PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

THE THERMAL SPECTRUM OF LOW-TEMPERATURE ENERGY USE IN THE UNITED STATES

Don B. Fox[1], Daniel Sutter[1, 2], and Jefferson W. Tester[1,*]

[1]Atkinson Center for a Sustainable Future and the Cornell Energy Institute
Cornell University
Ithaca, NY 14853, USA.
[2]Institute of Process Engineering, ETH Zurich
Sonneggstrasse 3, 8092 Zurich, Switzerland.
[*]Corresponding author: jwt54@cornell.edu

ABSTRACT

A detailed analysis of the U.S. energy consumption was performed as a function of its utilization temperature from 0 to 260°C. The study highlights the changes that have occurred in U.S. energy use since the 1970s and suggests how renewable energy could provide a large fraction of energy now used for direct use at low end-use temperatures that is currently mostly supplied by high grade fossil fuels. For example, most of the energy we need for water and space heating used at low temperatures is provided by combusting natural gas and oil at very high temperatures. This downgrades the thermodynamic potential of the fossil fuels for generating power resulting in large reduction of its exergy or availability. 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 or availability losses by geothermal or solar thermal energy resources, or by waste heat. In addition, direct thermal use of geothermal energy also has economic advantages over using it to generate electricity by avoiding the inherently large 2nd Law losses in converting geothermal energy to electricity.

Using the U.S. Energy Information Administration database as a primary source of information, we found that the total thermal energy from 0 to 260°C used in 2008 was 33.5 EJ (31.7 quads), about one third of the entire U.S. 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. Also quite importantly, almost 80% of 33.5 EJ is used to provide heat below 150°C. Space heating and water heating have end-use temperatures of 40 to 60°C and are responsible for 38% of the thermal energy consumption below 260°C in the residential and commercial sectors.

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). 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. The primary energy demand for the U.S. can be divided into four demand sectors, residential, commercial, industrial, and transportation.

Fossil fuels have remarkable properties as energy carriers, such as high specific energy (e.g. lower heating value of gasoline is 43 MJ/kg) and high combustion temperatures ranging from 1000 to 2500°C, depending on fuel-air composition, combustor design, and other factors. These characteristics enable fossil fuels to meet extreme energy demands of sophisticated machines such as jet engines and gas turbines and allow 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 are too high for various thermal end-uses. In U.S. residential buildings, 93.5% of the energy used for space heating is provided 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 process end-use temperature and would reserve the high grade fossil energy sources for combustion processes that require high temperatures. Correspondingly, a more efficient energy utilization approach would be to tailor the energy source used to the temperature needs of the process.

The International Energy Agency (2007) reports, that electricity production has received 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 process 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.

Literature in the field of direct thermal energy use from renewable sources includes the famous Líndal diagram shown in Figure 1. It presents a number of possible applications for direct thermal use in Iceland along with typical end-use temperatures. The idea of the Líndal 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 Líndal diagram illustrates the opportunity but does not quantify the potential of direct use, since it does not document how much thermal energy is used for the mentioned processes. The worldwide review of direct thermal 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 exact 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). Thus, there is a need to not only quantify the thermal demand, but also the demand temperatures to better understand how much of the current demand can be replaced by renewables such as geothermal and solar thermal. Thirty-five years ago, Reistad (1975) quantified the low temperature thermal energy consumption and correlated it with end-use temperatures. 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 due to 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 United States.

