# Geospatial Characterization of Low-Temperature Heating and Cooling Demand in the United States

## Preprint

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*National Renewable Energy Laboratory*

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# Geospatial Characterization of Low-Temperature Heating and Cooling Demand in the United States

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**Keywords:** Low temperature, geothermal, heating demand, cooling demand, geospatial, direct use, end-use energy consumption

## ABSTRACT

Geothermal resources at temperatures below 150°C have great potential as energy sources for various direct-use applications including heating and cooling in residential and commercial buildings. This study geospatially quantifies U.S. heating and cooling demand in residential, commercial, and manufacturing sectors; heating demand in the agricultural sector; and cooling demand in data centers at the county level through end-use energy consumption, expenditure, and commissioned power analyses. Heating and cooling demand in the residential sector was estimated using energy consumption data obtained from the U.S. Energy Information Administration accounting for different U.S. climate zones. For commercial sector analysis, the end-use major fuel energy intensity at the census division level was disaggregated to the county level with respect to principal building activities. Heating and cooling demand analysis for the manufacturing sector was based on end-use energy consumption for direct-use total process categorized by the North America Industry Classification System. Fuel expenditures in the U.S. Department of Agriculture Farm Production Expenditures were examined for heating demand analysis in the agricultural sector, particularly for the greenhouse, nursery, and floriculture production category. Lastly, commissioned power for data centers in the United States were explored for cooling demand analysis. Results indicated a significant fraction of U.S. primary energy consumption is used for low-temperature heating and cooling applications. Heating and cooling demand in residential and commercial sectors is significantly affected by the number of housing units and climate zone designations, while heating and cooling demand in manufacturing and agricultural sectors and data centers are mainly dependent on the number of facilities and their locations. Maps were generated visualizing where heating and cooling demand is high and, overlain with geothermal resource maps, can indicate locations where geothermal energy can supply this heating and cooling demand.

## 1. INTRODUCTION

The Geothermal Technologies Office at the U.S. Department of Energy defines low-temperature geothermal energy as heat obtained from the geothermal fluid in the ground at temperatures of 150°C (300°F) or less. Low-temperature geothermal resources are typically used for direct-use applications (e.g., district heating, greenhouses, industrial process heating) and ground-source (geothermal) heat pumps for space and water heating and cooling in buildings (Lienau and Lunis 1991; Sarbu and Sebarchievici 2014; Olasolo *et al*. 2016; Oh and Tinjum 2020), as well as electric power generation (DiPippo 2004; Van Erdeweghe *et al*. 2018; Beckers *et al*. 2022). In particular, the primary use of geothermal energy in the United States today is for baseload electricity and geothermal heat pumps, instead of direct-use heating for district energy or industrial processes (Tester *et al*. 2021).

Mullane *et al.* (2016) estimated that the U.S. low-temperature geothermal resource contains approximately 30,000 EJ and 6 million EJ in the relatively shallow subsurface (≤3 km) for hydrothermal systems (e.g., convective hydrothermal flow through heat exchangers) and enhanced geothermal systems, respectively. Nevertheless, the U.S. Energy Information Administration's (EIA's) Annual Energy Review demonstrated that fossil fuels—petroleum (36%), natural gas (32%), and coal (11%)—were major sources for U.S. primary energy consumption, and only 0.24% of the total was supplied by geothermal energy in 2021 (EIA 2022). Recently, the role of geothermal energy in decarbonizing the U.S. energy supply was comprehensively reviewed in Tester *et al*. (2021). The researchers concluded that more than 20% of the U.S. primary energy used for building and industrial process heating was predominantly supplied by burning fossil fuels. Geothermal energy provides a low-carbon alternative at a wide range of scales—from just a few to hundreds of thermal megawatts—and can have a significant impact on lowering carbon emissions.

According to McCabe *et al*. (2016), data on the U.S. heat market are very limited, with the majority of current data coming from the EIA's periodic energy consumption surveys. EIA conducts periodic surveys to collect and analyze energy consumption data in four major end-use sectors: residential, commercial, manufacturing, and transportation. In the surveys, the energy consumption is specified by consumption of electricity and primary energy, including fossil fuels, nuclear energy, and renewable energy, as well as electrical system energy losses, which is the amount of energy lost during generation, transmission, and distribution of electricity. Although the U.S. Environmental Protection Agency's Greenhouse Gas Reporting Program data were used for estimating U.S. industrial thermal energy demand (McMillan *et al*. 2016; McMillan and Ruth 2019), the EIA's consumption survey database has been widely used in the literature for analyzing energy consumption and demand (e.g., Fox *et al*. 2011; Sanders and Webber 2012; McCabe *et al*. 2016; Tester *et al*. 2021). Particularly, McCabe *et al*. (2016) analyzed the EIA's end-use energy consumption and the U.S. Department of Agriculture (USDA) database to geospatially characterize the U.S. heating demand (primarily focused on space and water heating demand) in residential, commercial, manufacturing, and agricultural sectors at the county level for potential application of low-temperature geothermal resources.

The objective of our study is to update these previous thermal demand analyses by incorporating the latest EIA energy consumption and fuel expenditure data, as well as to expand the analysis by estimating the cooling demand in addition to the heating demand. To understand where heating and cooling demand occur and where this demand may co-locate with geothermal resources, our study geospatially quantifies U.S. low-temperature (i.e., <150°C) heating and cooling demand at the county level in four major end-use sectors: residential, commercial, manufacturing, and agricultural. Heating demand includes space, water, and process heating, as well as cooking; cooling demand includes space cooling, refrigeration, and freezing. Data centers consume a significant amount of energy for cooling and were analyzed at the county level through commissioned power analysis.

