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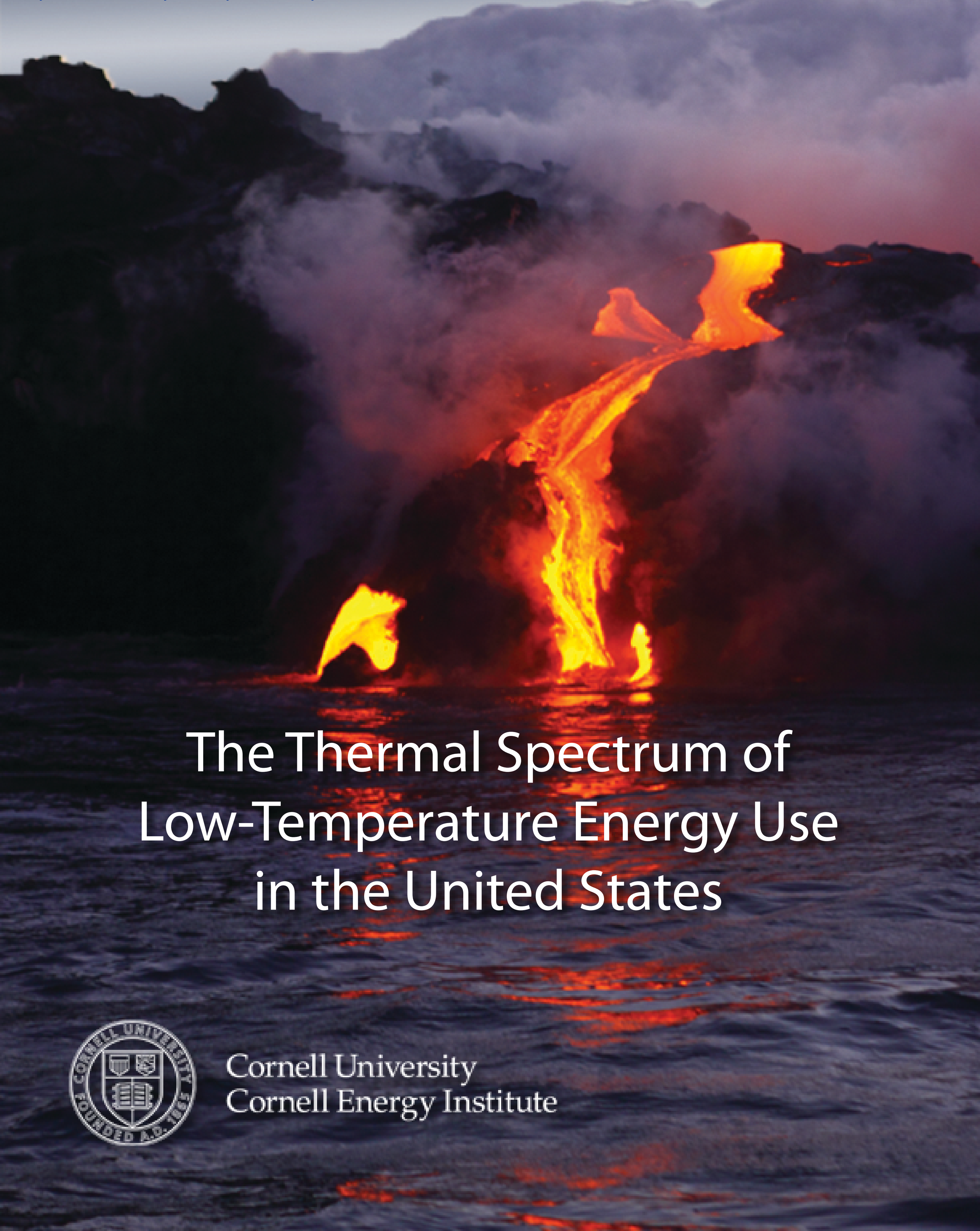

The Thermal Spectrum of Low-Temperature Energy Use in the United States

Cornell University
Cornell Energy Institute

Electronic Supplementary Material (ESI) for Energy and Environmental Science

The Thermal Spectrum of Low-Temperature Energy Use in the United States

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Abstract

A detailed analysis of the U.S. yearly energy consumption was performed as a function of its utilization temperature from 0 to 260°C. Using the U.S. Energy Information Administration database as a primary source of information, we found that the primary energy used to provide thermal energy up to 260°C in 2008 was 33.5 EJ (31.7 quads), about one third of the entire U.S. primary energy demand. More than half of the thermal energy demand below 260°C (55%) comes from the residential sector, while the rest comes from the industrial (24%) and commercial (21%) sectors. Almost 80% of the 33.5 EJ is used to provide heat below 150°C. Space heating and water heating in the residential and commercial sector, characterized by end-use temperatures of 40°C to 60°C, are responsible for 38% of the thermal energy consumption below 260°C. The study suggests how renewable energy could provide a large fraction of energy for direct use at low end-use temperatures that is currently mostly supplied by high grade fossil fuels. For example, most of the low temperature thermal energy we need for water and space heating is provided by combusting natural gas and oil at much higher temperatures. This downgrades the thermodynamic potential of the fossil fuels for generating power by reducing its exergy. By focusing attention on the thermodynamic losses inherent to our current energy system, we suggest a paradigm shift in the way we view and use energy by strategically matching the source providing the energy to the end-use temperature of the application. Thermal energy below 260°C could be supplied more sustainably without large exergetic losses by geothermal or solar thermal energy resources, or by waste heat. In addition, direct thermal use of such low temperature thermal energy results in higher overall efficiencies compared to electricity generation by avoiding the inherently large 2nd Law losses in converting the thermal energy to electricity.

About the Cover

The cover depicts the eruption of the Kilauea volcano on the island of Hawaii in February 2011. A volcanic eruption not only illustrates the massive thermal energy potential of geothermal resources – it also metaphorically symbolizes the way we currently use energy in the U.S. The photo depicts a high temperature molten lava flowing into the ocean, losing virtually all of its work and energy producing potential by being quickly cooled to the temperature of the ocean water. In a similar fashion, we combust large quantities of fossil fuels generating high grade thermal energy that is rapidly degraded by reducing its temperature from combustion temperatures of over 1,000°C to near the boiling point of water for heating our buildings and for supplying hot water.

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1 Background and Motivation

In 2008, the U.S. used 104.8 EJ (99.3 quadrillion Btu) of primary energy, of which 84% came from fossil fuels as reported by the U.S. Energy Information Administration [2009]. Figure 1.1 documents the energy consumption from 1949 to 2008 and shows increasing consumption in all four demand sectors (industrial, transportation, residential, and commercial). The primary energy demand can generally be divided into demand for mechanical drive and demand for thermal energy. About 40% of the total primary energy is consumed for electricity generation [U.S. Energy Information Administration, 2009]. Electricity, in turn, also provides thermal or mechanical energy for specific end-uses. In the transportation sector, fossil fuels are burned in internal combustion engines to generate mechanical energy. The industrial sector consumes fuels for mechanical drives and to meet thermal energy needs. The major part of the residential and commercial energy consumption is for thermal energy.

Fossil fuels have remarkable properties as energy carriers, such as high specific energy (e.g. lower heating value of gasoline: $\approx$ 43 MJ/kg) and high combustion temperatures ranging from 1000°C to 2500°C depending on fuel-air composition, combustor design and other factors. These characteristics enable liquid fuels to meet the extreme requirements of sophisticated machines such as jet engines and gas turbines allowing for highly efficient energy conversion. However, many of the end-uses currently powered by fossil fuels do not necessarily require these characteristics, and the fossil fuel energy is downgraded to meet their demands, imposing exergy/availability losses. Exergy or availability is the maximum work-producing potential of an energy source. The combustion temperatures of fossil fuels, for example, exceed the demands of various thermal end-uses. One such end-use is space heating with an end-use temperature of 40°C to 60°C. However, 93.5% of the energy used for space heating in U.S. residential buildings is provided by fossil fuels, specifically

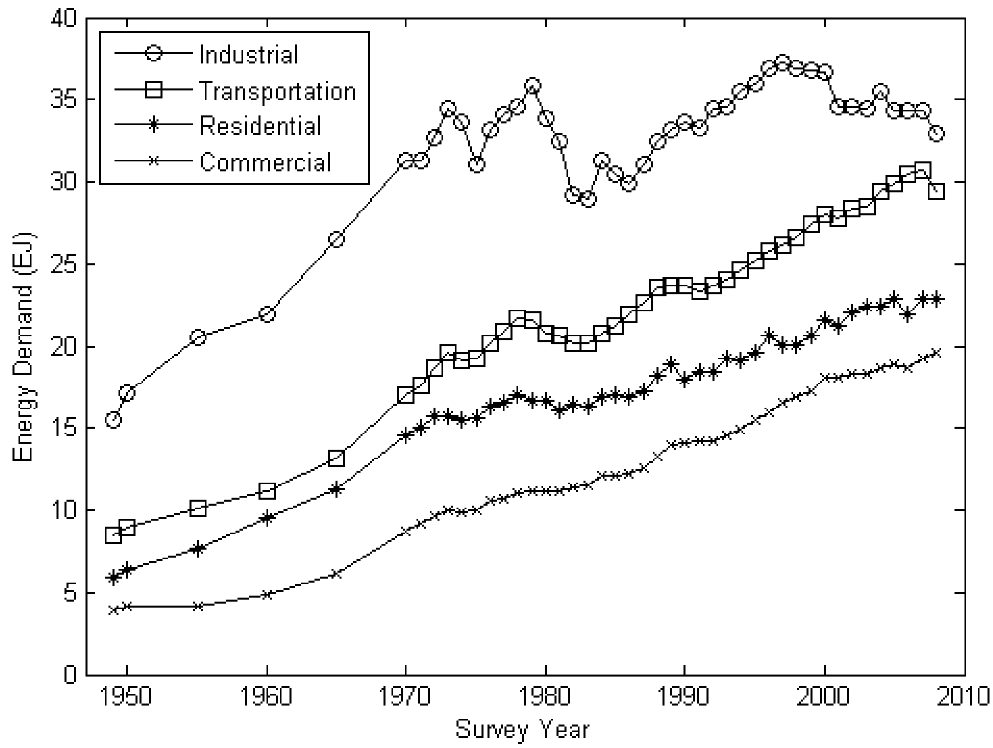

Figure 1.1: Energy consumption of the four demand sectors (industrial, transportation, residential, and commercial) from 1949 to 2008 as reported in the EIA Annual Energy Review [U.S. Energy Information Administration, 2009]. In 2008 the sectors' shares were 31%, 28%, 22%, and 19%, respectively.

by natural gas, fuel oil, liquefied petroleum gas, and kerosene [U.S. Energy Information Administration, 2009]. A logical energy use scheme would close the gap between source and end-use temperature by tayloring the energy source used to the temperature needs of the process, and would reserve the high grade fossil energy sources for combustion processes that truely require high temperatures.

The International Energy Agency [2007] reports that electricity production has gotten most of the attention with regards to the use of renewable energy. As a result, policies aimed at encouraging direct thermal use of renewables have not developed to the same extent as policies for electricity generation. In order to evaluate the potential of the direct thermal use of renewable energy, the actual demand for low temperature thermal energy as a function of temperature needs to be characterized. By quantifying the thermal energy demand spectrum with respect to required supply temperature, it is possible to determine the potential market for low temperature thermal energy. With the right infrastructure, energy sources like geothermal, solar, and waste heat could provide a significant portion of the low temperature thermal demand for the U.S. These energy sources would be more valuable from both a sustainability and economic perspective when used for direct thermal applications rather than incur the losses of thermodynamically upgrading them to electricity.

Deep source geothermal energy in the U.S., for example, is generally associated with electricity generation in both policy and public. The relatively low temperature of geothermal fluids of typically 100°C to 250°C entail substantially lower heat to power conversion efficiencies compared to fossil fuel-fired or nuclear power plants (typically 5-20% versus 35-60%) [Tester et al., 2005]. Due to an inherent Second Law thermodynamic limitation, this range of fluid temperatures results in low exergy or availability values relative to prevailing ambient conditions. This limits the maximum possible power that could be generated [Tester and Modell, 1987]. Traditionally, geothermal energy relies on naturally occurring hydrothermal reservoirs. Enhanced geothermal systems (EGS) create a system of fractures in dry rock (also called hot dry rock (HDR)) to exploit the thermal energy by flowing water through the fractures. The resource base for EGS was estimated by Tester et al. [2006] to be 14×10^6 EJ. Their conservative estimate for the recoverable resource is 2.8×10^6 EJ, almost 30,000 times the total yearly U.S. energy consumption.

Solar technologies include photovoltaic systems, which directly convert solar energy to electricity, and solar thermal systems, which heat a working fluid. Similar to geothermal energy, the conversion of the working fluid's thermal energy into electricity attracts major interest in the U.S. and other countries. Large-scale solar thermal operations requires the implementation of cost intensive parabolic troughs, power towers, and parabolic dishes to concentrate solar energy. The concentration results in working fluid temperatures and average solar to electric efficiencies of 100-400°C and 8-12% for parabolic troughs, 400-600°C and 12-18% for power towers, and 600-1,500°C and 15-30% for dish-engines [Tester et al., 2005]. Solar to electric efficiencies include the efficiency of two energy conversions: solar to thermal and thermal to electric. Solar to thermal efficiencies can be as high as 75% for concentrating solar collectors [Kalogirou, 2004]. Direct thermal use of the captured solar thermal energy for end-uses that require similar supply temperatures would avoid the additional losses in the thermal to electric conversion. Kalogirou [2003] describes how solar thermal energy would be able to provide energy for industrial process applications with demand temperatures between 60°C and 260°C. Furthermore, a growing number of solar thermal systems are being implemented in residential and commercial buildings to supply hot water, heating, and cooling. A resource assessment of solar energy shows that about 40,000 EJ are incident on the U.S. each year [Tester et al., 2005], far more than the annual U.S. energy demand of about 100 EJ.

Waste heat refers to any heat that is expelled from a process and regarded to have no useful value. The source of waste heat typically originates from the operation of equipment, chemical and industrial processes, and power generation. Following the Second Law of thermodynamics, not all available heat in power generation can be converted to electrical energy and waste heat is inevitable. Although the waste heat generally exists at lower temperatures than the original source, it might still be well above the temperatures demanded by certain thermal end-uses and allow to recuperate the heat, especially when waste heat originates from the combustion of high grade fuels. Unlike solar and geothermal, waste heat is not a primary energy source, but rather a byproduct from the degradation of high grade energy sources. As a consequence, the availability of waste heat will depend on how much primary energy is used and Second Law efficiencies, if a heat engine is involved. Energy losses in the electrical system make up a large part of the resource base for waste heat. According to the U.S. Energy Information Administration [2009], 42.9 EJ (40.7 quads) of primary energy were consumed to produce 15.7 EJ (14.9 quads) of gross electricity in 2008 (before power plant consumption, transmission and distribution, etc.). In other words, 27.2 EJ (25.8 quads) of the energy were lost via conversion. Assuming it is technically feasible to capture and utilize half of the conversion losses, the usable waste heat would still make up more than 10% of the total U.S. energy demand.

There are collateral benefits as well. Meeting low temperature thermal energy demand with geothermal, solar thermal, and/or waste heat directly avoids the losses of converting the energy in these systems to electricity *and* the exergy losses that would be incurred by combusting fossil fuels at high temperature to provide this low temperature thermal energy.

Literature in the field of direct thermal use of renewable energy includes the famous Lindal diagram shown in Figure 1.2. It presents a number of possible applications for direct thermal use in Iceland along with typical end-use temperatures. The idea of the Lindal diagram has been taken up by other authors, such as Kalogirou [2003], who shows a variation with a focus on solar thermal rather than geothermal. The Lindal diagram illustrates the opportunity but does not quantify the potential of direct use, since it does not document how much thermal energy is required for the mentioned processes. The worldwide review of direct application of geothermal energy [Lund et al., 2005] quantifies current worldwide use, but again, misses the existing potential. Vannoni et al. [2008] studied the potential for thermal energy from renewable sources but did not specify the temperatures required by the potential end-uses. Philibert [2006] reports that in 2004, 40-50% of the total world-wide energy demand in residential, commercial, and industrial demand sectors was used for heating and cooling (as cited in [International Energy Agency, 2007]). The International Energy Agency [2007] states that renewable energy sources could cover the "greater share" of the heating and cooling energy demand, but specific numbers cannot be derived because the temperature distribution of the thermal uses was not considered. The 40-50% estimate would include the demand of applications which require temperatures

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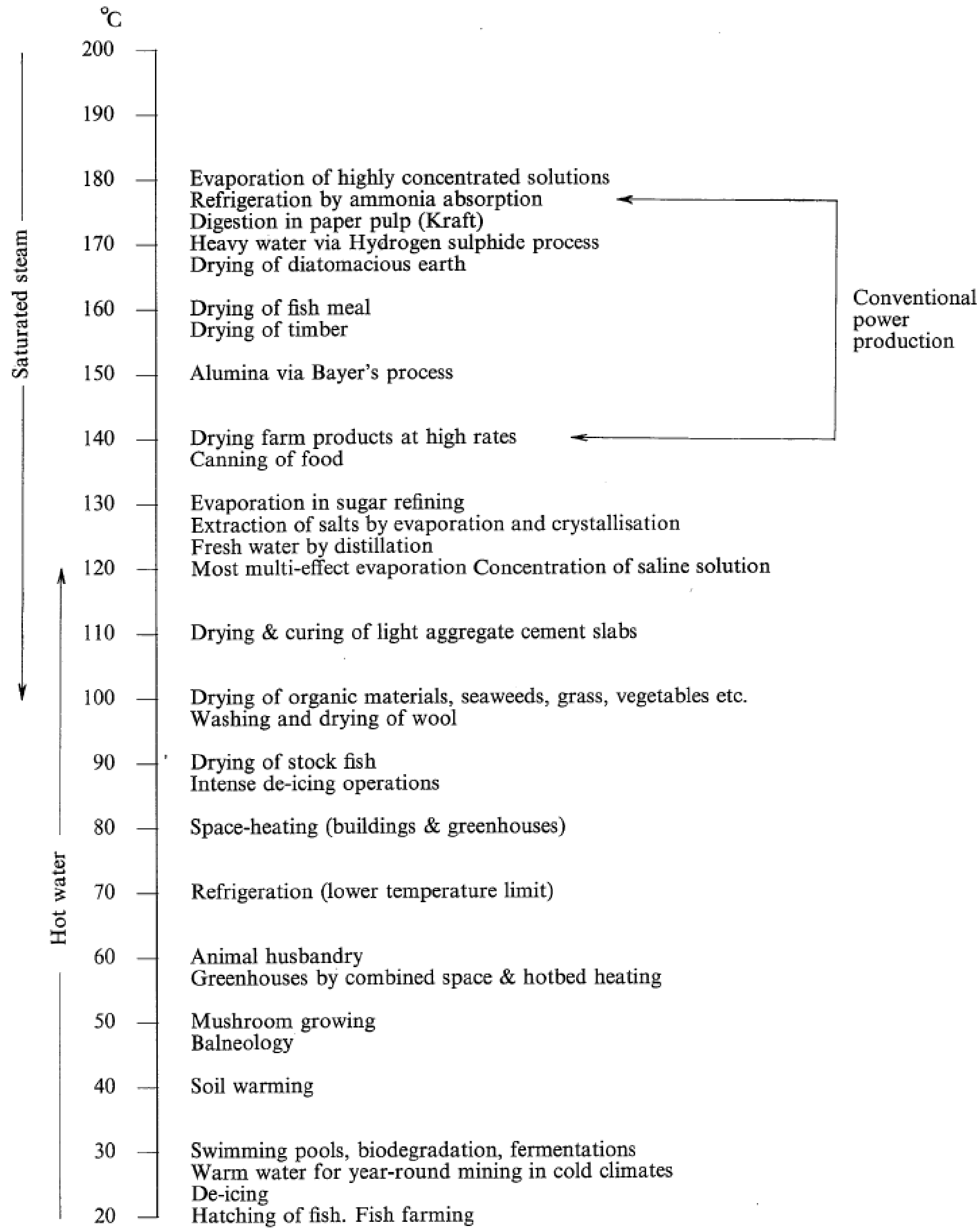

Figure 1.2: Industrial and other possible applications for direct thermal use of geothermal energy suggested by Lindal [1973] as cited in [Armstead, 1978].

beyond what could be provided by most renewable sources. There is a need to not only quantify the thermal demand, but also its temperature spectrum to better understand how much of the current demand can be replaced by renewables such as geothermal and solar thermal. Reistad (1975) quantified the low temperature thermal energy consumption and correlated it with end-use temperatures 35 years ago. This important study quantified the situation for the U.S. based on 1968 energy consumption data. Much has changed with respect to energy demand in the last 42 years, with an increase in population as well as structural changes in the manufacturing, transportation, and housing sectors. In addition, end-use or process temperatures might have changed due to technological development. A primary motivation for our work was to update the situation as it now exists in the U.S.