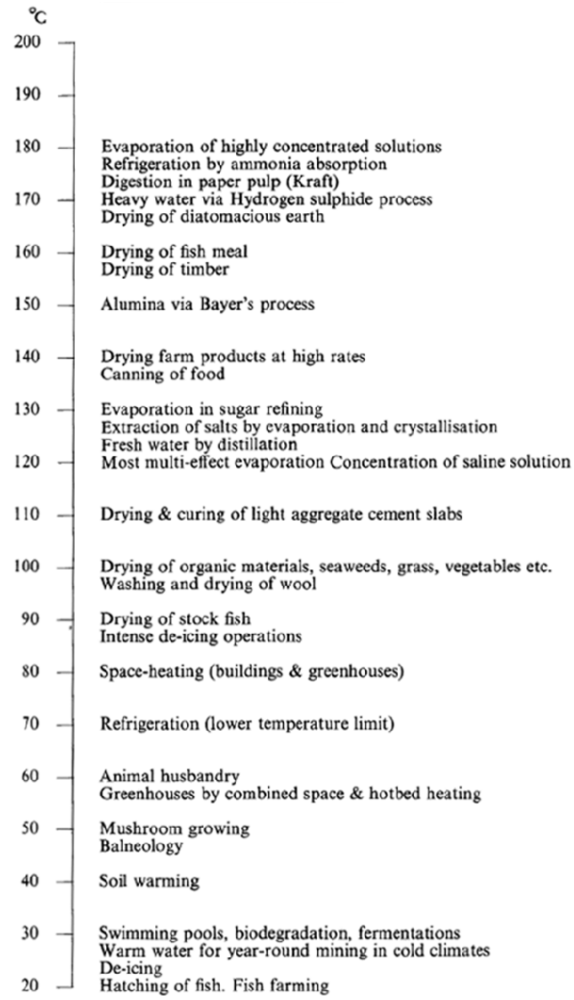

Figure 1: Industrial and other possible applications for direct thermal use of geothermal energy suggested by Líndal (1973) (as cited in Armstead, 1978).

METHODOLOGY

This study focuses on the temperature range 0 to 260°C (0 to 500°F) as "low temperature" because resources at higher temperatures would be used for electricity production to exploit the higher 2nd Law efficiencies before supplying lower temperature heat for direct thermal use. A 20°C temperature bin size was chosen to allow for coarse graining 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 their yearly energy consumption (U.S. Energy Information Administration, 2009). The transportation sector was left aside because its consumption of energy is for mechanical drive. For all four demand sectors, the EIA issues sector specific reports in a rotating basis such that a report for each sector is released every four years (U.S. Energy Information Administration, a, b, c).

While the AER reports useful general information, only the sector specific consumption surveys give details about end-use specific energy demand. Consequently, both reports were used for each sector. Extrapolation was applied because the sector specific surveys are not issued in the same years. 2008 was selected 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 their energy demand, determine their thermal and non-thermal character, and estimate their required 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. For more detailed information on the methodology including all made assumptions and numerical values for the energy consumption, interested readers are invited to look at the Cornell Energy Institute report #1, Thermal Energy Use in the United States from 1968 to 2008 below 260°C (2011).

Residential Sector

Space heating, appliances, water heating, and air conditioning are the end-uses in the residential sector. The appliances were carefully examined to only consider the ones requiring thermal energy for their end-use. The appliances with thermal end-uses were found to be refrigerators, clothes dryers, freezers, range tops, dishwashers, ovens, microwaves, clothes washers, pools/hot tubs/spa heaters, coffee makers, waterbed heaters, large heated aquariums, and humidifiers. 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). Generally, temperatures around and above 50°C (122°F) 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 to 60°C (104 to 140°F) range. Although many U.S. households set their water heater to a higher temperatures, 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 to 60°C (104 to 140°F). Dishwasher thermal energy contribution was also placed in the same bin because dishwashing draws its energy primarily from the household hot water heaters (U.S. Department of Energy, 1995).

The temperature assigned to air conditioning and refrigeration is based on the temperature requirements to run a sorption cooling system. For residential air conditioning, a heat source temperature of 60 to 80°C (140 to 176°F) is considered to be sufficient to operate such systems (Wang et al, 2009). Higher temperatures would allow achieving higher coefficients of performance (COP), which increases the economic competitiveness.

The temperature range for refrigeration and freezers were based on a review of Fan et. al (2007) and was chosen to be 100 to 120°C (212 to 248°F) and 120 to 140°C (248 to 284°F), 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). The temperature range 80 to 100°C (176 to 212°F) was ultimately chosen.

Energy requirements of pools/hot tubs/spa heaters, waterbed heaters, and large aquariums were collectively binned at 20 to 40°C (68 to 104°F). For cooking applications, the range tops and conventional ovens were collectively placed in the 240 to 260°C range (464 to 500°F) while microwave oven energy consumption was binned at 100 to 120°C (212 to 248°F) to reflect the nature of usage of the microwave ovens. Due to their need to boil water, coffee makers and humidifiers were placed in the 100 to 120°C (212 to 248°F) bin.

Commercial Sector

The energy consumption of the commercial buildings sector is made up of space heating, lighting, air conditioning, water heating, refrigeration, ventilation, cooking computers, office equipment, and other appliances. Of the listed end-uses, spacing heating, air conditioning, water heating, refrigeration, and cooking were considered thermal end-uses, similar to that of the residential sector. The end-use temperature