## 2. METHODOLOGY

Thermal demand in the residential, commercial, and manufacturing sectors was estimated using the EIA end-use energy consumption and expenditure (C&E) survey data for these sectors: (1) Residential Energy Consumption Survey (RECS), (2) Commercial Building Energy Consumption Survey (CBECS), and (3) Manufacturing Energy Consumption Survey (MECS). The energy consumption data in each sector are provided at the census division level and consist of different fuel usage depending on end-use categories (e.g., space heating, air conditioning). For example, the energy consumption for space heating end use in the residential sector is a sum of electricity, natural gas, propane, and fuel oil/kerosene usage, while electricity is the only energy source for air-conditioning end use. Fuel expenditures in the USDA Farm Production data were used to derive energy consumption in the agricultural sector. Finally, cooling demand in data centers appears lacking in the CBECS or MECS data and therefore was analyzed using commissioned power data obtained from a commercial platform, datacenterHawk, LLC.

For most thermal applications, the reported energy consumption data equal the thermal demand. For example, for space heating with natural gas, 1 kWh of natural gas consumption translates to 1 kWh of heat demand. However, if heating or cooling is provided with a heat pump or refrigeration cycle, the reported energy consumption in the EIA surveys no longer matches the thermal demand. For example, if the electricity consumption to operate a ground-source heat pump for space heating is 1 kWh, the heat provided by the pump would range from 2.5 to 4 kWh depending on environmental conditions, especially ambient and operating temperatures. Coefficient of performance (COP) describes the ratio of energy output to energy input, and the COP for this example case is 2.5–4. To estimate the heating and cooling demand in this study, the energy consumption data were incorporated with typical COPs of a heat pump, air conditioner, and refrigerator (operated by electricity) for the following specific end-use categories (Taylor and Solbrekken 2008; Zou and Xie 2017):

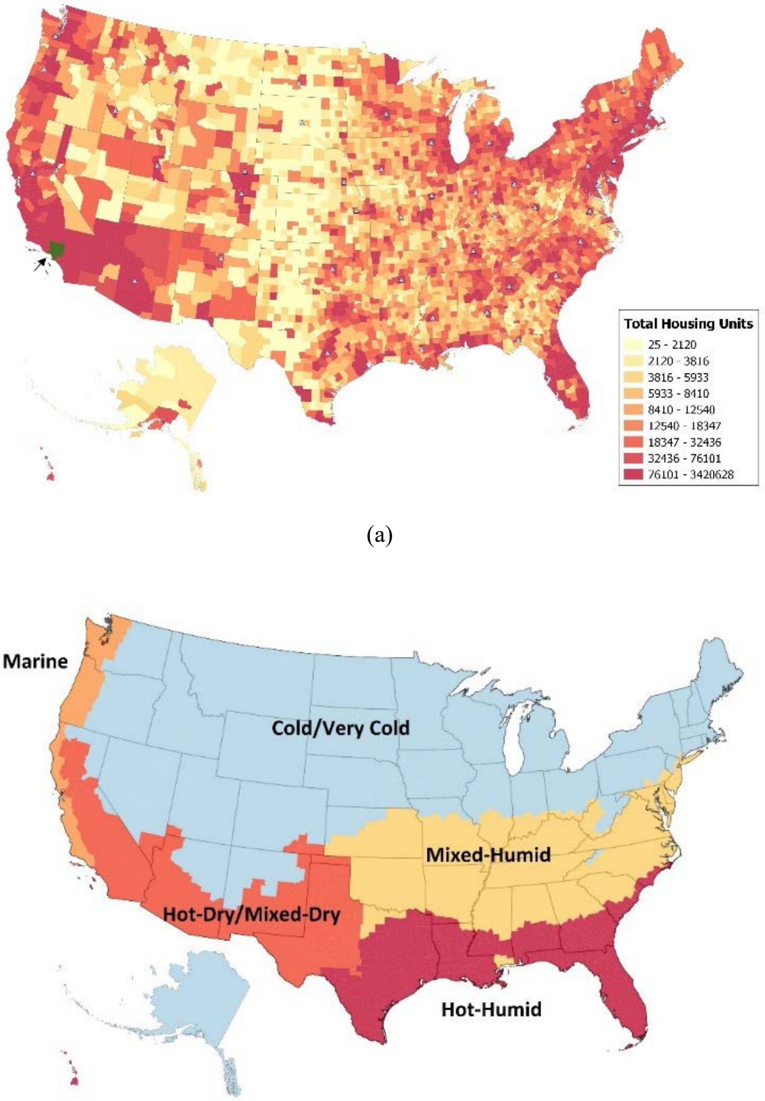
(1) Space heating in residential and commercial sectors filtered by heat pump equipment (COP = 2.5 considering both air- and ground-source heat pumps),
(2) Air conditioning in residential and cooling in commercial (COP = 2.5),
(3) Refrigerators in residential and commercial sectors (COP = 1.5), and
(4) Process cooling and refrigeration category in the manufacturing sector (COP = 2).

According to the 2015 RECS C&E database, for example, residential electricity consumption for space heating (main and secondary) in the South Atlantic census division was 47.2 billion kWh. As the COP of 2.5 was incorporated for electricity usage for heat pumps in the space heating category (i.e., the COP is not considered for natural gas, propane, and fuel oil usages), heating demand for space heating in the South Atlantic census division becomes 71.7 billion kWh. More simply, total site energy consumption in the residential sector for air conditioning is multiplied by 2.5 since electricity usage is the only energy consumption for air conditioning (e.g., the energy consumption of 2.8 billion kWh for air conditioning in the New England census division becomes air-conditioning demand of 6.9 billion kWh with a COP of 2.5).

### 2.1 Residential Sector

2015 RECS microdata (EIA 2018), which is the most recent version (release date May 2018), were customized for analyzing heating and cooling demand in the residential sector. Seven end-use energy consumption categories—space heating, water heating, cooking, microwave, clothes dryer, hot tub heater, and swimming pool heater—were used for heating demand analysis. Air conditioning, all refrigerators, and freezer end-use categories were used for cooling demand analysis. Although cooking may be associated with a temperature beyond 150°C (Fox *et al*. 2011), this study assumes that low-temperature geothermal energy can supply the thermal demand in this category.

