Quadracci Sustainable Engineering Laboratory (QSEL)

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How do we heat our homes in the US?

And what does it mean for greenhouse gas emissions?

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In this report, we look at the residential space heating landscape in the U.S. and provide quantitative estimates of the fuels used and associated greenhouse gas (GHG) emissions. When it comes to reducing greenhouse gas emissions, the focus tends to be on integrating more renewables into the electricity grid: Wind and solar farms, battery storage, smart grid and new utility structures. Turning to an individual home, actions like installing rooftop solar panels and how to implement efficiency and conservation come to mind. However, an individual home – whether a standalone house, one of a few units in a row house, or an apartment in a large multifamily building – and its heating system hardware are inextricably linked to larger energy infrastructure and delivery systems.

Hence emissions from buildings and actions needed to achieve deep emission reductions from them require an understanding of where we are today across the country (continental U.S. for now) in order to chart our path forward. It took us many decades to get to where we are. We still use buildings a century old even as we changed fuels and clamped on newer heating systems to old. This is why space heating is particularly challenging: The snapshot today reflects the diversity of fuels and housing stock, how these fuels are delivered to and used within our homes, and the diverse climate across the U.S. In this report, we illustrate the current status of space heating for residential building sector so that measures to reduce emissions can be understood as part of the broader energy decarbonization efforts. In a following report, we will look at specific pathways to deeper emission reductions in this sector.

Introduction

To keep our homes warm, we primarily burn a fossil fuel (natural gas, heating oil, propane) or use electricity (which is generated from some combination of fossil fuel and low-carbon resources). In 2018, residential buildings contributed 20% of all U.S. energy-related GHG emissions, including both on-site combustion of fossil fuels and emissions from electricity supply [1]. We estimate that more than half (57%) of residential GHG emissions are due to space heating, a scale that is not widely appreciated. (Note again that all computations presented in this report are for the continental U.S.) The emissions are caused by a combination of weather, heating fuel, the prevailing heating systems and regional electricity grid emissions rates. Hence the overall 57% figure does not capture how significantly the contribution of space heating varies across the U.S. Figure 1 shows the fraction of residential GHG emissions from space heating as computed for each census tract (Figure 1(a)) and as aggregated at the state level (Figure 1(b)). Observe that generally colder climates lead to higher fractions of emissions from space heating, but also that this does not explain all variability. (Appendix Table A5 contains the values shown in Figure 1(b).)

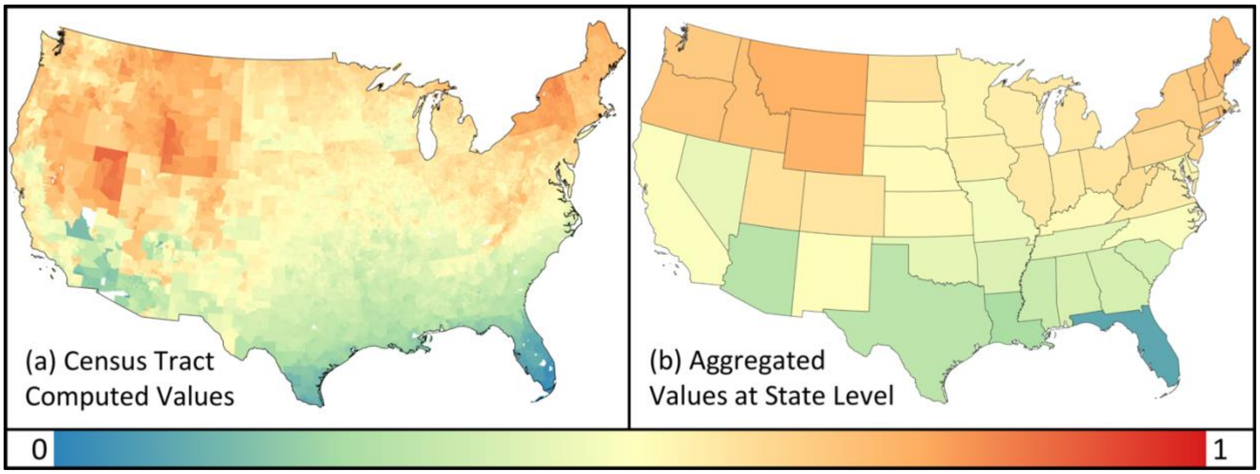


Figure 1 | Fraction of census tract residential greenhouse gas emissions from space heating (a) computed for each census tract and (b) aggregated at the state level. Note that color bar scale shown here and in the rest of the report is such that the values change linearly between the minimum value at the left and the maximum value at the right.

Aggregated across the U.S., we compute that annually over a billion tons of carbon dioxide equivalent (CO_2e) emissions were from *all* residential building energy usage. (CO_2 is the dominant greenhouse gas, so non-CO_2 GHG emissions are commonly converted using their global warming potential relative to that of CO_2 and added to the emissions of CO_2 to arrive at a single metric, CO_2e, where the “e” stands for “equivalent.”) Of these, more than half (588 million tons CO_2e, $MMtCO_2e$) are from space heating. Space heating emissions are either from on-site combustion of fossil fuels (about 58% or 339 $MMtCO_2e$) or from the electricity generated to supply buildings that use electric heating (remaining 42% or 250 $MMtCO_2e$). (These values are computed using 2008-2017 weather data and a model we described in [2].) On-site combustion is through the use of furnaces or boilers that heat air or water, which is then distributed within a building using fans or pumps to maintain warmth. It is important to recognize that while emissions from on-site combustion of one unit of a particular fuel are the same, those from electricity use change across the country and over time as the mix of generation sources used to produce that electricity changes. How exactly electricity is used to heat the home also matters enormously, and the dominant current systems are the least efficient approach of resistive heating (e.g. baseboards).