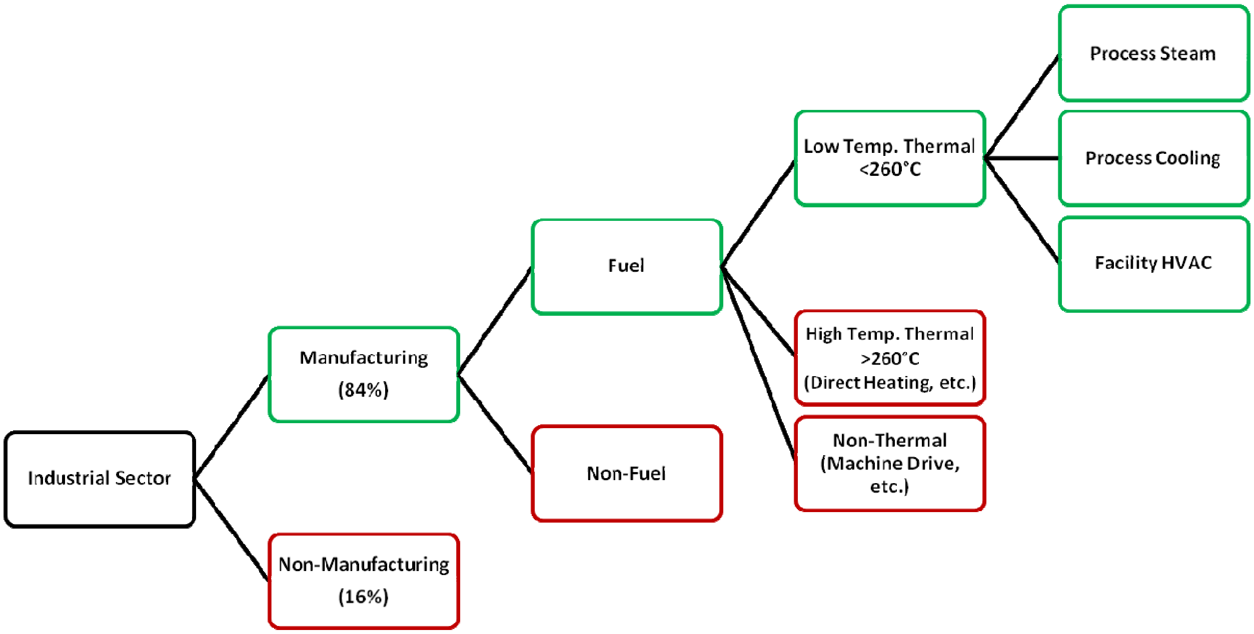

Figure 2: Breakdown of the industrial sector energy consumption. The industrial sector's energy demand is broken down into 84% and 16% for manufacturing and non-manufacturing in 2006, respectively. The boxes outlined in red were excluded in quantifying low temperature thermal energy demand.

designations for the five thermal end-uses are the same as for the residential sector.

Industrial Sector

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):

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

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 in its Manufacturing Energy Consumption Survey (MECS) (U.S. Energy Information Administration, c). For the three most recent MECS of 1998, 2002 and 2006, the manufacturing sector covers 84 to 90% of the industrial consumption.

Thermal energy consumption in the other industrial activities was estimated (Fox, Sutter, and Tester, 2011) and found to be small compared to the manufacturing energy consumption. The aim of this study is to provide a conservative estimate for the potential market for low temperature thermal energy. Due to the lack of detailed EIA data, only manufacturing activities were considered. Figure 2 shows a graphical representation of the breakdown of the industrial sector energy consumption to the end-uses of interest. For the quantification of the thermal energy demand, only process steam, process cooling, and HVAC are investigated.

The temperature distribution was 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.

The above manufacturing sectors are responsible for 76% of the total manufacturing fuel consumption and for 87% of the process steam fuel demand. Their weighted (by steam energy demand) average distribution of process steam temperature is assumed to be representative for the remaining 16 manufacturing subsectors and used to quantify the thermal energy distribution of the remaining "other" manufacturing sectors. Because process steam is often used at different temperature ranges, the process steam temperature distribution for each of the five main manufactures was individually determined using the sources of Resource Dynamic Corporation (2002), Ozalp and Hyman (2007), Brown et. al. (1985), and Lund et. al. (1980).

Quantifying process cooling and HVAC, as with process steam, were done by consulting of the MECS. The HVAC contribution was broken down in space heating and air condition whose temperature bin was chosen to be the same as the residential sector. For process cooling, the temperature range was increased to reflect industrial refrigeration processes demand for lower cooling temperatures on average than refrigeration in homes. Therefore, the end-use temperature for industrial cooling and refrigeration was increased to 120 to 140°C compared to 100 to 120°C for residential refrigeration.

Electrical System Energy Losses

If one Joule of electricity consumption is reduced, not only would the one 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 (U.S. Energy Information Administration, 2009). The overall system efficiency, η_{el}, can be calculated based on ERS and ESEL:

$$\eta_{el} = \frac{ERS}{ERS + ESEL} \quad (1)$$

The overall system efficiency for 2008 was 31.67%.

RESULTS AND DISCUSSIONS

Figure 3 illustrates the share of the total low temperature thermal energy use among the three demand sectors. It is important to note that this work calculated 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. 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. For example, for sorption cooling, the COP would be required. The presented estimates for the actual energy consumption however represent a valuable estimate of how much conventional energy could be saved by switching to renewable thermal energy sources.