The EIA consumption data were first adjusted with a COP as described above (e.g., electricity consumption for space heating with a heat pump is multiplied by 2.5). Then, the census division-level thermal demand data were disaggregated to the county-level resolution using the number of housing units obtained from the 2020 Decennial Census (Census 2021) (Figure 1(a)). As the EIA RECS excludes vacant housing units, seasonal units, second homes, military houses, and group quarters, the number of occupied housing units excluding vacant housing units was used in the analysis to minimize error. The disaggregated number of housing units at the county level was weighted relative to climate zone designations (i.e., the county-level number of housing units divided by total number of housing units in the same Census division and climate zone for weighting factors). In this study, the eight climate zone designations classified by the U.S. Department of Energy's Building America Program (DOE 2013) were grouped as five climate zones (Figure 1(b)): (1) subarctic (only appeared in Alaska), very cold, and cold zones; (2) mixed-humid zone; (3) hot-dry and mixed-dry zones; (4) hot-humid zone; and (5) marine zone. Similar to the weighting process for the number of housing units, the energy consumption data was weighted to the number of housing units at Census division level and climate zone (i.e., Census division-level energy consumption data weighted relative to the number of housing and climate zone) and then incorporated with the weighting factors for county-level heating and cooling demand.



(a)

(b)

**Figure 1: Spatial distribution of disaggregating and weighting parameters used in residential heating and cooling demand analysis at the county level:(a) the number of occupied housing units and (b) U.S. climate zone designations. The county where the number of occupied housing units is the highest is highlighted with a green background and black arrow.**

### 2.2 Commercial Sector

C&E data from the 2012 CBECS (release date May 2016) include end-use major fuel consumption and major fuel energy intensity, which is the total fuel consumption divided by the floor space in buildings that use any energy sources (thousand Btu/square foot) (EIA 2016).

In this study, the energy intensity data were primarily used for commercial heating and cooling demand analysis, and the total major fuel consumption data were used to validate the analysis result. The energy intensities for space heating, water heating, and cooking end uses and those for cooling and refrigeration end-use categories were used for heating and cooling demand analyses, respectively, and were selectively incorporated with the COPs (see Methodology section). In this study, it was assumed that the energy consumption used for any cooking activities can be supplied by the low-temperature geothermal resource. Similar to the 2015 RECS microdata, the 2012 CBECS microdata do not provide any temperature information in the cooking category or a filter option for cooking equipment.

In the CBECS C&E data, the major fuel consumption and energy intensity data are specified in terms of 16 principal building activities (PBAs) such as education, food sales, and health care. The CBECS microdata also provide PBA Plus, which further specifies the 16 PBAs into 53 PBA Plus designations. For example, the food sales category in PBA is separated into convenience store (code #12), convenience store with gas station (code #13), grocery store/food market (code #14), and other food sales (code #15) in PBA Plus. To disaggregate the EIA's regional data (i.e., nine census divisions) to the county-level resolution, the energy intensity specified by the 53 PBAs was reconciled with 18 building types in each county obtained from the Federal Emergency Management Agency's 2013 Hazus Comprehensive Data Management System (CDMS) database, as suggested by McCabe *et al*. (2016). The Hazus CDMS provides total building square footage of 18 building types at the county level (FEMA 2013). In other words, the county-level total building area (square footage) was multiplied by the division-level energy consumption intensity (thousand Btu/square foot) for the total energy consumption (trillion Btu) in each county considering relationships between PBA Plus and CDMS building types. For example, the CDMS building code COM6 for hospital and PBA Plus code #35 for hospital/inpatient health were matched in the disaggregation process, and the remaining 17 CDMS building types were similarly reconciled with PBA Plus. Then, all the estimated county-level energy consumption for each of the 18 building types was combined to represent total energy consumption in each county. The estimated total energy consumption was validated using the EIA's total major fuel consumption data.

### 2.3 Manufacturing Sector

The EIA's Annual Energy Outlook 2022 (Reference case for 2021) reported percentage shares of industrial energy consumption by four major industrial types: 81% manufacturing, 9% mining, 6% construction, and 3% agriculture (EIA 2022). This study thus analyzed the heating and cooling demand analysis in the manufacturing sector, which takes a significant part of the entire industrial section and is also only available in EIA's database (i.e., no EIA's database is available for mining, construction, and agricultural sectors). End-use energy consumption data in the 2018 MECS (release date February 2021) were used in the analysis (EIA 2021). North America Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments. NAICS code ranges from 2- to 6-digit hierarchical classification codes (e.g., 325 – Chemical Manufacturing under 31-33 Manufacturing). In the MECS, the database is specified for 82 manufacturing industries based on the NAICS codes, ranging from 3- to 6-digit hierarchical classification codes (i.e., subsectors under 31-33 manufacturing), with respect to four subcategories: (1) indirect uses – boiler fuel, (2) direct uses – total process, (3) direct use – total non-process, and (4) end use not reported. The four subcategories include a wide range of end-use energy consumption categories, some of them related to industrial heating and cooling demand such as conventional boiler and combined heat and power/cogeneration process in the indirect-use subcategory, process heating in the direct-use total process subcategory, and facility heating, ventilation, and air conditioning in the direct-use non-process subcategory. However, due to unavailability and uncertainties on detailed information and data (e.g., process heating temperature), only the direct-use total process subcategory was considered in this study for analyzing manufacturing heating and cooling demand: process heating end use for the heating demand analysis and process cooling and refrigeration end use for the cooling demand analysis. The process cooling and refrigeration category was incorporated with the COPs, while the energy consumption for process heating end use is considered equal to the manufacturing thermal demand.

