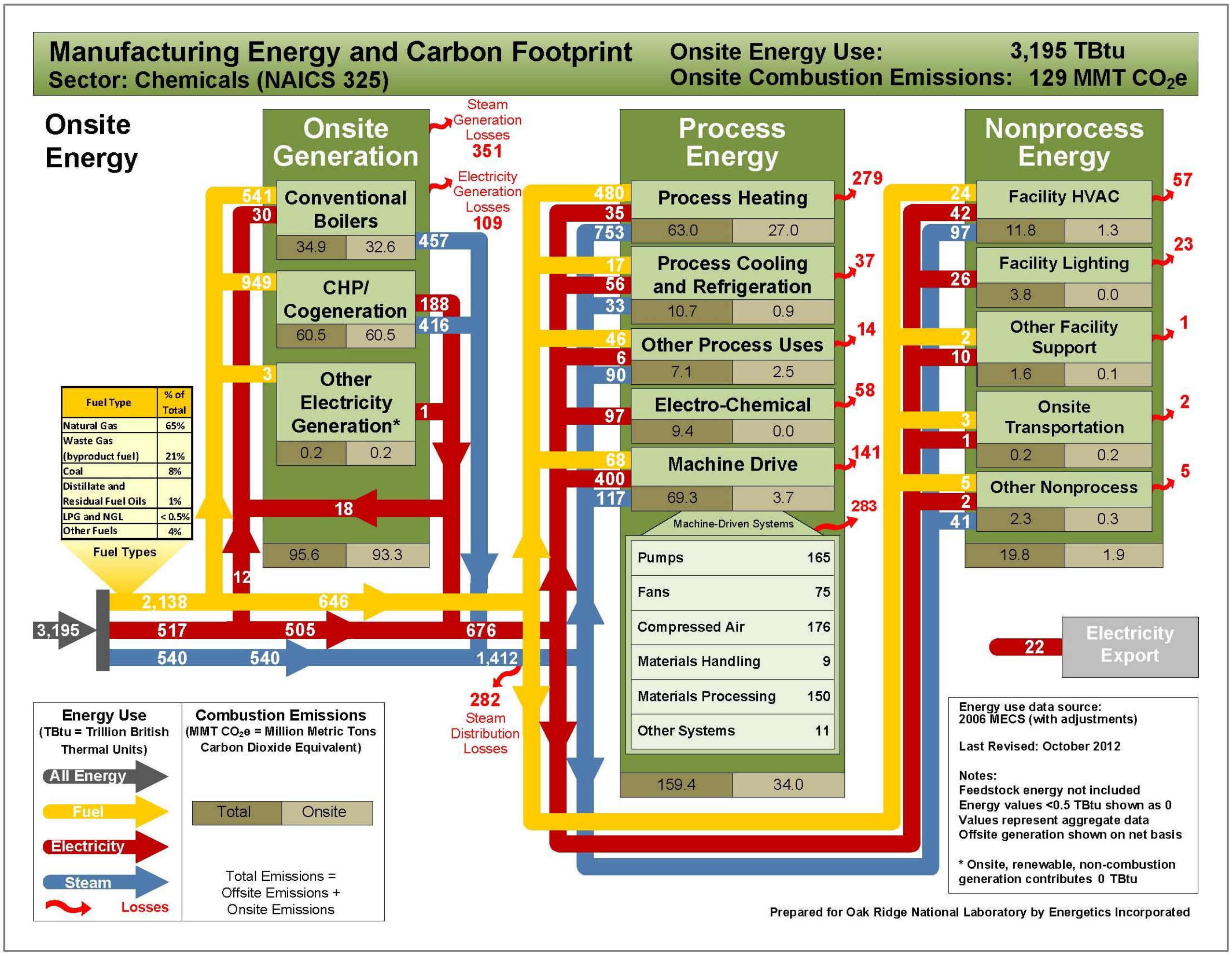


Fig. 1.2-3. Onsite energy and carbon emissions for the chemicals sector

Often, onsite generation of electricity creates more energy than is needed at the plant site. When this occurs, the excess electricity is exported offsite to the local grid or other nearby plants. Total primary and onsite energy use values in the footprint are based on net electricity and do not include exported electricity (though the value of electricity exports is provided on the footprint for reference). Steam can also be generated onsite and exported to other nearby plants; however, exported steam is accounted for in the MECS net steam data, and thus is not explicitly shown in the footprint.