Graph (b) in Figure 3 includes the 11.4 EJ (10.8 quads) of Electrical System Energy Losses (ESEL) related to the 5.27 EJ (5.00 quads) of Net Electricity included in Graph (A). This means a 51% increase of the total. The area of the disks in Figure 3 compares proportionally to the total. The 33.5 EJ (31.7 quads) in (b) represent 32% of the total U.S. energy

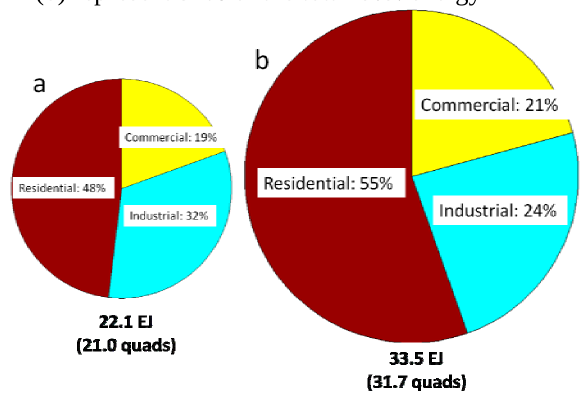

Figure 3: Total low temperature thermal energy demand and share of the three demand sectors residential, commercial, and industrial. (a) does not consider Electrical System Energy Losses, (b) includes Electrical System Energy Losses.

consumption of 105 EJ (99.3 quads) in 2008 (U.S. Energy Information Administration, 2009). As shown in the figure, the share of energy demand for the industrial sector drops when ESEL is considered while the residential and commercial sectors increase. The change in the share is due to the residential and commercial sector having more end-uses powered by electricity than the industrial sector, whose low temperature thermal demand is comprised mostly of process steam.

The residential sector has the highest potential for direct use of low temperature thermal energy but 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 generally larger than residential buildings and more centralized, which should result in lower complexity of a heat supply infrastructure.

The EIA data shows that 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 as that of the early 1990s and mid 1970s, in 2008. The low temperature thermal energy demand of the three sectors does not necessarily follow the exact same trends because the relative fraction of energy spent on each end-use also changes with time. The trends, however, underline the relative importance of the residential and commercial sector.

Nonetheless, thermal energy intensive industries may want to consider direct use of thermal energy from alternative sources 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 could promote a similar effect.

Figure 4 relates the thermal energy demand with its associated end-use temperature range with 20°C wide temperature bins. The industrial sector process steam demand is sub-divided into the five key manufacturing sectors and "Other Manufacturing". The end-uses with the largest contributions are annotated.

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 ESEL are not is considered, space heating accounts for a demand of 8.46 EJ (8.02 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 2.80 EJ (2.66 quads). Figure 5 incorporate ESEL to the appropriate end-uses such as air conditioning, refrigeration, and cooking. Interestingly, most of the thermal energy consumption in the investigated temperature range from 0 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. Figure 6 shows a continuous functional