2 Objectives and Approach

Using the most recent data available, our objective was to evaluate the U.S. thermal energy consumption over a range of end-use temperatures from 0°C to 260°C. The U.S. Energy Information Administration (EIA) database was used to estimate the amount of primary energy consumed to meet the energy demand of thermal end-uses in the year 2008. End-use temperature information was collected from various sources to determine the temperature distribution of the thermal energy consumption in the U.S. Section 3 introduces the sources of data specifically and gives a detailed explanation of the applied methodology for each of the demand sectors. The results are presented in Section 4 along with a discussion of their significance for the application of alternative thermal energy sources, such as direct thermal application of geothermal energy, solar thermal energy, waste heat and cogeneration. Section 5 then summarizes the main conclusions and gives an outlook and research recommendations.

3 Methodology

3.1 General Procedure and Data Sources

Given that a main focus of our group is geothermal energy utilization, we decided to examine the thermal energy demand in a temperature range that would be appropriate for geothermal resources. Reservoir temperatures vary, given different resource grades with a range of heat flows, temperature gradients and/or well depths. 260°C represents a ceiling for a moderate geothermal resource grade. Such temperatures can be reached within the maximum economically acceptable drilling depth of 6 km [Tester et al., 2005] for moderate geothermal gradients of 40°C/km. Resources with higher temperature gradients could be used for electric power production due to a higher Carnot-type conversion efficiency rather than solely for direct use. Consequently, the temperature range examined in this study was from 0°C to 260°C. Of course, both solar thermal and waste heat sources could provide thermal energy in this range as well. A 20°C temperature bin size was chosen to allow for coarse graining in determining the temperature required for the end-use of a process and to acknowledge that certain processes can be undertaken over a range of temperatures rather than requiring a specific temperature.

The EIA issues an Annual Energy Review (AER) for the United States that defines four demand sectors, i.e. residential, commercial, industrial, and transportation sector, and provides information about the development of their yearly energy consumption from 1949 to 2008 [U.S. Energy Information Administration, 2009]. For all four demand sectors, the EIA issues special reports on a quadrennial basis with more detailed information. The transportation sector was left aside, because transportation generally implies mechanical drive as the end-use and the focus of this study was low temperature thermal energy. The remaining three sector specific surveys are:

- Residential Energy Consumption Survey (RECS)
  [U.S. Energy Information Administration, a]
- Commercial Buildings Energy Consumption Survey (CBECS)
  [U.S. Energy Information Administration, b]
- Manufacturing Energy Consumption Survey (MECS)
  [U.S. Energy Information Administration, c]

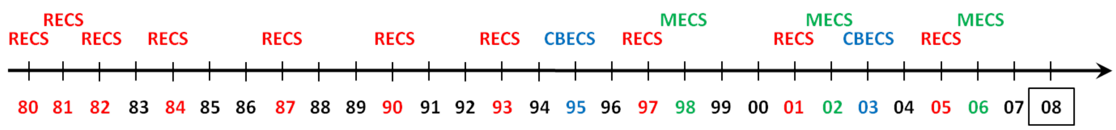

Figure 3.1: Timeline showing the demand-sector specific energy consumption surveys used in this work and their year of publication. The Annual Energy Review (AER) is published every year.

While the AER reports useful general information, such as total energy consumption of the sectors, only the sector specific consumption surveys give details about the end-use specific energy demand. The data collection methods for the AER and the sector survey applied by the EIA are different: The AER data are provided by energy suppliers, whereas the sector surveys are based on nationally representative samples of demand-side establishments. The timeline in Figure 3.1 underscores the need for extrapolation of data to a base year, since the specific surveys for each sector are not issued in the same year. We selected 2008 as the base year because it is the year of the most recent AER.

The generally followed procedure is to break the energy consumption down to the end-uses in order to quantify each end-use's energy demand, evaluate its thermal or non-thermal character, and estimate its end-use temperature based on reported practices. The relative fractions of energy demand for the end-uses can then be extrapolated to the base year, for which the total consumption of the demand sectors is given in the AER. The EIA data also provide relative standard error information for all presented values. The mean values were considered for this work. Interested readers are referred to the original EIA data tables [U.S. Energy Information Administration, 2009, a,b,c] for standard error information. All energy quantities mentioned in this work relate to a yearly basis, if not specified differently. Generally, this report uses Joules as the dimension for energy. British thermal units (Btu) are given for simple comparison to the EIA data tables. The conversion factor is 1055 J/Btu, which leads to the interesting result that 1 quad (10^{15} Btu) is approximately equal to 1 EJ (10^{18} J). The thermal energy demand is determined as the amount of primary energy which is consumed to provide thermal energy. Due to inefficiencies and heat transfer losses, the net amount of thermal energy eventually supplied to the process will be lower. If not specified differently the terms consumption or demand refer to this primary energy consumption.

3.2 Industrial Sector Methodology

3.2.1 Sector Definition

According to the AER [U.S. Energy Information Administration, 2009] the industrial sector consists of the following types of activity, categorized in the North American Industrial Classification System (NAICS) [2010]:

- agriculture, forestry, fishing and hunting (NAICS code 11),
- mining (21),
- construction (23), and
- manufacturing (31-33).

It is important to note, that the EIA provides a specific survey with the detailed information needed for this study only for the manufacturing sector, i.e. NAICS codes 31-33. Table 3.1 summarizes the 21 subsectors within the manufacturing sector covered in this specific survey, the Manufacturing Energy Consumption Survey (MECS) [U.S. Energy Information Administration, c]. For a detailed definition of the manufacturing sector, refer to the MECS survey methods [U.S. Energy Information Administration, 2002].

Table 3.2 shows the difference in the total energy consumption between the entire industrial sector as in the AER and the manufacturing sector as in the MECS. For the three most recent MECS of 1998, 2002 and 2006, the manufacturing sector covers 84% to 90% of the industrial consumption.

Although the agricultural sector (NAICS code 11) includes well known applications of direct geothermal and/or recovered waste heat use such as crop drying and greenhouse heating and the Lindal diagram also mentions applications in mining (21), both were not further considered in this study, same as construction (23). Purposely, all estimates for the amount of thermal energy demand were consistently based on EIA data and such data is not available for the non-manufacturing industry's energy demand. Other sources were studied to get a rough estimate of the thermal energy consumption in agriculture and mining that could potentially be included in future work. The total energy consumption

Table 3.1: List of the 21 manufacturing sectors [North American Industrial Classification System (NAICS), 2010].

NAICS Code	Sector Title
311	Food Manufacturing
312	Beverage and Tobacco Product Manufacturing
313	Textile Mills
314	Textile Product Mills
315	Apparel Manufacturing
316	Leather and Allied Product Manufacturing
321	Wood Product Manufacturing
322	Paper Manufacturing
323	Printing and Related Support Activities
324	Petroleum and Coal Products Manufacturing
325	Chemical Manufacturing
326	Plastics and Rubber Products Manufacturing
327	Nonmetallic Mineral Products Manufacturing
331	Primary Metal Manufacturing
332	Fabricated Metal Product Manufacturing
333	Machinery Manufacturing
334	Computer and Electronic Product Manufacturing
335	Electrical Equipment, Appliance, and Component Manufacturing
336	Transportation Equipment Manufacturing
337	Furniture and Related Product Manufacturing
339	Miscellaneous Manufacturing

Table 3.2: Comparison between energy demand of the entire industry as in AER [U.S. Energy Information Administration, 2009] and total manufacturing demand as in MECS [U.S. Energy Information Administration, c] for the three most recent MECS issues. The AER industrial sector total was calculated as the sum of the columns "Total Primary" and "Electricity Retail Sales". The MECS total includes "Net Electricity" (for a definition of Net Electricity see Section 3.5).

Year	**Total Energy Demand Industrial Sector (AER)**		**Total Energy Demand Manufacturing Sector (MECS)**		**Fraction of MECS Total out of AER Industrial Total**
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(%)**
1998	28.272	(26.798)	25.105	(23.796)	89
2002	26.624	(25.239)	23.913	(22.666)	90
2006	26.463	(25.083)	22.258	(21.098)	84

in agriculture is reported to be 1.161 EJ (1.100 quads) [Schnepf, 2004], when indirect use for fertilizers and pesticides is subtracted. 8% is used for crop drying, while 12% is used for livestock, dairy, and poultry and 5% is used for miscellaneous uses [Stout, 1984]. Not enough information is given to determine what fraction of livestock, dairy, and poultry and of miscellaneous uses is from thermal demand, but it is safe to assume it would not comprise more than half, resulting in at most 16.5% of agriculture energy demand being of a thermal nature (i.e. around 0.192 EJ, 0.182 quads). The U.S. mining industry consumed 1.187 EJ (1.125 quads) of energy in 2000 [BCS Incorporated, 2002]. Energy requirements vary widely for different commodities. Major requirements include electricity for ventilation systems, water pumping and grinding/crushing. Thermal end-uses account for a relatively small fraction only.

Figure 3.2 shows a graphical representation of the breakdown of the industrial sector energy consumption to the end-uses of interest. The EIA generally divides the energy consumption within the manufacturing sector into fuel use and nonfuel (feedstock) use. For definition details see MECS definitions of fuel [U.S. Energy Information Administration, 2005a] and nonfuel (feedstock) [U.S. Energy Information Administration, 2005b] use. For the quantification of the thermal energy demand, only fuel use is of interest. The table "Energy Consumption as a Fuel by End-Use" [U.S. Energy Information Administration, c,

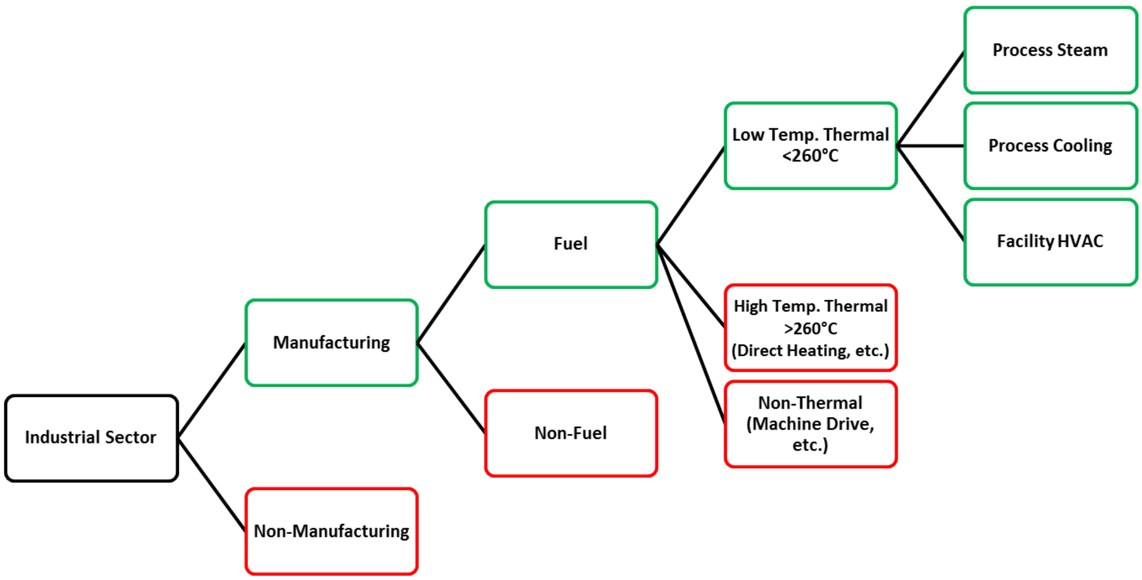

Figure 3.2: Breakdown of the industrial sector energy consumption. The green line color indicates the energy demand that was included in our analysis.

Table 5.2, 2006] distributes the fuel consumption to the different end-uses listed in Table 3.3.

3.2.2 Quantification of Energy Consumption for Process Steam Generation

By far the most significant source of thermal energy demand in the manufacturing sector is the generation of process steam [Reistad, 1975]. The two end-uses in the Indirect Uses - Boiler Fuel category in Table 3.3 define the energy demand for process steam generation. For other end-uses in the manufacturing sector considered thermal energy see Section 3.2.4. The Conventional Boiler Use[1] energy was considered to be used solely to produce process steam. For the CHP and/or Cogeneration Process, an electric conversion efficiency was assumed, and the non-converted energy was added to the process steam generation energy demand. The efficiency was assumed to be $\eta_{el} = 0.55$ for natural gas inputs into

[1] We use upper-case letters to identify energy sources and uses as they are defined in the EIA data tables. Lower-case letters are used when discussing them generically.

Table 3.3: End-Use categories as listed in the MECS and their share of the total manufacturing fuel consumption of 16.519 EJ (15.658 quads) in 2006 [U.S. Energy Information Administration, c, Table 5.2]. The boldly printed rows provide the sum of the subsequent rows. Additionally to the information shown here, the data in MECS-table 5.2 provide information on the different types of fuel that were used to provide the energy for each end-use. All manufacturing subsectors are listed separately in the MECS table providing detailed information.

End-Use	**Share of Total (%)**
Indirect Uses-Boiler Fuel	**18.34**
Conventional Boiler Use	9.88
CHP and/or Cogeneration Process	8.46
Direct Uses-Total Process	**35.75**
Process Heating	21.00
Process Cooling and Refrigeration	1.53
Machine Drive	10.56
Electro-Chemical Processes	1.32
Other Process Use	1.33
Direct Uses-Total Nonprocess	**6.81**
Facility HVAC	4.20
Facility Lighting	1.26
Other Facility Support	0.58
Onsite Transportation	0.42
Conventional Electricity Generation	0.17
Other Nonprocess Use	0.15
End-Use Not Reported	**39.12**
Total	**100.00**

this category and $\eta_{el} = 0.35$ for all other fuels (mostly coal, residual fuel oil, and wooden byproducts). These efficiency estimates are based on the assumption, that a combined cycle is used when combusting natural gas, and a steam turbine in the case of solid fuels. It should be noted that not all of the non-converted energy $(1 - \eta_{el})$ will be recovered as process steam energy. Nevertheless, the assumption is consistent with the aim to estimate the primary fuel energy that is consumed to meet the demand of thermal end-uses. Similarly, boiler efficiencies are not considered but rather the total fuel energy input to the boiler.

Some of the entries in the MECS data tables are withheld because the survey resulted in relative standard errors exceeding 50% or in order to avoid disclosing data for individual establishments. Some additional assumptions and estimates have been made to fill these data gaps, guided by earlier publications that analyze MECS data [Andersen and Hyman, 2001, Ozalp and Hyman, 2006, 2007, Ozalp, 2009]. Most often, the values could be revealed by simple summations and/or subtractions of the other values in the same row or column. Appendix A.1 lists the assumptions for data disclosure.

39% of the total fuel consumption in the manufacturing sector or 6.462 EJ (6.125 quads) was given without specified end-use in the 2006 MECS. Noticeably, most of the energy in this End-Use Not Reported (EUNR) category (95%) originates from the consumption of Other fuels, which is defined as the sum of Net Steam and other energy that survey respondents indicated was used to produce heat and power [U.S. Energy Information Administration, c, Table 5.2, 2006]. This indicates, that part of the EUNR should actually be allocated to the energy demand for process steam and that a more detailed investigation is needed.
Figure 3.3 shows the manufacturing subsectors' share of the fuel consumption. The nine subsectors with the highest fuel consumption ((324) Petrol, 22%, to (332) Fabricated Metals, 3%) were chosen as a representative sample and their energy consumption for the generation of process steam was investigated in detail. Firstly, the allocation of the EUNR energy to the process steam demand is described. Secondly, the temperature distribution of the process steam is determined. The given absolute values represent the consumption as reported by the MECS of 2006 to allow comparison to the original data. Note that the consumption is eventually extrapolated to the year 2008 and the absolute values are

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subject to change.

