

Characterizing U.S. Heat Demand for Potential Application of Geothermal Direct Use

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Abstract

In this paper, we assess the U.S. demand for low-temperature thermal energy at the county resolution for four major end-use sectors: residential buildings, commercial buildings, manufacturing facilities, and agricultural facilities. Existing publicly available data on the U.S. thermal demand market are characterized by coarse spatial resolution, with assessments typically at the state level or larger. For many uses, these data are sufficient; however, our research was motivated by an interest in assessing the potential demand for direct use (DU) of low-temperature (30° to 150°C) geothermal heat. The availability and quality of geothermal resources for DU applications are highly spatially heterogeneous; therefore, to assess the potential market for these resources, it is necessary to understand the spatial variation in demand for low-temperature resources at a local resolution. This paper presents the datasets and methods we used to develop county-level estimates of the thermal demand for the residential, commercial, manufacturing, and agricultural sectors. Although this analysis was motivated by an interest in geothermal energy deployment, the results are likely to have broader applications throughout the energy industry. The county-level resolution thermal demand data developed in this study may have far-reaching implications for building technologies, industrial processes, and various distributed renewable energy thermal resources (e.g., biomass, solar).

Introduction

In 2015, the Geothermal Technologies Office (GTO) at the U.S. Department of Energy (DOE) began the Geothermal Vision Study (GVS) to conduct analysis of potential growth scenarios across multiple market sectors (geothermal electric generation, commercial and residential thermal applications) for 2020, 2030, and 2050. The first phase of the GVS focuses on the electricity sector and is divided into specific topic areas and task forces led by GTO team members. The Thermal Applications Taskforce is divided into two parts: geothermal heat pumps, led by Oak Ridge National Laboratory, and geothermal direct use (DU) (a.k.a. “deep direct use”), led by the National Renewable Energy Laboratory (NREL). The heat demand analysis presented in this paper is one of several planned for DU for the GVS. Additional planned topics include: low-temperature resource assessment and technical potential, and cost and market potential analyses for geothermal DU in the United States.

Our focus in this paper on thermal demand in the range of 30° to 150°C was designed to avoid duplication with related GVS studies focused on the electric power sector, which focus on resources above 150°C. For the residential and commercial sectors, we focused on low-temperature thermal demand for space heating and water heating. In the manufacturing and agricultural sectors, we assessed end-use demand for low-temperature resources for space, water, and process heating. The data developed through this analysis will be combined with locally

resolved low-temperature geothermal resource data (Mullane et al. 2016) in NREL's distributed geothermal systems (dGeo) model to assess the market potential for DU applications in these end-use sectors. Data are available for download on the Geothermal Data Repository (GDR - <https://gdr.openei.org>), the submission point for data collected from researchers funded by the DOE's Geothermal Technologies Office.

In this paper we discuss:

- Background information on the U.S. heat market
- Available datasets for assessing the U.S. heat market
- The methodology used for disaggregating the heat demand data to the county level for each of the four sectors: residential, commercial, manufacturing and agriculture
- Results and next steps for future analysis.

Background

Data on the U.S. heat market is very limited, with the majority of current data coming from the Energy Information Administration's (EIA's) periodic surveys of energy consumption (EIA 2003, 2009, 2010, 2012). These surveys estimate that the total heat consumption in the United States for the residential, commercial, and manufacturing sectors is approximately 12 quadrillion Btu, or quads (Figure 1). Using EIA data and a separate analysis, Fox et al. (2011) estimated that 31.7 quads of thermal energy in the range of 0°–260°C were consumed in the United States in 2008. Approximately 80% (25.4 quads) of this total was used to provide heat for end uses at temperatures less than 150°C, including space and water heating, process heating, and refrigeration and cooling. In our analysis, heat is characterized by space and water heating demand in the residential and commercial sectors, process heat demand in the manufacturing sector, and space heating demand in the agricultural sector. One important detail to consider is that the data for each survey were released in different years. In particular, note that the Commercial Buildings Energy Consumption Survey (CBECS) has a 2003 release of granular data and a 2012 release of high-level demand data (with granular data forthcoming). Due to the complexity in extrapolating data to a single year, the demand in each sector is only reported with respect to the year its specific survey was released.

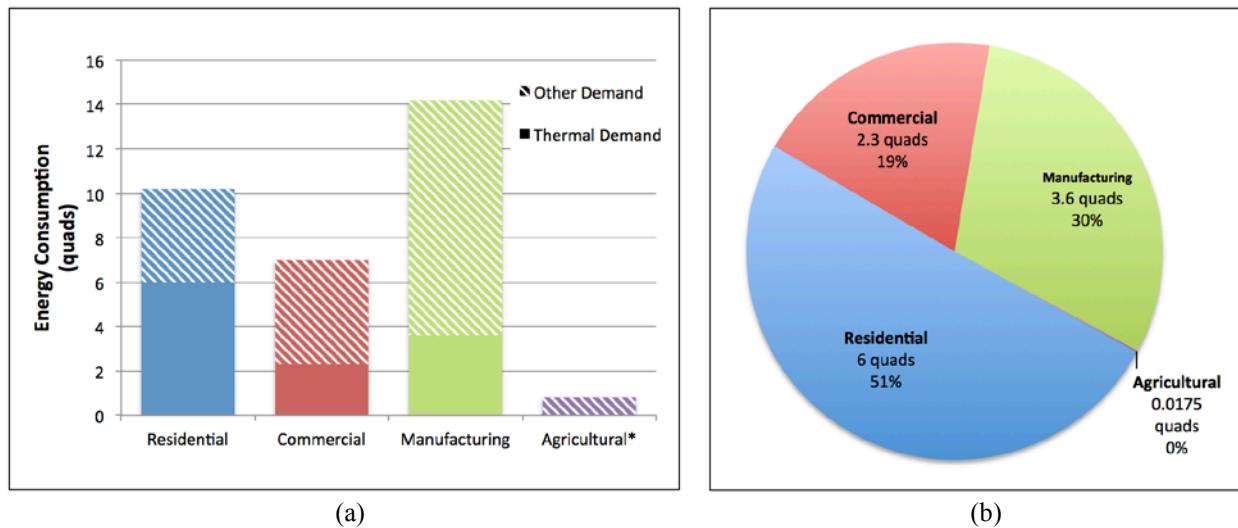


Figure 1: (a) Total energy demand in the United States by sector (~32 quads). Thermal demand is shown in solid colors in each bar. (b) Total thermal demand in the United States by sector. Source: EIA 2009, 2010, 2012.

Thermal demand in the residential sector constitutes about half (6.0 quads) of the 12 quads of thermal energy consumption in the United States (Figure 1b). In addition, natural gas was the most utilized fuel for thermal energy in the residential sector, supplying 70% of the thermal demand (EIA 2009). In the commercial sector, space and water heating consume roughly 2.3 quads annually, accounting for roughly one-third of the total commercial energy consumption (7 quads) in 2012 (Figure 1a). Despite a 14% increase in total building count and a 22% increase in total building size (i.e., floor space) between 2003 and 2012, total commercial energy consumption increased by only 7% in the same period (EIA 2012), reflecting increased building and appliance efficiency.

Total energy consumed in the manufacturing sector in 2010 totaled just over 14.2 quads, with process heating and facility heating/ventilating/air conditioning (space heating assumed to be included) constituting approximately 3.6 quads, or about 25% of the total energy consumed for manufacturing (EIA 2010) (Figure 1a). In the agricultural sector, an estimated 0.8 quads of total direct energy were consumed in 2012 (EIA 2014). This excludes indirect energy consumption, which is typically characterized as fertilizer and pesticide inputs. Despite the lack of energy data in the agricultural sector, specifically regarding heat consumption, our analysis estimated the thermal demand of greenhouses to be approximately 0.02 quads (Figure 1b).