Process energy systems consist of the equipment necessary for process heating (e.g., kilns, ovens, furnaces, strip heaters), process cooling and refrigeration, electro-chemical processes (e.g., reduction processes), machine drive (e.g., motors and pumps associated with process equipment), and other direct process uses. Another step in the energy pathway is the energy that is distributed to nonprocess end uses. This involves the use of energy for facility HVAC, facility lighting, other facility support (e.g., water heating and office equipment), onsite transportation, and other nonprocess use.

Energy losses occur along the entire energy pathway from generation and delivery to end use. Energy is lost in generating power and steam, in transmitting power and steam, and in process and nonprocess end use of power, steam, and fuel. In the footprint analysis these energy loss values are estimated. Energy losses vary greatly by industry and by facility, so conservative sector-wide energy loss estimates are assumed with the understanding that these estimates are highly dependent on the specific manufacturing plant site. A summary of footprint loss assumptions is presented in Table 1.2-2 and in Appendix D. In addition, process heating loss assumptions are detailed in Appendix F.

Energy losses do not equate to recoverable energy. While a portion of energy losses are recoverable, this report does not attempt to identify and distinguish between recoverable and non-recoverable losses. Identifying the portion of losses that is recoverable through use of more efficient technologies and practices is a worthwhile subject that requires further study. Some examples of non-recoverable energy losses include a) heat storage in a batch furnace where losses are not economically recoverable; b) transmission losses where low quality energy loss is impractical to recover over a long distance, c) frictional losses. The recovery of waste heat depends on many factors, including waste heat temperature, quantity, accessibility, quality/cleanliness, corrosiveness, and intended use. The distinction between recoverable and non-recoverable waste heat losses are discussed in more detail in the 2008 DOE ITP publication, Waste Heat Recovery: Technology and Opportunities in U.S. Industry [ITP EERE 2008b].

Table 1.2-2. Manufacturing energy footprint loss assumptions

Energy system	Percent energy lost
Energy generation, transmission, and distribution losses	
Offsite generation	Offsite electricity generation and transmission (grid) – 68.4% Offsite steam generation – 19% Offsite steam transmission – 10%
Onsite generation	Onsite steam generation (conventional boiler) – 20% Onsite CHP/cogeneration – 24.4%–36.3%, see Table D.2 Onsite steam distribution – 20%
Onsite process and nonprocess losses	
Process energy	Process heating – 18%–68%, see Table D.3 Process cooling and refrigeration – 35% Electro-chemical – 60% Other processes – 10% Machine drive (shaft energy) – electric 7%, fuel 60%, steam 50% Machine driven systems Pumps – 40% Fans – 40% Compressed air – 80% Materials handling – 5% Materials processing (e.g., grinders) – 90% Other systems – 5%
Nonprocess energy	Facility HVAC – 35% Facility lighting – 88% Other facility support – 10% Onsite transportation – 60% Other nonprocesses – 10%

Note: The values in this table are gross assumptions used to generate order-of-magnitude energy loss estimates. Energy generation and transmission loss assumptions are based on EIA data. Process and nonprocess loss assumptions are drawn from discussion with industry experts and have been substantiated where possible with review of relevant studies. In practice, these energy loss assumptions are heavily dependent on specific operating equipment and conditions and vary greatly within and across manufacturing sectors.