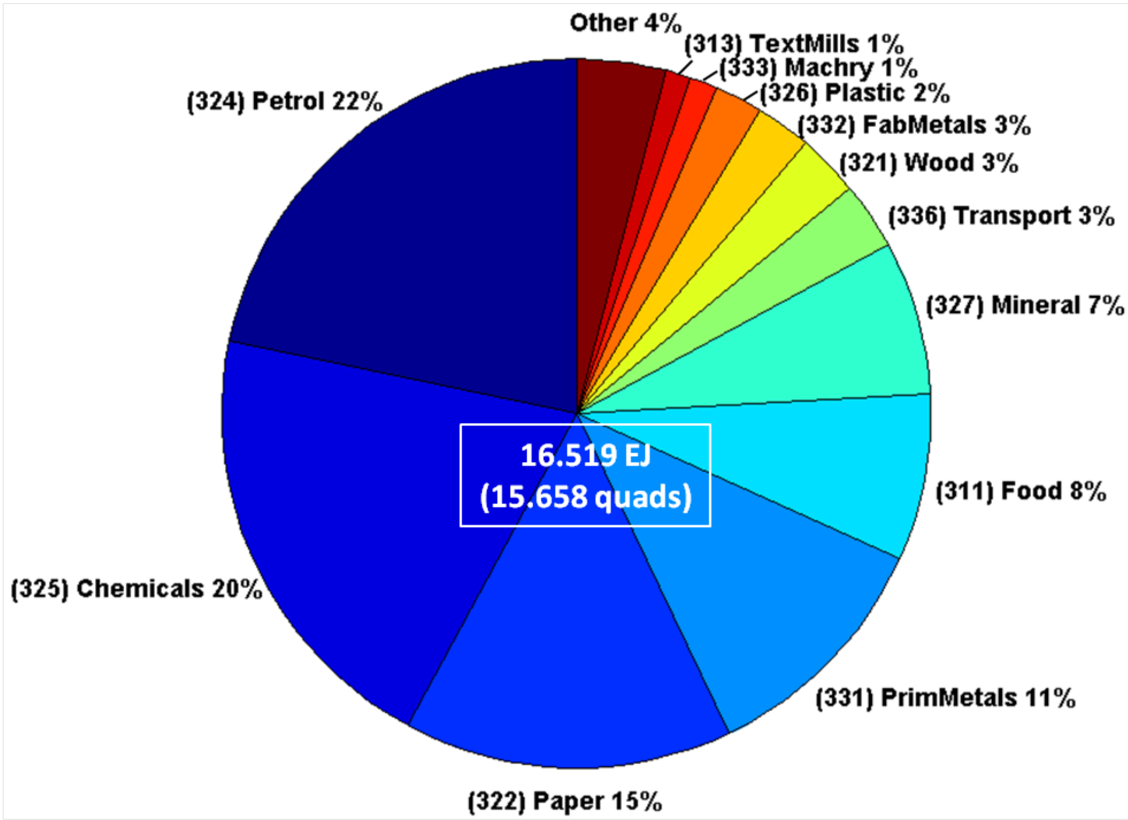

Figure 3.3: Share of manufacturing sectors of total fuel consumption. The subsectors with the highest fuel consumption are labeled with the NAICS code and an abbreviation for their name. The NAICS codes are listed in Table 3.1. “Other” presents the sum of the nine manufacturing sectors not shown explicitly, i.e. NAICS codes 312, 314-316, 323, 334, 335, 337, and 339. The total is given as in the MECS [U.S. Energy Information Administration, c, Table 5.2, 2006], excluding Electrical System Energy Losses (c.f. Section 3.5).

General Aspects for the Allocation of EUNR Energy

The table “Byproducts in Fuel Consumption by Mfg. Industry & Region” [U.S. Energy Information Administration, c, Table 3.5, 2006] lists byproducts that are used as energy sources in the manufacturing industry. Additionally, the table “Selected Wood & Wood-Related Products in Fuel Consumption” [U.S. Energy Information Administration, c, Table

3.6, 2006] lists energy from Agricultural Waste. The latter appears only for food and paper manufacturing. According to personal communication [Adler, 2010], this energy is integrated in the Other fuel energy in the end-use tables [U.S. Energy Information Administration, c, Table 5.2, 2006]. Following Ozalp [2009] the difference between the Other fuel energy and the byproduct energy can be assumed to be Net Steam,

$$Net\,Steam = Other - byproducts \tag{3.1}$$

which the EIA defines as the balance of steam purchases and sales plus steam from non-combustible renewables [U.S. Energy Information Administration, c, Table 5.2, 2006]. The Net Steam energy was added to the end-use category Conventional Boiler Use for all nine sectors. The byproduct energy was considered as steam energy depending on the nature of the respective byproducts, such as solid, liquid or gaseous appearance, purity, heating value, etc. and the dominating processes of the respective industry, as explained below. The only remaining part of the EUNR energy is the difference between EUNR and Other fuels. It is distributed to all end-uses according to the initial distribution for the respective manufacturing subsector in the MECS-table 5.2. This approach is based on Ozalp [2009] and Ozalp and Hyman [2007]. For the distribution, we calculate the fuel consumption ratio for each end-use and multiply it with the difference between EUNR and Other fuels. Eq. (3.2) shows an example for the calculation of the fuel consumption ratio for the Conventional Boiler Fuel end-use:

$$f_{Conv.B.Fuel} = \frac{Conventional\,Boiler\,Fuel}{Total\,Fuel\,Consumption - End\,Use\,Not\,Reported} \tag{3.2}$$

The following paragraphs present the detailed approach to determine the energy demand for process steam generation for each of the nine largest manufacturing subsectors. Tables 3.4 - 3.8, 3.10, and 3.12 - 3.14 summarize the resulting energy demand.

Chemical Manufacturing

The byproduct consumption was divided into cogeneration and the other end-uses following the ratio reported by Ozalp [2009]: 76% go into CHP and/or Cogeneration, 24% are distributed among all end-uses same as the remaining EUNR energy. It should be mentioned that Ozalp separates the byproduct consumption for electricity generation into

CHP/Cogeneration and Conventional Electricity Generation. However, since Conventional Electricity Generation made up only 0.14% of the reported fuel consumption in Chemical Manufacturing in 2006, the 76% of the byproduct energy were fully allocated to CHP and/or Cogeneration. Specifically, they were considered in the high efficiency proportion, because most of the energy originates from Waste Gas. Table 3.4 summarizes the allocation of EUNR energy to the process steam energy demand. The first column shows the energy originally assigned to the end-uses Conventional Boiler Fuel and CHP and/or Cogeneration [U.S. Energy Information Administration, c, Table 5.2, 2006] and the second column shows the allocation of the EUNR energy to these end-uses. Column 3 presents the resulting energy demand for process steam generation. The energy values in the CHP/Cogeneration end-use in column 1 and 2 are multiplied by $(1 - \eta_{eff})$ and added up to determine the energy demand in column 3. The value for η_{eff} is 0.35 for the low efficiency portion and 0.55 for the high efficiency portion.

Table 3.4: Allocation of EUNR energy in Chemical Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. The first column gives the energy consumption of the two end-uses as reported in the end-use table of the MECS [U.S. Energy Information Administration, c, Table 5.2, 2006]. The second column states the EUNR energy that has been allocated to the end-uses according to the procedure described in this section of the report. The last column presents the energy demand for process steam generation including the EUNR energy. The CHP/Cogeneration end-use energy is multiplied by $(1 - \eta_{eff})$ to find the process steam energy demand. The vertical sum in the last row might not match the sum of the displayed values due to rounding.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.500	0.474	0.637	0.604	1.137	1.078
CHP and/or Cogen.						
high eff.	0.465	0.441	0.381	0.361	0.381	0.361
low eff.	0.106	0.100	0.000	0.000	0.069	0.065
Sum	1.071	1.015	1.018	0.965	1.587	1.504

Petroleum and Coal Products Manufacturing

Based on the energy model for the petroleum and coal industry by Ozalp and Hyman [2007], 92% of the byproduct energy goes into indirect uses. The breakdown into Conventional Boiler Use and CHP/Cogeneration was done according to the same ratio as in Ozalp and Hyman's power and steam generation model. Given the information from their model, the remaining byproduct and EUNR energy was distributed among the direct end-uses only.

Table 3.5: Allocation of EUNR energy in Petroleum and Coal Products Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.135	0.128	2.010	1.905	2.145	2.033
CHP and/or Cogen.						
high eff.	0.169	0.160	0.000	0.000	0.076	0.072
low eff.	0.003	0.003	0.187	0.177	0.123	0.117
Sum	0.307	0.291	2.197	2.082	2.344	2.222

Food Manufacturing

The byproducts were allocated in the CHP and/or Cogeneration end-use category. Many processes in food processing industry require steam, whereas direct use of fuels is less common. Assigning the byproduct energy to CHP and/or Cogeneration is more conservative than assigning it to Conventional Boiler Use. It results in a more conservative estimate for the process steam energy demand because only a fraction of $(1 - \eta_{eff})$ of the CHP and/or Cogeneration energy is considered for process steam generation, the remaining part is converted to electricity. Consequently, all Food Manufacturing byproducts are assigned to the low efficiency portion of the cogeneration category.

Table 3.6: Allocation of EUNR energy in Food Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.400	0.379	0.094	0.089	0.494	0.468
CHP and/or Cogen.						
high eff.	0.027	0.026	0.000	0.000	0.012	0.012
low eff.	0.119	0.113	0.032	0.030	0.098	0.093
Sum	0.546	0.518	0.126	0.119	0.604	0.573

Paper Manufacturing

The main byproducts in the Paper Manufacturing sector are Pulping or Black Liquor and Wood Chips or Bark. All byproducts and the Agricultural Waste are allocated to the CHP and/or Cogeneration end-use with lower efficiency.

Wood Manufacturing

The byproducts in wood manufacturing include mainly Wood Chips and Bark and some waste materials. This energy was assigned to the the lower efficiency subgroup of CHP and/or Cogeneration.

Table 3.7: Allocation of EUNR energy in Paper Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.171	0.162	0.083	0.079	0.254	0.241
CHP and/or Cogen.						
high eff.	0.166	0.157	0.000	0.000	0.075	0.071
low eff.	0.244	0.231	1.330	1.261	1.023	0.970
Sum	0.580	0.550	1.414	1.340	1.352	1.281

Table 3.8: Allocation of EUNR energy in Wood Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.020	0.019	0.013	0.012	0.033	0.031
CHP and/or Cogen.						
high eff.	0.009	0.009	0.000	0.000	0.004	0.004
low eff.	0.000	0.000	0.229	0.217	0.149	0.141
Sum	0.030	0.028	0.242	0.229	0.186	0.176

Primary Metal Manufacturing

Andersen and Hyman [2001] mention double counting in the MECS database for the Primary Metals sector. Their analysis is confirmed by the 2002 MECS Survey Methods [U.S. Energy Information Administration, 2002] and personal communication [Adler, 2010]. Blast Furnace Gas, considered as a byproduct, originates from coal coke and breeze in the furnace, which is already included in the total energy consumption. The data was corrected for this double counting following the suggestions in the 2002 MECS Survey Methods. Table 3.9 summarizes the resulting byproduct, Other and EUNR energy in the Primary Metals sector and indicates the end-use they have been assigned to. The Blast Furnace/Coke

Table 3.9: Byproduct energy consumption in Primary Metal Manufacturing. The column on the right states the end-use to which the energy has been allocated.

Byproduct/End-Use	**Consumption (EJ)**	**(quads)**	**Allocated to End-Use**
Coal Coke	0.117	0.111	Direct Process Heating
Blast Furnace/Coke Oven Gas	0.258	0.245	CHP and/or Cogeneration
Petroleum Coke	0.008	0.008	Direct Process Heating
Wood Chips, Bark	0.002	0.002	CHP and/or Cogeneration
Waste Gas	0.001	0.001	CHP and/or Cogeneration
Net Steam	0.038	0.036	Conventional Boiler Use
Other	0.428	0.406	
Remaining EUNR	0.016	0.015	distributed to all
Total EUNR	0.444	0.421	

Oven Gases have been allocated to the low-efficiency cogeneration subcategory, because of their low heating value and inhomogeneous composition. Coal Coke is assumed to be used in blast furnaces or for similar direct process heating instead of being used for steam production.

Nonmetallic Mineral Products Manufacturing

Table 3.11 summarizes the byproducts in the Nonmetallic Mineral Products sector and indicates the end-use they have been assigned to. The EUNR energy allocation in this sector is based on the assumption that most processes rely on direct heating as opposed

Table 3.10: Allocation of EUNR energy in Primary Metal Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.033	0.031	0.038	0.036	0.071	0.067
CHP and/or Cogen.						
high eff.	0.030	0.028	0.000	0.000	0.013	0.013
low eff.	0.006	0.006	0.263	0.249	0.175	0.166
Sum	0.069	0.065	0.301	0.285	0.259	0.245

to indirect heating by process steam, as reflected in the consumption of the conventional fuels (those listed specifically in Table 5.2, MECS 2006). For example, the ratio of Direct Process Heating to Conventional Boiler Use is reported as 36:1. Therefore, all of the byproduct energy was allocated either to Direct Process Heating or distributed to all end-uses according to the original sharing.

Transportation Equipment Manufacturing

EUNR energy originates from several different energy sources, i.e. the byproducts Waste Gas and Waste Oils/Tar and Waste Materials, Net Steam and natural gas with non-reported end-use. The total of 0.023 EJ of EUNR energy were distributed among the end-uses according to the original distribution of the conventional fuels in the MECS end-use table [U.S. Energy Information Administration, c, Table 5.2, 2006].

Fabricated Metal Product Manufacturing

The entire EUNR energy for this subsector originates from the byproduct Waste Gas and from consumption of Natural Gas with non-reported end-use. Therefore, it was distributed among all end-uses according to the initial Natural Gas distribution in the MECS end-use table [U.S. Energy Information Administration, c, Table 5.2, 2006].

Table 3.11: Byproduct energy consumption in Nonmetallic Mineral Products Manufacturing. The column on the right states the end-use to which the energy has been allocated.

Byproduct/End-Use	**Consumption (EJ)**	**(quads)**	**Allocated to End-Use**
Coal Coke	0.012	0.011	Direct Process Heating
Waste Oil/Tars/Waste Materials	0.021	0.020	distributed
Petroleum Coke	0.077	0.073	distributed
Wood Chips, Bark	0.013	0.012	distributed
Waste Gas	0.001	0.001	Direct Process Heating
Net Steam	0.025	0.024	Conventional Boiler Use
Other	0.149	0.141	
Remaining EUNR	0.058	0.055	distributed to all
Total EUNR	0.207	0.196	

Table 3.12: Allocation of EUNR energy in Nonmetallic Mineral Products Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.021	0.020	0.028	0.027	0.050	0.047
CHP and/or Cogen.						
high eff.	0.001	0.001	0.000	0.000	0.000	0.000
low eff.	0.000	0.000	0.000	0.000	0.000	0.000
Sum	0.022	0.021	0.028	0.027	0.050	0.047

Table 3.13: Allocation of EUNR energy in Transportation Equipment Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.051	0.048	0.003	0.003	0.054	0.051
CHP and/or Cogen.						
high eff.	0.004	0.004	0.000	0.000	0.002	0.002
low eff.	0.006	0.006	0.000	0.000	0.004	0.004
Sum	0.061	0.058	0.003	0.003	0.060	0.057

Table 3.14: Allocation of EUNR energy in Fabricated Metal Product Manufacturing to the end-uses which are considered sources of process steam: Conventional Boiler Use and CHP and/or Cogeneration. A detailed explanation for each column is given in Table 3.4.

End-Use	**Energy Consumption MECS**		**Allocated EUNR Energy Cons.**		**Process Steam Energy Demand**	
	(EJ)	**(quads)**	**(EJ)**	**(quads)**	**(EJ)**	**(quads)**
Conv. Boiler Use	0.038	0.036	0.002	0.002	0.040	0.038
CHP and/or Cogen.						
high eff.	0.000	0.000	0.000	0.000	0.000	0.000
low eff.	0.000	0.000	0.000	0.000	0.000	0.000
Sum	0.038	0.036	0.002	0.002	0.040	0.038

Remaining Manufacturing Sectors

After determining the energy consumption for process steam generation for the nine manufacturing subsectors with the largest fuel consumption as described above, the ratio of fuel consumption for process steam and the total fuel consumption of the respective subsector was calculated. An average ratio for the nine large subsectors was determined. The amount of energy used for process steam in all remaining sectors was then estimated by multiplying their total fuel consumption with the average ratio. The approach is justified by the fact that the nine chosen sectors account for 92% of the total fuel consumption. The resulting estimate for energy demand for process steam generation is illustrated in Figure 3.4. The twelve remaining sectors are accumulated in "Other".

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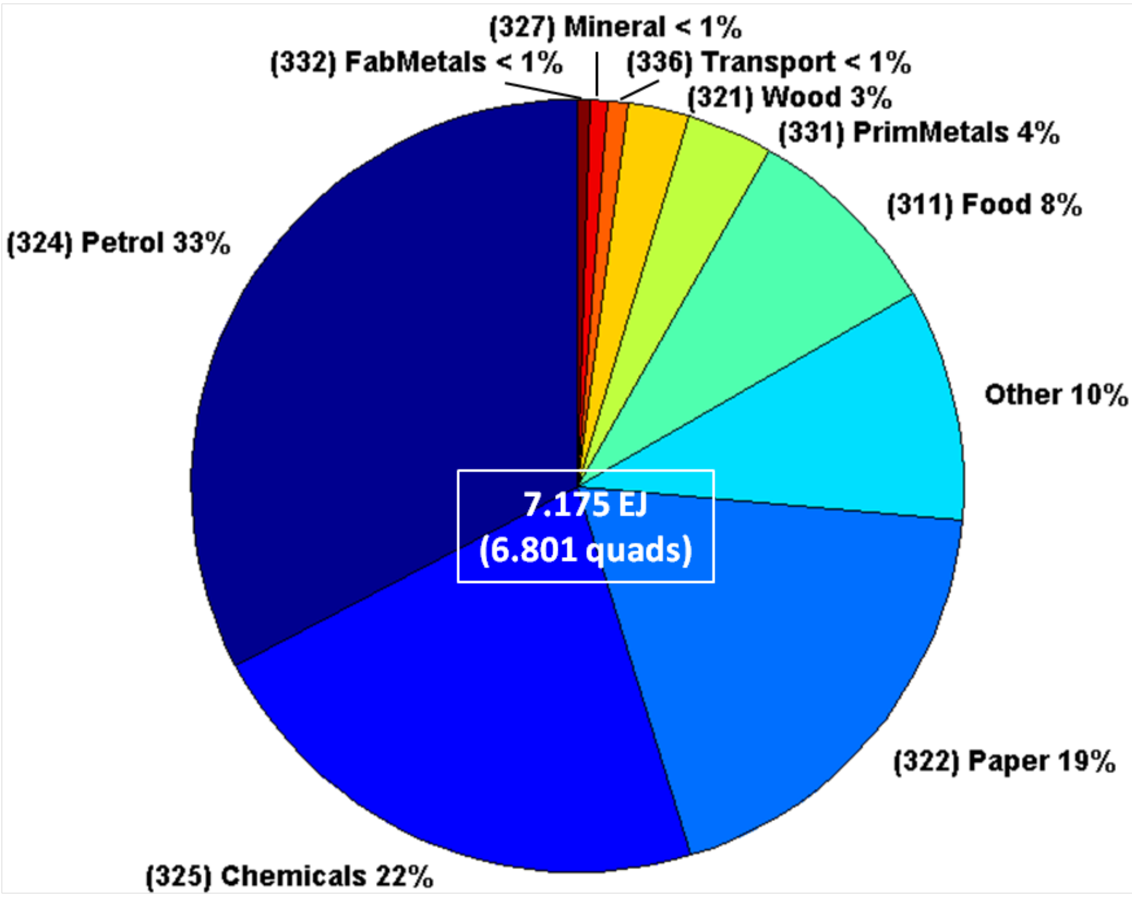

Figure 3.4: Fuel consumption for process steam generation as determined in Section 3.2.2. The nine subsectors with the highest fuel consumption are labeled with the NAICS code and an abbreviation for their name. The NAICS codes are listed in Table 3.1. The 12 remaining subsectors are combined in "Other".

3.2.3 Process Steam Temperature Distribution

The temperature distribution is investigated for the five subsectors with the highest energy demand for process steam:

- (324) Petroleum and Coal Products Manufacturing,
- (325) Chemical Manufacturing,
- (322) Paper Manufacturing,
- (311) Food Manufacturing, and
- (331) Primary Metals Manufacturing.