The total thermal energy consumption across these sectors (an estimated 11.9 quads) represents a significant opportunity for the adoption of geothermal DU heat. However, the spatial resolution of the currently available data is too coarse for a more detailed geo-spatial technical potential analysis. In the residential sector, demand data are available at the resolution of individual states or small multi-state regions comprising two to five states each. In the commercial and manufacturing sectors, data are only available at the level of Census Divisions and Census Regions, respectively. In the agricultural sector, demand data are not explicitly reported; instead, fuel consumption data are given at the Farm Production Region level, which consists of groups of between six and 16 states. An initial unpublished analysis completed by NREL in 2015 was performed at the census division level, which resulted in the very coarse thermal energy demand map shown in Figure 2.

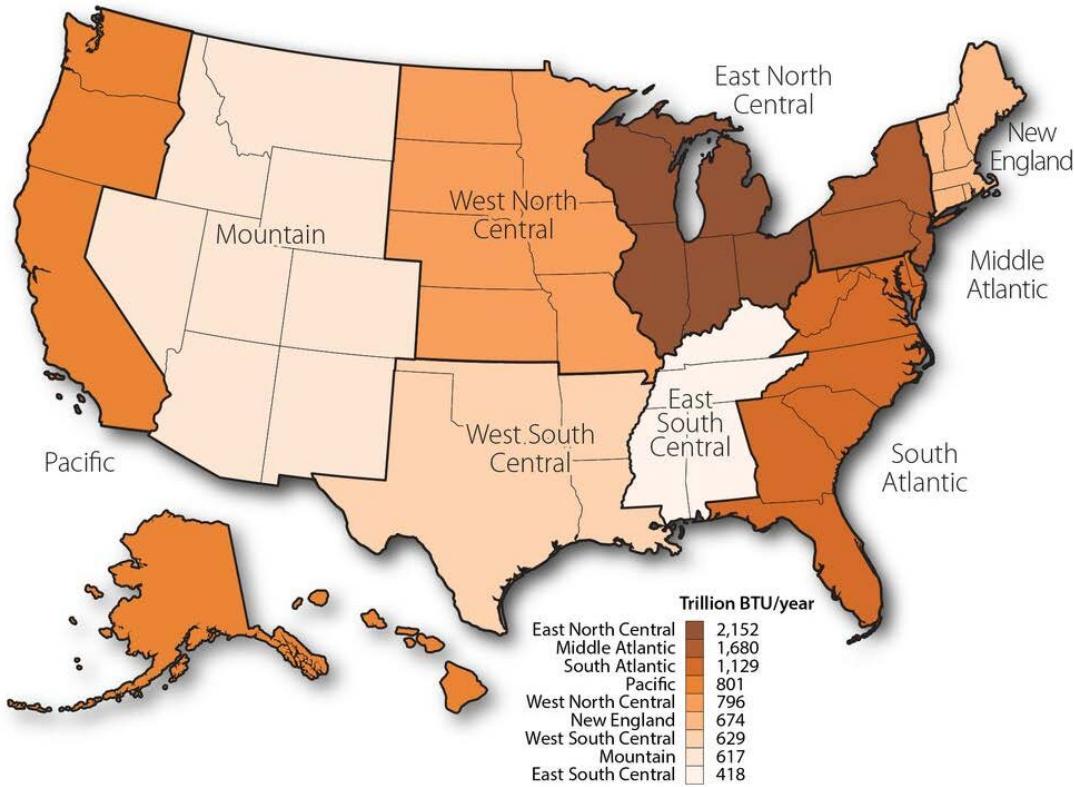


Figure 2: U.S. Heat Demand. Includes residential, commercial, and industrial heat demand. Industrial heat demand for each division was estimated from the regional data based on population. Note that this map does not include estimates of manufacturing heating/ventilating/air conditioning or any analysis of agriculture, resulting in energy totals less than the ~12 quads reported by EIA. Data source: EIA 2009, 2010, 2012. Map made by Billy Roberts NREL.

Our interest in the heat demand market is motivated by the potential demand for DU of low-temperature (30° to 150°C) geothermal heat. The highly localized variation in the availability and quality of geothermal resources for DU applications, coupled with limitations on our ability to transport thermal energy long distances, necessitates an equally localized understanding of patterns of thermal demand. Therefore, our initial regional assessment of thermal demand in the United States was insufficient. To capture the full potential of geothermal DU technology, we performed an analysis to assess the U.S. demand for low-temperature thermal energy at the county resolution for each of four major end-use sectors: residential buildings, commercial buildings, manufacturing facilities, and agricultural facilities. This involves looking at each sector individually and supplementing the EIA surveys along with additional data to disaggregate the demand totals to a finer resolution (e.g., county level).

Datasets

For the analyses of the thermal demand in each of the four sectors, we started with data from the EIA's periodic consumption surveys as well as sources from the U.S. Department of Agriculture (USDA). Several other datasets and publications were added to these to supplement the analysis, as outlined in Table 1, and detailed further below.

Table 1: Data used in the Analysis of U.S. Heat Market Demand

Sector	Source	Vintage	Data Available	Geospatial Resolution
Residential	EIA	2009	Space heating and water heating demand totals	Reportable domain – individual states or aggregates of states (27 total domains) Climate regions – residential entries categorized based on geographical location
	U.S. Census Bureau – American Community Survey (ACS)	2009–2013 (5-year survey)	Housing unit totals for each county in the United States	County level
Commercial	EIA	2003 & 2012	Space heating and water heating demand totals	Census division – Nine total divisions in the United States, each consisting of between three and eight states
	Federal Emergency Management Agency (FEMA)	2013	Total area (sq. ft.) of each building type for each county	County level
Industrial	EIA	2010	Process heat and space heating demand totals for manufacturing industries only	Census region – Four total regions in the United States, each consisting of between nine and 17 states
	<i>Energy Analysis of 108 Industrial Processes</i> (Brown et al. 1985)	1985	Energy usage of 108 most energy-intensive processes in manufacturing; Fluid temperatures of processes	N/A
	U.S. Census Bureau – County Business Patterns (CBP)	2013	Number of establishments (by 6-digit NAICS code) in each county	County level
Agricultural	USDA – Farm Production Expenditures	2012	Fuel expenditures for individual and aggregates of states	Region level (individual states and aggregates of states)
	USDA – Census of Agriculture	2012	Number of farms in each county, for 15 agriculture NAICS codes	County level

Residential Sector

EIA’s Residential Energy Consumption Survey (RECS): The most recent data for end-use demand totals for space and water heating come from EIA’s 2009 RECS survey (EIA 2009). Data are reported at the EIA-defined *reportable domain level*, consisting of either individual states or aggregates of states.¹ The RECS also includes climate region distinctions for each residence based on its geographical location. The definitions of these regions are based on the

¹ EIA selected certain geographic domains to allow for “geographic control of the sample allocated to the Census Divisions and selected states.” The individual states were chosen (as opposed to those that were grouped) based on factors such as population and climatic or geographic diversity. There are nine total aggregates, with the number of states in each ranging from two to five.

DOE's Building America program (DOE 2010). Fluid temperatures for space and water heating are assumed to be within the study temperature bounds (30° to 150°C).²

U.S. Census Bureau – American Community Survey (ACS): Five-year survey data for the 2009–2013 period were extracted from the National Historical Geographic Information System (Minnesota Population Center 2011) for the count of housing units at the state and county levels. Totals were used to disaggregate residential thermal demand totals at the EIA reportable domain level (states, aggregates of states) to the county level.

Commercial Sector

EIA's CBECS: The most recent granular data for end-use demand totals for space and water heating come from 2003 CBECS survey (EIA 2003). Fluid temperatures for space and water heating are assumed to be within the study temperature bounds. Data are reported at the EIA-defined *census division* level, of which there are nine in the United States, each consisting of between three and eight states. Note that a more recent CBECS was performed in 2012 (EIA 2012), for which granular data has yet to be released, but can be incorporated in a data update relatively easily once it becomes available.