The numbers presented in the previous paragraph are large and, hence, difficult to visualize. Scaling down to 1000 square feet (sf) of residential space, the national average annual heating emissions would be 3.2 tCO_2e. Note that 1000 sf is not uncommon for an apartment unit; however, a single-family home in the U.S. is nearly 2500 sf on average and the emissions from heating such a home would be 8 tons of CO_2e annually. But again, national averages alone hide the complexity of the space heating emissions, and we can better understand the current situation by investigating the underlying drivers of space heating emissions and how they vary across the U.S.

We focus primarily here on emissions, but cost cannot be ignored: Space heating costs are a combination of upfront costs to purchase and install a system, the cost of maintaining those systems and, of course, the recurring cost of the fuel or electricity. In this report, we provide average values for the fuel cost components across the U.S. These costs are strongly dependent on the home's heating fuel and location, which shapes both the demand and the local cost of fuel and electricity. Even beyond these higher-level effects, every home is different in how it is built (e.g. thermal insulation levels), its heating system efficiency, and its occupants' use and comfort expectations. Readers should note that our estimates are a reflection of the current building stock and heating systems and are not an estimate of what's *possible* for a new, efficient home.

Drivers of Residential Space Heating Emissions

Space heating needs are highly temperature-dependent and the local climatology that drives temperatures also may affect how thermally efficient the local construction practices are. Further, the availability of heating fuels depends both on the supply chains within a region of the country and whether you are in an urban or rural setting. Homes themselves are also diverse in size, type of construction, insulation thickness and effectiveness, air leakage, heating equipment, and occupancy and how they are used. Rather than attempt to capture all of these effects – which is not possible at the scale of the U.S. given our limited knowledge of the full array of considerations – in this report, we investigate primary drivers of residential heating demands: (1) Climate, (2) heating fuel and (3) GHG emissions rate of electricity supply.

Climate

Cold winters are a primary driver of household heating needs and the resulting GHG emissions. A common measure used to capture local climate effects is "heating degree days," the number of degrees that a day's average temperature deviates below a reference temperature aggregated over one year or multiple years. The annual heating degree days with a typical reference temperature of 65°F (HDD65) are shown in Figure 2 at the census tract level, based on climate "normals" for 1981-2010 [3]. If all homes were identically built and used, then Figure 2 alone would provide an accurate relative measure of the heating demand across the country.

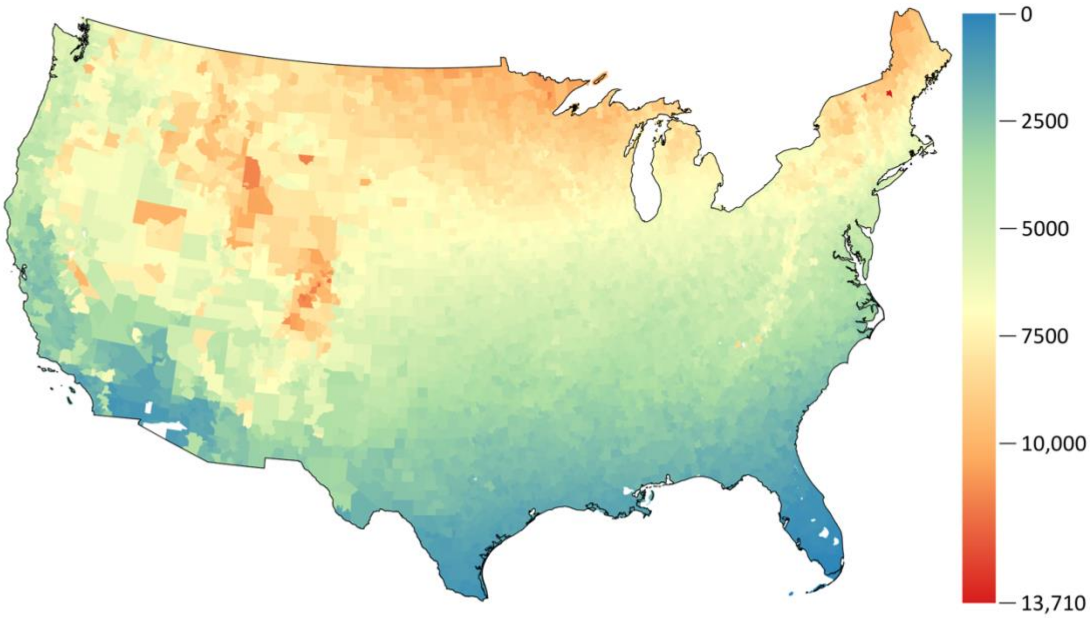
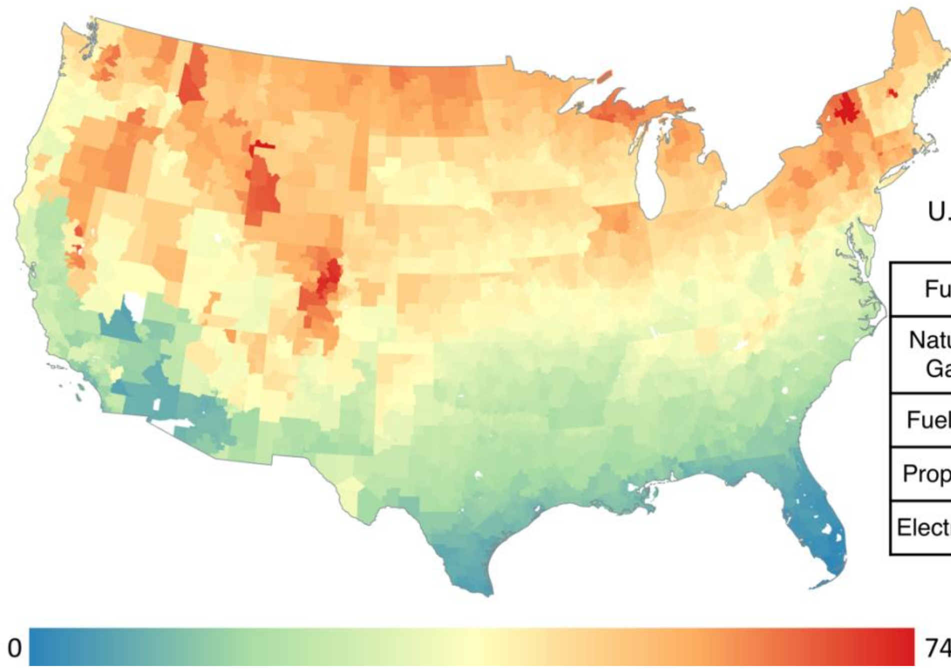