They are responsible for 76% of the total manufacturing fuel consumption as shown in Figure 3.3 and for 87% of the process steam fuel demand, as can be seen in Figure 3.4. Their weighted (by steam demand) average distribution of process steam temperature is assumed to be representative for the remaining 16 manufacturing subsectors. Table 3.19 at the end of Section 3.2.3 summarizes the steam temperature distribution of the five investigated subsectors and the weighted average.

Petroleum and Coal Products Manufacturing
The analysis of the steam temperature distribution for the manufacturing subsector Petroleum and Coal Products Manufacturing is based on Petroleum Refineries (NAICS code 324110), which make up 95% of the energy consumption in this subsector. The processes with the highest consumption of process steam are summarized in Table 3.15. The steam use in these processes includes end-uses such as stripping, fractionation, quenching, dilution, and vacuum draw [Resource Dynamics Corporation, 2002]. Therefore, the steam is not necessarily at the temperature of the respective process/reactor. Nevertheless, since the steam is added to exploit its thermal properties and/or liquid water could not be used instead, the steam use was defined as consumption of thermal energy.
Temperature data for the steam is based on an energy analysis of industrial processes by Brown et al. [1985]. There is a lack of literature with more recent temperature data for steam usage in petroleum refineries. The boiler temperature in industrial refinery plants

Table 3.15: Processes with high consumption of process steam in petroleum and coal products manufacturing and their share of process steam use [Ozalp and Hyman, 2007]. Total does not sum up to 100% because of rounding.

Process	**Proportion of Total Steam Consumption for Process Heat (%)**
Atmospheric Distillation	28.8
Catalytic Hydrotreating	24.8
Alkylation	16.3
Vacuum Distillation	14.4
Catalytic Reforming	12.3
Catalytic Hydrocracking	3.5
Fluid Catalytic Cracking	0.1

is reported to be 217°C (422°F), and hence, all process steam of the manufacturing subsector 324 (NAICS code) is binned into the 200°C to 220°C temperature range. Although, some of the steam might be reused and might be at a lower temperature when it actually enters the process, this temperature range was chosen as a conservative assumption. It represents the maximum temperature, and hence, the highest requirement for alternative energy sources to provide the steam.

Chemical Manufacturing

A report on steam system opportunities [Resource Dynamics Corporation, 2002] analyzes the energy quantity and temperature of steam used for various process steps in the manufacturing of the 20 chemical products that account for most of the industry's energy use. The report was prepared for the DOE Office of Energy Efficiency and Renewable Energy (EERE) and covers the subsector Paper Manufacturing as well. We refer to the report as "EERE report" in the following. Table 3.16 is an example of the data provided by the EERE report for the manufacturing of ethylene. Our estimate for the amount of process steam is based on MECS data, which generally does not include recovered waste heat [Ozalp and Hyman, 2007, Adler, 2010]. Therefore, the process step Mechanical Drive (Recovered Steam) in Table 3.16 is excluded from further analysis. The required steam temperatures are binned in 20°C ranges. From the thermal energy for each process step and the total thermal energy for the production of 1 kg of ethylene, the percentage of steam energy used for each step can be calculated (Table 3.17).

Table 3.16: Thermal energy and production data for ethylene manufacturing adapted from [Resource Dynamics Corporation, 2002].

Process Step	**Thermal Energy (kJ/kg)**	**Steam Temperature (°C)**	**Total Annual Production (10^6 kg)**	**Total Steam Energy (10^{12} kJ)**
Dilution	1,181	177		
Acetylene Removal	121	121		
Fractionation	323	149		
Mechanical Drive (Process Steam)	301	316		
Mechanical Drive (Recovered Steam)	1757	316		
Total	3,682		20,200	362

Table 3.17: Steam energy temperature distribution for each process step in the production of ethylene.

Process Step	**Thermal Energy (kJ/kg)**	**Temperature Bin (°C)**	**Distribution (%)**
Dilution	1,181	160-180	61
Acetylene Removal	121	120-140	6
Fractionation	323	140-160	17
Mechanical Drive (Process Steam)	301	>260	16
Total	1,926		

A similar analysis can be done for all the processes in the EERE report. Each generated distribution is then weighted according to the total thermal energy use of the individual process to generate the total steam temperature distribution for the Chemical Manufacturing (NAICS code 325) subsector. Because the 20 listed chemicals represent 90% of the steam usage for Chemical Manufacturing [Resource Dynamics Corporation, 2002], the collective steam distribution for these chemicals adequately represents the steam distribution for the entire Chemical Manufacturing. For our analysis, we have left out the Caprolactam process because the EERE report does not list the required steam temperatures. Caprolactam's steam demand only represents about 2% of the total steam energy of the 20 chemicals listed. Table 3.19 shows the resulting cumulative distribution. The distribution was simplified for better readability of the final thermal energy use temperature distribution graphs (Figure 4.2 and Figure 4.3). The temperature bins 100°C to 120°C, 180°C to 200°C, and 200°C to 220°C in sum represented only 5% of the steam distribution. The steam use in these small bins was lumped into the next higher temperature bin.

Paper Manufacturing

The EERE report gives temperature information for the most important processes in paper manufacturing and the amount of energy required per ton of product. The amount of thermal energy for the processes is given as a range; we considered the mean value of each range for our analysis. Different types of pulping processes (Kraft, sulfite, mechanical, chemi-thermomechanical, etc.) are mentioned, but Kraft pulping accounted for 85% of the pulp produced in the U.S. in 1994 [Resource Dynamics Corporation, 2002]. Hence, the Kraft process is considered to be representative for the steam demand of the pulping process. Other processes in manufacturing paper which require steam are combined with the Kraft mill process to represent a model for an integrated pulp and paper mill. With the total thermal energy for our model integrated mill and the thermal energy used for each step of the process (both normalized for one ton of product), the percentage of steam energy used for each step can be calculated. Table 3.18 is the result of this procedure with the steam temperature binned to a 20°C temperature range. Table 3.19 condenses the information in Table 3.18 to be easily used as a model for the distribution of process steam in the entire Paper Manufacturing industry.

Food Manufacturing

Lund et al. [1980] provide a list of important processes in the food sector and their temperature requirements. The processes are mentioned with their Standard Industrial Clas-

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Table 3.18: Steam energy temperature distribution for each process step in an integrated pulp (Kraft) and paper mill.

Process Step	Thermal Energy Av. (kJ/kg)	Temperature Bin (°C)	Distribution (%)
Digestion	2,940	160-180	14
Chemical Recovery	4,500	140-160	22
Bleaching	5,410	120-140	26
Pulp Drying	4,940	120-140	24
Washing	890	120-140	4
Refining	2,040	120-140	10
Total	20,720		100

sification (SIC) number, which allowed us to relate them to today's NAICS classification system. Their temperature distribution was then weighted with the total fuel consumption of the corresponding NAICS category to determine an average temperature distribution for the Food Manufacturing sector. The resulting distribution is shown in Table 3.19.

Primary Metals Manufacturing
The subsector Iron and Steel Mills accounts for 66% of the sector's fuel consumption. Its process steam temperature distribution is assumed to be representative for the whole Primary Metals Manufacturing sector. Information about process steam temperature is given in the abovementioned report by Brown et al. [1985]. For the resulting distribution see Table 3.19.

3.2.4 Further Thermal End-Uses in Manufacturing

The Process Heating end-use in Table 3.3 clearly represents thermal energy use, but it was assumed to be at temperatures above 260°C. The main energy source for the Process Heating category is natural gas (NG). The assumption of end-use temperatures above 260°C corresponding to an exclusion from our analysis is justified by the high temperature of NG combustion gases and the fact that they are applied directly, following the definition of the end-use category. Additionally, there might be requirements for the processes that

Table 3.19: Resulting steam energy distribution with temperature for the five manufacturing subsectors with highest process steam use. The column "Other Manufacturing" represents the weighted average of the five main sectors and was used to distribute the remaining 16 sectors' process steam energy with temperature.

Temp. range (°C)	**Steam Energy Temperature Distribution (%)**					
	(326) Petroleum and Coal	**(325) Chemical**	**(322) Paper**	**(311) Food**	**(331) Primary Metals**	**Other Manu-facturing**
>260		22			38	7
240-260		9				2
220-240						
200-220	100			2		38
180-200		9		6		3
160-180		32	14	8	62	15
140-160		5	22			6
120-140		23	64	11		21
100-120				16		2
80-100				16		2
60-80				20		2
40-60				21		2
Sum	100	100	100	100	100	100

use direct heating which cannot be met by steam, and hence by using renewable sources for thermal energy. Our study generally intended to provide a conservative estimate of the amount of process steam used in industry in order to prevent an overestimation of the potential for renewable sources.

Process Cooling and Refrigeration were considered potential applications for thermal energy utilization based on the assumption that they could be provided by (ad/ab)sorption cooling systems (see following paragraph). Facility HVAC (Heating, Ventilation and Air Conditioning) also includes thermal end-uses. All other listed end-uses are considered to be non-thermal or at temperatures above the considered range.

Refrigeration & Cooling

The energy consumption for Refrigeration & Cooling in the manufacturing sector as reported in the MECS is 0.252 EJ (0.239 quads). Although parts of the EUNR consumption could possibly be allocated to this end-use additionally, the originally reported value was considered as a conservative estimate for the thermal energy consumption.

Sorption cooling systems are based on the phenomena of adsorption or absorption and can be powered by low-grade heat. The adsorption process concerns separation of a substance from one phase, accompanied by its accumulation or concentration on the surface of another. Absorption is the process in which material transferred from one phase to another, (e.g. liquid) interpenetrates the second phase to form a solution. Based on Fan et al. [2007], the absorption cooling system's working principle is as follows: The vapors of refrigerant are sent towards the traditional cycle of condenser, expansion valve and evaporator. Cold is produced by the evaporation of refrigerant in the evaporator at low pressures. Then the refrigerant vapors are absorbed by the respective absorbent material and the refrigerator-enriched solution is brought to the high-pressure zone. The solution is then heated by the thermal energy source (solar thermal, geothermal, waste heat) to allow the separation of refrigerant and absorbent and start the cycle again.

The required temperature of the heat source depends on the desired cold side temperature. With increasing temperatures of the energy source on the hot side, the accessible cold side temperature decreases and the coefficient of performance (COP) of the system, a parameter describing the efficiency, increases. Section 3.3.2 discusses required hot side temperatures for residential refrigerators and freezers. Industrial refrigeration processes are assumed to demand lower cooling temperatures on average than refrigeration in homes. Also, a higher coefficient of performance (COP) value might be required to make sorption cooling economical. Therefore, the end-use temperature for industrial cooling and refrigeration was increased to 120°C to 140°C compared to 100°C to 120°C for residential refrigeration.

Space Heating and Air Conditioning

The end-use category Facility HVAC as used in the MECS does not include steam and hot water [U.S. Energy Information Administration, c, Table 5.2, 2006]. Accordingly, the part of the energy consumption for space heating that is met by steam or hot water is included in the Conventional Boiler Use category. To estimate the amount of steam used for space heating, the following procedure was applied.

First, we looked into the fuel inputs into Facility HVAC shown in Table 3.20. We assumed that electricity is used for air conditioning and ventilation only and that the combustible fuel inputs (the vast majority being natural gas) in Facility HVAC are used in forced-air furnaces to provide space heating.

We assume that the ratio of energy demand for air conditioning and ventilation and energy demand for space heating f_{HVAC} is the same for the industrial sector and the commercial sector. The end-uses air conditioning, ventilation and space heating are treated separately in the CBECS [U.S. Energy Information Administration, b], and hence, f_{HVAC} for the commercial sector is known.

$$f_{HVAC} = \frac{air\,conditioning + ventilation}{space\,heating} \tag{3.3}$$

We can calculate the total amount of energy consumed for space heating in the manufacturing sector to be 0.694 EJ (0.658 quads). The combustion fuels shown in Table 3.20 account for 0.414 EJ (0.393 quads) and the remaining 0.280 EJ (0.265 quads) was assumed to be included in the Conventional Boiler Use category.

The 0.280 EJ (0.265 quads) of space heating energy from boiler use had to be subtracted from the amount of process steam calculated before, to avoid double counting. The en-

Table 3.20: Total manufacturing sector fuel consumption for Facility HVAC [U.S. Energy Information Administration, c, Table 5.2, 2006]. Values given in EJ and (quads).

End-Use	Electricity	Natural Gas	LPG	Fuel Oil	Coal	Total
Facility HVAC	0.280 (0.265)	0.399 (0.378)	0.005 (0.005)	0.008 (0.008)	0.002 (0.002)	0.694 (0.658)

ergy was subtracted from all manufacturing subsectors' Conventional Boiler Use energy, according to their contribution to the Facility HVAC total.

For the calculation of the air conditioning energy demand in manufacturing, the same ratio of air conditioning to ventilation energy as in the commercial sector was assumed. The specific energy demand of both has to be determined because air conditioning is considered a thermal end-use, whereas ventilation is not. The electricity consumption in Facility HVAC (Table 3.20) was assumed to equal the total energy demand for air conditioning and ventilation.

$$\begin{aligned} air\ conditioning &= (electricity\ consumption) \\ &\times \left[\frac{air\ conditioning}{air\ conditioning + ventilation}\right]_{commercial} \end{aligned} \tag{3.4}$$

For the above described calculations concerning Facility HVAC we considered the original EIA values, before our allocation of the EUNR category. The space heating and cooling demands vary significantly for the different manufacturing sectors and the nine sectors for which the EUNR allocation was done, were found not to be a representative sample for this particular end-use. This procedure results in a conservative estimate for the thermal energy demand in space heating and air conditioning. The end-use temperature for space heating and air conditioning is assumed to be 40°C to 60°C and 60°C to 80°C, respectively. For more information on end-use temperature for space heating and air conditioning see Section 3.3.2.

3.2.5 Extrapolation of Data to 2008

We considered the MECSs for the years 2006, 2002 and 1998. The effect of extrapolation is less significant in the industrial sector compared to residential and commercial, because there is only a two year period between the latest MECS (2006) and the chosen base year (2008). A ratio of the total fuel consumption (as reported in the three mentioned MECS) and the total industrial energy consumption (as reported in the AER for the same years), $f_{fuel,A}$, can be calculated for each of the five main manufacturing subsectors as follows

$$f_{fuel,A} = \frac{Total\,Fuel\,Consumption\,Subsector\,A\,(MECS)}{Total\,Industrial\,Energy\,Consumption\,(AER)} \tag{3.5}$$

Using a mean least square fit, a linear trend can be obtained and used to project the ratio $f_{Fuel,A}$ into the year 2008. The ratio for 2008 is then used to estimate the total fuel consumption of those manufacturing sectors in 2008 based on the AER 2008 total industrial energy consumption.

$$\begin{aligned} [Total\,Fuel\,Cons.\,Subsector\,A]_{2008} &= f_{fuel,A}^{2008} \\ \times [Total\,Industrial\,Sector\,Consumption(AER)]_{2008} \end{aligned} \tag{3.6}$$

The same procedure was followed for the "Other" subsectors, i.e. the consolidated remaining manufacturing sectors. The ratio of energy consumed for process steam production and the total fuel consumption of the sector was assumed to be constant at the level of 2006. Refrigeration & Cooling and Facility HVAC were assumed to follow the same trend as the factor f_{fuel}

$$f_{fuel} = \frac{Total\,Manufacturing\,Fuel\,Consumption\,(MECS)}{Total\,Industrial\,Energy\,Consumption\,(AER)} \tag{3.7}$$

The residential and commercial demand sectors are analyzed in the following sections.

3.3 Residential Sector Methodology

3.3.1 Sector Definition

The AER defines the residential sector as consisting of "living quarters for private households" [U.S. Energy Information Administration, 2009]. Institutional living quarters are specifically excluded and not covered in this work. The RECS's definition is analogous, for details see U.S. Energy Information Administration [2001].

3.3.2 Energy Consumption and End-Use Temperature of Residential End-Uses

The RECS differentiates the end-uses Space Heating, Water Heating, Air Conditioning, and Appliances. Figure 3.5 illustrates their share of the residential energy consumption.

Space Heating

The energy demand for space heating reported in the RECS [U.S. Energy Information Administration, a] is assumed to be purely for thermal energy. Electricity use for pumps, etc. is considered negligible compared to thermal energy. Generally, temperatures around and above 50°C (122°F)[2] are used in space heating, but using temperatures as low as 40°C (104°F) is feasible [Bloomquist, 2003]. Therefore, space heating is included in the 40°C to 60°C (104°F to 140°F) temperature range.

Water Heating

Same as for space heating, the total reported energy demand for water heating [U.S. Energy Information Administration, a] was assumed to be thermal. Although many U.S. households set their water heater to a higher temperature, the U.S. Department of Energy [1995] points out that a temperature of 48.9°C (120°F) is sufficient as opposed to most manufacturers' setting of 60°C (140°F). Therefore, the temperature category for water heating is chosen to be 40°C to 60°C (104°F to 140°F).

[2] Temperatures for the residential sector are additionally given in °F for simple comparison to appliances settings in the U.S.

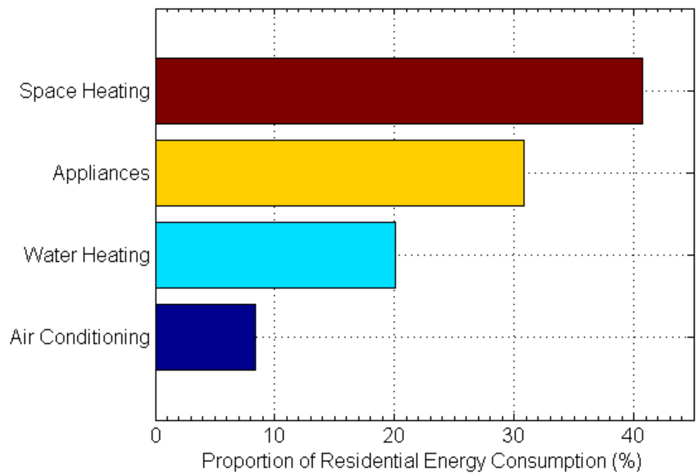


Figure 3.5: Proportions of single end-uses of total residential energy consumption according to the RECS 2005. The total for 2005 is 11.130 EJ (10.550 quads) [U.S. Energy Information Administration, a].

Air Conditioning

The entire energy demand for Air Conditioning reported in the RECS is considered thermal energy. The temperature assigned to Air Conditioning is based on the temperature requirements of a sorption cooling system. The main driver for research in these systems is the possibility of using solar energy from solar collectors, but the thermal energy could as well be provided by waste heat, geothermal heat, or any other heat source. For residential air conditioning, a heat source temperature of 60°C to 80°C is considered to be sufficient to operate such systems [Wang et al., 2009]. Higher temperatures would allow to achieve higher coefficients of performance (COP), which increases the economic competitiveness.