FEMA's Comprehensive Data Management System (CDMS): The CDMS (FEMA 2013) is a complementary tool to FEMA's Hazus-MH, a risk-assessment and loss-estimation methodology. The CDMS contains facility-specific information on several different building-type definitions and gives estimates of total square footage of each type on a countywide basis. These data were used to disaggregate commercial thermal demand totals at the EIA reportable domain level (census division) to the county level.

Manufacturing Sector

EIA's Manufacturing Energy Consumption Survey (MECS): The most recent data for end-use demand totals for process steam and space heating in only the manufacturing industries come from the 2010 MECS survey (EIA 2010). Agricultural uses—also classified as “industrial”—are not included in the MECS. Process steam temperatures are variable and not are reported in the MECS. Data are reported at the EIA-defined *census region* level, of which there are four in the United States, each consisting of between nine and 17 states.

Energy Analysis of 108 Industrial Processes (Brown et al. 1985): This report, prepared by researchers at Drexel University for the DOE, gives detailed information about the 108 most energy-intensive processes, based on energy consumption reported in the 1976 Annual Survey of Manufacturers. The report provides data for fluid temperatures, mass flows, and energy usage per industry-specific unit (e.g., Btu/lb.-product). These data were used to identify which industry processes could use geothermal resources in the range of 30° to 150°C as a heat source.

U.S. Census Bureau – County Business Patterns (CBP): The CBP is an annual series that provides subnational economic data by industry (e.g., employment and payroll statistics). The 2013 CBP (U.S. Census Bureau 2013) report provided data on the number of establishments of

² We can safely assume space and water heating in residences/commercial buildings is well under 150°C; however, no single temperature represents space/water heating for an entire sector.

each industry (by 6-digit NAICS code³) at the county level. These data were used to disaggregate the manufacturing sector thermal demand from the national level to the county level.

Agricultural Sector

USDA – Farm Production Expenditures: USDA produces an annual summary released through the National Agricultural Statistics Service that contains annual estimates of farm production expenditures such as feed, farm services, and labor. This study used the reported fuel expenditures for farm production regions to estimate energy consumption. Data from the 2012 release (USDA 2013) was used in conjunction with the 2012 Census.

USDA – Census of Agriculture: This USDA report is a comprehensive source of U.S. agricultural data, including statistics on land use and ownership, operator characteristics, and expenditures. The relevant data from the most recent census (USDA 2012) were the farm totals at the county level, which were used to disaggregate demand at the regional and state level.

Methodology

The demand analyses for the residential and commercial sectors include disaggregating thermal demand totals at higher levels of reporting (e.g., state, census division) to the county level. This allows for more localized technical and market potential analyses to be carried out by NREL's geo-spatial analysis team using dGeo; these analyses will be key products of the GVS. The manufacturing analysis follows a similar approach, with nationwide totals for process heat being disaggregated to the county level. However, the manufacturing analysis must undergo an intermediate step to combine available data on process heat temperatures to filter industries based on the temperature bounds of the study. The agricultural analysis uses fuel expenditure data combined with fuel prices and energy density values to estimate total energy consumption at the county level. Further analysis of the greenhouse subsector utilizes typical greenhouse energy consumption statistics to estimate the thermal demand. Research into energy consumption in other subsectors (e.g., aquaculture, poultry production) is suggested as future work to supplement the analysis in this paper.

Residential Sector

The ACS housing-unit totals at the state and county levels were used to disaggregate the thermal demand totals using a weighting process (Table 2). County weights were calculated based on the proportion of each *county*'s housing unit total to the *state/reportable domain* total. For example, ACS reported that Autauga County, Alabama, had 1.02% (22,220 housing units) of the total Alabama housing units (2,178,116 houses). Therefore, 1.02% (0.91 trillion Btu) of the residential thermal demand for Alabama (69.59 trillion Btu) would be attributed to Autauga County.

However, initial analysis indicated that the thermal demand might not be properly allocated by disaggregating from the reportable domain level (states) alone, especially in areas where climate plays a more substantial role. For example, demand in the greater Los Angeles area appeared to be unnaturally high for a region with a warmer climate. Intuition would dictate that regions with warmer climates would require less space heating and potentially less water heating as well.

³ NAICS is the North American Industry Classification System. It is the standard used by federal statistical agencies in classifying business establishments. These classifications are reported at varying levels of detail from 3- to 6-digit codes that describe sub-industries in detail.

To rectify this, demand totals were disaggregated from a cross-section of both *reportable domain* and *climate region* distinctions. These totals were then further disaggregated to the county level for further analysis. For example, California as an individual state is a reportable domain and is composed of two climate regions, “Hot-Dry/Mixed-Dry” and “Marine.” Our procedure grouped the counties within each climate region and summed the county demand in each group. The demand for the counties within the “Hot-Dry/Mixed-Dry” climate region summed to 141 trillion Btu. Similarly, the demand for the counties within the “Marine” climate region summed to 58 trillion Btu. The housing unit totals within each climate zone are then summed and used in conjunction with individual county totals in the disaggregation procedure.

The simplified expressions below help to illustrate the procedure used to calculate weighting factors for each county. The ACS data give housing unit totals for each county in the United States. These values are summed within their *reportable domain-climate region* (RD-CR) distinction to give the RD-CR total housing units. Then, the county-level total is divided by this RD-CR total to calculate a county weight (Eq. 1). This weight can then be multiplied by the demand from the RECS for the corresponding RD-CR to give the estimated county-level demand (Eq. 2).

$$\left(\frac{\text{County}}{\text{RD-CR Total}} \right)_{\text{Housing Units}} = \text{County Weight} \quad (1)$$

$$(\text{County Weight}) * (\text{RD-CR Thermal Demand}) = \text{County Thermal Demand} \quad (2)$$

The application of the above method results in a list of every county in the United States with disaggregated demand values for space and water heating, a sample of which is shown in Table 2.

Table 2: Excerpt from the data table showing the data and results of the disaggregation of residential thermal demand.
Full data table is available on the GDR.

EIA Reportable Domain	County	Climate Region	Housing Units			Residential Thermal Demand					
			County	RD-CR	County Weight	Space Heating		Water Heating		Total Space & Water	
						EIA	NREL calc.	EIA	NREL calc.		
			# of units	# of units	weight	trillion Btu	trillion Btu	trillion Btu	trillion Btu	trillion Btu	trillion Btu
AL-KY-MI	Autauga	Hot-Humid	22220	1202293	0.0102	14.5	0.45	14.2	0.26	0.91	0.91
AL-KY-MI	Baldwin	Hot-Humid	104648		0.048		2.12		1.22		3.34
AL-KY-MI	Barbour	Hot-Humid	11790		0.0054		0.24		0.14		0.38
AL-KY-MI	Bullock	Hot-Humid	4468		0.0021		0.09		0.05		0.14
AL-KY-MI	Butler	Hot-Humid	9931		0.0046		0.2		0.12		0.32
...
AL-KY-MI	Bibb	Mixed-Humid	8939	4183503	0.0041	94.5	0.18	49.3	0.1	0.28	0.28
AL-KY-MI	Blount	Mixed-Humid	23767		0.0109		0.48		0.28		0.76
AL-KY-MI	Calhoun	Mixed-	53192		0.0244		1.08		0.62		1.7

EIA Reportable Domain	County	Climate Region	Housing Units			Residential Thermal Demand				Total Space & Water	
			County	RD-CR	County Weight	Space Heating		Water Heating			
						EIA	NREL calc.	EIA	NREL calc.		
			# of units	# of units	weight	trillion Btu	trillion Btu	trillion Btu	trillion Btu	trillion Btu	
		Humid									
AL-KY-MI	Chambers	Mixed-Humid	16928		0.0078		0.34		0.2	0.54	
AL-KY-MI	Cherokee	Mixed-Humid	16180		0.0074		0.33		0.19	0.52	
...	

Commercial Sector

The commercial sector demand analysis required a similar disaggregation to the county level as the residential analysis.