Figure 2 | Heating degree days with 65°F basis. 1981-2010 climate normals [2]. The maximum census tract HDD65 is 13,710; 0.1% of census tracts have HDD65 greater than 10,000.

But as noted before, actual space heating demand also depends on other factors such as the building stock, insulation, and efficiency of the systems in buildings themselves. Based on a novel model developed for a recent publication [2], we first computed the space heating energy required per 1000 sf at the census tract level, as shown in Figure 3. Note that information on building stock efficiency (as opposed to climate) is not available at census-tract level, and hence we are not unable to fully capture the intra-state diversity in Figure 3. (We have included the underlying model heating demand temperature-dependence coefficients, which were determined at the state level, in Appendix Table A2.) Figure 3 also includes a table of the range of fuel costs across the U.S. (2018 values per the U.S. Energy Information Administration) to reference for computing average energy costs. Note that Figure 3 shows the amount of heat delivered to the space and does not include efficiency losses in heating equipment. It is not uncommon for boilers and furnaces to only deliver 85% to 90% of the heat possible from burning the fuel purchased even though newer technologies can push this figure to 95%. Based on U.S. average values, one can deduce that heating with fuel oil or propane in 2018 cost approximately 2-2.5 times as much as heating with natural gas; because electric resistance does not have the same efficiency losses as combustion fuels, its heating costs would be expected to be approximately 3 times those of natural gas heating. (There are other electric heating technologies discussed later in this report.) Note that these energy costs vary considerable across the country and readers should refer to Appendix Tables A1 and A2 for location-specific values.

Let us look at a couple brief examples to illustrate how one could use the values presented in this report for average heating needs and fuel prices, depending on where you are in the U.S. We estimate the median U.S. home needs an average annual 35 MMBtu heat per 1000 sf; with efficiency losses, this would likely require 40 MMBtu natural gas (or 400 therms on a utility bill). At the average U.S. natural gas price of $10/MMBtu, heating this space would cost approximately $400 per year. Now, let us consider New York City, a place colder than the median U.S. and with higher fuel prices. Here, we estimate 50 MMBtu of heat is needed for 1000 sf. If we again consider natural gas heating with efficiency losses that necessitate more than 55 MMBtu of fuel, heating an average 1000 sf space would cost about $900 per year if the delivered natural gas price is the $16/MMBtu. Note that these prices are location-specific and could change, as we see even during the writing of this in April 2020 with crude oil prices collapsing.



U.S. Residential Energy Prices ($/MMBtu)

Fuel	Min	Max	Avg
Natural Gas	6.86	20.60	10.14
Fuel Oil	17.85	29.42	23.56
Propane	14.54	52.31	26.47
Electricity	23.77	49.59	36.63

Figure 3 | Computed annual residential space heating energy per 1000 sf floor area at census tract level. As computed per [2]; see Appendix Figure A1 for underlying space heating energy temperature dependence. Inset table presents the range of 2018 state-level average fuel prices (natural gas [4], fuel oil and propane [5]), eGRID region electricity prices [6], and average U.S. prices for each fuel source for residential customers. Note: Heating energy values are for heating delivered to the space and do not account for the efficiency of heating equipment.