Appliances

The Appliances category contains a sum of different end-uses. The main source of information about the specific energy use of common appliances was the “end-use consumption of electricity” report [U.S. Energy Information Administration, 2001]. We refer to this part of the RECS as “EUCE report” in the following. Table 3.21 summarizes the processes that require thermal energy mentioned in the EUCE report and their share of the total Appliances electricity consumption. Some appliances, such as range tops and ovens or clothes dryers, are not exclusively run by electricity, but also by natural gas (NG) or liquefied petroleum gas (LPG). Using additional RECS data, a thermal energy factor f_{th} was calculated to consider this additional non-electric thermal energy. Table 3.21 shows the calculated factors that were multiplied with the electric energy to find the true thermal energy consumption. The following paragraphs give detailed information about the approach to define these thermal energy factors and the end-use temperature for each appliance. If not further specified, the thermal energy factor is assumed to be 1. If other energy sources are used for the same end-use additionally to electricity, the factor is larger than 1. If electricity is the only used energy source but not the entire electricity consumption is for thermal energy, the factor is smaller than 1. For completeness, all appliances with thermal energy use listed in the EUCE report have been taken into account, even if their energy consumption seems negligible compared to other end-uses such as Space Heating.

Refrigerators and Freezers

Sorption cooling systems are considered to specify an end-use temperature for refrigerators and freezers, analogous to Air Conditioning. Based on the review of Fan et al. [2007], the temperature range for sorption systems for refrigeration was chosen to be 100°C to 120°C (212°F to 248°F). Similar to air conditioning, the COP would increase with an increase in heat supply temperature. As mentioned above, sorption cooling systems require higher hot side temperatures for lower cooling temperatures. Hence, freezers require higher heat source temperatures than refrigerators, and thus, a value of 120°C to 140°C (248°F to 284°F) was assigned. However, in the case of freezers further exploration of sorption cooling systems is necessary to enable widespread use. According to Fan et al. [2007], several successful attempts to modify refrigeration system to produce ice have been reported, and congelation applications (freezing in low temperature range around -18°C) is proven but in an early experimental stage.

Clothes Dryers

Most residential dryers are tumble dryers, where the heated, dry air enters a rotating drum that houses the clothes. A tumble dryer requires mechanical energy to spin the drum and thermal energy to evaporate the water. The thermal energy part can be provided by electricity, natural gas, or LPG. We used Eq. (3.8), derived in Appendix A.2 to estimate

Table 3.21: Processes in the Appliances end-use category, their share of the electricity consumption of all Appliances [U.S. Energy Information Administration, 2001], and the thermal energy factor, f_{th}, used to determine their thermal energy consumption. See the respective paragraph for information on how f_{th} was determined.

Appliance/Process	**Share of Appliances Electricity Consumption (%)**	**Thermal Energy Factor f_{th} (-)**
Refrigerators	21.17	1.00
Clothes Dryers	8.94	1.14
Freezers	5.33	1.00
Electric Range Tops	4.34	2.23
Dishwashers	3.93	0.70
Electric Ovens	2.85	1.68
Microwave Ovens	2.62	1.00
Clothes Washers	1.37	0.00
Pool/Hot Tub/Spa Heaters	1.03	1.47
Coffee Makers	0.81	1.00
Waterbed Heaters	0.77	1.00
Large, Heated Aquariums	0.34	1.00
Electric Toasters	0.24	1.00
Humidifiers	0.22	1.00
Total	100.00	

the thermal energy factor.

$$f_{th} = \frac{Q_{total}}{E_{total}} = f^Q_{elect} \frac{N_{elect} + N_{NG} + N_{LPG}}{N_{elect} + f^W_{elect}\,(N_{NG} + N_{LPG})} \tag{3.8}$$

Given the number of residential clothes dryers of each type (N_{elect}, N_{NG}, and N_{LPG}), and the fraction of total energy used for thermal energy f^Q_{elect} and mechanical energy f^W_{elect}, the total thermal demand Q_{total} can be calculated. Divided by the total electricity used by residential clothes dryers, E_{total}, we get an expression for f_{th}. The EUCE report provided total electricity used by clothes dryers. The breakdown of the different types of clothes dryers is given in table "home appliances characteristics by type of housing" [U.S. Energy Information Administration, a, Table HC2.9, 2005]. Based on Deans [2001] and Bansal et al. [2010], the fraction of thermal and mechanical energy used was chosen to be $f^Q_{elect} = 0.9$ (-) and $f^W_{elect} = 0.1$ (-) respectively. The temperature for the clothes drying end-use varies from 40°C to 120°C for different literature sources [Conde, 1997, Bansal et al., 2001, Han and Deng, 2003, Ng and Deng, 2008, Yadav and Moon, 2008, Bansal et al., 2010]. We chose 80°C to 100°C at the higher but not extreme end of the range.

Dishwashers

Dishwashers need thermal energy to further heat the water entering from the water heater tank to the desired operating temperature and for heating the dishwasher chamber during the drying cycle. Mechanical work is needed for spinning, spraying of the water, running a fan to improve drying, etc. The amount of required thermal energy varies, because the user has control over the operating conditions, such as rinsing and drying settings. Additionally, the water heater temperature setting affects the energy demand. Boost heaters allow for the reduction of the water heater temperature to 48.9°C (120°F) from the standard 60°C (140°F) [U.S. Department of Energy, 1995]. Persson [2007] estimated that 70%-90% of the electricity used by electric dishwashers is used for heating the water, the DOE cites an estimate of 80% [U.S. Department of Energy, 1995]. We chose the lower end of the reported range of 70% to reflect that a portion of the energy has already been accounted for by the Water Heating energy demand. According to the DOE report [U.S. Department of Energy, 1995] temperatures no higher than 60°C (140°F) are optimal for operating a dishwasher. We placed the thermal need of dishwashers in the 40°C to 60°C (104°F to

140°F) temperature range.

Range Tops, Ovens, Coffee Makers, and Microwave Ovens
Cooking devices powered by natural gas and LPG or propane are not included in the EUCE electric energy consumption for cooking processes. Appendix A.2 derives Eq. (3.9), used to determine the thermal energy factor for range tops and ovens.

$$f_{th} = \frac{1}{N_{elect}} \left(N_{elect} + n \times N_{NG} + n \times N_{LPG/Propane} \right) \tag{3.9}$$

The numbers of each type of range top or oven (N_{elect}, N_{NG}, $N_{LPG/Propane}$) are given in table "home appliances characteristics by type of housing" [U.S. Energy Information Administration, a, Table HC2.9, 2005]. The factor n is a ratio of the energy use for natural gas (NG) and LPG/Propane ovens and the energy use for electric ovens (c.f. Appendix A.2). The thermal energy factor for Microwave Ovens, Toaster Ovens, and Coffee Makers is assumed to be 1. The temperature range for cooking varies from 100°C to 250°C (212°F to 482°F). Contrary to water heating, where the upper limit of the commonly applied temperature range is higher than actually necessary, the high temperature limit in cooking is crucial to guarantee full operability. Therefore, stove and oven energy use is collected in the 240°C to 260°C (464°F to 500°F) temperature range, except for microwave ovens. Microwaves ovens are predominantly used to warm up precooked food at temperatures around the boiling point of water and their energy demand is considered in the 100°C to 120°C (212°C to 248°F) range.

Humidifiers
Despite the fact that not all humidifiers evaporate water, the humidifier electricity use was not divided into further subcategories and considered to be thermal energy at 100°C to 120°C (212°C to 248°F).

Clothes Washers
Clothes washing does not require temperature exceeding the suggested temperature for water heating [U.S. Department of Energy, 1995]. Following the RECS-table "total households by water heating fuel" [U.S. Energy Information Administration, a, Table WH2, 2005], more than 90% of the American households reported "warm" or "cold" as their

usually used temperature setting. Only the setting “hot” would require higher water temperatures than the suggested setting for the central water heater. Therefore, the majority of the thermal energy demand from clothes washers has already been considered in Water Heating, since most clothes washers are connected to the warm water supply. Hence, the electric energy use for clothes washers mentioned in the EUCE report was assumed to be non-thermal.

Pool/Hot Tub/Spa Heaters

The energy listed in the category called Pool/Hot Tub/Spa Heater in the EUCE report is assumed to be purely thermal energy, since energy consumption for pool-related mechanical drive is listed in the separate category Pool Filter/Pump. The number of pools heated by electricity (N_{elect}) and natural gas (N_{NG}) is listed in the RECS-table “total households by water heating fuel” [U.S. Energy Information Administration, a, Table WH2, 2005]. By assuming the same thermal energy demand for both electricity and NG-heated pools, the thermal energy factor for NG-heated pools can be calculated by Eq. (3.10). The derivation is given in Appendix A.2.

$$f_{th} = 1 + N_{NG}/N_{elect} \tag{3.10}$$

The chosen end-use temperature bin is 20°C to 40°C (68°F to 104°F). Waterbed Heaters and Large Heated Aquariums are placed in the same temperature bin, their thermal energy factor is assumed to be 1.

3.3.3 Extrapolation of Data to 2008

Ten Residential Energy Consumption Surveys from 1980 to 2005 were considered to study trends in the residential energy consumption. For each survey, we normalized the consumption of the four major end-use categories Space Heating, Water Heating, Air Conditioning and Appliances by the total residential energy consumption. Then, a linear trend was fitted to the normalized consumption using a least square fit to the mean values as shown in Figure 3.6. With these trends, we extrapolated the four major end-use categories’ normalized energy demand to the base year. The extrapolated percentage was applied to the total residential energy consumption in 2008, which is reported in the AER. The distribution of the energy demand within the Appliances category is based on the EUCE report [U.S.

Energy Information Administration, 2001] and was not changed for 2008, due to a lack of more recent data.

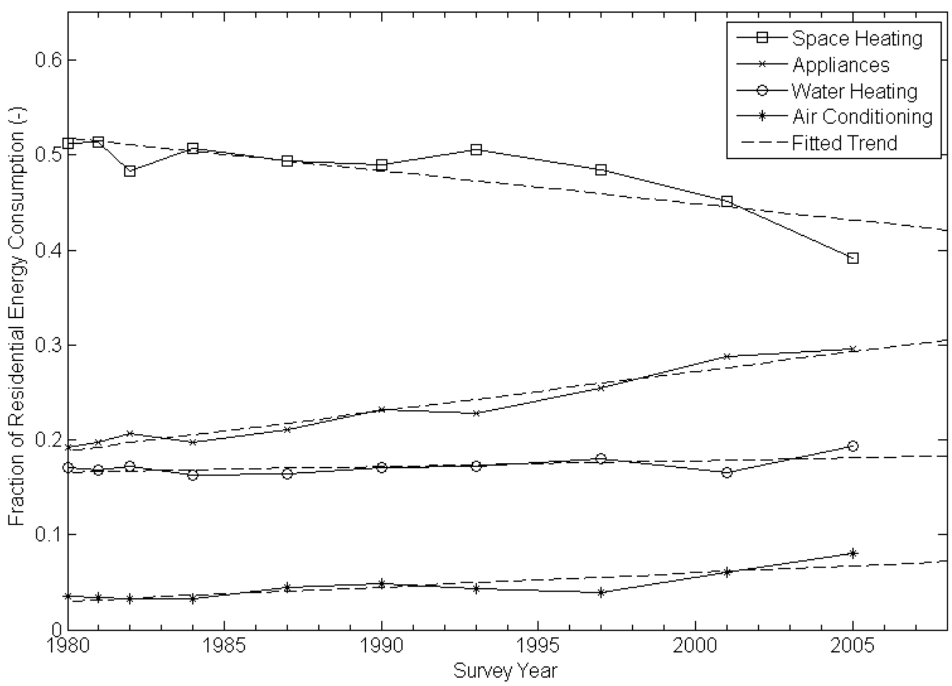


Figure 3.6: Fractions of energy consumption for the four main residential end-uses and total residential energy consumption, for all available RECS. For each survey year, the sum of the four fractions is normalized to 1. The points indicate RECS values, while the dashed lines show the fitted linear trends. The proportions for 2008 are: Space Heating 42%, Appliances 30%, Water Heating 18%, Air Conditioning 7%. The total does not sum up to 100% because of trend fitting and rounding..

Electronic Supplementary Material (ESI) for Energy and Environmental Science

3.4 Commercial Sector Methodology

3.4.1 Sector Definition

The Commercial Buildings Energy Consumption Survey (CBECS) [U.S. Energy Information Administration, b] provides statistical information about energy consumption in U.S. commercial buildings. To be considered a commercial building, more than half of the floor space of the building has to be devoted to activities that are neither residential, industrial nor agricultural, as defined in the CBECS sample methods [U.S. Energy Information Administration, 2003]. The major activities covered in the commercial sector are listed in Figure 3.7 along with the share of the respective activity's energy consumption.
The definition of the commercial sector in the AER is slightly different. The sector's consumption is not restricted to consumption in enclosed buildings, and the data is collected from energy suppliers, whose definition of commercial is likely to be different from the CBECS definition [Michaels, 2010]. The commercial energy consumption not covered in the CBECS, i. e. the consumption outside buildings, was not considered in this work due to the lack of detailed data in the EIA database.

3.4.2 Energy Consumption and End-Use Temperature of Commercial End-Uses

The CBECS provides information about the amount of energy consumed by each end-use. Figure 3.8 illustrates the main end-uses and their share of the total commercial buildings energy consumption of 6.9 EJ (6.5 quads) in 2003. The end-uses classified as thermal energy are similar to those in the residential sector:

- Space Heating
- Air Conditioning
- Water Heating
- Refrigeration
- Cooking

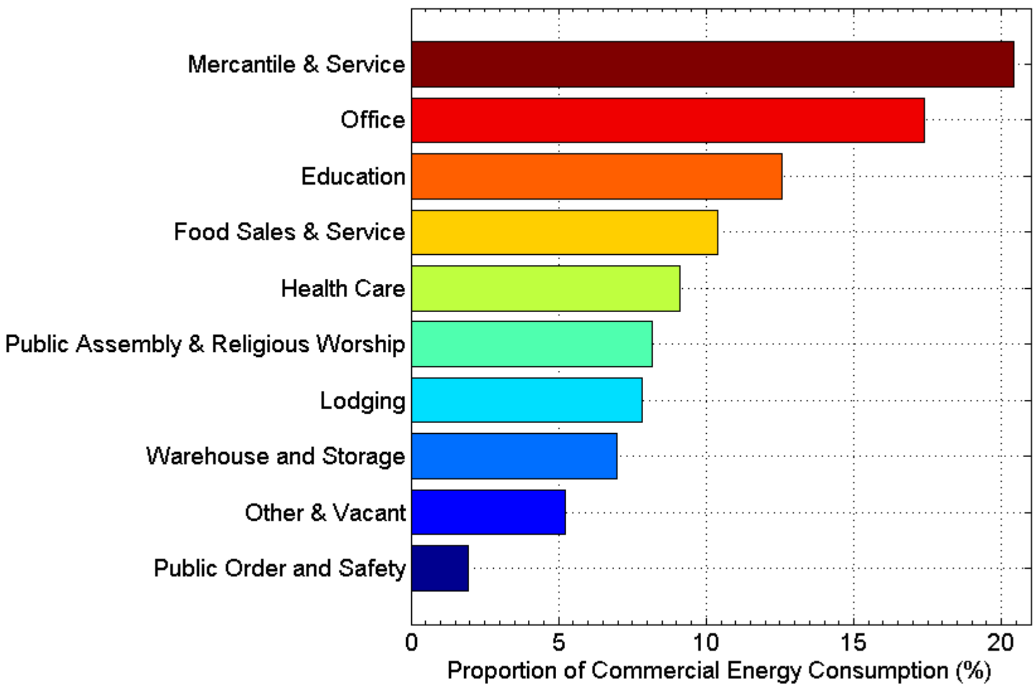


Figure 3.7: Activities in the commercial sector with their share of the total commercial buildings energy consumption of 6.882 EJ (6.523 quads) in 2003 [U.S. Energy Information Administration, b, Table E2A, 2003].

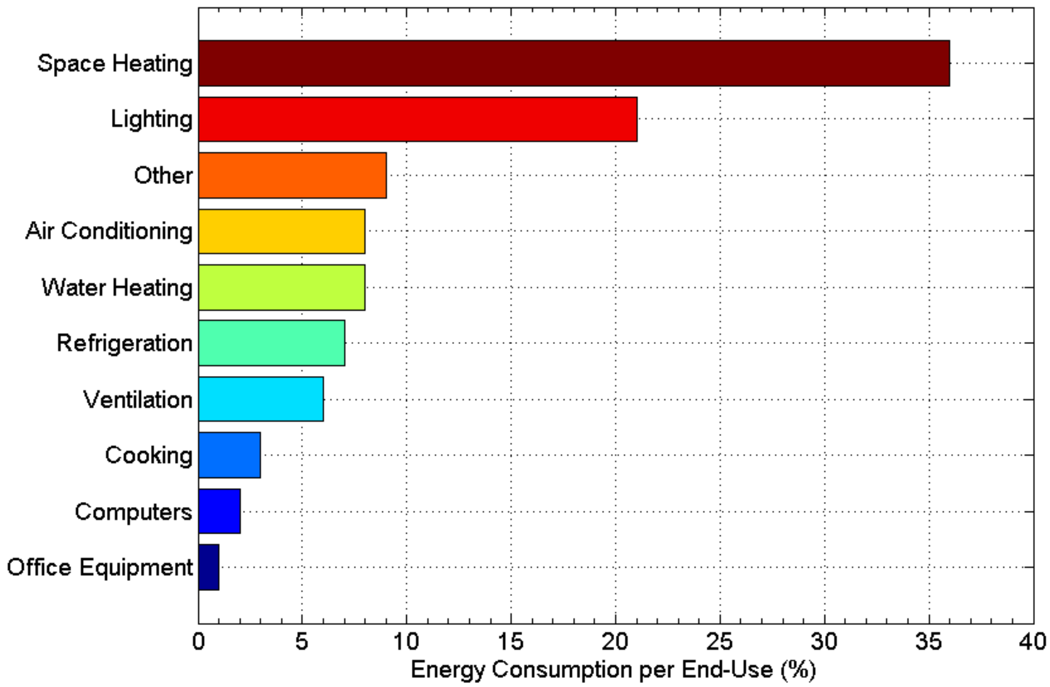


Figure 3.8: End-uses in commercial sector as listed in CBECS and their share of the total commercial buildings energy consumption of 6.882 EJ (6.523 quads), based on [U.S. Energy Information Administration, b, Table E2A, 2003]. The presented total does not include Electrical System Energy Losses (see Section 3.5).

The end-use category named Other in the CBECS is assumed to be non-thermal. As defined in CBECS sample design [U.S. Energy Information Administration, 2003], the Other end-use contains "unspecified uses of electricity". The end-use temperature estimates for the five thermal end-uses are the same as for the residential sector.

3.4.3 Extrapolation of Data to 2008

Extrapolation of energy demand trends to the base year was not possible for the commercial demand sector. Comparable end-use estimates are reported for the years 1995 and 2003 only. The 1999 CBECS does not contain end-use specific energy consumption information. Data from older CBECS is not suitable for trend extrapolation since the sample design was changed for the 1995 and later surveys. We assume that the 2003 data presents a more reliable approximation of the situation in 2008, than a trend fitted to only two data points in 1995 and 2003 would. Therefore, we assumed the same distribution of the commercial demand sector energy consumption among its end-uses in 2008 as in 2003.