EIA's CBECS database provided two types of information: total thermal demand (trillion Btu) and thermal demand intensity (mBtu/sq. ft.). Demand totals and intensity are provided at the EIA census division level (nine divisions in the United States) and by principal building activity (PBA), and are further broken down into more detailed building activity (PBA-PLUS) categories (Figure 3).

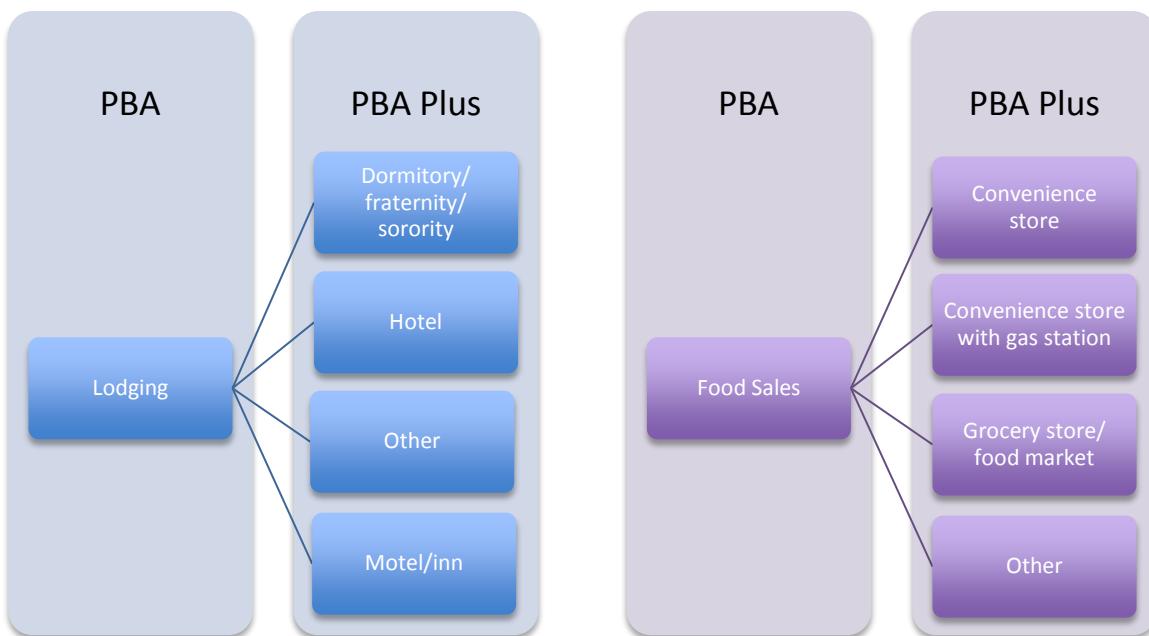


Figure 3: Examples of PBAs and subcategories (PBA-PLUS)

To disaggregate these data into usable county-level information, we used FEMA's CDMS data, which provide information on the total area of each building type for each county, using the formula described in Equation 3.

$$\begin{aligned}
 & \text{Building Type 1 (EIA) Thermal Demand Intensity} \left(\frac{\text{mBTU}}{\text{sq ft}} \right) \\
 & \times \text{Building Type A (FEMA) Total Area} \left(\frac{\text{sq ft}}{\text{county}} \right) \\
 & = \text{Total County Thermal Demand for Building Type 1/A} \left(\frac{\text{mBTU}}{\text{county}} \right)
 \end{aligned} \tag{3}$$

This exercise was not quite as straightforward as shown in the equation, however, since EIA building activities and FEMA building types do not directly align and therefore had to be manually reconciled. Figure 4 demonstrates a portion of the mapping procedure and shows an example of the building types that matched between PBA-PLUS and CDMS categories.

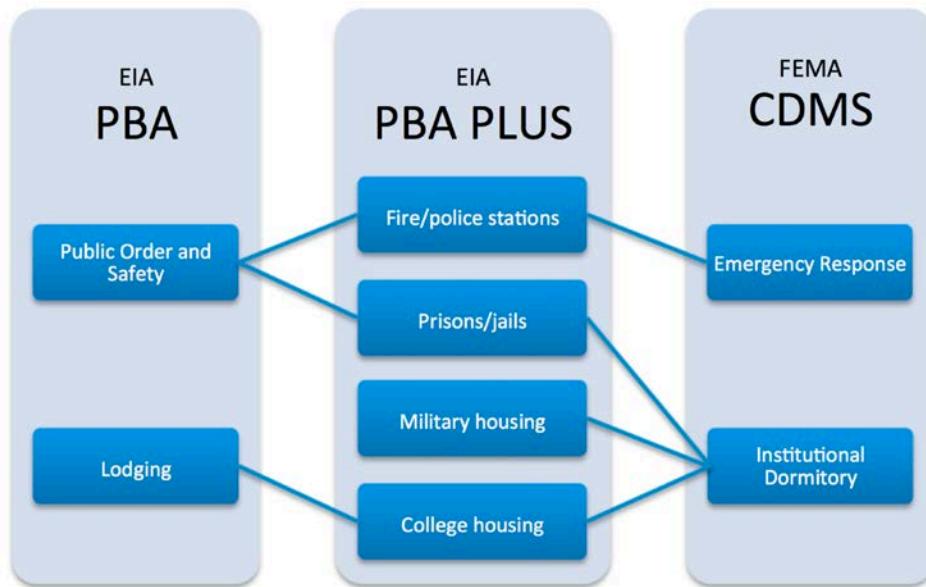


Figure 4: Example mapping of EIA PBAs to FEMA's building types

To verify our results, we summed the total estimated demand for each county across building types and compared the sums to the total thermal demand values provided by EIA at the census division levels. Where results differed from the EIA regional totals, we linearly recalibrated the estimates for each county and building type to ensure an aggregate sum matching the reported total from EIA. Figure 5 illustrates the overall workflow of the analysis.

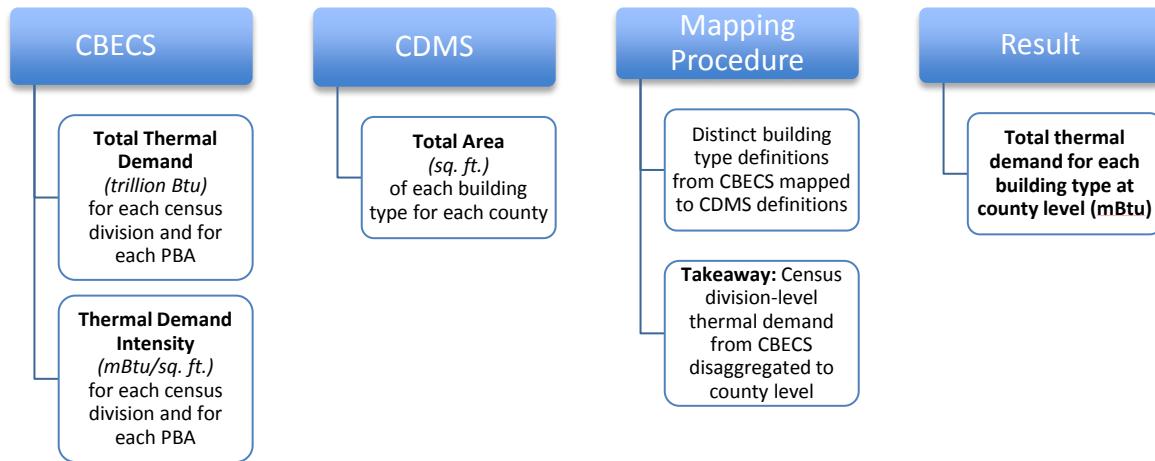


Figure 5: General workflow for reconciling commercial analysis datasets

The result of this analysis is partially shown in Table 3, which displays a subset of counties in Alabama and their space heating totals, as well as a subset of the 18 total CDMS building types.