As the temperature information for the process heating was not available in the MECS, the process temperature database provided by Brown *et al*. (1985) was incorporated to identify manufacturing industries where process heating temperature is less than 150°C. Specifically, each of the 82 manufacturing industries available in MECS consisted of various distinct processes with a wide range of process temperatures (e.g., 427 °C of boiler unit process for 'coke oven and blast furnace products' in 331111 – Iron and Steel Mills, -18°C of boiler unit process for 'liquefied refinery gases (aliphatics), not made in a refinery' in 325110 – Petrochemical Manufacturing). Any manufacturing industries where the process temperature is above 150 °C were excluded and fourteen categories with 6-digit NAICS codes were selected for the manufacturing heating demand analysis.

For the cooling demand analysis, 66 manufacturing industries were selected, excluding overlapped 3- to 4-digit NAICS categories. For example, 3254 – Pharmaceuticals and Medicines consists of four subcategories: (1) 325411 – Medicinal and Botanical Manufacturing, (2) 325412 – Pharmaceutical Preparation Manufacturing, (3) 325413 – In-Vitro Diagnostic Substance Manufacturing, and (4) 325414 – Biological Product (except Diagnostic) Manufacturing. However, the EIA MECS database provides 3254 – Pharmaceuticals and Medicines and only one subcategory, 325412 – Pharmaceutical Preparation. To avoid data overlaps and any uncertainties, the 4-digit NAICS category was excluded, and the available 6-digit subcategory was used in the analysis. If 5- to 6-digit NAICS subcategories were not available in the MECS database (e.g., 326 – Plastics and Rubber Products in the 2018 MECS), accessible 3- to 4-digit NAICS categories were used in the cooling demand analysis.

In addition to the unavailable process heating temperature, the MECS data do not provide any regional information (i.e., the MECS reports U.S. total energy consumption for each manufacturing category). Accordingly, the MECS energy consumption data were processed with the U.S. Census Bureau's County Business Patterns (Census 2018), which provide the number of establishments categorized by the NAICS codes at the county level, similar to the county-level number of housing units in the Decennial Census used for the residential heating and cooling demand analysis. As a first step, energy intensity per manufacturing establishment was calculated by the energy consumption data divided by the number of manufacturing establishments obtained from the 2018 MECS database. Then, the energy intensity was matched using NAICS codes in the County Business Patterns to disaggregate the NAICS code-based U.S. total energy intensity to the county-level energy consumption. The energy intensity (trillion Btu per establishment) was multiplied by the number of establishments in each county for the county-level energy consumption (trillion Btu).

## 2.4 Agricultural Sector

The EIA's periodic energy consumption surveys for the industrial sector exclude the agricultural sector categorized by NAICS code 11 – Agriculture, Forestry, Fishing and Hunting sector, and there are few resources available for energy consumption analysis in this sector. In this study, county-level energy consumption in the agricultural sector was estimated using the 2017 USDA Census of Agriculture (USDA 2019), 2017 USDA Farms and Land in Farms (USDA 2018a), and 2017 major fuel expenditures in the USDA Farm Production Expenditures (USDA 2018b). Whereas both "Census of Agriculture" and "Farms and Land in Farms" were mainly used for disaggregation and weighting processes, the expenditure database was incorporated with fuel price and energy content to estimate the energy consumption as suggested by McCabe *et al.* (2016):

$$\text{Fuel Expenditure (\$) / Fuel Price (\$/volume)} \times \text{Energy Content (Btu/volume)} = \text{Energy Consumption (Btu)} \qquad (1)$$

The USDA Farm Production Expenditures specifies the fuel expenditure database by four fuel types—diesel, gasoline, liquid propane gas, and other fuel (e.g., natural gas, coal, fuel oil)—in five USDA farm production expenditure regions: Atlantic, South, Midwest, Plains, and West. Due to limited data availability, the "other fuel" category was assumed as natural gas, which was the highest industrial energy use by source in 2017 (EIA 2022). As the USDA Farm Production Expenditures exclude Alaska and Hawaii, the two states were excluded in the analysis for the agricultural sector. Table 1 summarizes the fuel prices and energy content used to estimate the agricultural energy consumption.

**Table 1: 2017 average fuel prices (EIA 2017a, 2017b, 2017c) and energy content (DOE 2014; EIA 2022)**

| | Diesel | Gasoline | Propane | Natural Gas |
|---|---|---|---|---|
| **Fuel Price** | 2.65 ($/gallon) | 2.41 ($/gallon) | 0.94 ($/gallon) | 4.07 ($/thousand cubic ft) |
| **Energy Content** | 122,364 (Btu/gallon) | 138,490 (Btu/gallon) | 91,420 (Btu/gallon) | 1,036 (Btu/thousand cubic ft) |

The USDA's National Agricultural Statistics Service conducts the Census of Agriculture every 5 years, and the Census of Agriculture provides the number of farms in each county in terms of NAICS codes under 11 – Agriculture, Forestry, Fishing and Hunting, ranging from 1111 – Oilseed and Grain Farming to 1129 – Other Animal Production. In particular, this study focused on 1114 – Greenhouse, Nursery, and Floriculture category, where significant heating demand is expected for climate control. Using the USDA Census of Agriculture (a ratio of the number of farms in the county to the total number of farms in the state), the estimated energy consumption in the five regions was disaggregated to the county-level resolution. Then, the disaggregated energy consumption was divided up for greenhouse farms. The county-level energy consumption was weighted relative to the average farm size in each county obtained from Farms and Land in Farms. The total energy consumption in greenhouse farms consists of various end-use subcategories such as lighting, heating, and ventilation, and about 70% of the greenhouse total energy consumption is allocated for heating purposes (Sanford 2011; McCabe *et al.* 2016). Accordingly, the thermal demand in the agricultural sector was approximated by the estimated total energy consumption multiplied by 0.7.