The energy consumption from outside buildings has to be subtracted from the AER commercial energy consumption for 2008, before the energy can be distributed to the end-uses. The reason is the slight difference in the definition of the commercial sector in AER and CBECS as mentioned in Section 3.4.1. The ratio of energy that is consumed outside buildings and the total commercial energy consumption as in the AER is assumed to be constant from 2003 to 2008.

3.5 Electrical System Energy Losses (ESEL)

Losses in the electricity generation system are related to the energy consumption of the appliances, that finally consume the electricity. If the electricity consumption is reduced by 1 Joule, not only would the 1 Joule of electrical energy itself be saved, but the entire fuel energy that had to be invested for generating the electricity. Hence, losses in the electricity generation system in the U.S. were also considered in this work. The AER accounts for losses in the generation, transmission, and distribution of electricity in a category called Electrical System Energy Losses (ESEL) [U.S. Energy Information Administration, 2009]. The category Electricity Retail Sales (ERS) covers the electricity sold to the ultimate customers by the utilities. An overall system efficiency η_{el} can be calculated based on that data:

$$\eta_{el} = \frac{ERS}{ERS + ESEL} \tag{3.11}$$

The overall system efficiency for 2008 is 31.67%. We estimated the electrical conversion losses associated with electricity consumption for thermal end-uses, applying this system efficiency. The electricity consumption, including ESEL, E_{el}^{ESEL}, equals the Net Electricity consumption, E_{el}^{net}, divided by the system efficiency.

$$E_{el}^{ESEL} = \frac{E_{el}^{net}}{\eta_{el}} \tag{3.12}$$

In the example case of a reduction of the electricity consumption by 1 Joule, the saved primary fuel energy would be $E_{el}^{ESEL} = \frac{1}{\eta_{el}}$ J. The electric energy demand of each end-use can be divided by the system efficiency to determine the "true" or "gross" energy demand, including conversion and distribution losses in the electricity system. We refer to the "true/gross" energy demand as demand "including ESEL" in the following.

Some manufacturing industries generate significant amounts of electricity on-site. This on-site generated electricity is not included in the Net Electricity consumption in the "fuel consumption by end-use" MECS-table [U.S. Energy Information Administration, c, Table 5.2, 2005]. There is, however, no need to consider losses associated with this on-site generation. The losses are already accounted for in the MECS table, as the fuel inputs are covered, not the produced electricity.

4 Results and Discussion

4.1 Demand Sectors

Figure 4.1 illustrates the share of the total low temperature thermal energy use among the three demand sectors: residential, commercial, and industrial. It is important to note again, that this work aims to determine the consumption of primary energy to provide heat for thermal end-uses in the year 2008. Covering the energy demand of these end-uses by other energy sources, such as geothermal, solar thermal or waste heat would not necessarily require the same amount of primary energy. For process steam generated in a boiler, for example, the combustion fuel energy was considered as thermal energy demand. However, the actual energy content of the produced process steam is lower, due to inefficiencies in the energy conversion and in the heat transfer from the combustion gases to the steam. A source that supplies steam directly would have to cover the actual process steam energy only. For air conditioning and other cooling demands, the assigned end-use temperature is based on sorption cooling systems. The amount of energy is, however, based on the current technologies' demand. The actual required energy for sorption cooling systems depends on the specific technology applied and the COP achieved. Hence, in order to estimate the amount of thermal energy that would have to be generated from renewable sources to cover all low temperature thermal energy demands, the technological implementation would have to be investigated in detail for each end-use. The presented estimates for the actual energy consumption, however, represent a valuable estimate of how much conventional energy could be saved by using renewable thermal energy sources.

Figure 4.1 shows the total primary energy consumption for thermal energy in the considered temperature range for the three investigated demand sectors. Graph (b) includes the 11.373 EJ (10.780 quads) of Electrical System Energy Losses (ESEL) related to the 5.271 EJ (4.996 quads) of Net Electricity included in Graph (a), equivalent to a 51% increase of the

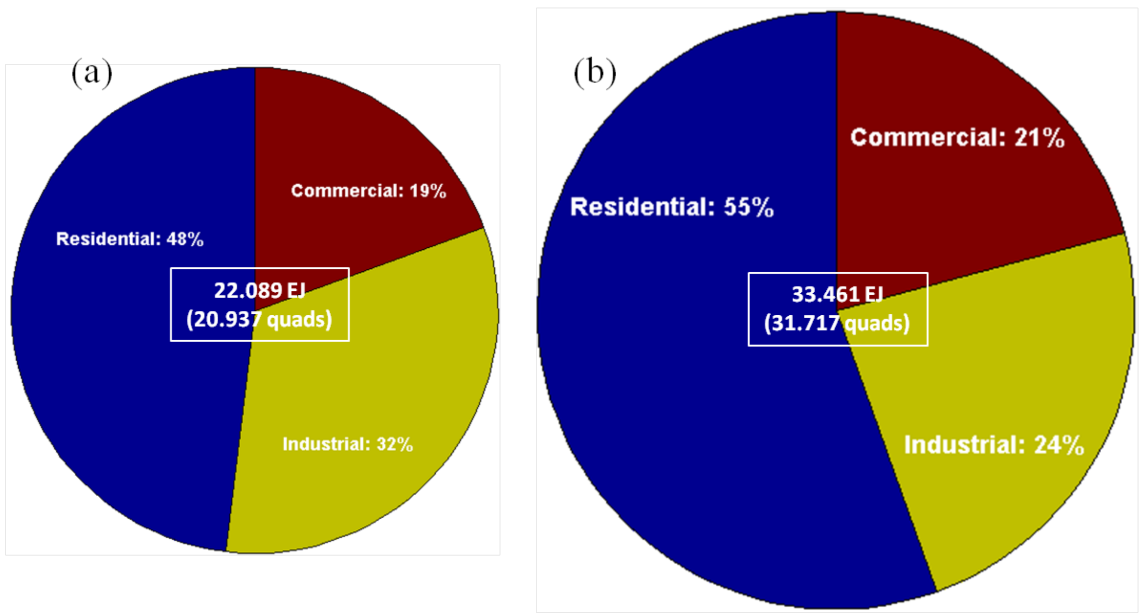


Figure 4.1: Total low temperature thermal energy demand and share of the three demand sectors residential, commercial, and industrial. (a) considers energy including Net Electricity, (b) additionally includes Electrical System Energy Losses.

total energy demand. The area of the disks in Figure 4.1 compares proportionally to the total. The 33.461 PJ (31.717 quads) in (b) represent 32% of the total U.S. energy consumption of 104.766 EJ (99.304 quads) in 2008 [U.S. Energy Information Administration, 2009].

The share of the industrial sector decreases from 32% to 24% when ESEL are considered. The majority of the industrial sector's low temperature thermal energy demand is met by process steam, which in turn is generated in a fired boiler. ESEL are allocated to the end-uses according to their electricity consumption and thermal energy supplied by electricity is restricted to air conditioning, refrigeration and cooling in the industrial sector. Hence, only the end-use categories Air Conditioning and Refrigeration & Cooling with their relatively small energy demand increase due to ESEL. Residential and commercial sector increase their shares from 48% to 55% and from 17% to 21%, respectively. The considerable increase in the residential sector is mostly due to its high electricity consumption for Air Conditioning and some of the Appliances (refrigeration, cooking, clothes drying, etc.).

Although the residential sector has the highest quantitative potential for direct use of low temperature thermal energy, the decentralized nature of the residential sector complicates large scale geothermal, solar or waste heat recovery projects. Investments are too high for single households while infrastructure needs, such as district heating networks, are enormous. Therefore, local communities should be encouraged to pursue such solutions. Geothermal heat pumps and flat plate solar collectors present small scale alternatives for single houses. The thermal end-uses in the commercial sector have very similar requirements to the residential sector. Commercial buildings are commonly larger than residential buildings and more centralized, which should result in lower complexity of the heat supply infrastructure.
Figure 1.1 in Section 1 supports the importance of incentives to the residential and commercial sectors. It illustrates the progress of the energy demand of the three demand sectors (residential, commercial, and industrial) from 1949 to 2008. The residential and commercial sectors' energy demand has been increasing following an almost linear trend in the past 40 years, whereas the industry's demand decreased from its 1997 high to reach a similar level in 2008 as in the early 1990s and mid 1970s. Reasons for this decrease include higher

energy prices and their call for more efficient production in the competitive industrial sector. Furthermore, exportation of manufacturing to lower-wage foreign markets decreased the U.S. industrial sector energy use. The low temperature thermal energy demand of the three sectors does not necessarily follow the exact same trends as the overall energy consumption, because the relative fraction of energy spent on each end-use also changes with time. For example, the fractional energy demand for space heating in residential houses decreased over the last 15 years, contrary to the increase in the overall energy consumption of the residential sector. Possible reasons include better insulation of buildings, somewhat lower thermostat settings and more waste heat from appliances. The decrease in heating degree days was not found to be significant enough to be the only reason. Establishing trends specifically for the thermal energy demand of the sectors exceeds the scope of this study, and generally, the trend should be similar to the total primary energy consumption.

Given the presented potential, thermal energy intensive industries may want to consider direct use of thermal energy to supply part of their demand. In 2008, 25% of the total manufacturing industry's energy demand, including ESEL, powered thermal end-uses below 260°C. Additionally, regions in the U.S. with moderate to high geothermal temperature gradients might be able to attract thermal energy intensive industries to create tax revenue and jobs. A prominent example for this effect is aluminum production in Iceland. The electricity-intense economy grew due to the availability of cheap electricity from geothermal power plants and now, bauxite is shipped to the country to be processed into aluminum [Hreinsson, 2007]. Although this example relies on cheap electricity and hence indirect use of geothermal resources, abundant thermal energy might promote a similar effect, depending on the future economics of geothermal heat compared to alternative energy sources.

4.2 Thermal Energy Use Temperature Spectrum

Figure 4.2 relates the thermal energy demand with its associated end-use temperature range with 20°C wide temperature bins. The three demand sectors are distinguished by different colors. The industrial sector process steam demand is sub-divided into the five key

manufacturing sectors and "Other Manufacturing". The end-uses with the largest energy demand are noted in the figure. Table A.1 in Appendix A.3 lists the demand of all end-uses and their end-use temperature.
By far the largest energy use is in the temperature range from 40 to 60°C, with space and water heating as major contributors. When Net Electricity is considered, space heating accounts for a demand of 8.457 EJ (8.016 quads). This corresponds to 38% of the total energy demand for low temperature thermal use and 8% of the total U.S. energy consumption in 2008. Water heating makes up 2.803 EJ (2.657 quads) corresponding to 13% and 2.7%, respectively. Another peculiar end-use is the petroleum and coal products manufacturing sector's process steam which was binned in a single temperature range. As mentioned earlier, this represents a conservative assumption, i.e. a high requirement for the temperature of the thermal energy source that would be applied.

Figure 4.3 shows the temperature distribution of the thermal energy use including ESEL. Applications that are powered mainly by electricity, such as air conditioning, refrigeration, and cooking, increase their share significantly compared to Figure 4.2. Interestingly, most of the thermal energy consumption in the investigated temperature range from 0°C to 260°C occurs in the lower half of the temperature range. Besides cooking, all residential and commercial contributions require end-use temperatures below 140°C. Industrial process steam and cooking are the only end-uses above 140°C. The cumulative energy demand in Figure 4.6 will clarify these observations.

Figure 4.4 shows a continuous functional approximation of the discrete data of Figure 4.2. The figure approximates Figure 4.2 if the resolution was set to an infinitesimal value as opposed to the 20°C stack width. To construct the figure, a piecewise cubic Hermite polynomial (PCHIP) was used, employing the built-in pchip-function from MATLAB (The MathWorks Inc, USA). Before implementing the PCHIP, the values of Figure 4.2 were plotted at the mean value of each temperature bin. For example, the ordinate value for the 20°C to 40°C bin is plotted at 30°C. The result is a "saw-toothed" graph on which a PCHIP is applied to smooth the plot. The continuous representation takes into account that the end-use temperature of each process might vary slightly due to different settings or conditions and the temperature ranges are not sharply confined but rather overlap and

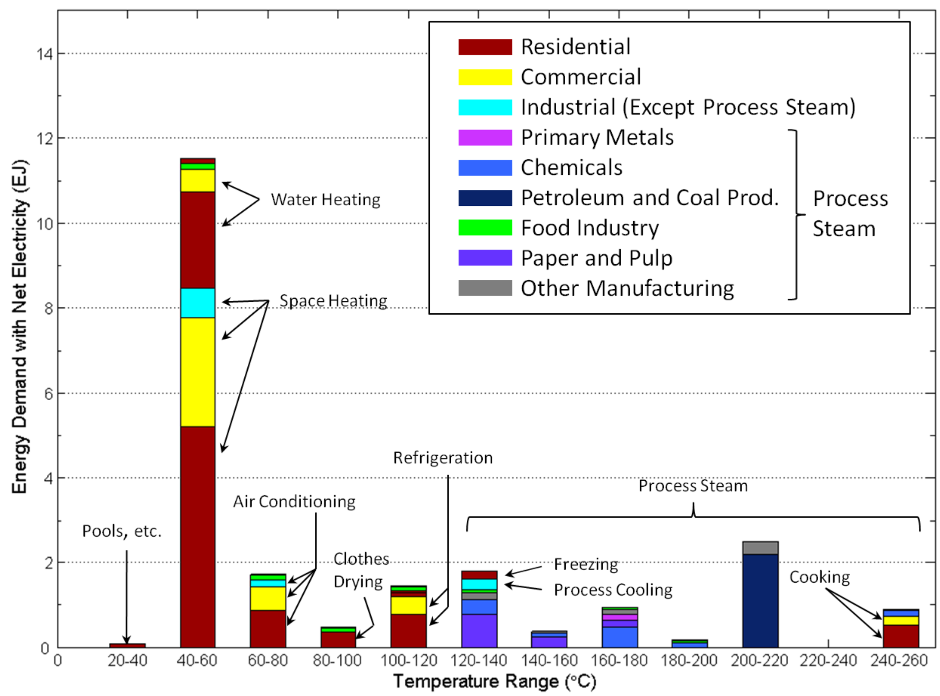


Figure 4.2: Thermal energy use temperature distribution from 0°C to 260°C with Net Electricity. The end-uses with the largest contribution are annotated. The total thermal energy demand from 0°C to 260°C is 22.089 EJ (20.937 quads). Refer to Table A.1 in Appendix A.3 for detailed information about the end-uses in each temperature bin.

Electronic Supplementary Material (ESI) for Energy and Environmental Science

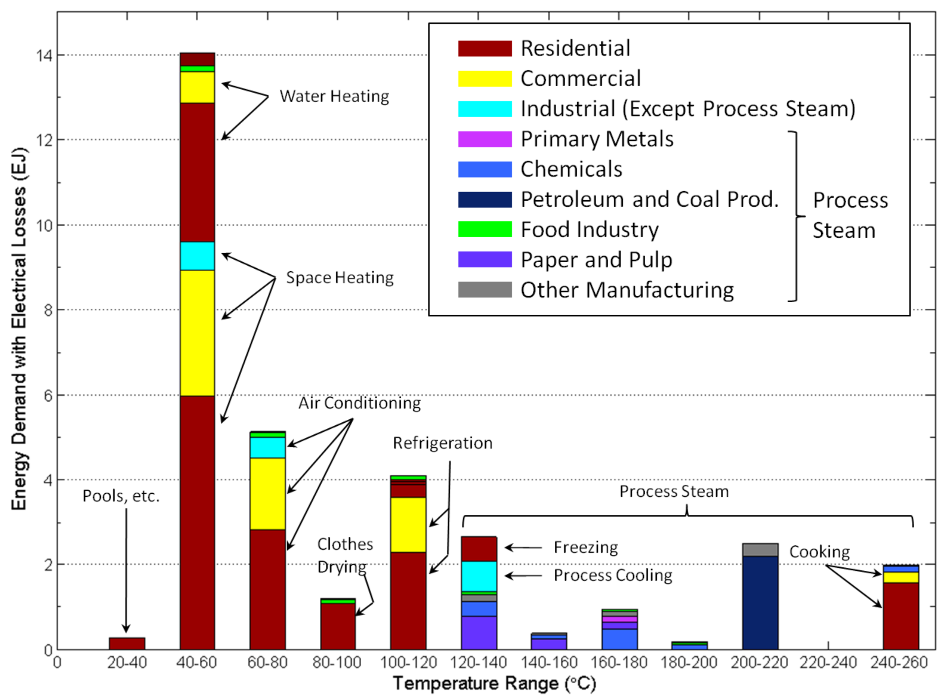


Figure 4.3: Thermal energy use temperature distribution from 0°C to 260°C with Electrical System Energy Losses (ESEL). The end-uses with the largest contribution are annotated. The total thermal energy demand from 0°C to 260°C is 33.461 EJ (31.717 quads). Refer to Table A.2 in Appendix A.3 for detailed information about the end-uses in each temperature bin.

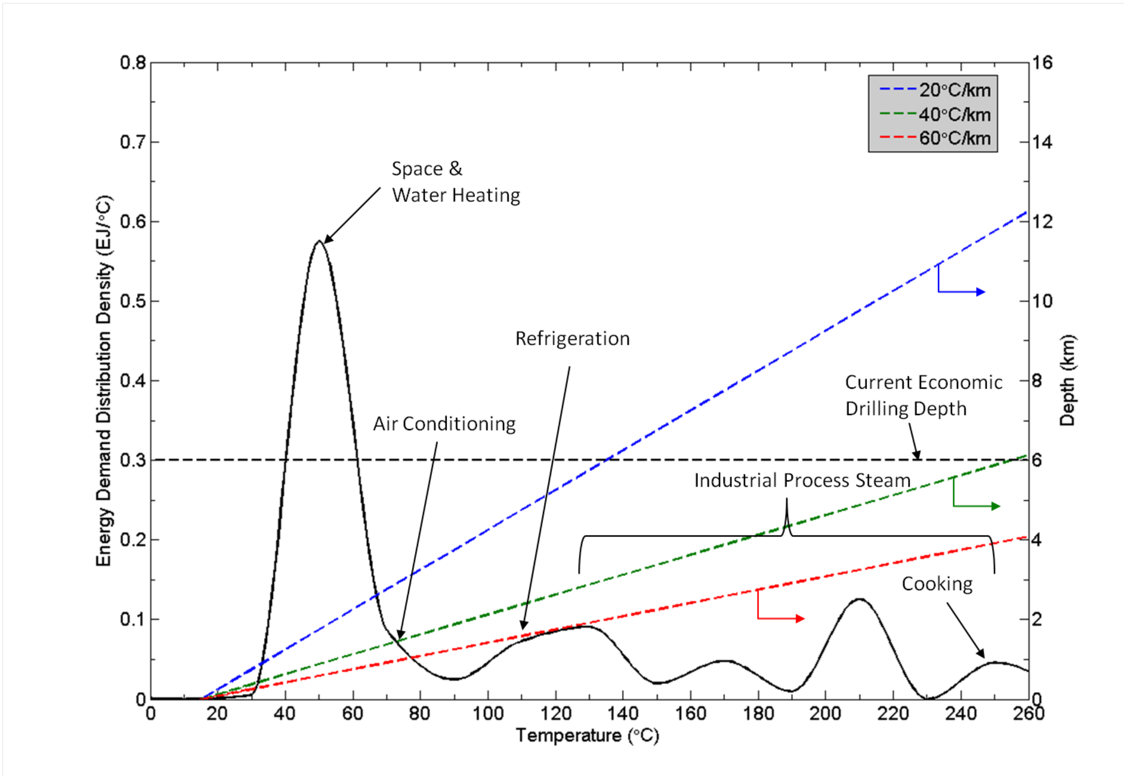


Figure 4.4: Continuous approximation of the energy demand distribution density with Net Electricity. The energy demand is normalized by the temperature, i.e. the total area under the curve represents the total thermal energy demand. The scale on the right-hand side indicates the depth needed to achieve the corresponding temperature for three different temperature gradients (20, 40, 60°C/km). The dashed horizontal line presents the current maximum economic drilling depth.