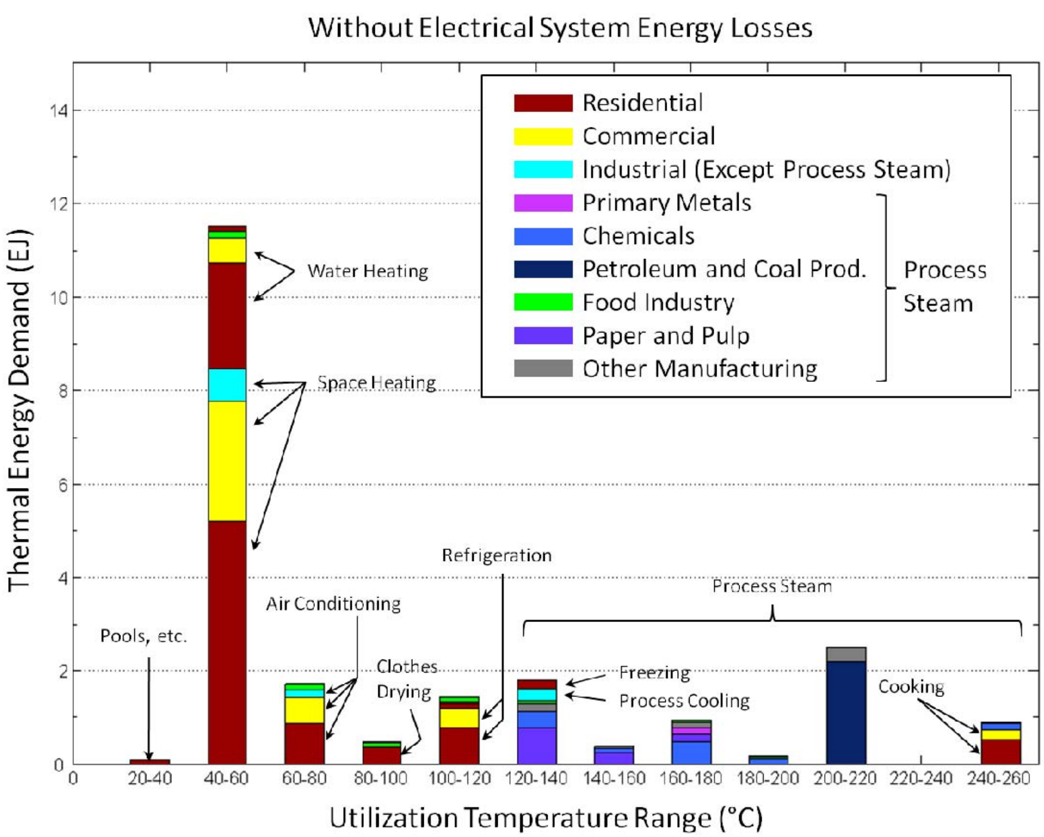

Figure 4: Thermal energy use temperature distribution from 0 to 260°C without Electrical System Energy Losses. The end-uses with the largest contribution are annotated. The total thermal energy demand from 0 to 260°C in 2008 was 22.1 EJ (20.9 quads). See Appendix A for tabulated values.

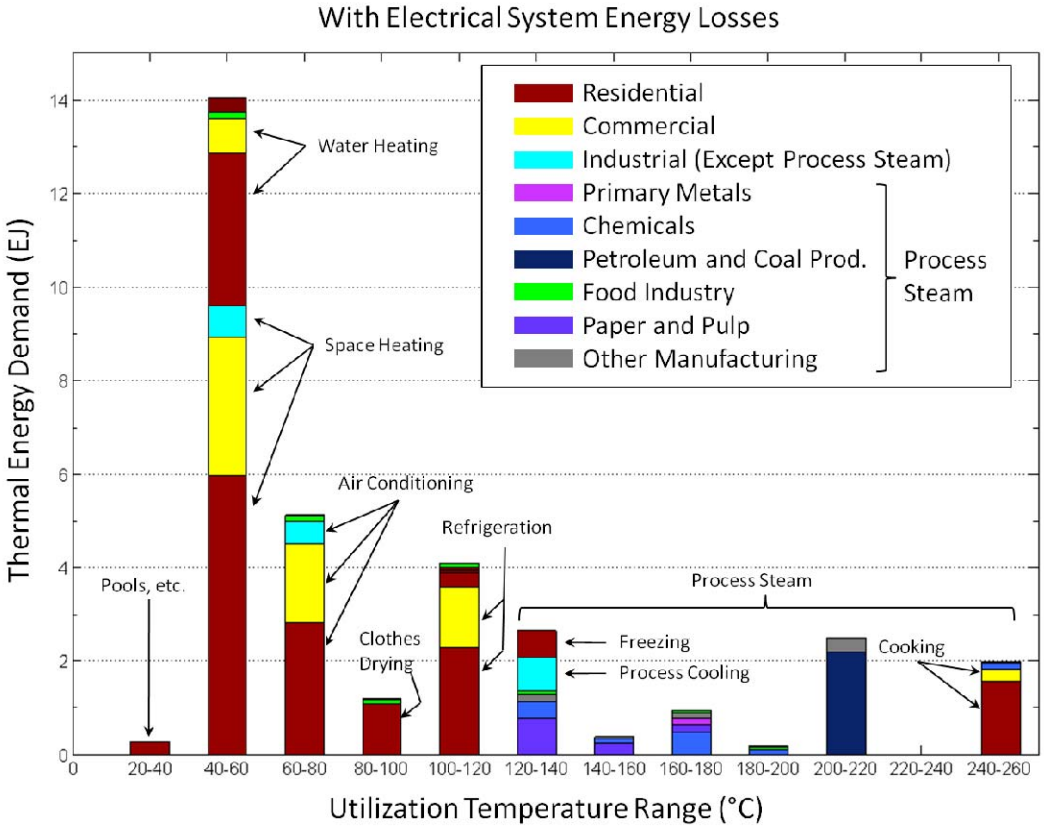

Figure 5: Thermal energy use temperature distribution from 0 to 260°C with Electrical System Energy Losses (ESEL). The end-uses with the largest contribution are annotated. The total thermal energy demand from 0 to 260°C in 2008 was 33.5 EJ (31.7 quads). See Appendix B for tabulated values.

