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

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ABSTRACT

Significant opportunities exist for improving energy efficiency in U.S. manufacturing. A first step in realizing these opportunities is to identify how energy is being used. Where does it come from? What form is it in? Where is it used? How much is lost? Answering these questions is the focus of this paper and the analysis described herein.

Manufacturing energy and carbon footprints map energy consumption and losses, as well as greenhouse gas emissions, for the fifteen most energy intensive manufacturing sectors and for the entire U.S. manufacturing sector. A breakdown of energy consumption by energy type and end use allows for comparison both within and across sectors. The footprints provide a macro-scale benchmark from which to evaluate the benefits of improving energy efficiency and for prioritizing opportunity analysis.

In this paper the manufacturing energy footprint analysis approach is described. Peer review was an important element in finalizing the analysis. Two topics were identified during peer review as deserving more rigorous study; one topic related to steam energy use, and the other related to process heating energy loss. Given the lack of published data in these areas and the range of assumptions necessary, two industry-led working groups were formed to devise a reasonable approach for estimating missing values. The results of these peer review efforts and the overall footprint results are summarized in this paper.

Introduction

The U.S. manufacturing sector depends heavily on energy resources to provide fuel, power and steam for the conversion of raw materials into usable products. More-efficient use of energy lowers production costs, conserves limited energy resources and also reduces emissions of greenhouse gases and air pollutants. The efficiency of energy use, as well as the cost and availability of energy, consequently have a substantial impact on the competitiveness and economic health of U.S. manufacturers.

It is clear that increasing the efficiency of energy use could result in substantial benefits to both industry and the nation. Unfortunately, the sheer complexity of the thousands of processes used in the manufacturing sector is daunting; justifying investment in energy efficiency upgrades and equipment is a challenge. Significant opportunities can be justified, however, when considering common energy systems that are used across manufacturing, such as onsite power systems, fired heaters, boilers, pumps, HVAC equipment and others. A first step in realizing these opportunities is to identify how different manufacturing sectors are using energy. Where does it come from? What form is it in? Where is it used? How much is lost? Answering these questions is the focus of Energetics' manufacturing energy footprint analysis.

Manufacturing energy and carbon footprints map energy from supply to end use. The footprints were prepared for the U.S. Department of Energy (DOE) Advanced Manufacturing Office (AMO). Sixteen two-page footprints representing the most energy intensive manufacturing sectors are published on the AMO website (U.S. DOE 2013) and a comprehensive presentation of the results was published in November 2012 in the form of a report titled *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis* (Brueske, Sabouni, Zach, and Andres 2012).

Manufacturing Energy and Carbon Footprints

The footprints provide a quantitative portrayal of manufacturing energy use and loss and associated greenhouse gas emissions. Three main energy types – fuel, electricity, steam – are reported in units of sector-wide, trillion Btu's (TBtu) of energy. Footprints have been published for the following fifteen energy-intensive sectors representing 94% of manufacturing energy use (listed in alphabetical order): aluminum, cement, chemicals, computers and electronics, fabricated metals, food and beverage, forest products, foundries, glass, machinery, petroleum refining, plastics, iron and steel, textiles, and transportation. A sixteenth footprint was created to represent energy use for all of U.S. manufacturing.

Two footprints are provided for each sector, one showing a primary (source) energy perspective and a second showing onsite energy by end use. Onsite end uses of energy are grouped in the footprint as either generation end uses, process end uses, or nonprocess end uses. Providing a breakdown of energy type by end use area allows for a comparison of energy use and emissions sources both within and across sectors.

The footprint color legend is provided in Figure 1 (also shown at the bottom of Figure 2): dark gray = all energy, yellow = fuel, dark red = electricity, and blue = steam. Energy losses are represented as wavy red arrows. Carbon emissions appear in the boxes along the bottom of each pathway stage. Offsite, onsite, and total carbon emissions are distinguished by color as shown in the legend: dark brown = offsite carbon, light brown = onsite carbon, and medium brown = total carbon (offsite + onsite).

The footprint pathway captures both energy supply and demand. On the supply side, the footprints provide details on energy purchases and transfers into a plant site, as well as onsite generation of steam and electricity. Byproduct fuels, such as black liquor and wood byproducts in pulp and paper mills and waste gas from petroleum refineries, are included in the fuel supply. 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 HVAC and lighting. 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 and carbon footprint for the U.S. manufacturing sector is shown in Figure 2 (primary energy) and Figure 3 (onsite energy).