Table 3: Space heating demand totals (billion Btu) by county and CDMS building type

State	County	Retail Trade	Wholesale Trade	Personal and Repair Services	Professional/Technical Services	Banks	Hospitals	Grade Schools	Colleges/ Universities
Alabama	Autauga	22.11	1.70	10.22	75.74	1.03	2.57	5.27	0.23
Alabama	Baldwin	136.08	11.39	41.01	522.30	4.46	53.08	17.32	25.20
Alabama	Barbour	19.00	1.86	7.50	46.96	1.14	2.59	5.28	2.01
Alabama	Bibb	9.26	0.71	3.86	26.98	0.51	4.02	3.07	0.00
Alabama	Blount	23.01	2.45	9.60	98.26	2.26	6.48	4.48	0.43
Alabama	Bullock	3.33	0.39	1.51	12.71	1.09	0.00	1.47	0.89
Alabama	Butler	14.55	1.07	4.66	34.13	0.63	6.79	2.85	0.29
Alabama	Calhoun	80.94	10.36	33.92	227.92	3.45	17.29	15.74	6.60
Alabama	Chambers	21.19	1.27	9.10	44.16	0.55	12.43	6.19	2.41
Alabama	Cherokee	14.91	4.01	4.85	43.20	0.82	2.91	2.16	0.15
Alabama	Chilton	22.40	1.78	7.82	51.78	1.01	0.00	4.29	2.08
Alabama	Choctaw	8.38	1.35	3.08	17.77	0.53	0.50	2.33	0.79
Alabama	Clarke	23.93	1.14	11.64	40.30	0.74	1.61	5.99	2.18
Alabama	Clay	7.45	0.34	2.62	14.85	0.39	3.76	2.04	0.36
Alabama	Cleburne	6.39	0.33	2.71	9.14	0.32	0.25	2.20	0.00
...

Manufacturing Sector

For the manufacturing subsector analysis, EIA's MECS database provides demand data on two low-temperature end-uses: process steam and facility heating, ventilating and air conditioning (not explicitly space heating). For process heat, the variability of the fluid temperatures between industries complicates the analysis. The use of the publication *Energy Analysis of 108 Industrial Processes* (Brown et al. 1985) allows us to filter the most energy-intensive processes based on their operating temperatures. The resulting list of processes can then be evaluated for thermal demand that fits the study's temperature bounds. Figure 6 illustrates the general workflow of the analysis.

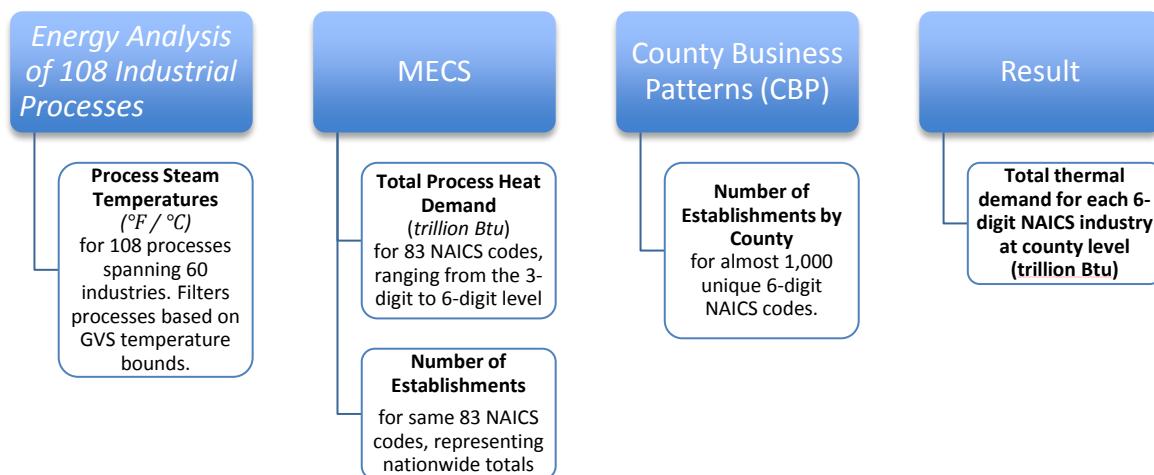


Figure 6: General workflow of manufacturing sector analysis

We digitized the information contained in Brown et al. (1985), allowing us to filter the fluid temperatures and analyze only the industries that utilize process steam within the temperature bounds of the study. This resulted in a list of 49 industries, a sample of which is shown in Table 4. The energy use for each process in this document is based on industry-specific units (e.g., Btu/lb. of meat products), rendering cross-industry comparison of aggregate intensity difficult without further analysis.

It is important to note that some industries reported multiple steam temperatures required for distinct processes. If a single industry contained any process above 150°C , the entry was discarded; it is expected that such a facility would simply invest in a higher-rated boiler for its higher temperature needs instead of employing a combination of DU for lower temperatures and boilers for higher temperatures.

Table 4: Sample list of processes including steam and space heating (Sp Ht) energy demand per industry-specific unit.

SIC Code	Detailed SIC	NAICS Code	Process	Unit Operation		Outlet		
				Desc.	Temp (°C)	Flow	Temp (°C)	Energy (Btu)
2011	2011	311611	Meat Packing Plants	Boiler	120	Steam Sp Ht	120 120	895.5 46
2026	2026	311511	Fluid Milk	Boiler	120	Steam Sp Ht	120 120	127.5 28.7
2033	2033-1	311421	Canned Fruits and Specialties	Boiler	120	Steam Sp Ht	120 120	16,500 8,200
2033	2033-3	311421	Canned Fruits and Specialties	Boiler	120	Steam Sp Ht	120 120	8,000 5,600
2046	2046	311221	Wet Corn Milling	Boiler	120	Steam Sp Ht	120 120	1,420 125

SIC – Standard Industrial Classification

The data from Brown et al. (1985) was then merged with MECS thermal demand data, based on the 6-digit NAICS codes that were common between the two datasets. While MECS reported a total of 83 industries at various levels, 47 had data at the 6-digit level and only 14 codes were common between the two datasets. This analysis resulted in fewer industries and thus less national coverage than we initially expected due to the temperature bounds of the study. Figure 7 ranks the down-selected industries by thermal demand (trillion Btu), with the bar colors corresponding to the remaining two steam temperatures utilized by the 14 industries. Note that entries with zero demand represent industries that withheld data to preserve facility-specific anonymity.