approximation of the discrete data of Figure 5. The figure approximates Figure 5 if the resolution was set to an infinitesimal value as opposed to the discrete 20°C bins. A piecewise cubic Hermite polynomial (PCHIP) was used by employing the built-in pchip-function from MATLAB (The MathWorks Inc, USA). The values of Figure 5 were plotted at the mean value of each temperature bin and then a PCHIP was applied to obtain the smooth graph. The continuous representation takes into account that the end-use temperature of each process might vary slightly and the temperature ranges are not sharply confined but rather overlap and merge. The total area under the curve represents the total thermal energy demand. The dashed horizontal line indicates the maximum economic drilling depth of 6 km (Tester et al., 2005). The temperature at this depth of the three temperature gradients shown in the figure would be 135°C (20°C/km gradient), 255°C (40°C/km), and 375°C (60°C/km). Even with the lowest gradient, the temperature at 6 km would be sufficient to meet the demands of some of the largest contributors: space and water heating, air conditioning, and refrigeration. The cumulative thermal energy use is shown in Figure 7 for both with and without ESEL. 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 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. 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. 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.

An alternative technology that has the capability to cover space heating, water heating, and cooling is geothermal groundsource heat pumps (GHP). Typically, GHP have a coefficient of performance (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.

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, lower temperatures in a cascaded heat system. Armstead and Tester (1987) illustrate the general idea of such a system 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 approach can be applied to the U.S. heat market. According to Figure 5 the residential and commercial thermal energy demand for space heating, water heating, and air conditioning 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, etc.). Consider a heat source at 200°C. The working fluid would first be introduced to a 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 η_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, the waste heat from power production could also be used for space heating. The remaining energy left could be used for snow melting, 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 kWe and 6MWt, respectively (Lund et al., 2005). Heat systems can also be cascaded bottom up, i.e. for preheating of certain processes. Cascaded heat systems generally minimize the earlier criticized gap between the source of heat and the process temperature.

As discussed in the industrial sector methodology, byproducts are used as fuel to help improve the economics of a process by reducing the amount of imported energy. 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

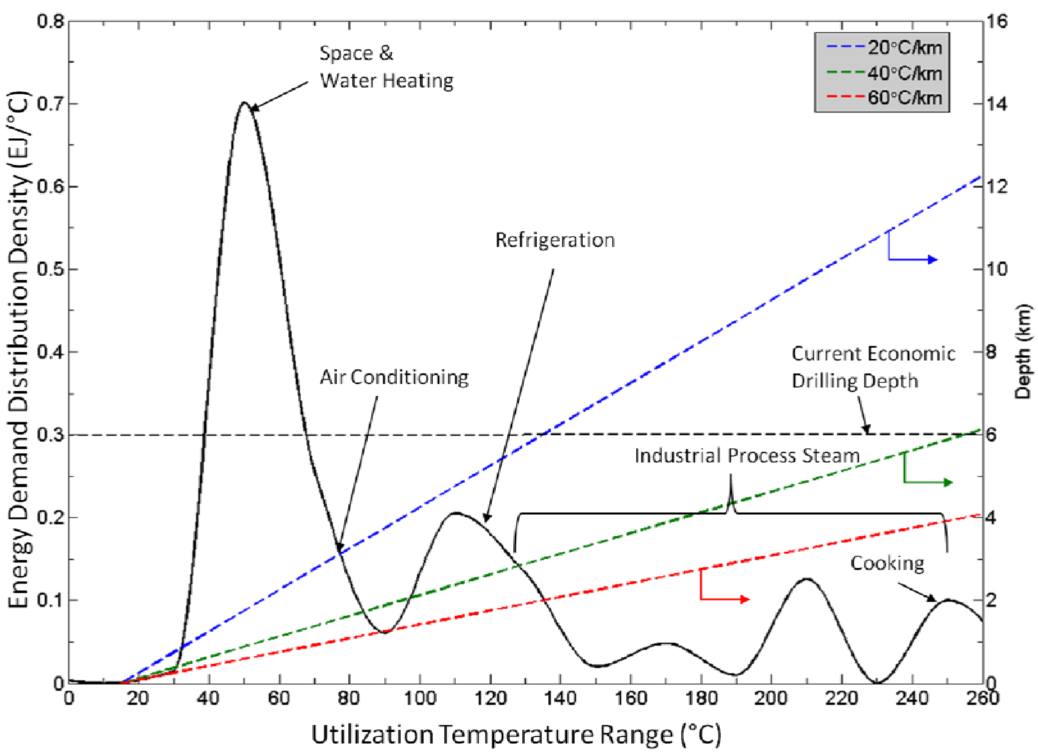

Figure 6: Continuous approximation of the energy demand distribution density with Electrical System Energy Losses (ESEL). The energy demand is normalized by the temperature, i.e. the total area under the curve represents the total thermal energy demand. The scale on the right-hand side indicates the 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.