## 2.5 Data Centers

A data center is a facility where data are processed, stored, and communicated and generally consumes electricity to operate the facility (Geng 2014). Data centers can be over 40 times as energy-intensive as conventional office buildings (Greenberg *et al.* 2006), and large data centers more closely resemble industrial facilities than commercial buildings in terms of the energy consumption (Brown *et al.* 2007). According to Brown *et al.* (2007), data centers consumed about 61 billion kWh in 2006, which is roughly 1.5% of total U.S. electricity consumption, and the energy demand in data centers has significantly increased over time (Brown *et al.* 2007; Geng 2014; Dayarathna *et al.* 2016). More than 50% of the total energy in data centers is consumed for information and communications technology (ICT) equipment, and cooling end use is the second highest category in the total energy consumption, ranging from approximately 30% to 50% (Brown *et al.* 2007; Covas *et al.* 2013; Geng 2014; Dayarathna *et al.* 2016; Rong *et al.* 2016; Shehabi *et al.* 2016). Power usage effectiveness (PUE) describes the ratio of total power used in the data center to the power used by ICT equipment (Brady *et al.* 2013; Horner and Azevedo 2016). The U.S. Department of Energy national average PUE for data centers is 1.75 (i.e., 57.1% of total data center energy was used for ICT equipment), and the PUE evolved from 1.65 in 2009 to 1.47 in 2011 (Lucido 2011), which means the energy efficiency in data centers has increased.

As the cooling equipment in data centers broadly ranges from central cooling plants to evaporative cooling systems depending on various factors, such as the facility size (Geng 2014), it is difficult to estimate the data center cooling demand using the energy consumption for cooling end use (i.e., uncertainties in the COP in particular). For analyzing the data center cooling demand, it is assumed that operating ICT equipment generates heat that needs to be removed. Hence, this study assumed that the electricity used for ICT equipment is equivalent to the cooling demand:

$$\text{Electricity Used for ICT Equipment} = \text{Heat Generated from Equipment Operation} = \text{Cooling Demand} \qquad (2)$$

Commissioned power is power to operate and/or bring the facility into working condition as intended. The commissioned power for data centers in the United States was collected using a commercial platform (datacenterHawk, LLC). The platform provides the commissioned power and space and physical address for colocation (private companies for leasing) and enterprise (for own uses) data centers, as well as hyperscale data centers built by a hyperscale company or designed specifically to meet the needs of a hyperscale company including Amazon, Facebook, Google, Microsoft, Oracle, and Apple. For the cooling demand analysis, the collected commissioned power was incorporated with a PUE of 1.5 (i.e., 66.67% of total data center energy consumption was used for ICT equipment) and 80% power factor, which is a ratio of useful power to total power. Then, all the estimated cooling demand in the same county was combined to represent the total data center cooling demand at the county resolution.

## 3. RESULTS

Total low-temperature heating and cooling demand in the sectors considered in this study were 9.96 EJ and 4.43 EJ, respectively (Figure 2). The residential sector had the highest heating and cooling demand among the four end-use sectors. Particularly, most of the residential heating and cooling demand was for space heating (64.9%) and air conditioning (77.7%). Residential heating demand in other end-use categories was relatively low: water heating = 27.2%, cooking = 3%, microwave = 0.7%, clothes dryer = 3.7%, hot tub heater = 0.3%, and swimming pool heater = 0.2%. Residential cooling demand in other categories were refrigeration = 19.3% and freezer = 3%. In the commercial sector, the space heating end-use category also showed the highest thermal demand (space heating = 63.2%, water heating = 18.2%, cooking = 18.6%), while the commercial cooling and refrigeration demand were similar (cooling = 49.4%, refrigeration = 50.6%).

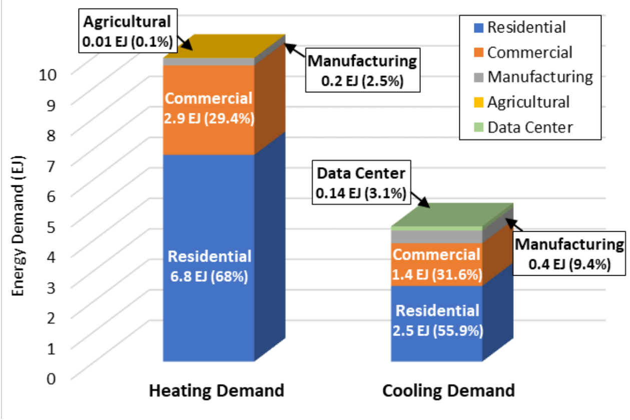


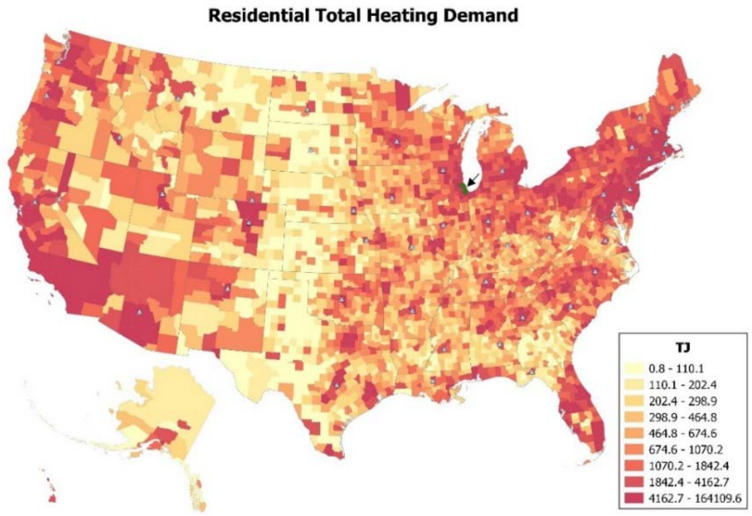
**Figure 2: U.S. low-temperature heating and cooling demand in the end-use sectors/categories considered in this study**

The total low-temperature heating and cooling estimated in our study was 14.39 EJ. This is lower than the total low-temperature thermal demand in 2008 estimated by Fox *et al.* (2011) at 17 EJ. A potential reason is overall changes in U.S. primary energy consumption. The EIA reports that the energy consumption continually increased from the early 1980s to 2000 and has then fluctuated (EIA 2022).