Heating Fuels

The ability of a homeowner – and certainly a renter – to choose what heating fuel to use can be limited. As seen in Figure 3, delivered prices of natural gas are generally lower than those of fuel oil and propane. But while fuel oil and propane can be stored in tanks on customer premises, natural gas distribution relies on pipeline infrastructure that does not extend everywhere. Figure 4 shows the distribution of household heating fuels (by energy provided) across the contiguous U.S. at the census tract level. In addition to natural gas, fuel oil and propane, electric heating is also widespread in the U.S. as shown in Figure 4. How electric heating is used and the emissions from its use are discussed later. (The underlying aggregate residential areas were only available for 2010 [7] and are shown for each state in Appendix Table A3.)

The dominant heating fuel, natural gas is shown as the areas that "light up" in Figure 4. The need for distribution infrastructure makes it particularly common in densely populated areas- also making it difficult to visualize in Figure 4. We estimate natural gas to heat 49% of residential floor area and provide 53% of all residential space heating energy (due to its being more prevalent in colder climates), while contributing 44% of all space heating-related GHG emissions. Note that while emissions from combustion are 53 $kgCO_2e$/MMBtu [8], when one includes an estimated additional 13 $kgCO_2e$/MMBtu due to methane leakage [9], one arrives at GHG emissions of 66 $kgCO_2e$/MMBtu. Methane leakage rates are small, but since it is a potent greenhouse gas uncertainties this leakage can make a large difference in overall GHG emissions.

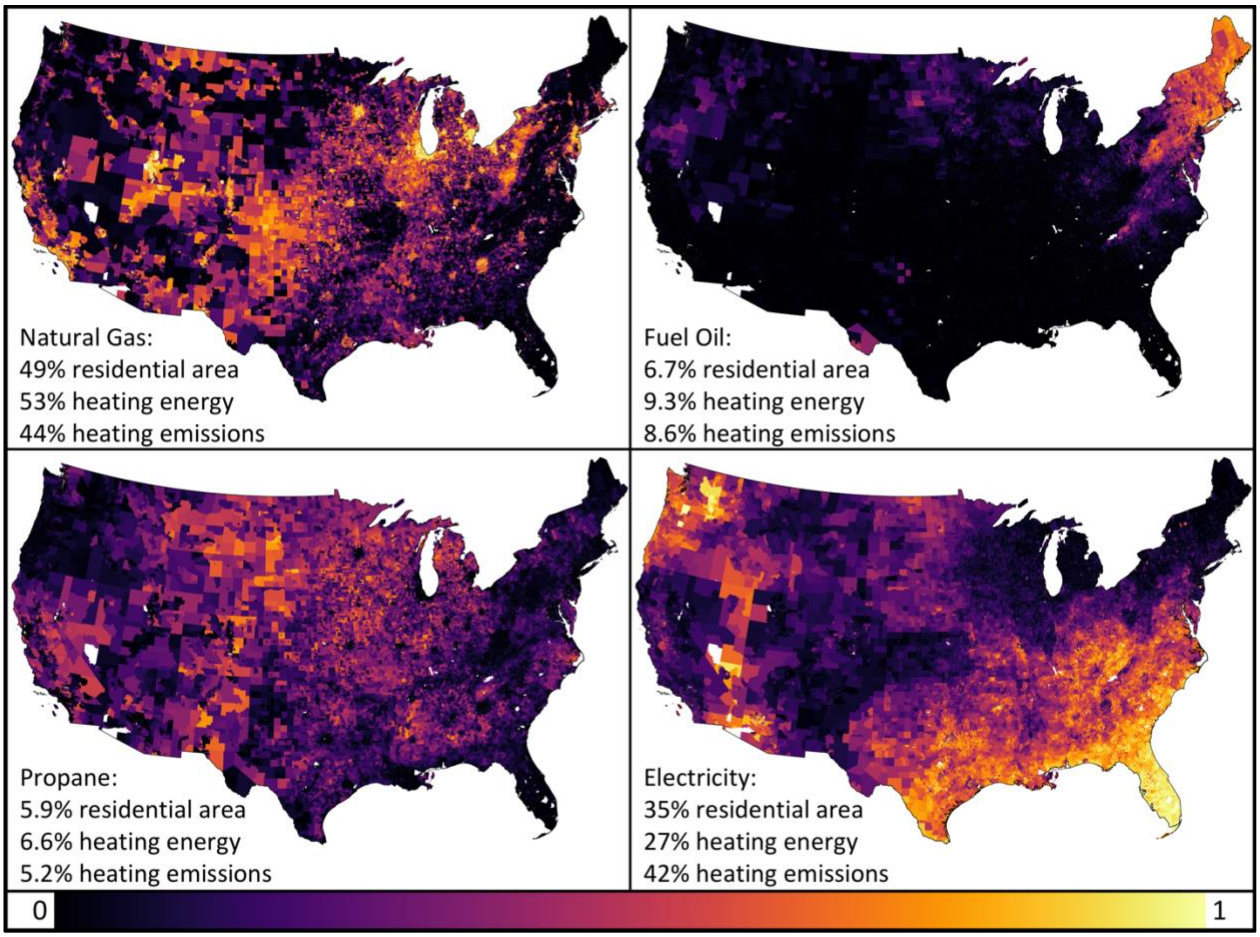


Figure 4 | Fraction of household heating provided by each fuel at census tract level [2]

Figure 4 also shows the fraction of households using fuel oil and propane. These fuels are predominantly used in more rural areas, while some fuel oil continues to be used in legacy building stock in older cities. Heavier grades of fuel oil are responsible for high particulate matter and hence some cities are restricting their use. When it comes to GHG emissions however, when associating impacts of methane leakage with natural gas, the difference in GHG emissions rates between fuel oil (74 $kgCO_2e$/MMBtu), propane (63 $kgCO_2e$/MMBtu) and natural gas (66 $kgCO_2e$/MMBtu) are fairly small.