Table 1.2-3. Steam allocation assumptions

Sector	Steam end use allocation					
	Process heating	Machine drive	Process cooling/ refrigeration	Other process uses	Facility HVAC	Other nonprocess uses
Alumina and aluminum	31%	13%	0%	27%	21%	7%
Cement	45%	6%	1%	16%	27%	6%
Chemicals	67%	10%	3%	8%	9%	4%
Computers, electronics and electrical equipment	16%	0%	1%	7%	73%	4%
Fabricated metals	35%	1%	1%	16%	46%	2%
Food and beverage	69%	4%	5%	8%	10%	3%
Forest products	70%	9%	2%	5%	9%	4%
Foundries	13%	15%	0%	9%	60%	3%
Glass	5%	5%	0%	22%	63%	5%
Iron and steel	46%	7%	0%	8%	38%	1%
Machinery	24%	29%	1%	7%	37%	1%
Petroleum refining	66%	16%	2%	10%	4%	2%
Plastics	71%	1%	0%	7%	18%	3%
Textiles	63%	2%	2%	10%	21%	2%
Transportation equipment	27%	2%	7%	9%	53%	2%
All manufacturing	66%	10%	3%	8%	11%	3%

1.2.4.1. Direct vs. indirect end use

In the MECS data, *purchased energy* and *end use energy* are reported by NAICS sector, in addition to a number of other energy use measures. The resulting energy balance is complicated by a number of factors,[2] one of which is the indirect energy use and loss associated with boilers, CHP units, and other onsite generation equipment. The term "indirect" here means that energy is converted in to another form (e.g., steam or electricity) prior to direct use in process or nonprocess applications. Indirect end use is shown as Onsite Generation in the energy footprint and includes associated onsite generation losses.

EIA does not report the indirect generation of steam, nor does EIA report the end use of steam onsite. In the footprint model, the onsite energy generated in the form of steam and electricity is taken into account and distributed to process and nonprocess end uses. As shown in the onsite energy footprint (second page of the footprint), the indirect energy use for onsite generation (which is primarily fuel) is used to generate steam and electricity that is applied towards direct process and nonprocess end uses. Taken as a whole, the onsite energy footprint presents *indirect* end use, *direct* end use, and the intermediate onsite generation losses that complete the energy balance.

In the sector profiles herein, onsite steam and electricity is typically not equal to the direct end use of steam and electricity due to the conversion of indirect energy. Onsite steam and electricity is a lesser value as it does not include onsite generation, and instead represents only the offsite supply entering the plant boundary. The distinction between the terms *primary energy*, *onsite energy*, *indirect end use*, and *direct end use* has been clarified in Fig. 1.2-4 to avoid misinterpretation of the results.

[2] There are a number of adjustments that were made to the EIA-reported data in the footprint model, including adjustments for