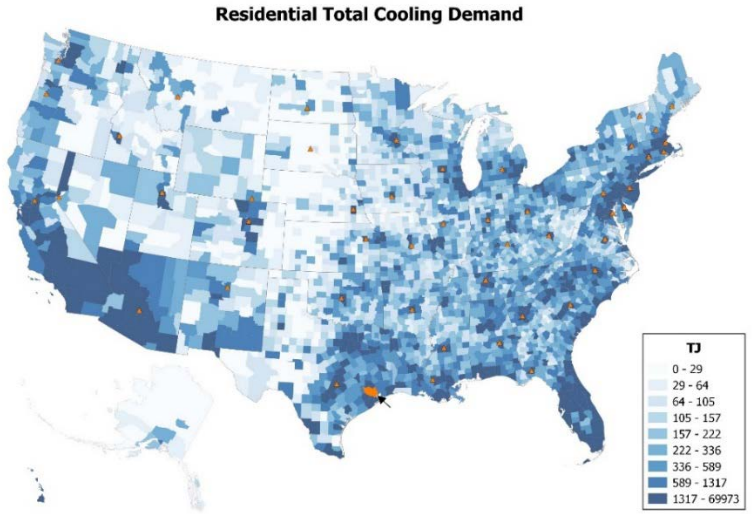
While the EIA's Annual Energy Outlook 2022 (Reference case for 2021) reported that total energy consumption in the industrial sector (including manufacturing, agriculture, mining, and construction sectors) is higher than those in residential and commercial sectors (EIA 2022), the low-temperature thermal and cooling demand calculated for the manufacturing sector in our study was significantly lower. In our study, the total low-temperature heating demand in the manufacturing sector (0.24 EJ) was lower than the total manufacturing cooling demand (0.42 EJ). The reason for the low manufacturing heating demand in our study was that we excluded various manufacturing subsectors, as their reported application temperature was higher than 150°C (Brown *et al*. 1985; Fox *et al*. 2011). The MECS also analyzed that manufacturers' capability to switch fuels (among the most commonly substitutable fuels) decreased from 24% in 1994 to 10% in 2014 (MECS 2018).

### 3.1 Residential Sector

Figure 3 shows the residential heating and cooling demand by U.S. county. Blue and orange triangles represent state capitals in heating and cooling maps, respectively. Cook County, Illinois, had the highest residential space heating demand, which takes the highest portion in the entire heating demand in the residential sector and corresponding total heating demand as highlighted in Figure 3(a). New York County, New York, had the highest heating demand density (i.e., total heating demand divided by the county land area) as a result of the relatively smaller county land area. The demand density maps are available on the Geothermal Data Repository (https://gdr.openei.org). Although Los Angeles County was classified as hot-dry climate where lower heating demand may be expected, it had the highest energy consumption for six heating end-use categories (i.e., all except space heating end use—water heating, cooking, microwave, clothes dryer, hot tub heater, and swimming pool heater), mainly due to its very high number of housing units. As highlighted in Figure 1(a), Los Angeles County had the highest number of housing units (3,420,628) and was remarkably higher than the second highest county, Cook County, Illinois (2,086,940). Overall, the heating demand was significantly affected by both the number of housing units and climate zone designations.



(a)



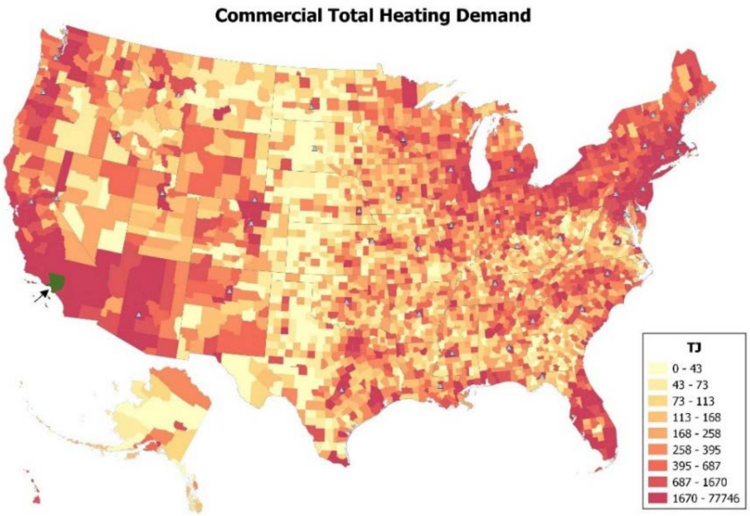
(b)

**Figure 3: Residential (a) heating and (b) cooling demand by U.S. county. The county where heating and cooling demand is highest is highlighted with green or orange background and black arrow.**

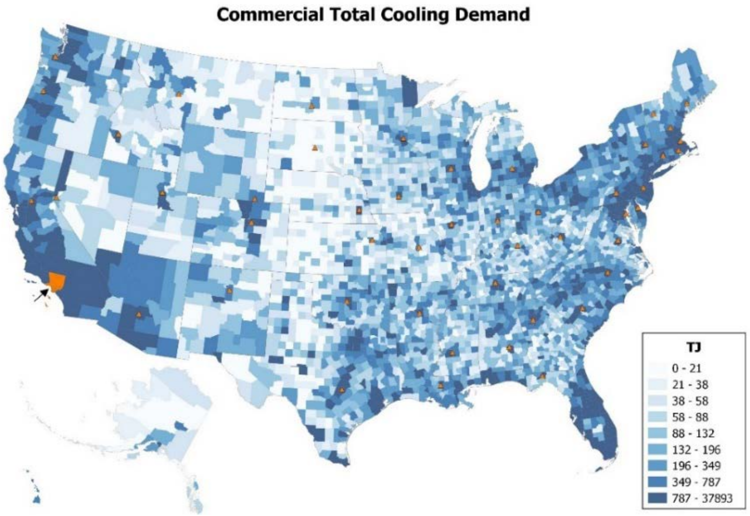
The highest residential total cooling demand occurred in Harris County, Texas, as highlighted in Figure 3(b). Harris County has the third highest number of housing units (1,692,730) in the United States, and the climate designation is classified as hot-humid. The highest cooling demand for refrigerators and freezers was observed in Los Angeles County and Cook County, respectively.