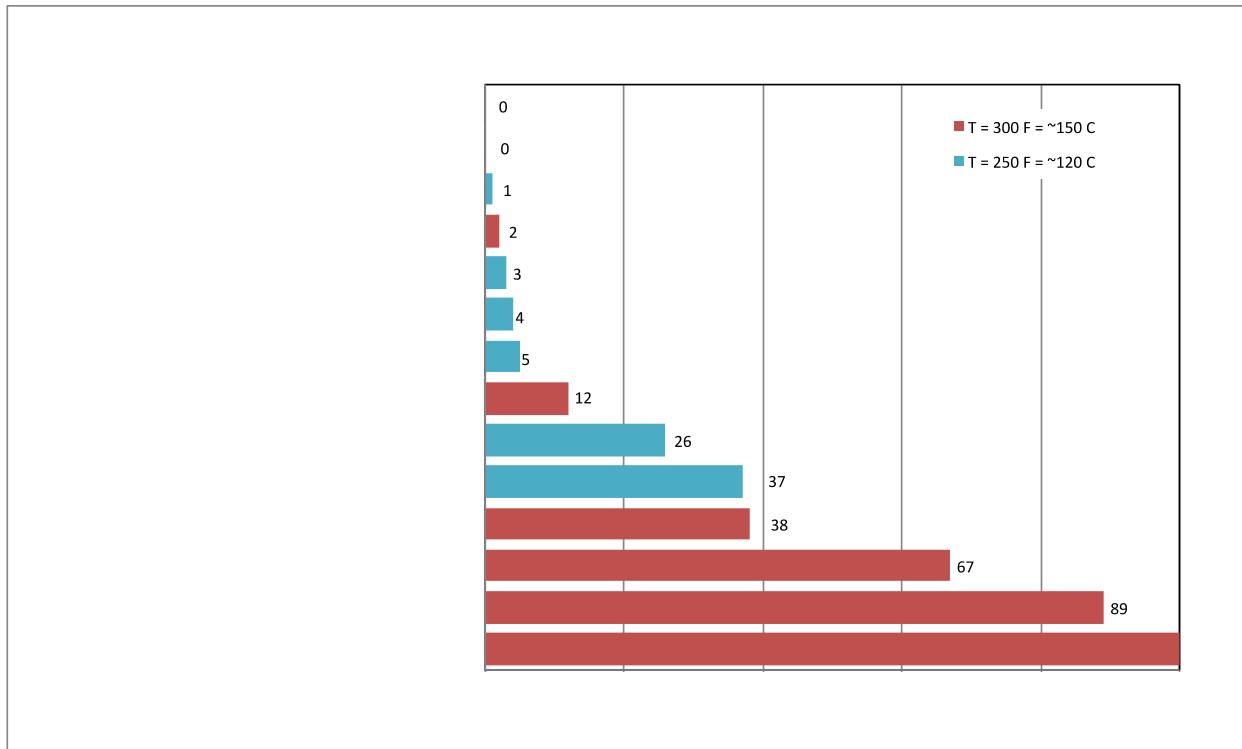


Figure 7: Thermal demand totals (trillion Btu) by industry; color coded by process steam temperature.

Finally, these thermal demand data were disaggregated to the county level using a combination of additional data from MECS and the U.S. Census Bureau's CBP. In addition to energy data, MECS also reports the number of establishments that responded to the survey, categorized by the same NAICS codes as reported in the energy end-use data. This allowed us to calculate an energy "intensity" value for each 6-digit NAICS code by dividing the total thermal demand by the number of establishments for that specific code, resulting in a unit of trillion Btu per establishment. Table 5 lists the 14 industries in the analysis and their calculated demand intensity values.

Table 5: Listing of 6-digit NAICS codes and the calculated demand intensity values (trillion Btu/establishment)

NAICS Code	Description	Thermal Demand (trillion Btu)	Establishment Count	Demand Intensity (trillion Btu/est.)
325193	Ethyl Alcohol	100	185	0.541
325199	Other Basic Organic Chemicals	89	476	0.187
322121	Paper Mills, except Newsprint	67	203	0.330
322130	Paperboard Mills	38	177	0.215
311221	Wet Corn Milling	37	59	0.627
325312	Phosphatic Fertilizers	26	65	0.400
322110	Pulp Mills	12	41	0.293
321113	Sawmills	5	1,659	0.003
325120	Industrial Gases	4	486	0.008
325412	Pharmaceutical Preparation	3	609	0.005
322122	Newsprint Mills	2	26	0.077
325992	Photographic Film, Paper, Plate, and Chemicals	1	138	0.007
325110	Petrochemicals	0	40	0.000
325212	Synthetic Rubber	0	126	0.000

Combining the demand intensity values with the number of establishments in each county (reported by the CBP), we were able to calculate the thermal demand for the 14 filtered industries at the county level. Table 6 gives a subset of counties and their corresponding total thermal demand, calculated by summing the demand for each 6-digit NAICS code; the full list of counties will be uploaded to the GDR. By using establishment counts as the disaggregation metric, we inherently assume that each manufacturing facility with the same NAICS code uses an equal amount of energy. While this assumption is not ideal, the available data are not sufficient to accurately capture intra-industry variation in demand intensity. This initial analysis represents a first cut in resolving local variation in industrial manufacturing thermal demand across the United States, and further analysis will be conducted once more specific data become available.

Table 6: Total county demand (trillion Btu) for process steam

State	County	Total County Demand (trillion Btu)
Alabama	Autauga	0.21
Alabama	Baldwin	0.39
Alabama	Barbour	0.60
Alabama	Bibb	0.01
Alabama	Calhoun	0.21
...
Colorado	Adams	0.01
Colorado	Arapahoe	0.63
Colorado	Boulder	0.83
Colorado	Broomfield	0.01
Colorado	Denver	0.46

Agricultural Sector

For the agricultural sector analysis, no source was identified that reports agricultural energy consumption directly. Instead, data on farm production expenditures were obtained, with expenses for fuels by type reported at the regional level. These data were combined with price data (EIA 2016a; 2016b; 2016c; 2016d) and energy content values (DOE 2014) for each fuel type, which included gasoline, diesel, LP gas (propane), electricity, and “other” fuels (natural gas, coal, fuel oil, kerosene, wood, etc.). This resulted in an estimation of energy consumption by fuel type for each farm production region. We assumed that 100% of the expenditures in the “other” fuels category were for natural gas due to the lack of clarification as to the proportion that each “other” fuel represented. Equation 4 illustrates the procedure used to estimate total energy consumption, which was applied to all fuel types in each region, with values then summed for total consumption in that region.

$$\text{Fuel Expenditure} (\$) * \text{Fuel Price} \left(\frac{\text{volume}}{\$} \right) * \text{Energy Content} \left(\frac{\text{BTU}}{\text{volume}} \right) = \text{Consumption (BTU)} \quad (4)$$

This procedure estimated total energy consumption at the regional level. The USDA defines five regions, each containing between 6 and 16 states. While the 2012 USDA Farm Production Expenditures report (USDA 2013) included data for some individual states, disaggregation from the regional level to the state level was still required as an intermediate step. This was completed by using the total number of farms in each state as a weighting factor to disaggregate regional energy consumption to individual states.

The second publication utilized for the agricultural analysis was the USDA’s “2012 Census of Agriculture” (USDA 2012). The census reports data at the state and county levels, including statistics on various farm characteristics, inventory, expenses, and land use. For this analysis, the county-level totals of farms were used to disaggregate the state-level energy consumption totals to the county level. Both the disaggregation procedure discussed above and the procedure outlined here follow the residential sector disaggregation strategy, and are illustrated in Equations 5 and 6.

$$\left(\frac{\text{County}}{\text{State Total}} \right)_{\text{Farms}} = \text{County Weight} \quad (5)$$

$$(\text{County Weight}) * (\text{State Thermal Demand}) = \text{County Thermal Demand} \quad (6)$$

The procedure to this point in the analysis has resulted in county-level demand estimates for *total* energy consumption from fuel, with no distinction made regarding the end-use portion of this total (e.g., tractors/machinery, space heating, drying, on-site electric generation, etc.). The lack of agricultural consumption data does not allow us to further calculate these proportions.

To include the agricultural sector, we chose to further analyze greenhouses, which are often considered as potential facilities for DU adoption. Analyses of other areas within the agricultural subsector, such as aquaculture or poultry production, require further time and resources to research in depth and could be considered for future inclusion.

In addition to the information discussed above, the “Census of Agriculture” also reports farm totals at the county level with respect to 15 different agriculture-related NAICS codes. The relevant sub-industry for greenhouses is described as “Greenhouse, nursery, and floriculture production (1114)” (USDA 2012). The county-level demand was further proportioned into the various NAICS categories, again based on the number of farms reported in each category. Finally, additional sources were consulted to determine the energy consumption in a typical greenhouse and the proportion that is allocated for heating. Greenhouses on the Cornell University campus were estimated to use approximately 65% of the total consumption for heating (Cornell University 2014), and an Illinois utility company estimated that 70%–80% of energy use is allocated to heating in a typical greenhouse (Brinker 2012). Therefore, we assumed that 70% of the total energy consumption for greenhouses is allocated for heating purposes.

The result of this strategy was a list of counties that contained farms under the “Greenhouse, nursery, and floriculture production (1114)” NAICS distinction and their corresponding thermal demand.