r Legend

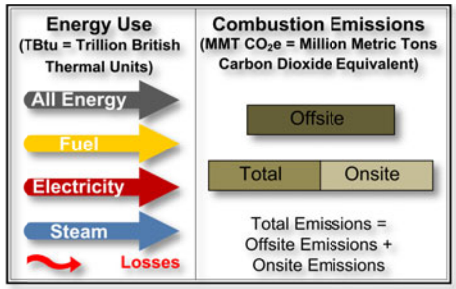


Figure 2. U.S. Manufacturing Energy Footprint, Primary Energy

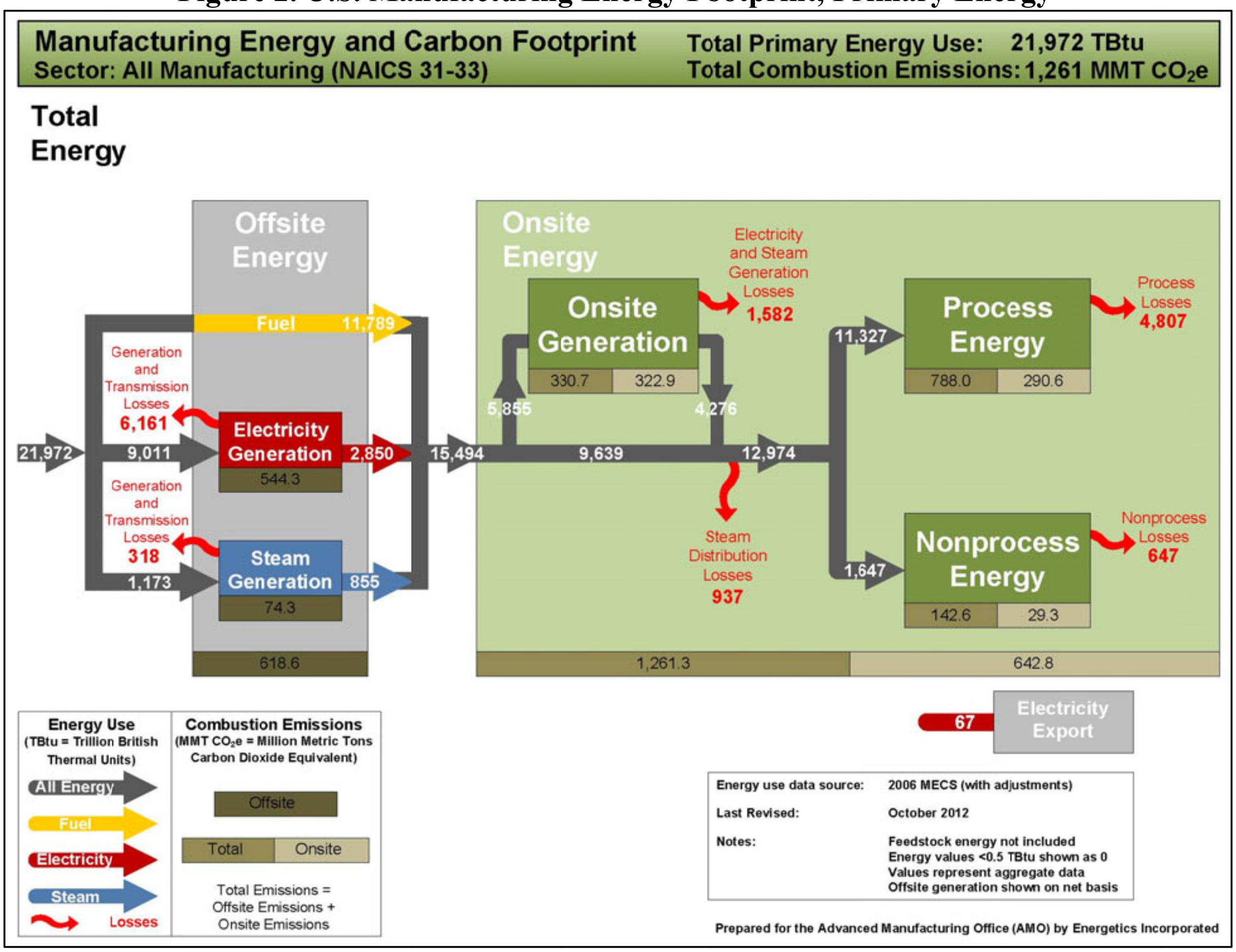
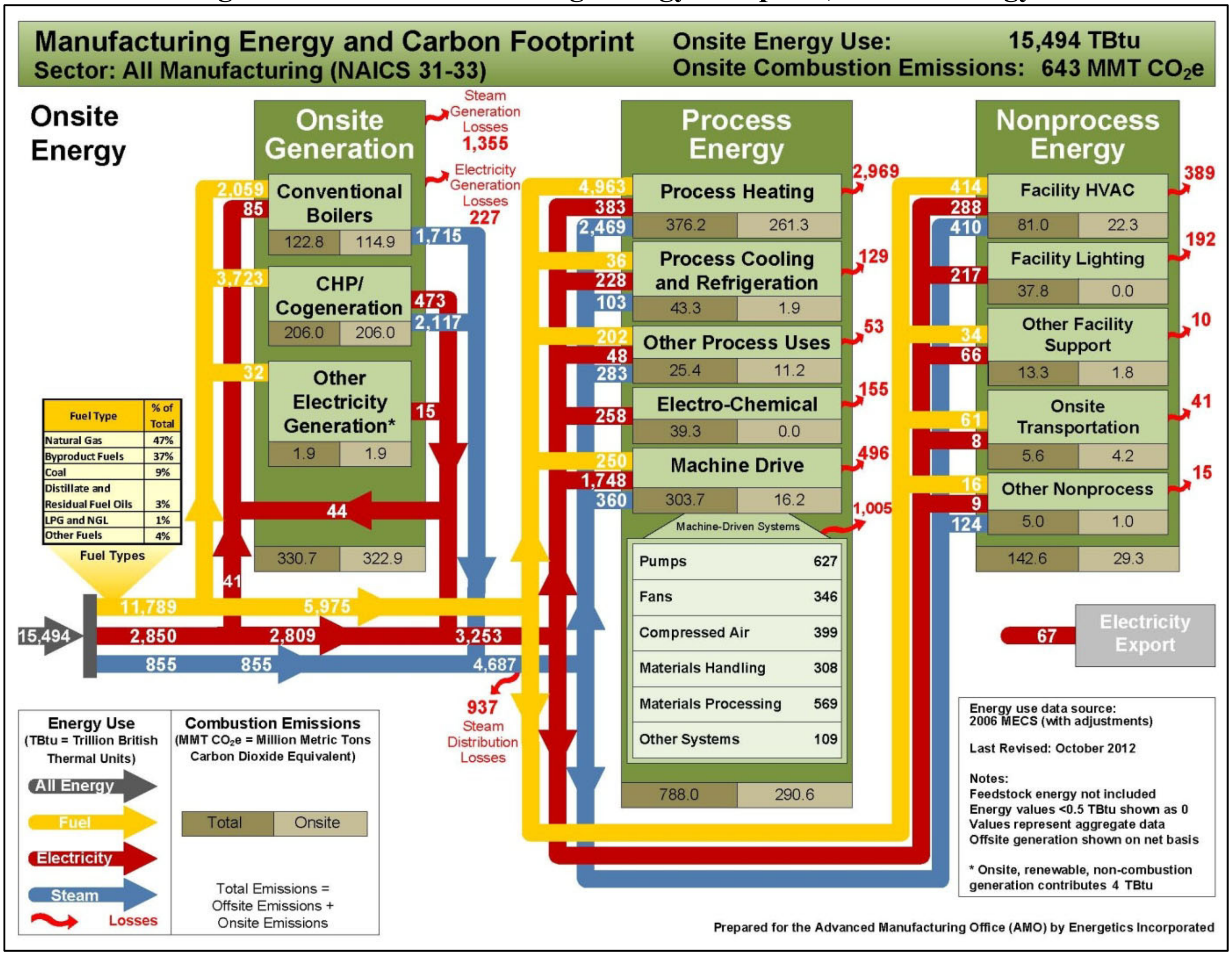