### 3.2 Commercial Sector

Figure 4 presents the total heating demand in the commercial sector. Similar to heating demand in the residential sector, Cook County had the highest space heating, and Los Angeles County had the highest water heating, cooking, and total heating demand (Figure 4(a)). New York County showed the highest heating demand density in the commercial sector. The commercial cooling demand for space cooling was the highest in Harris County, Texas, at about 16,500 TJ. Los Angeles County represented the highest refrigerator and total cooling demand in the commercial sector (Figure 4(b)). Hence, Los Angeles County is a county with high heating and cooling demand in both the residential and commercial sectors. This finding suggest thermal demand in residential and commercial sectors are to some level correlated to each other, which will be studied with statistical analysis in future work.



(a)

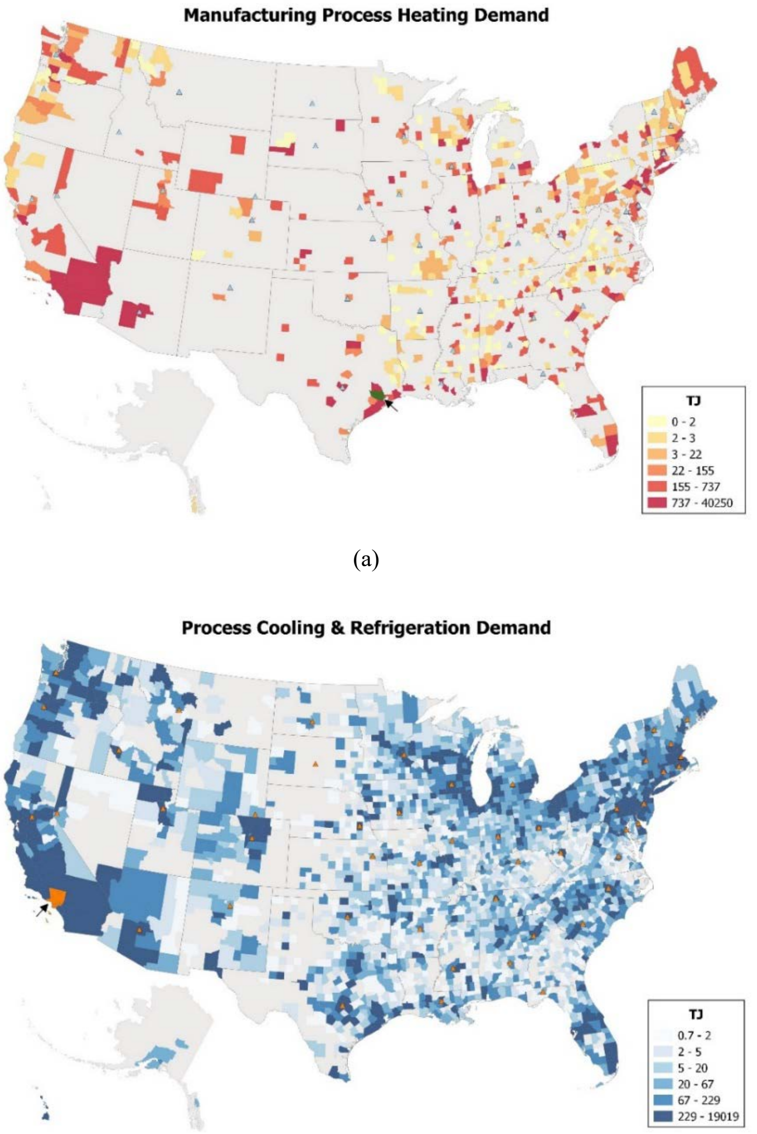


(b)

**Figure 4: Commercial (a) heating and (b) cooling demand by U.S. county. The county where heating and cooling demand is highest is highlighted with green or orange background and black arrow.**

### 3.3 Manufacturing Sector

The low-temperature heating and cooling demand in the manufacturing sector was mainly dependent on the number of facilities and their locations (Figure 5). For example, the heating demand map in Figure 5(a) includes several vacant counties, as these counties did not have low-temperature (i.e., <150°C) manufacturing industries in the EIA's MECS. Harris County, Texas, had the highest heating demand (40,250 TJ) from seven different manufacturing/industrial categories—particularly petrochemical manufacturing (25,673 TJ) and all other basic organic chemical manufacturing (13,756 TJ) categories. The high heating demand in these two manufacturing categories is aligned with the report from the 2018 MECS that four industries—chemical, petroleum and coal products, paper, and primary metals—account for most of manufacturing energy consumption. On the other hand, the highest heating demand density was represented in the city of Bristol, Virginia, due to the small land area, despite only one phosphatic fertilizer manufacturing facility (384 TJ).



(a)

(b)

**Figure 5: Manufacturing low-temperature (a) heating and (b) cooling demand by U.S. county. The county where heating and cooling demand is highest is highlighted with green or orange background and black arrow.**

The highest process cooling and refrigeration demand occurred in Los Angeles County, while the highest cooling demand density was in New York County. Los Angeles County included a wide range of manufacturing industries from 3114 – Fruit and Vegetable Preserving and Specialty Food to 339 – Miscellaneous (total number of manufacturing industries = 33). The category 3116 – Animal Slaughtering and Processing had the highest process cooling and refrigeration demand (3,288 TJ). New York County included 14 manufacturing categories, and the process cooling and refrigeration demand in each manufacturing category was similar (average = 79.6 TJ). Because of the small county land area, the manufacturing process cooling and refrigeration demand density was the highest in New York County despite the relatively small total cooling demand (1,115 TJ).