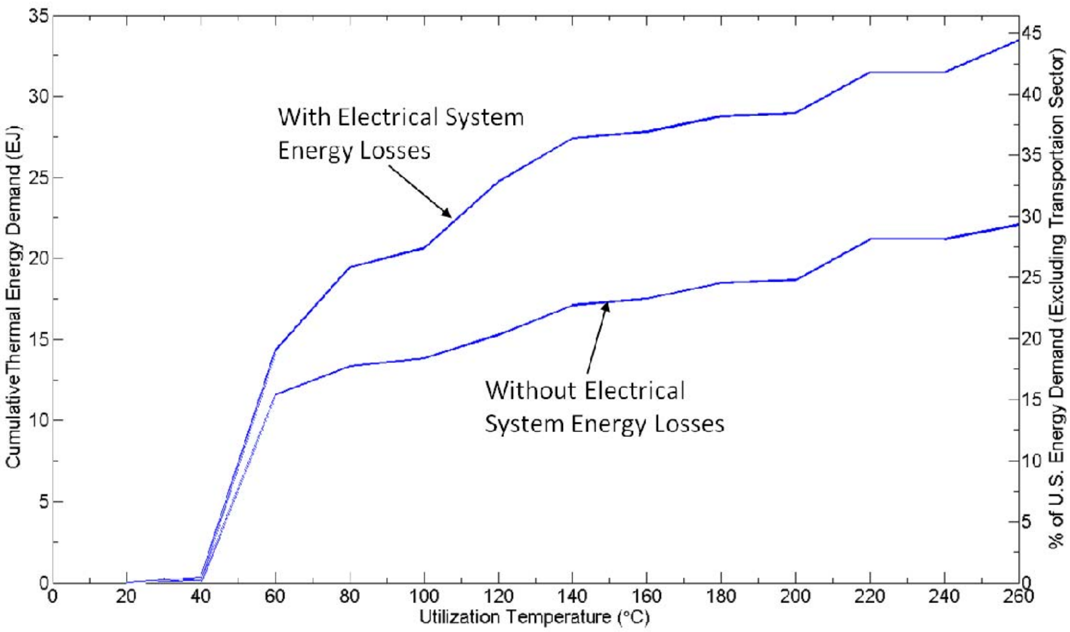

Figure 7: Cumulative thermal energy demand with and without Electrical System Energy Losses (ESEL).

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.

CONCLUSIONS AND OUTLOOK

We evaluated the U.S. thermal energy consumption over a range of temperatures from 0 to 260°C. The resulting estimate for the total thermal energy demand below 260°C in 2008 is 33.5 EJ (31.7 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 geothermal resources, solar thermal 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. Further information about the technical and economic requirements for widespread deployment for low enthalpy renewable heat supply options are needed to overcome the anticipated barriers to implementation.

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 resources varies depending on latitude and incident solar irradiation. For geothermal, thermal gradients and other geologic conditions are important. However, since a large portion of the thermal demand spectrum occurs at temperatures below 120°C, lower grade geothermal resources can be effectively utilized over a large region of the United States. The availability of large waste heat resources also varies widely and will require infrastructure changes to make them useable.

In general, the availability of existing or new infrastructure and the scale of the thermal demand 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 thermal energy in the form of steam or hot water. Clearly, there are multiple more sustainable options for meeting the 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 is best served with the use of the locally available resources, including the application of cascaded heat systems. The thermal structure and location of the heat market relative to the supply both have significant impact on the feasibility and economics of any alternative thermal energy sources. The economic attractiveness of using 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 and Figure 5. The thermal energy use temperature 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 does 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.

REFERENCES

Armstead, H. C. H. (1978), Geothermal Energy, London, New York, E. & F. Spon.

Armstead, H. C. H. and Tester, J. W., (1987), Heat Mining. London, New York, E. & F.N. Spon. R.

Bansal, P. K., Braun, J. E. and Groll, E. A. (2001). “Improving the energy efficiency of conventional tumbler clothes dryi ng systems.” *International Journal of Energy Research*, 25(15): 1315–1332.

Bansal, P. K., Sharma, K. and Islam, S. (2010), “Thermal analysis of a new concept in a household clothes tumbler dryer,” *Applied Energy*, 87(5): 1562–1571.

Bloomquist, G. (2003), “Geothermal space heating,” *Geothermics*, 32(4-6): 513–526.

Brown, H. L., Hamel, B. B., Hedman, B. A., Koluch, M., Gajanana, B. C. and Troy, P. (1985), Energy Analysis of 108 Industrial Processes, U.S. Department of Energy.