Fuel oil tends to be concentrated in colder areas, almost exclusively in the Northeast: 80% of all fuel oil heating is in the states from Pennsylvania and New Jersey north through New England. Because of this geographic concentration in cold climates, we estimate fuel oil to provide 9.3% of all U.S. residential space heating energy despite heating only 6.7% of residential floor area, and to contribute 8.6% of all heating emissions. The corresponding figures for propane are 6.6% of energy, 5.9% of area and 5.2% of emissions. Propane heating is found in rural areas throughout much of the U.S.

Because natural gas is more prevalent in denser areas, and fuel oil and propane are more common in rural areas, the computations shown at the census tract level (Figure 4) can mask the very significant reliance on natural gas for heating. Figure 5 makes it easier to visualize the fraction of heating in each state provided by each of the same fuels. Natural gas provides more than 50% of space heating in 20 states and the District of Columbia; it is also the most common heating source in another 13 states. (Appendix Tables A3 shows state-level residential floor area heated by each fuel; Appendix Table A4 shows computed state-level residential heating energy provided by each fuel, the values shown in Figure 5; and Appendix Table A5 shows computed state-level residential heating emissions contributed by each fuel.)

Fuel oil is the dominant fuel in Connecticut, New Hampshire, Vermont and, especially, Maine. Beyond the mid-Atlantic and Northeast states, North Dakota is the only state with more than 5% of heating from fuel oil. Electricity is the dominant source of heating in 15 states, including all of the southeast plus Washington, Oregon and Arizona. In these 15 states, natural gas is also a significant source of heating (more than 25%) with the exception of Florida. Propane is more evenly distributed across the U.S., though it is much more common in colder rural states. (Note that these are general comments on the states' heating energy fuel composition; many factors, including socioeconomic ones, drive what fuel is used in particular buildings where multiple fuels are available.)

Electric heating is widespread in the U.S and heats 35% of residential floor area. Prevalence of electric heating has generally been associated with factors such as lower local electricity prices, shorter heating seasons and smaller heating loads, smaller living spaces, and whether a residence is owner-occupied or a rental unit. Since it tends to be used in areas with lower heating loads, it provides only 27% of heating energy. However, aside from the hydropower-rich Pacific Northwest, electric heating tends to be used in areas where electricity is largely generated by coal (and fossil fuels more broadly). The inefficiency in conversion of coal (itself a high GHG emitting fuel at 90 to 100 $kgCO_2e$/MMBtu) or natural gas to electricity can more than double the emissions per MMBtu of electricity. Hence a coal- and gas-based grid can lead to emissions as high as 200 $kgCO_2e$/MMBtu (note this is now a MMBtu of electricity) when compared to 63 to 74 $kgCO_2e$/MMBtu for the other heating fuels burned within a building system. The actual emissions from electricity vary with the sources that are used. Moreover, how electricity is used to produce heat also changes the emission picture dramatically. For the current means of electricity generation and use, we compute that electric heat contributes 42% of all residential heating emissions while providing only 27% of the heating energy. Further, despite being the leading source of heating *energy* in 15 states, electricity is the leading source of heating *emissions* in 25 states.