Figure 3. U.S. Manufacturing Energy Footprint, Onsite Energy



Footprint Analysis Approach

The energy and carbon values portrayed in the footprint are the result of a complex analysis effort. Energy-use statistics, relevant emissions guidelines, and industry expertise were all utilized to devise an analytical model for detailing sector-specific energy use and loss and associated carbon emissions. Energetics compiled a network of spreadsheets representing various energy use and emissions calculations and efficiency statistics, and bundled these in to a model that is linked to a software diagramming tool. Energy use statistics were obtained from the DOE, Energy Information Administration (EIA)-published Manufacturing Energy Consumption Survey (MECS), for survey year 2006 (U.S. DOE 2009). (At the time of submitting this paper to ACEEE MECS 2006 was the most current data set; MECS 2010 data has since been released by EIA and Energetics is currently in the process of updating the energy footprint model.)

The MECS is a mandatory self-administered nationally representative sample survey of approximately 15,500 U.S. manufacturing establishments. The survey is conducted by EIA every four years; the U.S. Census Bureau, with guidance from EIA, selects the manufacturing population using the North American Industry Classification System (NAICS). In order to complete an accurate balance of manufacturing energy use, several adjustments and assumptions were applied to the MECS data table.[1] As a result, the energy use and loss values in the footprints do not directly represent MECS data, and should not be cited as MECS output.

Scope of the footprints. The footprint analysis examines a large subset of U.S. manufacturing, with the objective of capturing the bulk share of energy consumption and carbon emissions. Table 1 shows the fifteen manufacturing sectors selected for footprint analysis which collectively contribute 94% of overall manufacturing primary energy use. A sixteenth footprint represents all of U.S. manufacturing energy use.