Results

The primary results of the above analyses are the preliminary demand maps for the residential (Figure 8), commercial (Figure 9), manufacturing (Figure 10), and agricultural (Figure 11) sectors for use in future technical, economic, and market potential modeling with dGeo. In addition, Table 7 ranks the top three counties for total thermal demand in each sector, and Table 8 ranks the top three counties for “thermal demand density” in each sector, a metric that reports demand per square foot of land within the county.

Many of the top counties by demand, especially in the residential and commercial sectors, are also those with large populations, reflecting the strong linkage between thermal energy consumption and population centers. While these counties may potentially represent strong candidates for geothermal DU applications, further analysis is required to determine whether and to what degree these thermal demand centers are co-located with suitable geothermal resources.

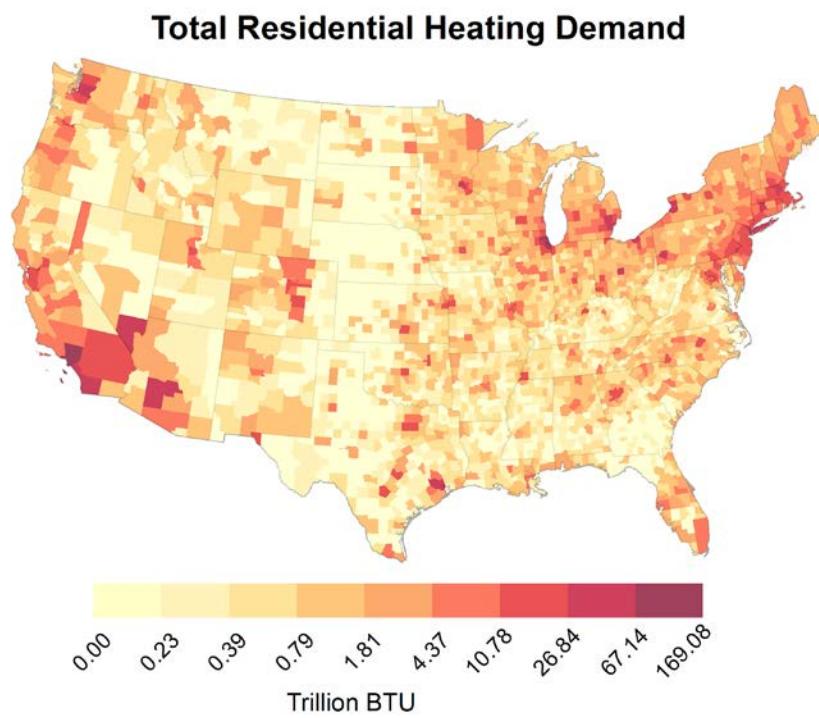


Figure 8: Residential sector thermal demand map of United States

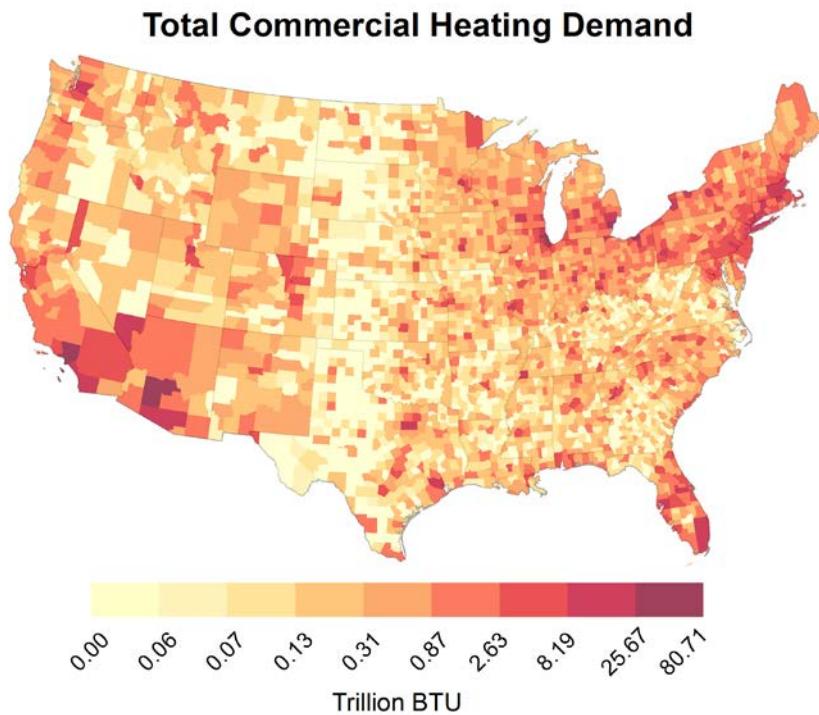


Figure 9: Commercial sector thermal demand map of United States

In the manufacturing sector, the lack of nationwide data renders further discussion of the results difficult. Nonetheless, an interesting result from Table 7 is the top county for thermal demand, Harris County, Texas, in which the city of Houston is located. The prevalence of chemical manufacturing operations associated with this city also corresponds to the total demand in the county, where a high number of “basic organic chemical manufacturing” (EIA 2010) facilities contribute to the overall consumption. In fact, the number of facilities with this NAICS distinction in Harris County (58) is nearly four times greater than the next closest county (15, in Cuyahoga County, Ohio). Additionally, a regional trend can be discerned from the map, where many of the areas of high demand in the Midwest may be attributed to corn ethanol manufacturing and wet corn milling operations. As with the residential and commercial sectors, the manufacturing sector thermal demand will be considered in parallel with the location of geothermal resources in future geothermal DU potential studies.

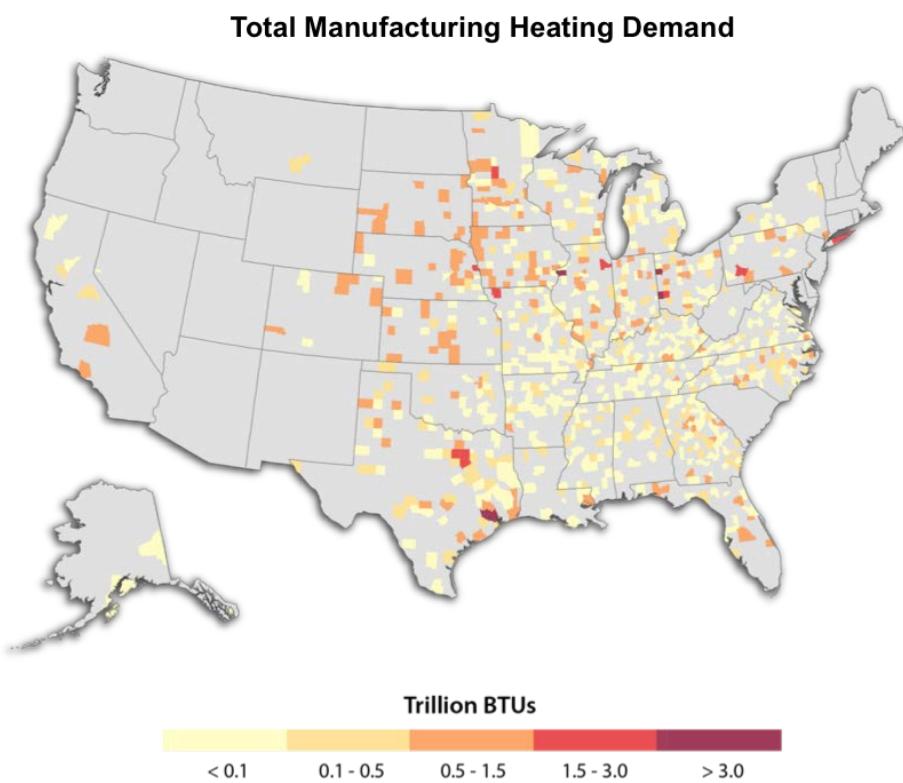


Figure 10: Industrial (manufacturing) sector thermal demand map of United States

In the agricultural sector, the demand map shows clear distinctions where greenhouse space heating is most prevalent, including the west coast and much of Florida. While California and Florida, to some extent, are certainly states with well-known records of agricultural and farming operations, further analysis is necessary to understand the existence of greater demand in the less well-known areas, such as the Pacific Northwest. In addition, further research would allow for a better understanding of the lack of demand in the central United States, where the climate would seemingly require greenhouses for those specific types of agricultural operations.