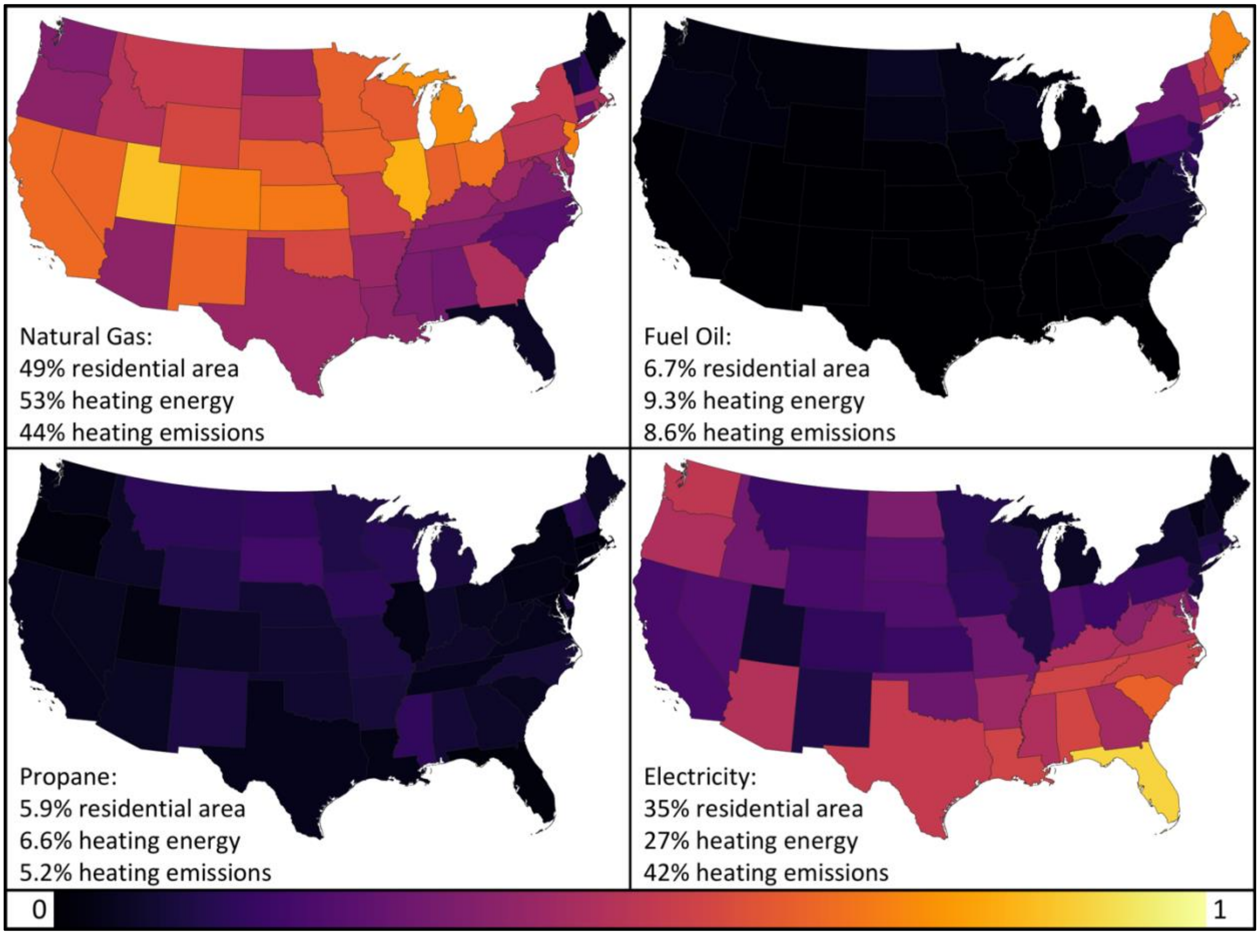


Figure 5 | Fraction of aggregate state space heating energy provided by each fuel

Electric resistance heat (commonly baseboard electric systems, essentially a room-by-room installation of an electric heating element) is the least expensive system to install, but with the most expensive energy costs almost everywhere in the U.S. Electric resistance heat works on the same principle as the perhaps more familiar portable electric space heater. While electric resistance heating is technically nearly 100% efficient, such systems are costly to operate and produce high GHG emissions because of the energy sources used to produce that electricity (see below). An alternative that can significantly reduce energy demand and hence recurrent costs is an electric heat pump (EHP). An EHP, for the unfamiliar reader, is the same technology as in most air conditioning systems; a reversing valve allows such systems to provide warm air to a living space directly or through a central fan-duct system[1].

[1] Heat pumps that heat water are also available. These are currently more common in Europe. In this report, we focus on air-to-air or air-source heat pumps (ASHPs). Another alternative is a ground-source

Some EHPs are capable of operating with an “efficiency” that exceeds 500%; this efficiency metric is called the “coefficient of performance” (COP) of the heat pump, the amount of heating delivered per unit electricity consumed. While such high performance is possible at more moderate outside temperatures, both COP and capacity degrade as temperatures drop, and electric resistance heating is eventually required. Given these temperature effects and higher upfront costs, EHPs were not widely used in much of the U.S. Even when used, much of that use was in moderate climates and user experience was unfavorable in colder climates. They are becoming more common, now representing 27% of all electricity-based heating [10]. This is largely due to continuous improvement of EHP technology and the emergence of "cold climate heat pumps." For example, older EHP models may have operated as electric resistance below 32°F, but many modern EHPs can maintain a COP of 300% at that temperature, even reaching 200% at 0°F. With advances in technology, they have become more sophisticated and they do require higher upfront investment, skilled installation and maintenance. Moreover, the GHG emissions from EHP heating are highly dependent on outside air temperatures and the source of its electricity supply.

Electricity Emissions Rate

The energy resources used to generate electricity can vary considerably depending on where you are located in the U.S. The Environmental Protection Agency (EPA) eGRID subregions (see Appendix Figure A1 for subregion bounds and abbreviations) are useful for evaluating emissions from electricity in different parts of the U.S. Some areas of the U.S. are still highly reliant on coal (exceeding 70% in parts of the Midwest), whereas others have eliminated its use (New York State). Some areas have large amounts of renewable energy (58% in the hydropower-rich Northwest Power Pool and 25% non-hydro renewables in California) or total amounts of low-carbon electricity (70% in upstate New York with both hydropower and nuclear power), while others remain nearly entirely dependent on fossil fuels (more than 90% in parts of the upper Midwest and 99% in Long Island, NY). As a result, electricity emissions rates can vary significantly across the U.S. (Figure 6 and Appendix Table A1).[2]

The operation of individual generators and the resulting time-dependent grid emissions rates require complex models that are beyond the scope of the current report. However, it is useful to understand the difference between baseload emissions rates and non-baseload emissions rates, particularly in areas where there are significant contributions from nuclear power and hydropower (almost exclusively considered baseload generation) given the low-emissions of these technologies.

heat pump, which has improved performance at low temperatures, but with significantly higher cost, complexity and site-specific feasibility; a GSHP could certainly be the best choice for some homes.