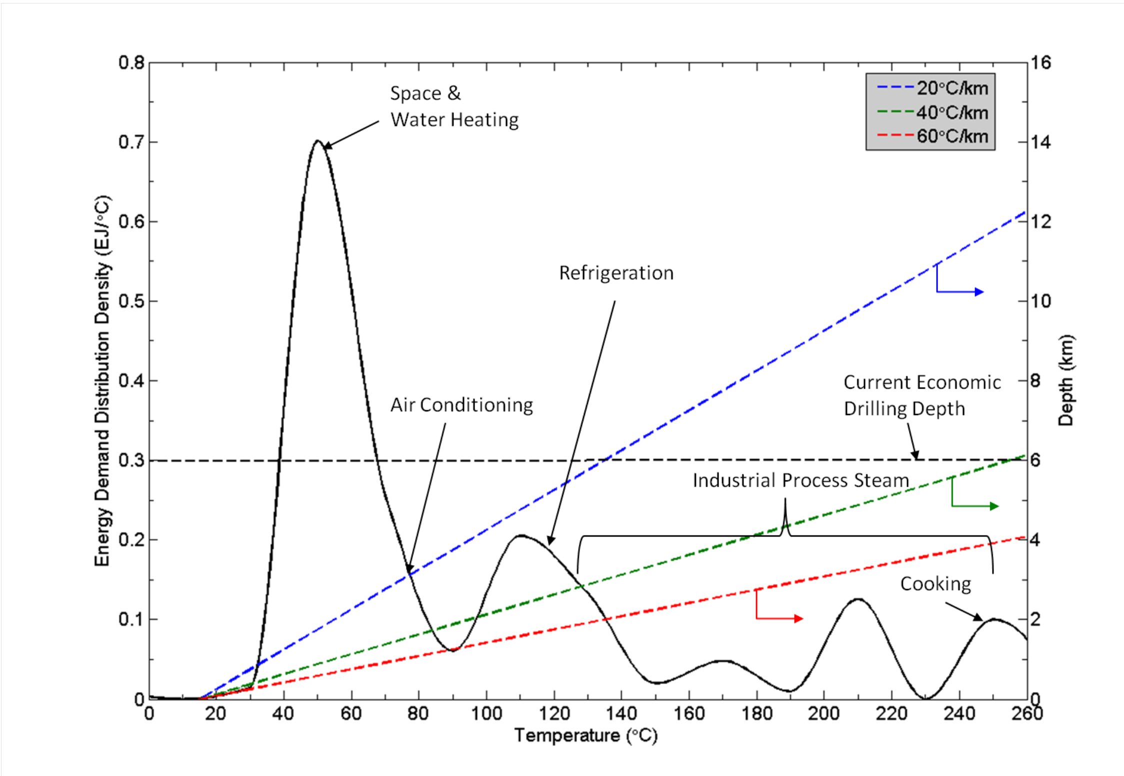


Figure 4.5: Continuous approximation of the energy demand distribution density with Electrical System Energy Losses (ESEL). The energy demand is normalized by the temperature, i.e. the total area under the curve represents the total thermal energy demand. The scale on the right-hand side indicates the depth needed to achieve the corresponding temperature for three different temperature gradients (20, 40, 60°C/km). The dashed horizontal line presents the current maximum economic drilling depth.

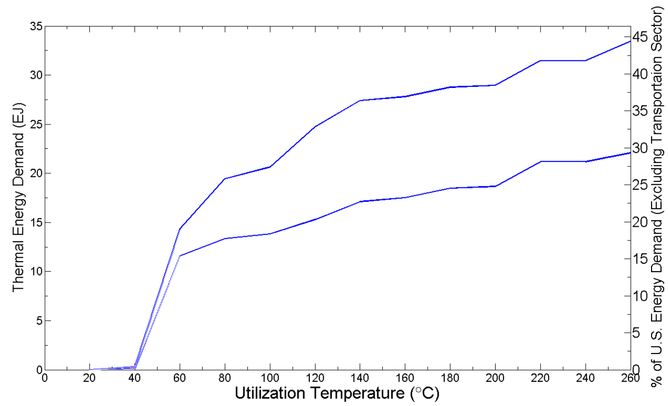


Figure 4.6: Cumulative thermal energy use with Net Electricity and Electrical System Energy Losses (ESEL).

merge. The total area under the curve represents the total thermal energy demand. The three linear functions relate to the right-hand side scale and show the necessary depth a geothermal system would have to access, to reach the according temperature on the horizontal axis. Each function represents a different geothermal temperature gradient. The gradients are assumed to be constant and the surface temperature is set to 15°C. A dashed horizontal line indicates the maximum economic drilling depth at 6 km [Tester et al., 2005]. The temperature at this depth would be 135°C (20°C/km gradient), 255°C (40°C/km), and 375°C (60°C/km), respectively. Even with the lowest gradient, the temperature would be sufficient to meet the demands of some of the largest contributors: space and water heating, air conditioning, and refrigeration. Figure 4.5 illustrates the same correlations with ESEL being included in the energy demand.

The cumulative thermal energy use is shown in Figure 4.6. The progress of the demand within the 20°C temperature bins was assumed to be linear. For example, the value at 20°C is zero, and the value linearly increases to match the whole demand of the 20°C to 40°C temperature bin at 40°C. The scale on the right shows the proportion of the U.S. total energy demand excluding the transportation sector. The figure includes both, thermal energy with Net Electricity and with ESEL being considered. The steep increase from 40°C to 60°C corresponds to the large energy demand of space and water heating.

Note that a temperature of 150°C would be sufficient to supply more than 35% of the U.S. industrial, commercial, and residential energy demand. With respect to substituting geothermal energy to meet this demand, we note that a temperature of 150°C can be reached within the 6 km drilling depth limit for most regions in the U.S. where average geothermal temperature gradients are higher than 22°C/km. A map of the U.S. indicating the temperature at a depth of 6.5 km is shown in Figure 4.7. The color scheme shows the temperature in 50°C ranges. Even in the eastern part, which is commonly considered less suitable for geothermal energy utilization, temperatures between 100°C and 150°C can be reached almost everywhere.

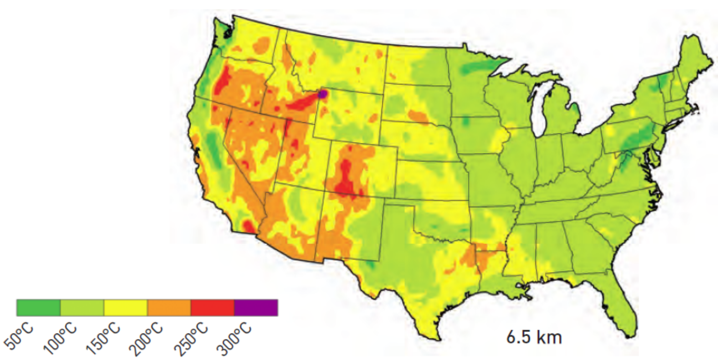


Figure 4.7: Temperatures at a depth of 6.5 km in the U.S. [Tester et al., 2006].

4.3 Geothermal Heat Pumps

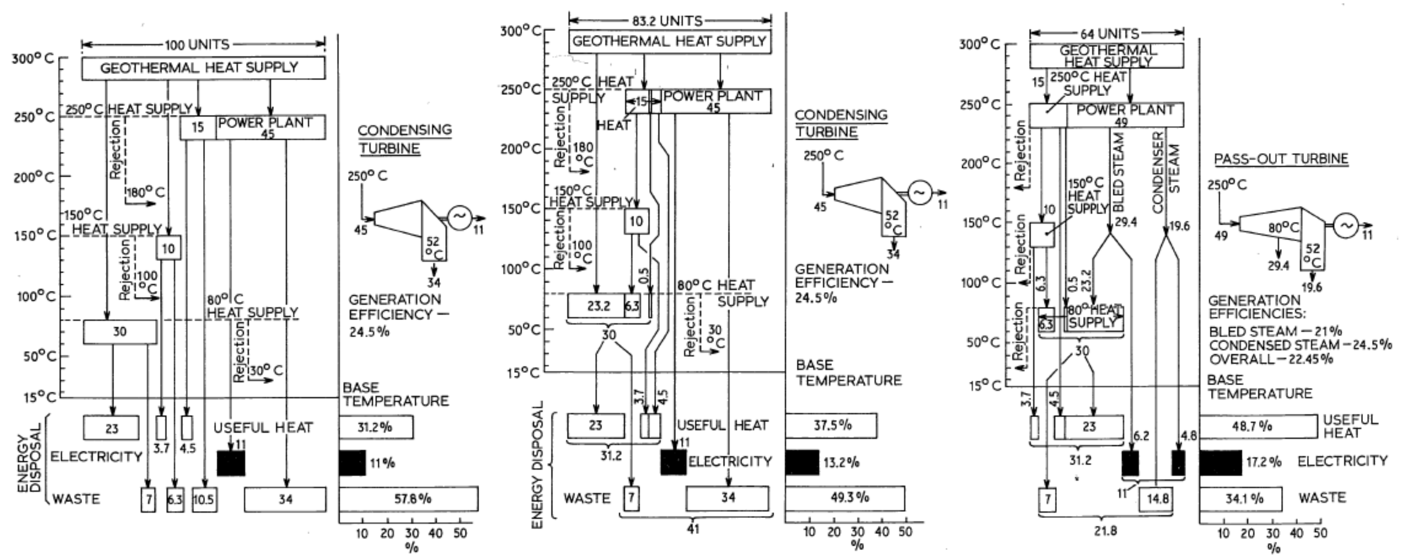
There are several possibilities to provide space heating, water heating, and air conditioning using the proposed low exergy thermal resources. District heating systems can directly provide hot water for space and water heating. Presupposing the water temperature is high enough (60°C to 80°C), a sorption cooling system can be driven by the same hot water source to provide air conditioning.

An alternative technology that has the capability to cover all three end-uses is geothermal groundsource heat pumps (GHP). However, depending on the coefficient of performance (COP), heat pumps require varying amounts of electricity to upgrade the low temperature heat they extract from the subsurface (or to reject heat to the ground in the case of air conditioning). The COP, in turn, changes with the temperature of the heat source (or sink, respectively) relative to the heating or cooling supply temperature. Typically, GHP have a COP of 4 or more, meaning that 4 units of thermal energy are transferred for every 1 unit of electrical energy [Tester et al., 2005]. Hence, providing residential and commercial space heating, water heating, and air conditioning demands by GHP systems would replace significant amounts of fossil fuel use, but increase electricity consumption. The proposed direct use of thermal energy in other applications would help to free up existing electrical capacity and thus avoid that additional capacity had to be built. In total, 5.3 EJ (5.0 quads) of electrical energy are currently used to provide thermal energy below 260°C. When the Net Electricity values are considered, residential and commercial space heating, water heating, and air conditioning consume about 12 EJ (11.4 quads) of primary energy. Subtracting conversion losses, the actual thermal energy demand would be lower than the 12 EJ. Assuming a COP of 4, at most 3 EJ of electricity would be needed to provide enough thermal energy with GHP.

4.4 Cascaded Heat Systems

Demanding thermal energy at different temperatures does not necessarily require multiple thermal energy sources at different temperatures. A single thermal energy source can supply end-uses at different temperatures in a cascaded heat system. Armstead and Tester [1987] illustrate the general idea of such a system (Figure 4.8) and show how a source of thermal energy at a given temperature would supply all of the thermal energy demand of a hypothetical market along with electricity production. They demonstrate the importance of knowing the thermal energy demand of a given market to effectively plan an energy use scheme. The same systematic can be applied to the U.S. heat market. According to Figure 4.3, the residential and commercial thermal energy demand for space heating, water heating, and air conditioning, for example, makes up 17.4 EJ (16.5 quads). A cascaded district heating system would be able to serve all these demands, and at the same time provide electricity powering applications whose energy use cannot be displaced with thermal energy (lighting, computers, cooking, etc.).

As an example, let us assume a heat source (geothermal, solar thermal, waste heat, etc.)



Case (a). Non-cascaded heat supply. Case (b). Fully-cascaded heat supply. Case (c). Fully-cascaded heat supply with co-generation.

Figure 4.8: Hypothetical example for a cascaded heat system showing three options for energy distribution from a geothermal source of heat to an industrial plant requiring electricity and also process heat at three different temperatures. Note that the electricity generation is kept constant [Armstead and Tester, 1987].

at 200°C. The working fluid could first be introduced to a turbine (cogeneration pass-out turbine or condensing turbine) to generate electricity. To enable air conditioning in a sorption cooling system, the fluid should leave the turbine at about 80°C, resulting in a Carnot efficiency of $\eta_c = 0.25$. The exhausted fluid would be used for cooling via a sorption cycle and could then cascade further down to provide any hot water needs. Depending on the seasonal need for cooling or heating, the waste heat from power production could also be used for space heating. Because space heating requires a lower end-use temperature (40°C to 60°C), the Carnot efficiency of the turbine theoretically increases to 0.30. The remaining energy could still be used for melting snow, soil warming, or other end-uses below 40°C. Similar cascaded systems have already been implemented, specifically the geothermal power plant in Neustadt-Glewe, Germany, which has an electric and thermal capacity of $230\,kW_e$ and $6\,MW_t$, respectively [Lund et al., 2005].

Heat systems can also be cascaded bottom up, i.e. low temperature thermal energy can be used to preheat working fluids that are finally required at a higher temperature. Cascaded heat systems generally minimize the earlier criticized gap between the source of heat and the process temperature.

4.5 Shifting Byproduct Use

Byproducts are used as fuel to help improve the economics of a process by reducing the amount of imported energy, as discussed in the industrial sector methodology in Section 3. One might argue that this byproduct use should not be considered in the potential for the discussed renewable, low temperature thermal energy sources, because the byproducts should not be wasted. However, these byproducts could be used to meet other energy requirements, especially those that cannot be displaced by direct thermal energy use, such as electricity generation, machine drive, or direct fired processes. Transportation fuel production is another option for byproducts that become abundant, as their former thermal end-use is met by the mentioned renewable sources. Forest industry byproducts from paper manufacturing, for example, could be used to generate biofuels. The goal should be to shift the byproduct use to applications, that make use of their relatively high exergy and combustion temperatures to generate electricity or power mechanical drives as well as process heat in cascaded or co-generation-systems, and thus, implement a more efficient energy use scheme.

5 Conclusions and Outlook

We evaluated the U.S. thermal energy consumption over a range of temperatures from 0°C to 260°C. The resulting estimate for the total thermal energy demand below 260°C in 2008 is 33.461 EJ (31.717 quads), when electrical system energy losses are included. More than half of the demand (55%) is from the residential sector. Detailed information about the distribution of this energy consumption with end-use temperatures is provided. Almost 80% of the total is used to provide heat below 150°C. Space and water heating and air conditioning in residential and commercial buildings are the end-uses with the largest thermal energy demand. The results show that there is a vast potential for renewable solar thermal and geothermal resources and waste heat. By redirecting our energy system, renewable sources could provide a much higher fraction of our thermal energy demand at temperatures below 260°C and offset the massive consumption of natural gas and oil used today to supply heat in this range. The proposed transformation in the energy system would have immediate environmental benefits and would lower the dependence on fossil fuels.

While it is clear that much opportunity exists for providing thermal energy using geothermal, solar, and waste heat sources, it would be misleading to presume that these resources could technically supply the thermal energy demand for *all* end-uses below 260°C. Obviously, appliances such as blow dryers, toaster ovens, and coffee makers would be unwieldy and impractical, if their thermal energy was supplied by anything else besides electricity. Note that these appliances do not contribute significantly to the total thermal demand. Other examples, such as whirlpools and hot tubs, would be clearly feasible from a technical point of view, but the capital costs to install needed infrastructure might make these applications uneconomical. Technical feasibility and economics of the single thermal end-uses should be investigated, most importantly for those that have the highest thermal energy demand. Quantitative information about the potential, and the technical and economic requirements for widespread deployment should stimulate research to overcome these barriers.

The geographical availability of solar, geothermal, and waste heat energy is an important issue, but exceeds the scope of this study. The quality of the solar and geothermal resources varies depending on latitude and incident solar irradiation for solar and regional geothermal gradients and other geologic conditions for geothermal. Likewise, the exergy of large waste heat resources varies widely. Furthermore, the availability of infrastructure and the demand market structure lead to different scenarios. A housing community already connected to a district heating or cooling grid presents a different situation than a single home in a rural area. The interruptible nature of solar energy requires storage or backup energy sources. Further research should also investigate the geographical correlation of high industrial thermal energy demands and suitable sites for geothermal plants. Waste incineration plants close to industrial centers could provide both, electricity and steam energy. Clearly, there is more than one solution to meet low temperature thermal energy demand in the U.S. Different resources often complement each other suggesting a portfolio approach to deliver the best solution.
City and regional planning should aim at establishing communities whose heat market allows to make best use of the locally available resources, including the application of cascaded heat systems. The structure of the heat market has a significant impact on the economics of the mentioned alternative thermal energy sources. The economics of direct use of renewable or waste heat thermal energy are not specifically covered in this work. Of course, they depend heavily on fossil fuel prices and might be affected by CO_2 management policies in the future. A CO_2 tax or cap and trade system would create additional incentives for companies and communities to invest in alternatives.

Although time constraints prevented a more detailed analysis for the individual industrial sectors, the general approach and methodology presented in this study could be applied to a specific sector or even to a specific plant or operation with greater resolution and less coarse graining. The analysis could generate specific thermal energy use temperature distribution data similar to Figure 4.2 and Figure 4.3. The thermal energy use tempera-

ture distribution information would then enable to find solutions optimized for the specific industry or plant.
The agricultural and mining industries were not considered in this study because the EIA database did not include these sectors. Other sources indicate, that their thermal energy demand appears to be relatively low compared to the manufacturing industries. Nonetheless, some of the most prominent applications of direct geothermal heat, nowadays, are greenhouses and drying processes in agriculture. One may want to undertake a sector specific analysis to determine the potential for the mentioned alternative energy sources in these sectors.
The EIA does not collect data about thermal energy use specifically. Their data had to be carefully analyzed and additional assumptions had to be made to quantify the thermal energy demand. The differences in sector definitions between the AER and the sector specific surveys burdened the analysis of the EIA data. End-use temperature information was collected from various sources. Especially for the industrial sector, information about typical process steam temperature distributions of single industrial branches is rare. Additional analysis that considers this area would be worthwhile.