Table 1. Manufacturing Sectors Selected for Footprint Analysis

Percent of Manufacturing Primary Energy Use		Percent of Manufacturing Primary Energy Use	
All Manufacturing NAICS 31-33	**100%**	**Foundries** NAICS 3315	**1%**
Alumina and Aluminum NAICS 3313	**3%**	**Glass and Glass Products** NAICS 3272 Glass and Glass Products NAICS 327993 Mineral Wool	**2%**
Cement NAICS 327310	**2%**	**Iron and Steel** NAICS 3311 Iron and Steel Mills, Ferroalloys NAICS 3312 Steel Products	**7%**
Chemicals NAICS 325	**21%**	**Machinery** NAICS 333	**2%**
Computers, Electronics, and Appliances NAICS 334 Computer and Electronics NAICS 335 Electrical Equip, Appliances	**2%**	**Petroleum Refining** NAICS 324110	**16%**
Fabricated Metals NAICS 332	**3%**	**Plastics and Rubber Products** NAICS 326	**3%**
Food and Beverage NAICS 311 Food NAICS 312 Beverage and Tobacco Products	**9%**	**Textiles** NAICS 313, 314 Textile and Textile Product Mills NAICS 315, 316 Apparel and Leather Products	**2%**
Forest Products NAICS 321 Wood Products NAICS 322 Paper	**16%**	**Transportation Equipment** NAICS 336	**4%**

Peer Review

Multiple rounds of peer review have taken place to finalize the manufacturing energy and carbon footprints, including review and input from U.S. DOE, Advanced Manufacturing Office, Oak Ridge National Laboratory, and U.S. Energy Information Administration, and representatives from various industry organizations and associations. As a result of the review process, two analysis topics were identified as deserving more rigorous study: 1) estimation of steam allocation to process and nonprocess end uses (steam end use is not provided in MECS), and 2) estimation of energy loss from process heating end use (to include system and exhaust losses). Realizing that there was insufficient published data in these areas to support the analysis and that there were a range of assumptions necessary, Energetics convened two industry-led peer review working groups to guide the analysis approach and peer review the results.

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[1] All footprint analysis assumptions and adjustments are discussed in more detail in the "Definitions and Assumptions" document available at the AMO Manufacturing Energy and Carbon Footprints webpage (U.S. DOE 2013).

Steam end use working group. A working group comprised of representatives from seven industrial organizations was convened in 2011 to perform a short-term, focused peer review effort. Organizations that voluntarily participated in the steam end use working group meetings included Spirax Sarco (working group lead), Armstrong International, Kumana and Associates, Council of Industrial Boiler Owners (CIBO), Oak Ridge National Laboratory, Dow Chemical Company, Energetics Incorporated, and U.S. Energy Information Administration (EIA).

The manufacturing energy and carbon footprints show two sources for steam end use – offsite supply (purchased and transferred in) and onsite generation. Onsite steam generation is estimated based upon the energy consumption and efficiency of steam-producing equipment (such as combined heat and power (CHP systems) and boilers). In the MECS data set, end use of fuel and electricity is reported by sector; steam end use, however, is not reported. For this reason, steam end use allocation must be assumed in the energy footprint model. The steam end use working group was convened to address this specific assumption. The working group decided that an industry survey was the best approach for determining site-based steam use estimates. Over 80 industry respondents contributed to the survey; these included plant engineers, equipment providers, and industry consultants with experience in all of the sectors studied.

The following six end use categories were found to have varying levels of steam use:

1. **Process heating**: the direct process end use in which energy is used to raise the temperature of substances involved in the manufacturing process (e.g., heaters, heat exchangers, evaporators, dryers). Examples of process heating include the use of heat to separate components of crude oil in petroleum refining, to dry paint in automobile manufacturing, and to cook packaged foods.
2. **Machine drive:** the direct process end use in which thermal or electric energy is converted into mechanical energy and is used to power machine-driven systems, such as compressors, fans, pumps, and materials handling and processing equipment. Machine drivers such as electric motors or steam turbines are found in almost every process in manufacturing.
3. **Process cooling and refrigeration:** the direct process end use in which energy is used to lower the temperature of substances involved in the manufacturing process. An example is an absorption refrigeration cycle used to lower the temperature of chemical feedstocks below ambient temperature for use in reactions in the chemicals industry.
4. **Other process uses:** other direct process end uses not falling under a specified process end use category. Examples include steam tracing, stripping, vacuum, purging, humidification, and fuel oil atomization.
5. **Facility HVAC**: the direct nonprocess end use that includes energy used to provide heating, ventilation, and air conditioning for building envelopes within the plant boundary.
6. **Other nonprocess uses**: other direct nonprocess end uses not falling under a specified nonprocess end use category. An example is steam cleaning equipment during maintenance.