[2] The picture is actually more complex: on the one hand, loads closer to low-carbon resources could be thought of as having lower emissions rates than those farther away; however, large hydropower, nuclear plants and wind/solar facilities that reduce this local grid emissions rate might only make economic sense if there are (perhaps distant) dense loads to serve. On the other hand, the electricity system is a massive interconnected machine and the source of an individual electron cannot necessarily be tracked. De Chalendar et al have quantified the differences between generation- and consumption-related emissions [16]. For straightforwardness and to make use of readily available data, we use the eGRID values [11].

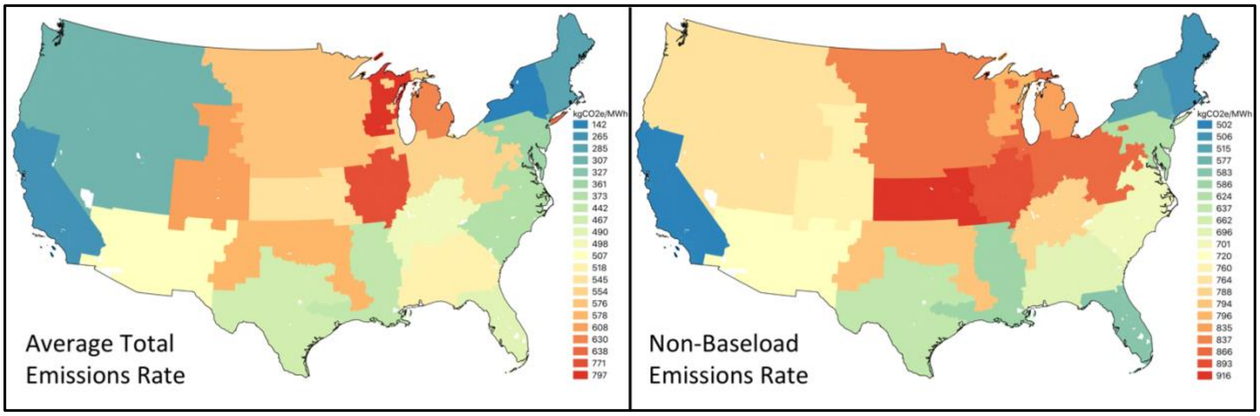


Figure 6 | Total and non-baseload grid subregion greenhouse gas emissions rates. Values as reported by EPA eGRID 2018 [11] and adjusted to reflect methane leakage in natural gas production, processing and transportation [9] and the most recent IPCC-published global warming potential of methane [12]. Note that the values shown are in kgCO2/MWh and range from 142 to 797 in the left panel, whereas on the right panel they range from 502 to 916.

In this report, we consider electricity for heating to be non-baseload; where current heating electricity exceeds regional non-baseload electricity generation, the balance is assumed to be from baseload generation. One further note: Not only is the current state of the grid highly regional, but so is the evolution of the grid and the incorporation of more low-carbon electricity – the vast majority of which is likely to be wind and solar power – to reduce GHG emissions and meet policy goals. We leave this rich topic for separate reports.

Greenhouse Gas Emissions from Home Heating Systems

Here we compile results from emissions computed for six different heating sources: Natural gas, fuel oil, propane, electric resistance and two EHP technologies. Heating efficiencies of 95% for natural gas and 85% for fuel oil are assumed based on the U.S. Environmental Protection Agency's EnergyStar ratings [13]; propane heating efficiency is assumed to be the same as natural gas. The two EHPs considered here are both ASHPs and represent the median performance and 90th percentile performance ("state-of-the-art") "cold climate" EHPs in a regularly updated database [14]. Combining these performance metrics of heating technologies and the heating demands (Figure 3), we computed the expected residential space heating GHG emissions of each of these heating sources for each census tract; Figure 7 shows these computations in tons of CO_2e per 1000 sf per year.