### 3.4 Agricultural Sector

The heating demand in the greenhouse, nursery, and floriculture category is dependent on the facility numbers and locations and the local climate zone designation (Figure 6). Although Alaska and Hawaii have many greenhouse farms (e.g., 1,138 greenhouse farms in Hawaii), these states were excluded from the analysis due to lack of expenditure data in the USDA expenditure survey. Miami-Dade County, Florida, had the highest heating demand in the agricultural sector for the greenhouse category (127 TJ), which is close to the second highest county—Clackamas County, Oregon (126 TJ). While the number of greenhouse farms in Clackamas County was 838 with an average farm size of 477 acres, the number of greenhouse farms in Miami-Dade County was 714 with an average farm size of 201 acres, implying a higher energy intensity. The third largest heating demand was observed in San Diego County, California, at 62 TJ, which is significantly lower than the first and second highest counties. Avery County, North Carolina, had the highest heating demand density, corresponding to the relatively small county land area.

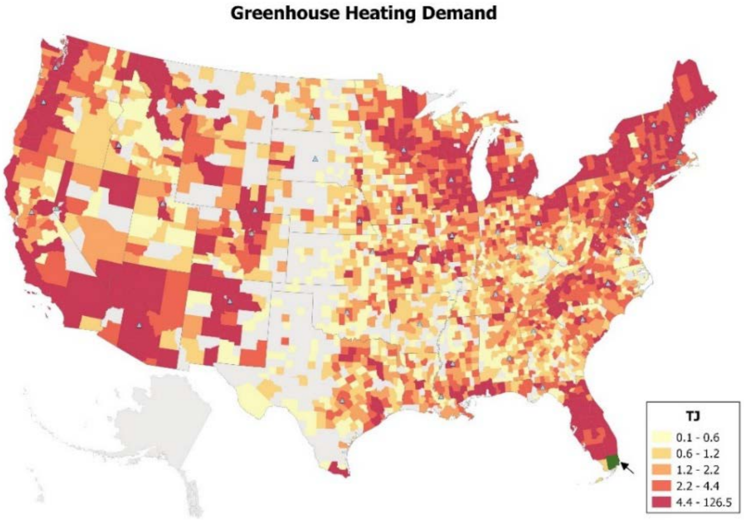


**Figure 6: Greenhouse heating demand by U.S. county. The county where heating demand is highest is highlighted with green background and black arrow.**

### 3.5 Data Centers

Figure 7(a) shows that the data center cooling demand was concentrated in specific regions. Numerous data centers (176) were in northern Virginia (i.e., near Washington, D.C.), and high concentrations were also found in northern California, Chicago, and Atlanta. The highest data center cooling demand was observed in Loudoun County, Virginia (31,571 TJ), and the second highest in Santa Clara County, California (10,086 TJ), implying high market potentials for the low-temperature geothermal resource. In addition to the colocation and enterprise data centers, the cooling demand in hyperscale data centers were analyzed. In the preliminary analysis, the total cooling demand in hyperscale data centers was 0.16 EJ, which is slightly higher than the total cooling demand in colocation and enterprise data centers (0.14 EJ).

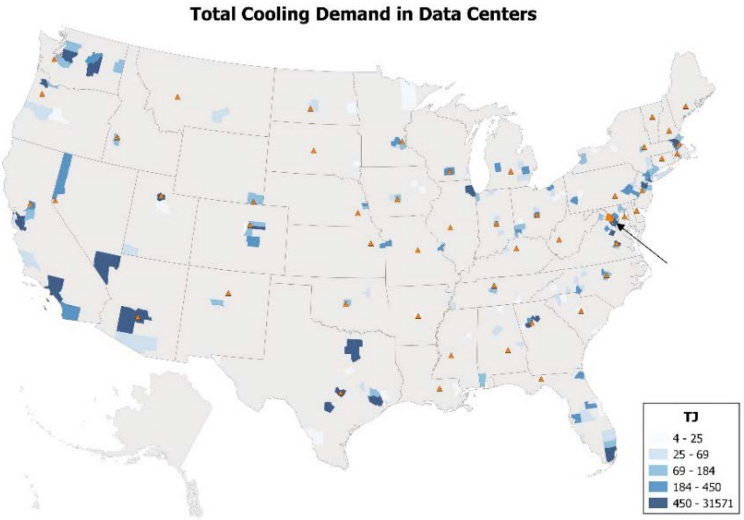


**Figure 7: Co-location and enterprise data center cooling demand by U.S. county. The county where cooling demand is highest is highlighted with orange background and black arrow.**

## CONCLUSION

U.S. low-temperature heating and cooling demand in four major end-use sectors and data centers were geospatially analyzed at the county level. Analysis was based on various sources, including energy consumption and expenditure data reported by the EIA; total numbers of housing units, manufacturing establishments, and greenhouse farms; and data center commissioned power. The EIA reported that U.S. total primary energy consumption in 2021 was 102.7 EJ and the total energy consumption by end-use sector (i.e., excluding electrical system losses) was 77.5 EJ. End-use energy consumptions in residential, commercial, and industrial sectors were 12.3 EJ, 9.6 EJ, and 27.3 EJ, respectively (EIA 2022). Total low-temperature thermal energy demand analyzed in this study was about 15 EJ with the residential sector having the highest heating and cooling demand and takes about 14.6 % of the U.S. total primary energy consumption. Thermal demand in the residential and commercial sectors was present in each county, while thermal demand in manufacturing and agricultural sectors and data centers was more geospatially concentrated in certain counties. This analysis highlights the large consumption of low-temperature thermal energy in the country, a potential market for low-temperature geothermal energy or other energy sources such as waste heat or solar thermal heat. This study will be extended with additional statistical and geospatial analyses for more in-depth characterization of the U.S. heating and cooling demand.

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