The Manufacturing Steam End Use Working Group used the results from the manufacturing steam end use survey to determine the final end use allocations of steam in the 15 individual manufacturing sectors as well as an average for all of U.S. manufacturing. A complete summary of the working group's final results are given in Table 2.

Table 2. Results for Steam Allocation from the Manufacturing Steam End Use Working Group

Sector	Steam end use					
	Process heating	Machine drive	Process cooling/ refrigeration	Other process uses	Facility HVAC	Other nonprocess uses
All manufacturing	66%	10%	3%	8%	11%	3%
Aluminum and alumina	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%

Process heating loss working group. In practice, process heating system losses, especially exhaust losses, vary widely depending on the process heating equipment and application. A working group was convened in Jan. 2012 to perform a short-term, focused peer review effort. Organizations that voluntarily participated in the working group meetings are listed in Table 3.

Table 3. Process Heating Energy Loss Working Group Organizations

Advanced Energy *	Eclipse, Inc.
Alcoa Inc. *	Energetics Incorporated *, ^
Alzeta Corporation *	U.S. Energy Information Administration *
Briggs and Stratton Corporation *, ^	Fives North American Combustion, Inc.
CHT Analytics *, ^	Hauck Manufacturing Company *
Diamond Engineering *	Invensys Eurotherm *, ^
The Dow Chemical Company *	Karl Dungs Inc. *
Duke Energy Corporation *, ^	Lawrence Berkeley National Laboratory *
E3M, Inc. *, ^	Oak Ridge National Laboratory *, ^
Emerging Technology Application Center	Southern Company *, ^
Organizations that participated in more than one working group meeting are noted with (*) symbol in the list, organizations that participated in the final consensus meeting are noted with (^) symbol in the list.	

The Process Heating Energy Loss Working Group met on three separate occasions between January 2012 and August 2012 and conducted additional analysis between meetings during the seven month peer review effort. The working group agreed that the best approach to determine realistic, sector-wide process heating energy loss results would be to speak with manufacturers directly and build an estimate from the ground up, rather than trying to modify an existing model (Brown, Hamel and Hedman 1985) with outdated results. It was agreed that a range of subsector estimates would add greater substantiation to the sector-wide estimate. In the period from March through August 2012 representatives from Energetics Incorporated and ORNL met with a number of plant operation managers and energy managers both by phone and in person to explain the analysis and solicit plant-based estimates of process heating energy loss. Estimates in various forms of completeness were obtained from 13 manufacturing organizations that contributed to the process heating energy loss analysis: ArcelorMittal, Carus Corporation, Darigold, Davisco Foods, Del Mar Food Products, Didion Dry Corn Milling, Foster Farms, Hilmar Cheese Company, Phillips 66, Saint Gobain, Shell, Spreckels Sugar, and Tenova Core.

To guide conversation during these meetings a simple energy balance spreadsheet tool was developed detailing key processing heating equipment by manufacturing subsector (e.g., furnace, dryer, melter, oven, evaporator, etc.). Since process heating equipment varies greatly by sector and by plant, a simplified energy balance (based on key inputs and outputs) was referenced to gather energy loss estimates uniformly. Similar process heating energy balance methodology is referenced in other DOE publications and tools (U.S. DOE 2008, U.S. DOE 2010). In addition to process heating loss estimates by plant engineers, various data sources were consulted to add detail to the tool. U.S. DOE Save Energy Now Assessment data was referenced, and a number of technical studies were cited in support of some sector estimates.

Table 4. Results for Process Heating Energy Loss from the Manufacturing Process Heating Energy Loss Working Group

Manufacturing sector	NAICS code	Process heating energy loss estimate	Process heating energy use (TBtu)	Percent of total U.S. manufacturing process heating energy use
Petroleum refining ^	324110	18%	2,346	30%
Chemicals ^	325	22%	1,268	16%
Forest products ^	321-322	68%	1,102	14%
Iron and steel ^	3311-3312	51%	723	9%
Food and beverage ^	311-312	68%	555	7%
Cement ^	327310	40%	311	4%
Glass ^	3272, 327993	56%	255	3%
Fabricated metals *	332	38%	201	3%
Transportation equipment *	336	38%	117	1%
Foundries *	3315	51%	106	1%
Plastics and rubber *	326	22%	101	1%
Textiles *	313-316	68%	100	1%
Alumina and aluminum *	3313	51%	100	1%
Computers, electronics, and electrical equipment *	334-335	38%	51	1%
Machinery *	333	38%	37	<0.5%
All manufacturing *	31-33	38%	7,814	100%

^ Seven sectors studied by Process Heating Working Group
* Seven-sector average (38% loss) applied to All Manufacturing, Fabricated Metals, Transportation Equipment, Computers, and Machinery. Iron and steel (51% loss) applied to Aluminum and Foundries. Chemicals (22% loss) applied to Plastics.