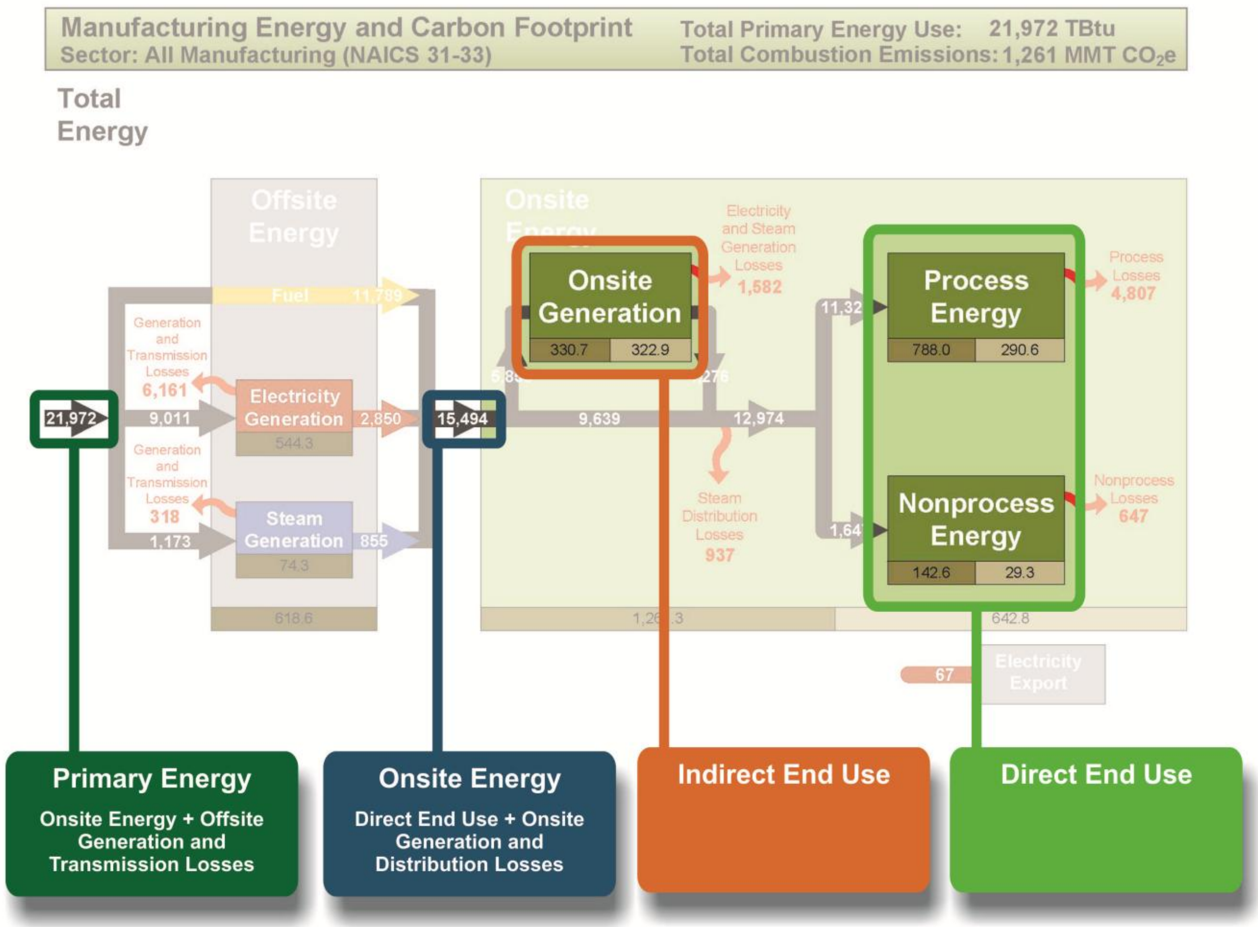


Fig. 1.2-4. Energy profile terminology guide

1.2.5. Applying Footprint Results

The energy and carbon footprints are based on actual plant survey data; therefore, they represent a genuine distribution of energy use and losses across the manufacturing sector as a whole. Through them, the magnitude of energy consumption and losses can begin to be assessed, both by end use and fuel type. They also provide a baseline from which to calculate the benefits of improving energy efficiency. The carbon values in the footprint can be used to support carbon management planning and analysis.

In this report, the results of the footprint analysis are presented from various perspectives to help guide the top energy consumers by energy type or energy application area, and propensity for onsite versus offsite power and steam generation. Section 2.1 examines the U.S. manufacturing sector and ranks sectors by energy consumption in key energy use areas.

These rankings also reveal a select subset of the U.S. manufacturing sectors that warrant further study and analysis. Five manufacturing sectors, each of which utilizes over 1 quad of primary energy, were the chosen focus for the remainder of Chapter 2 in this report: chemicals, forest products, petroleum refining, food and beverage, and iron and steel. Profiles of primary energy; fuel, electricity, and steam use; onsite generation; direct and applied end use; and emissions are highlighted in each sector.