Conde, M. R. (1997), “Energy conservation with tumbler drying in laundries,” *Applied Thermal Engineering*, 17(12): 1163–1172.

Fan, Y., Luo, L. and Souyri, B. (2007), “Review of solar sorption refrigeration technologies: Development and applications,” *Renewable & Sustainable Energy Reviews*, 11(8): 1758–1775.

Fox, D. B., Sutter, D., and Tester, J. W. (February, 2011), "Thermal Energy Use in the United States from 1968 to 2008 below 260°C," Cornell Energy Institute report #1-2011, Cornell University, Ithaca, NY.

Han, H. and Deng, S. M. (2003). "A study on residential clothes drying using waste heat rejected from a split-type room air conditioner (rac)," *Drying Technology*, 21(8): 1471–1490.

Hreinsson, E. B. (2007), "Deregulation, environmental and planning policy in the Icelandic renewable energy system," In *International Conference on Clean Electrical Power*, pages 283–291, Capri, Italy.

International Energy Agency (2007), "Renewables for heating and cooling - untapped potential," Report, International Energy Agency.

Kalogirou, S. A. (2003), "The potential of solar industrial process heat applications," *Applied Energy*, 76(4): 337–361.

Líndal, B. (1973), "Industrial and Other Applications of Geothermal Energy," volume 12 of *Geothermal Energy*, Unesco Paris.

Lund, J. W., Allen, E., Higbee, C., Lienau, P., Phillips, P. and Shreve, J. (1980), "Assessment of the geothermal potential within the bpa marketing area," Report, DE-AC79- 79BP15325, Geo-Heat Utilization Center - Oregon Institute of Technology.

Lund, J. W., Freeston, D. H., and Boyd, T. L. (2005), "Direct application of geothermal energy: worldwide review," *Geothermics*, 34(6): 691–727.

Ng, A. B. and Deng, S. M. (2008), "A new termination control method for a clothes drying process in a clothes dryer," *Applied Energy*, 85(9): 818–829.

Ozalp, N. and Hyman, B. (2007), "Allocation of energy inputs among the end-uses in the US petroleum and coal products industry," *Energy*, 32(8): 1460–1470, 2007.

Philibert, C. (2006), "Barriers to technology diffusion: The case of solar thermal technologies," Report, International Energy Agency (IEA).

Resource Dynamics Corporation (2002), "Steam system opportunity assessment for the pulp and paper, chemical manufacturing, and petroleum refining industries," Report, DOE/GO-102002-1639, U.S. Department of Energy - Office of Energy Efficiency and Renewable Energy.

Reistad, G. M. (1975), "Analysis of potential nonelectrical applications of geothermal energy and their place in the national economy," Report, Lawrence Livermore Laboratory.

Tester, J. W., Drake, E. M., Golay, M. W. Driscoll, M. J. and Peters, W. A. (2005), Sustainable Energy: Choosing Among Options. Cambridge, MA, The MIT Press.

U.S. Department of Energy (1995), "Energy-efficient water heating," Report, DOE/GO-10095-063, U.S. Department of Energy.

U.S. Energy Information Administration (2001), "End-Use Consumption of Electricity, volume 2010," U.S. Energy Information Administration (EIA).

U.S. Energy Information Administration (2009). "Annual energy review 2008," Report, DOE/EIA-0384(2008), U.S. Department of Energy.

U.S. Energy Information Administration, "Residential Energy Consumption Survey (RECS)," U.S. Departement of Energy (DOE), http://www.eia.doe.gov/emeu/recs/contents.html, a.

U.S. Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS)," U.S. Departement of Energy (DOE),http://www.eia.doe.gov/emeu/cbecs/contents.html, b.

U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS)," U.S. Departement of Energy (DOE), http://www.eia.doe.gov/emeu/mecs/contents.html, c.

Vannoni, C., Battisti, R. and Drigo, S. (2008), "Potential for solar heat in industrial processes," Report, University of Rome La Sapienza.

Wang, R. Z., Ge, T. S., Chen, C. J., Ma, Q. and Xiong, Z. Q. (2009), "Solar sorption cooling systems for residential applications: Options and guidelines," *International Journal of Refrigeration-Revue Internationale Du Froid*, 32(4): 638–660.

Yadav, V. and Moon, C. G. (2008), "Modeling and experimentation for the fabric-drying process in domestic dryers," *Applied Energy*, 85(5): 404–419.

APPENDIX

A. **Tabulated values of Figure 4**

Temperature Bin (°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
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	0.0290
	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
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
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

B. Tabulated values of Figure 5

Temperature Bin (°C)	End Use	Energy Demand (EJ)	(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
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
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
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