More research focused on the U.S. thermal energy market and infrastructure requirements is needed to provide a complete picture in order to make the right policy and investment decisions that would enable the country to transform to a more sustainable energy future.

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Abbreviations

AER	Annual Energy Review
Btu	British thermal unit (equivalent to 1,055 J)
CBECS	Commercial Buildings Energy Consumption Survey
CHP	Combined Heat and Power
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy
EGS	Enhanced Geothermal System
EIA	U.S. Energy Information Administration
EJ	Exajoule (i.e. 10^{18} J)
ESEL	Electrical System Energy Losses
ERS	Electricity Retail Sales
EUCE	End-Use Consumption of Electricity (2001), a report in the Residential Energy Consumption Survey database
EUNR	End-Use Not Reported, category in MECS 2006, table 5.2
GHP	Geothermal Heat Pumps
HVAC	Heating, Ventilation, Air Conditioning
HDR	Hot Dry Rock

LBNL	Lawrence Berkeley National Laboratory
LPG	Liquefied Petroleum Gas
MECS	Manufacturing Energy Consumption Survey
MMBTU	one million Btu (British thermal unit)
NAICS	North American Industrial Classification System
NG	Natural Gas
quads	quadrillion (10^{15}) British thermal units (Btu)
RECS	Residential Energy Consumption Survey

Nomenclature

E_{el}^{ESEL}	electricity consumption including ESEL	(J)
E_{el}^{net}	net electricity consumption	(J)
η_{eff}	electrical conversion efficiency	(-)
η_{el}	overall electrical system efficiency	(-)
$f_{Conv.B.Fuel}$	ratio of Conventional Boiler Fuel energy and fuel consumption without EUNR energy	(-)
f_{elect}^{Q}	fraction of thermal energy from electricity	(-)
f_{elect}^{W}	fraction of mechanical energy from electricity	(-)
$f_{fuel,A}$	ratio of fuel consumption of subsector A according to MECS and total fuel consumption according to AER	(-)
f_{fuel}	ratio of total manufacturing fuel consumption and total industrial fuel consumption AER	(-)
f_{HVAC}	ratio of air conditioning + ventilation energy demand and space heating energy demand	(-)
f_{th}	thermal energy factor	(-)
N_i^p	number of devices of type p driven by fuel i	(-)
Q_i	thermal energy demand from appliances driven by fuel i	(J)

q_i	thermal energy demand of a single appliance driven by fuel i	(J)
Q_{total}	total thermal energy demand	(J)
U_{elect}	total electricity demand for mech. work and thermal energy	(J)
u_i	total energy demand of a single appliance driven by fuel i	(J)
n	ratio of energy demand of a NG-fired oven and an electric oven	(-)
W_{elect}	electricity demand for mechanical work	(J)
w_i	mechanical energy demand of a single appliance driven by fuel i	(J)

A Appendix

A.1 Disclosure of Withheld Data from MECS

The data tables in the MECS contain asterisks for numerical values less than 0.5 trillion Btu, "Q" for data withheld because the relative standard error exceeds 50% and "W" for values withheld by MECS to avoid disclosing data for individual establishments. The procedures to disclose withheld or missing data in the table "Fuel consumption by end-use" [U.S. Energy Information Administration, c, Table 5.2, 2006] is described below. The reader is referred to the original table to reconstruct the described procedures.

Petroleum and Coal Products Manufacturing
The value for the total EUNR energy is withheld to avoid disclosing data for individual establishments. The value was calculated by subtracting the consumption of reported end-uses from the total fuel consumption:

$$\begin{aligned} EUNR = {} & Total\, Fuel\, Consumption - (Indirect\, Uses;\, Boiler\, Fuel \\ & + Direct\, Uses;\, Total\, Process + Direct\, Uses;\, Total Nonprocess) \end{aligned} \tag{A.1}$$

The Indirect Uses-Boiler Fuel consumption was difficult to calculate because the proportion for Residual Fuel Oil was withheld. This missing value could not be reconstructed by subtracting all other end-use consumptions from the sum, similar to what was done above, because the amount of Residual Fuel Oil consumed with non-reported end-use is also withheld. Therefore, the Indirect Uses-Boiler Fuel consumption of Residual Fuel Oil was assumed to be zero. The EUNR row of Residual Fuel Oil was then calculated

$$\begin{aligned} EUNR = {} & Total\, Fuel\, Consumption - (Direct\, Uses;\, Total\, Process \\ & + Direct\, Uses;\, Total\, Nonprocess) \end{aligned} \tag{A.2}$$

Paper Manufacturing
The consumption of Residual Fuel Oil for Conventional Boiler Use was withheld by the EIA. To estimate the value, the also withheld EUNR part of Residual Fuel Oil consumption was assumed to be zero.

Nonmetallic Mineral Products Manufacturing

Both the value for Process Heating and for EUNR had been withheld for the Coal fuel column, which hindered the calculation of the total EUNR. If only one of the two values would be withheld, it could be disclosed by subtracting all other entries in the column from the total. The EUNR fraction was assumed to be zero and the value for Process Heating was calculated by subtracting all existing entries from the total.

A.2 Residential Sector Thermal Energy Factors

Estimating Total Thermal Demand of Clothes Dryers

Dryers can be run either with electricity, natural gas, or LPG. The electricity consumption reported for clothes dryers in the EIA report includes the electricity to run all dryers, regardless of fuel type, leading to the following equation for the total electricity demand from clothes dryers E_{total}

$$E_{total} = U_{elect} + W_{NG} + W_{LPG} \tag{A.3}$$

where U_{elect}, W_{NG}, and W_{LPG} are the electricity demand for electricity-, NG-, and LPG-driven dryers. For the NG and LPG dryers, only the mechanical component contributes to the electrical energy consumption. For the electric dryer, the electrical consumption is used for both thermal (Q_{elect}) and mechanical work (W_{elect})

$$U_{elect} = Q_{elect} + W_{elect} \tag{A.4}$$

The thermal and mechanical requirements for an electric dryer can be related to the total energy introducing a fraction for mechanical energy (f^{Q}_{elect}) and thermal energy (f^{W}_{elect})

$$f^{Q}_{elect} \equiv \frac{Q_{elect}}{U_{elect}} \tag{A.5}$$

$$f^{W}_{elect} \equiv \frac{W_{elect}}{U_{elect}} \tag{A.6}$$

Additionally, we can assume that the mechanical energy consumed per electric dryer is the same as the mechanical energy required by an NG and LPG dryer. A new variable w_i describing the mechanical work per single dryer is defined as

$$w_i \equiv \frac{W_i}{N_i} \tag{A.7}$$

where N_i represents the total number of dryers of each specific type. The index i represents the type of dryer. Similarly, q_i and u_i describe the thermal energy and total energy per single dryer of each type.

$$q_i \equiv \frac{Q_i}{N_i} \tag{A.8}$$

$$u_i \equiv \frac{U_i}{N_i} \tag{A.9}$$

Thus, the approximation of equal mechanical energy demands can be written as

$$w_{elect} \approx w_{NG} \approx w_{LPG} \tag{A.10}$$

and Eq. (A.3) is rewritten as follows

$$E_{total} = \frac{w_{elect}}{f^W_{elect}} N_{elect} + w_{elect} N_{NG} + w_{elect} N_{LPG} \tag{A.11}$$

and solved for w_{elect}

$$w_{elect} = \frac{E_{total}}{\frac{N_{elect}}{f^W_{elect}} + N_{NG} + N_{LPG}} \tag{A.12}$$

With the total thermal demand per type of dryer being

$$Q_i = \frac{f^Q_{elect}}{f^W_{elect}} \times N_i \frac{E_{total}}{\frac{N_{elect}}{f^W_{elect}} + N_{NG} + N_{LPG}} \tag{A.13}$$

the total thermal demand from all types of dryers is found to be

$$Q_{total} = E_{total} \times f^Q_{elect} \times \frac{N_{elect} + N_{NG} + N_{LPG}}{N_{elect} + f^W_{elect} (N_{NG} + N_{LPG})} \tag{A.14}$$

Introducing the thermal energy demand factor f_{th}, we get

$$f_{th} = \frac{Q_{total}}{E_{total}} = f^Q_{elect} \times \frac{N_{elect} + N_{NG} + N_{LPG}}{N_{elect} + f^W_{elect} (N_{NG} + N_{LPG})} \tag{A.15}$$

According to a Lawrence Berkeley National Laboratory (LBNL) report [Wenzel et al., 1997], the energy consumed per electric and gas clothes dryers were 3.4 MMBTU/yr and 3.9 MMBTU/yr, respectively (a 10% difference). According to these numbers, our approximation in Eq. (A.10) is valid.

Estimating Total Thermal Demand of Ovens and Range Tops

The EUCE report [U.S. Energy Information Administration, 2001] gives the amount of electricity used by ovens and range tops, but not all such devices run on electricity. Thus, a method to estimate the total thermal demand of all range tops and ovens given the data provided in the EUCE report is needed. Three different energy sources for the supply of thermal energy for an oven were considered: electricity, natural gas, and LPG. The thermal energy demand from all range tops and ovens Q_{total} is

$$Q_{total} = Q_{elect} + Q_{NG} + Q_{LPG} \tag{A.16}$$

where Q_{elect}, Q_{NG}, and Q_{LPG} are the thermal demands from the respective fuel types. Contrary to the clothes dryer appliances above, we assume that the EUCE electricity consumption (E_{total}) comes solely from electric range tops and ovens, i.e. ovens running on other fuels do not contribute to the electricity consumption. Furthermore, the electricity use is assumed to meet thermal energy demands only. Non-thermal energy requirements for example for lighting or digital clocks connected to the device are neglected. Thus, the thermal energy demand from electric range tops and ovens is

$$Q_{elect} = E_{total} \tag{A.17}$$

The thermal energy consumption for a single device can be defined as

$$q_i \equiv \frac{Q_i}{N_i} \tag{A.18}$$

with i as an index for the three types of fuel. Additionally, parameter n describes the relation between the thermal energy demand per device for the different fuel types

$$n \equiv \frac{q_{NG}}{q_{elect}} = \frac{q_{LPG}}{q_{elect}} \tag{A.19}$$

The total thermal energy demand for range tops and ovens is finally determined by

$$Q_{total} = \frac{E_{total}}{N_{elect}} \times (N_{elect} + nN_{NG} + nN_{LPG}) \tag{A.20}$$

and the thermal energy factor can be defined as

$$f_{th} = \frac{Q_{total}}{E_{total}} = \frac{1}{N_{elect}} \times (N_{elect} + nN_{NG} + nN_{LPG}) \tag{A.21}$$

Eq. (A.21) applies to both range tops and ovens. Based on the energy consumption of different types of range tops and ovens reported by Wenzel et al. [1997], our estimates for parameter n are $n = 2$ for ovens and $n = 1$ for range tops.

Estimating Total Thermal Demand for Pool/Hot Tub/Spa Heater

The EUCE report groups pools, hot tubs, and spas in one category, whereas the RECS-table "total households by water heating fuel" [U.S. Energy Information Administration, a, Table WH2, 2005] which gives information about the quantity of such appliances has two categories: Hot Tubs or Spas and Swimming Pools. N_{Elect} is the sum of the quantity of electrically heated appliances in both categories.

$$N_{elect} = N_{elect}^{HotTub\,or\,Spa} + N_{elect}^{Swimming\,Pools} \tag{A.22}$$

Furthermore, N_{NG} summarizes the quantities of natural gas heated hot tubs and spas and swimming pools and additionally contains the LPG-heated swimming pools $N_{LPG}^{Swimming\,Pools}$ given in the mentioned RECS-table.

$$N_{NG} = N_{NG}^{HotTub\,or\,Spa} + N_{NG}^{Swimming\,Pools} + N_{LPG}^{Swimming\,Pools} \tag{A.23}$$

By assuming the same thermal energy demand for electricity and NG-heated pools, the total thermal energy consumption of pool-appliances can be calculated to be

$$Q_{total} = E_{elect} \times \left(1 + \frac{N_{NG}}{N_{elect}}\right) \tag{A.24}$$

Hence, the thermal energy factor becomes

$$f_{th} = \frac{Q_{total}}{E_{elect}} = 1 + \frac{N_{NG}}{N_{elect}} \tag{A.25}$$

A.3 Thermal Energy Demand per End-Use Tables

Table A.1: Energy Demand with Net Electricity and temperature range for all considered thermal end-uses. This table corresponds to the values that are plotted in Figure 4.2. The first entry of each temperature bin corresponds to the first stack from the bottom in Figure 4.2 while the second entry corresponds to the second stack of Figure 4.2 and so forth.

Temperature (°C)	**End-Use**	**Energy Demand (EJ)**	**(quads)**
0-20	-	0	0
20-40	Pools, spas, Heated Aquariums, etc.	0.0991	0.0939
40-60	Residential Space Heating	5.1987	4.9277
	Commercial Space Heating	2.5726	2.4385
	Industrial Space Heating	0.6850	0.6493
	Residential Water Heating	2.2579	2.1402
	Commercial Water Heating	0.5449	0.5165
	Food Process Steam	0.1235	0.1171
	Other Process Steam	0.0158	0.0150
	Dish Washer	0.1037	0.0983
60-80	Residential AC	0.8878	0.8415
	Commercial AC	0.5612	0.5319
	Industrial AC	0.1498	0.1420
	Food Process Steam	0.1176	0.1115
	Other Process Steam	0.0158	0.0150

Table A.1 – continued from previous page

Temperature (°C)	**End-Use**	**Energy Demand (EJ)**	**Energy Demand (quads)**
80-100	Clothes Drying	0.3835	0.3635
	Food Process Steam	0.0941	0.0892
	Other Process Steam	0.0158	0.0150
100-120	Residential Refrigeration	0.7995	0.7578
	Commercial Refrigeration	0.4143	0.3927
	Microwave Ovens	0.0989	0.0937
	Coffee Makers	0.0306	0.029
	Humidifiers	0.0083	0.0079
	Food Process Steam	0.0941	0.0892
	Other Process Steam	0.0158	0.0150
120-140	Paper Process Steam	0.7915	0.7502
	Chemical Process Steam	0.3522	0.3338
	Other Process Steam	0.1666	0.1579
	Food Process Steam	0.0647	0.0613
	Industrial Cooling	0.2488	0.2358
	Freezers	0.2007	0.1902

Table A.1 – continued from previous page

Temperature (°C)	End-Use	Energy Demand (EJ)	Energy Demand (quads)
140-160	Paper Process Steam	0.2721	0.2579
	Chemical Process Steam	0.0766	0.0726
	Other Process Steam	0.0476	0.0451
160-180	Chemical Process Steam	0.4899	0.4644
	Paper Process Steam	0.1731	0.1641
	Primary Metals Process Steam	0.1263	0.1197
	Other Process Steam	0.1190	0.1128
	Food Process Steam	0.0471	0.0446
180-200	Chemical Process Steam	0.1378	0.1306
	Food Process Steam	0.0352	0.0334
	Other Process Steam	0.0238	0.0226
200-220	Petroleum & Coal Products Process Steam	2.2012	2.0864
	Other Process Steam	0.3014	0.2857
	Food Process Steam	0.0117	0.0111
220-240	-	0	0

Table A.1 – continued from previous page

Temperature (°C)	**End-Use**	**Energy Demand (EJ)**	**(quads)**
240-260	Residential Cooking	0.5537	0.5248
	Commercial Cooking	0.2065	0.1957
	Chemical Process Steam	0.1378	0.1306
	Other Process Steam	0.0158	0.0150
Total		22.089	20.937

Table A.2: Energy Demand with ESEL and temperature range for all considered thermal end-uses. This table corresponds to the values that are plotted in Figure 4.3. The first entry of each temperature bin corresponds to the first stack from the bottom in Figure 4.3 while the second entry corresponds to the second stack of Figure 4.3 and so forth.

Temperature (°C)	**End-Use**	**Energy Demand (EJ)**	**Energy Demand (quads)**
0-20	-	0	0
20-40	Pools, spas, Heated Aquariums, etc.	0.2834	0.2686
40-60	Residential Space Heating	5.9722	5.6609
	Commercial Space Heating	2.9364	2.7833
	Industrial Space Heating	0.6850	0.6493
	Residential Water Heating	3.2464	3.0772
	Commercial Water Heating	0.7476	0.7086
	Food Process Steam	0.1235	0.1171
	Other Process Steam	0.0158	0.0150
	Dish Washer	0.1037	0.0983
60-80	Residential AC	2.8234	2.6762
	Commercial AC	1.6944	1.6061
	Industrial AC	0.4735	0.4487
	Food Process Steam	0.1176	0.1115
	Other Process Steam	0.0158	0.0150

Table A.2 – continued from previous page

Temperature (°C)	End-Use	Energy Demand (EJ)	Energy Demand (quads)
80-100	Clothes Drying	1.0967	1.0395
	Food Process Steam	0.0941	0.0892
	Other Process Steam	0.0158	0.0150
100-120	Residential Refrigeration	2.2862	2.1670
	Commercial Refrigeration	1.3129	1.2445
	Microwave Ovens	0.2825	0.2678
	Coffee Makers	0.0874	0.0828
	Humidifiers	0.0237	0.0225
	Food Process Steam	0.0941	0.0892
	Other Process Steam	0.0158	0.0150
120-140	Paper Process Steam	0.7915	0.7502
	Chemical Process Steam	0.3522	0.3338
	Other Process Steam	0.1667	0.1579
	Food Process Steam	0.0647	0.0613
	Industrial Cooling	0.7115	0.6744
	Freezers	0.5737	0.5438

Table A.2 – continued from previous page

Temperature (°C)	End-Use	Energy Demand (EJ)	Energy Demand (quads)
140-160	Paper Process Steam	0.2721	0.2579
	Chemical Process Steam	0.0766	0.0726
	Other Process Steam	0.0476	0.0451
160-180	Chemical Process Steam	0.4899	0.4644
	Paper Process Steam	0.1731	0.1641
	Primary Metals Process Steam	0.1263	0.1197
	Other Process Steam	0.1190	0.1128
	Food Process Steam	0.0471	0.0446
180-200	Chemical Process Steam	0.1378	0.1306
	Food Process Steam	0.0352	0.0334
	Other Process Steam	0.0238	0.0226
200-220	Petroleum & Coal Products Process Steam	2.2012	2.0864
	Other Process Steam	0.3014	0.2857
	Food Process Steam	0.0117	0.0111
220-240	-	0	0

Table A.2 – continued from previous page

Temperature (°C)	**End-Use**	**Energy Demand (EJ)**	**Energy Demand (quads)**
240-260	Residential Cooking	1.5831	1.5006
	Commercial Cooking	0.2610	0.2474
	Chemical Process Steam	0.1378	0.1306
	Other Process Steam	0.0158	0.0150
Total		33.461	31.717