As a final result, the data used to create the maps and tables in this paper have been uploaded to the GDR for public use in future studies.

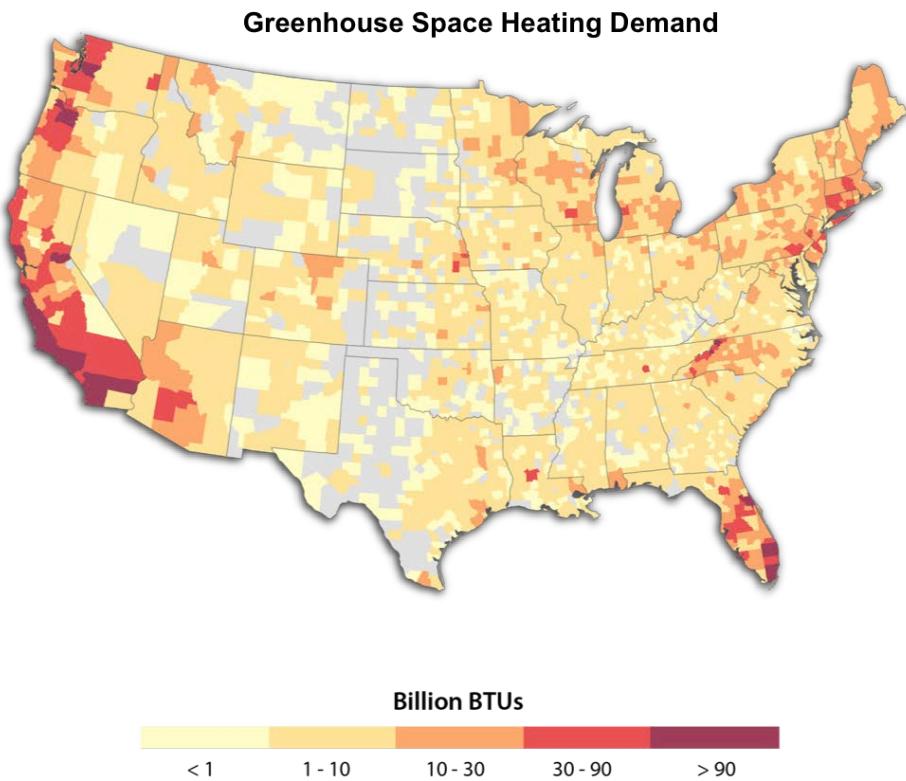


Figure 11: Greenhouse space heating demand map of United States

Table 7: Top three counties by sector for total thermal demand

State	County	Total County Demand (trillion Btu)
Residential Sector		
Illinois	Cook	169.08
California	Los Angeles	95.83
Michigan	Wayne	61.30
Commercial Sector		
Illinois	Cook	80.71
New York	New York	41.28
California	Los Angeles	41.05
Manufacturing Sector		
Texas	Harris	13.48
California	Los Angeles	6.52
Illinois	Cook	3.95
Agricultural Sector		
California	San Diego	0.60
Oregon	Clackamas	0.32
Florida	Miami-Dade	0.26

Table 8: Top three counties by sector for thermal demand density (mBtu/sq. ft.)

State	County	Thermal Demand Density (mBtu/sq. ft.)
Residential Sector		
New York	New York	869.2
New York	Kings	328.4
New York	Bronx	282.6
Commercial Sector		
New York	New York	703.3
New York	Bronx	119.2
New York	Kings	114.4
Manufacturing Sector		
Virginia	Hopewell City	24.0
Virginia	Covington City	15.2
Virginia	Bristol City	11.9
Agricultural Sector		
North Carolina	Avery	0.23
North Carolina	Ashe	0.14
California	Santa Cruz	0.10

Conclusion and Future Work

To date, we have completed a thorough analysis of available data, disaggregation of data to the county-level, and preliminary presentation of these data. Further data processing of the data is underway, including research into the use of geothermal DU to meet these heating demands, such as retrofitted district heating systems. According to a 2010 study (Thorsteinsson and Tester), there are an estimated 21 geothermal district heating systems in the United States, operating with a total capacity of about 100 MW_t. In addition, carbon dioxide emissions from space and water heating (as well as cooking activities) in the residential and commercial sectors in 2006 amounted to about 470 million metric tons, representing an even greater opportunity for low-temperature geothermal DU deployment in reducing carbon emissions.

Planned work by NREL in the progression of the GVS includes integrating the resource potential analysis (Mullane et al. 2016) that was completed in parallel with this heat demand analysis. This will give a collocated resource-demand map for use in future economic and market potential studies. Note that these future studies will incorporate costs and market effects of geothermal DU integration. The study presented here does not include any economic implications.

In future analyses of the heat market, the weighting strategies utilized in the study could be improved. The current strategies of assigning county weights based on housing units (residential), establishments (manufacturing), and farms (agricultural) have an inherent assumption that each unit within the county uses the same amount of heat. We know this to be an overly simplified assumption. However, these metrics do provide an intuitive and transparent way to proceed with the analysis. A more rigorous assessment would involve finding the most

statistically significant attributes of a residence or manufacturing/agricultural facility that determine the amount of heat usage, such as the tenancy status (rented/owned) or construction year for the residential analysis and emissions totals (e.g., of carbon dioxide) or outputs (by dollar or product) for the manufacturing/agricultural analysis. These factors could be decided using statistical methods, such as regression analysis.

In the manufacturing sector, a distinct lack of data rendered the analysis difficult. Future studies that expand on this work would benefit from increased coverage of manufacturing industries that included data on both process heat temperatures within each NAICS category as well as the corresponding thermal demand. The combination of the publication by Brown et al. (1985) with the MECS dataset resulted in an analysis that included only 14 industries at the 6-digit NAICS code level. Additionally, the Brown et al. work, while widely referenced in literature, is rather outdated, and it could be posited that technological advances in the past 20 years have created more efficient industrial processes with different temperature needs.

In the agricultural analysis, future analyses could focus on a bottom-up approach of each of the listed NAICS categories to determine improved estimates of heat consumption. A similar approach was taken in this study for the greenhouse subsector, where typical consumption values were calculated based on individual facilities.

Finally, much more work could be completed in the broader industrial sector, as the current analysis only examines the manufacturing and agricultural subsectors. Other subsectors not considered in the current analysis include the mining, oil and gas, and construction industries. While this is due primarily to the available data, further analysis could work to integrate other data sources to include more of the industrial sector.

To our knowledge, this assessment of locally resolved heat demand in the United States represents the first study of its kind. It has applications to a wide variety of technologies and domains beyond geothermal, including building technologies, industrial processes, and various distributed renewable energy thermal resources (e.g., biomass, solar). The county-level and sector-specific heat demand totals developed in this study contribute to U.S. research in renewable heat energy and work toward facilitation of a similar type of market transformation for the heat market that the electricity sector has done with great success for years.

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Acronyms

ACS	American Community Survey
Btu	British thermal units (mBtu = 1,000 Btu; quad = 1 quadrillion Btu)
CBECS	Commercial Buildings Energy Consumption Survey
CBP	County Business Patterns

CDMS	Comprehensive Data Management System
DOE	U.S. Department of Energy
DU	direct use
EIA	Energy Information Administration
FEMA	Federal Emergency Management Agency
GDR	Geothermal Data Repository
GVS	Geothermal Vision Study (GeoVision)
MECS	Manufacturing Energy Consumption Survey
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
PBA	Principal Building Activity
PBAPLUS	Principal Building Activity PLUS (subcategories)
RECS	Residential Energy Consumption Survey
RD-CR	reportable domain-climate region cross-section
USDA	United States Department of Agriculture

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