Process heating loss estimates were derived for seven manufacturing sectors representing 84% of manufacturing process heating energy use, the results are summarized in Table 4. Based on the weighted average of the seven sectors, average process heating loss for the U.S. manufacturing sector was calculated to be 38%. Process heating energy use, which is the sum of sum of fuel, electricity and steam energy, is also shown in Table 4, along with the contributing percent of total U.S. manufacturing process heating energy use.

Manufacturing Energy Use Results

In addition to the footprints themselves, analysis of the footprint results is also available in the November 2012 U.S. *Manufacturing Energy Use and Greenhouse Emissions Analysis* report (Brueske, Sabouni, Zach, and Andres 2012). Readers of this ACEEE paper are encouraged to access the 2012 report for a full summary of results and explanation of terminology.

Table 5 lists the total primary energy use and onsite energy use for the sixteen footprints studied; primary energy includes offsite losses associated with generating and transporting electricity and steam to the manufacturing plant gate. The table values represent energy use in the year 2006, and the sectors are listed in descending order of primary energy use. The table also shows each sector's percentage of primary energy use and the percentage of primary energy use that is consumed onsite. Given that the energy losses are higher for offsite electricity generation than for offsite steam generation, those sectors with proportionally greater electricity usage (e.g., computers and electronics) have higher offsite loss, and therefore the percentage of primary energy consumed onsite is lower.

Table 5. Primary and Onsite Energy Use for Sixteen Footprint Sectors

Manufacturing Sector	Total Primary Energy Use, TBtu *	Percentage of Primary U.S. Manufacturing Energy Use *	Onsite Energy Use, TBtu *	Percentage of Primary Energy Consumed Onsite *
Chemicals	4,519	21%	3,195	71%
Forest Products	3,553	16%	2,799	79%
Petroleum Refining	3,546	16%	3,231	91%
Food and Beverage	1,935	9%	1,295	67%
Iron and Steel	1,481	7%	1,043	70%
Transportation Equipment	904	4%	480	53%
Plastics and Rubber Products	729	3%	336	46%
Fabricated Metals	706	3%	397	56%
Alumina and Aluminum	603	3%	273	45%
Computers and Electronics	527	2%	228	43%
Textiles	472	2%	265	56%
Cement	471	2%	382	81%
Glass and Glass Products	466	2%	330	71%
Machinery	444	2%	204	46%
Foundries	281	1%	158	56%
All Manufacturing	21,972	100%	15,494	71%

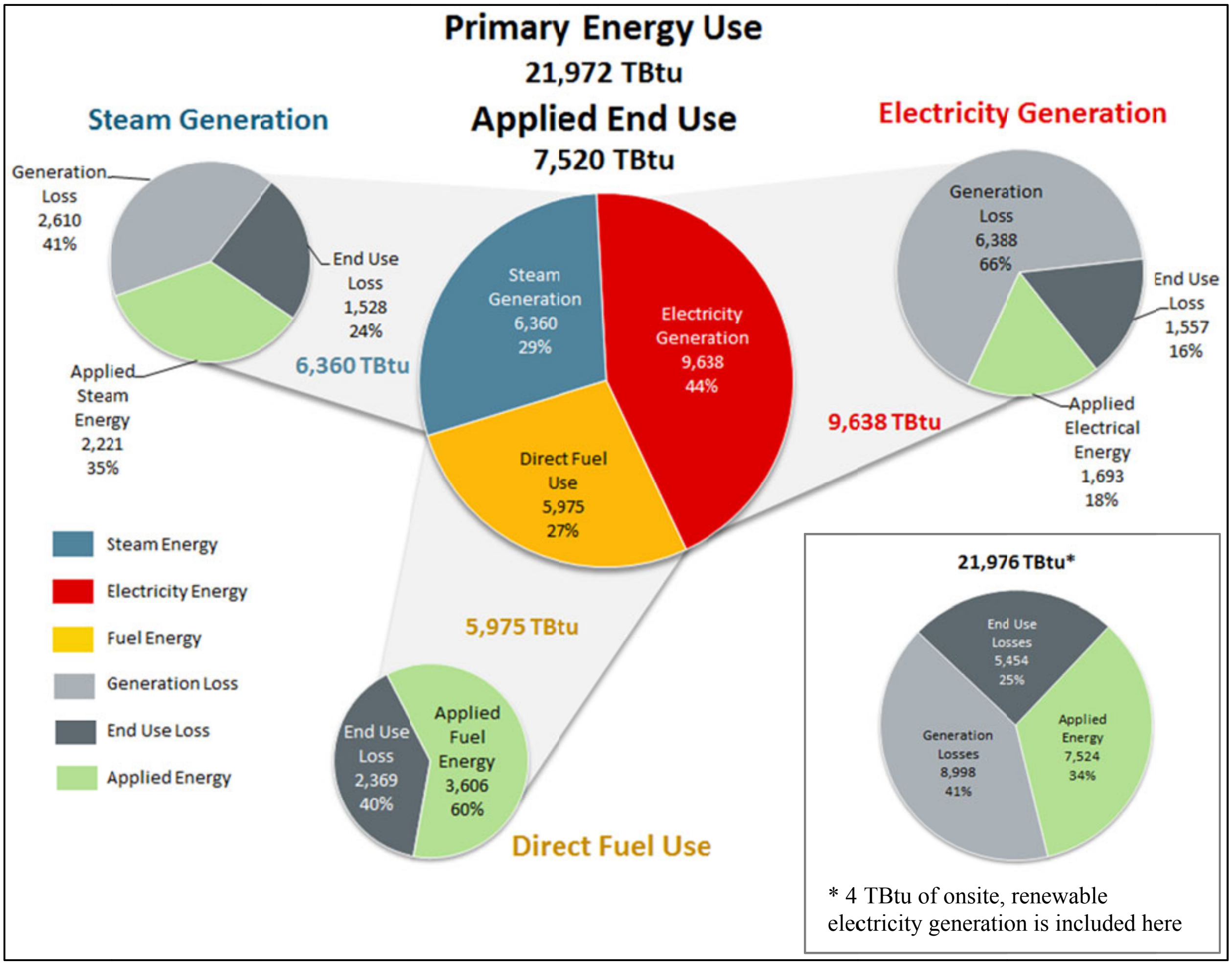
* The values in this table are not directly obtained from published MECS data; they are obtained from the energy footprint model developed by Energetics Incorporated which relies on MECS input data.

Applied End Use Energy

Contained within the footprints are both generation losses and end use losses. Both electricity and steam have associated onsite and offsite generation losses that are incurred during energy generation (and transmission and distribution). While the majority of electricity generation losses take place offsite, the majority of steam generation losses are onsite, and direct fuel use is assumed to have no associated generation losses. A further portion of the remaining energy is lost in direct end use, due to process and nonprocess system and equipment inefficiencies. When both generation and end use losses are accounted for, the energy that remains is referred to as "Applied Energy".

Applied energy is calculated and shown for the U.S. manufacturing sector in Figure 5. The inset figure in the lower right corner shows manufacturing sector primary energy generation losses, end use losses, and total applied energy for fuel, electricity and steam combined. When examining all energy types combined, the figure shows that 34% of all primary energy input is "applied" to process and nonprocess end uses. Generation losses account for 41% of input and end use losses account for the remaining 25% of input.

Figure 5. Primary Energy Use and Applied Energy by Energy Type for U.S. Manufacturing

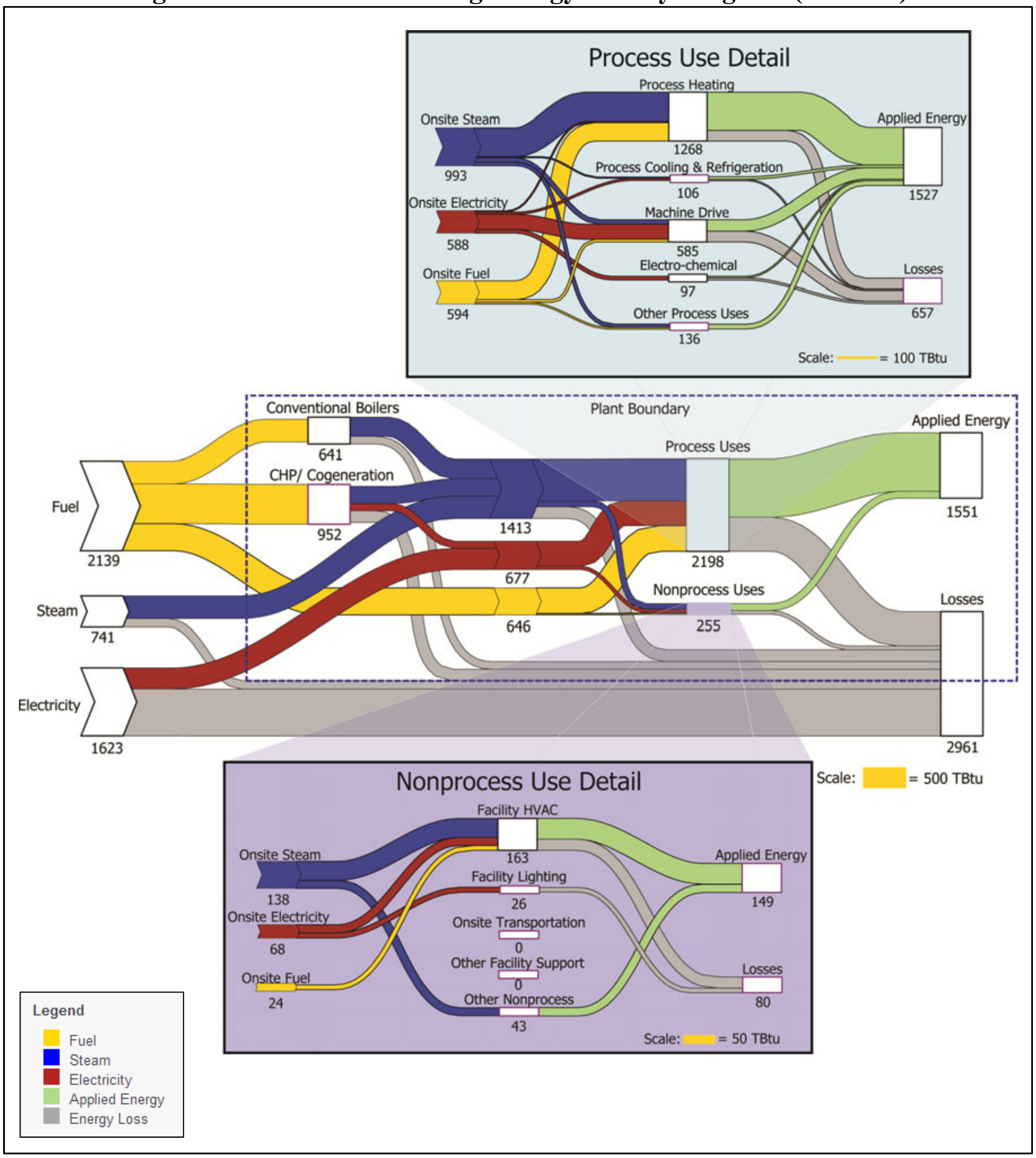


* 4 TBtu of onsite, renewable electricity generation is included here

Manufacturing Energy Use Sankey Diagram

Energetics has also recently initiated efforts to present the results of the energy footprints in the form of a Sankey diagram, where energy flow is visualized proportionally. A draft version of clustered manufacturing energy use Sankey diagrams for the Chemicals sector is shown Figure 6. When finalized, the Sankey diagram will be an interactive reference to appear alongside the each manufacturing sector energy footprint on the DOE AMO website. Users will be able to click on the energy boxes in the Sankey to drill down to energy type and equipment end use details.

Figure 6. U.S. Manufacturing Energy Sankey Diagram (DRAFT)



Conclusions

The footprint diagrams provide a powerful visual representation of the flow of energy (in the form of fuel, electricity, and steam) to major manufacturing end use. The footprints also estimate energy losses for the generation, transmission, and end use of energy, which serves as a baseline from which to calculate the benefits of improved energy efficiency. The footprint analysis is based on plant survey data (EIA MECS) and has undergone industry peer review. The peer review process was particularly important to estimate process heating energy losses and the distribution of steam energy to end uses. Energetics is currently updating the footprint model with MECS 2010 data. These updated footprints are anticipated to be published by September 2013 on the DOE AMO website.

References

Brown, Larry, Bernard Hamel, and Bruce Hedman. *Energy Analysis of 108 Industrial Processes*. The Fairmont Press. 1985.

Brueseke, Sabine, Ridah Sabouni, Chris Zach and Howard Andres. 2012. *U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis*. http://info.ornl.gov/sites/publications/files/Pub39685.pdf. Oak Ridge, TN. Energetics Incorporated for Oak Ridge National Laboratory.

U.S. Department of Energy (U.S. DOE). 2013. *Manufacturing Energy and Carbon Footprints*. Advanced Manufacturing Office 2013 [cited 30 May 2013]. Available from www1.eere.energy.gov/manufacturing/resources/footprints.html.

U.S. Department of Energy (U.S. DOE). 2008. *Process Heating System Performance: A Sourcebook for Industry*. 2008 [cited 30 May 2013]. Available from www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/proc_heat_sourcebook.pdf.

U.S. Department of Energy (U.S. DOE). 2008. *Process Heating Assessment and Survey Tool. PHAST Version 3.0.* Advanced Manufacturing Office. 2010 [cited 30 May 2013]. Available from www1.eere.energy.gov/manufacturing/tech_assistance/software_phast.html.

U.S. Department of Energy (U.S. DOE). 2009. *Manufacturing Energy Consumption Survey (MECS) 2006 MECS Survey* Data. U.S. Energy Information Administration 2009 [cited 30 May 2013]. Available from www.eia.gov/consumption/manufacturing/data/2006/.