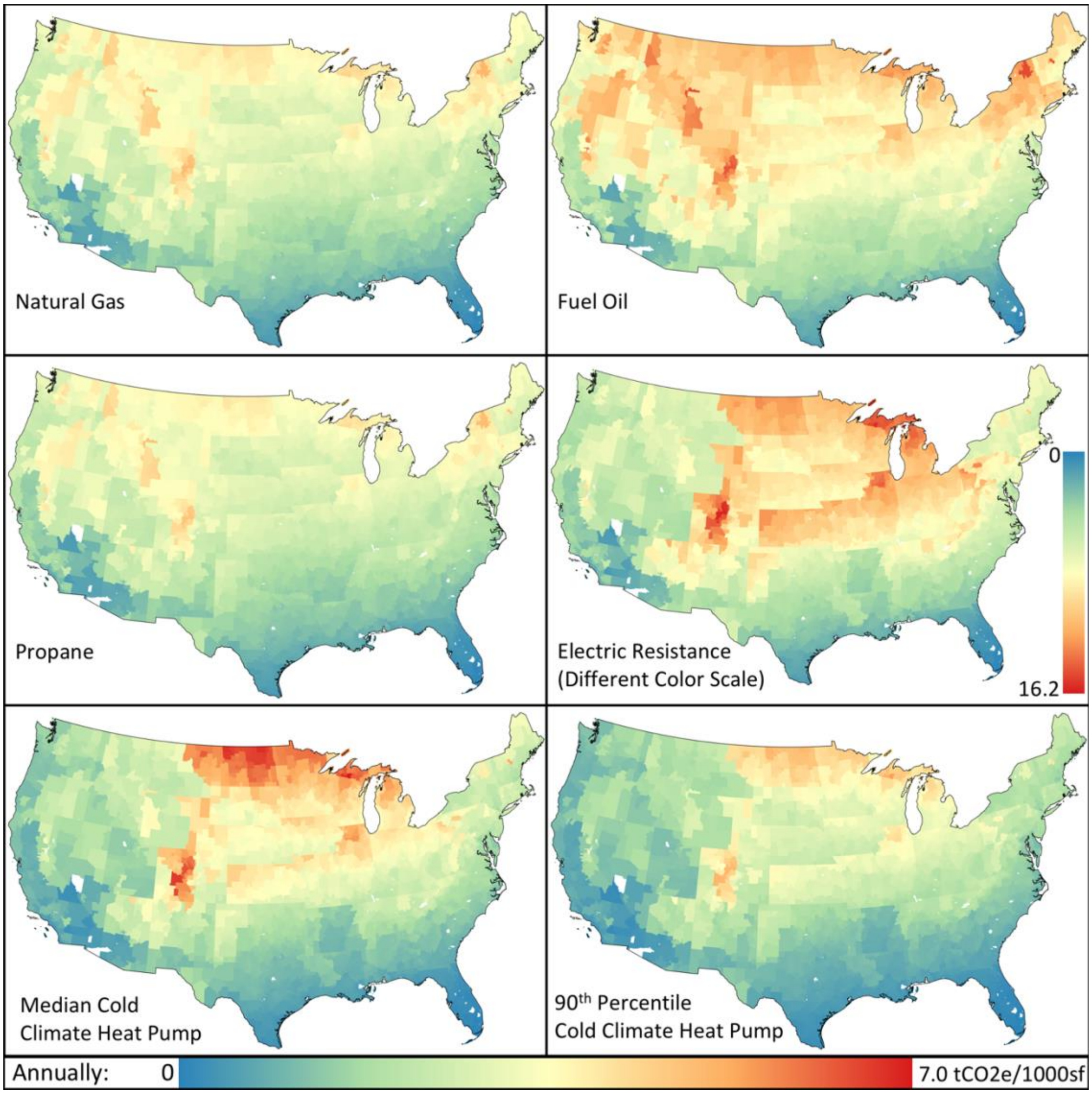


Figure 7 | Computed annual residential space heating greenhouse gas emissions per 1000 sf for different fuels and electric heating equipment. Note: A different color scale is used for electric resistance and a separate inset color scale is shows that scale.

The most straightforward interpretation of the figures is that GHG emissions from using fuel oil, propane or natural gas are not very different, with approximately 21% reduction from a switch from fuel oil to the other fossil fuels. Overall effects of such a shift to natural gas would likely be modest, particularly in the context in which deep emissions reductions are needed and current fuel oil use is fairly limited (less than 7% of nationwide heating energy). A more complex situation is observed for electric resistance heating. (Note that a separate inset color scale is used for electric resistance than all other options.) Here we can see that the combination of cold climates (Figure 2) and high emissions rates (Figure 6) results in very high home heating emissions in much of the upper Midwest and Rocky Mountain areas.

While the location-specific electricity grid emissions rates complicate the landscape of electricity based space heating, there is one clear takeaway: Computed GHG emissions from electric resistance heating are higher than natural gas heating in all census tracts. This is largely because even where low-carbon resources are used for electricity generation, non-baseload electricity is largely dependent on fossil fuels throughout the U.S. Therefore, the *marginal* emissions rate associated with electric heating is almost always higher than the overall emissions rate.

The higher COPs of EHPs do lead to lower emissions when compared to electric resistance heating, sometimes very significantly so. We compare EHP emissions to those from natural gas heating: With current median cold climate EHPs, emissions are lower than natural gas heating in 67% of census tracts; with current 90th percentile state-of-the-art EHPs, computed emissions are lower than natural gas heating in 91% of the census tracts. Because these census tracts tend to be in warmer locations, these census tracts represent 59% and 87% of total residential space heating, respectively. Another consideration is, of course, cost (here considering only fuel and electricity costs, not equipment costs). Natural gas is generally the least expensive heating fuel, often even when accounting for an EHP's COP. Census tracts where we compute both emissions reductions and cost reductions with median cold climate EHPs represent 27% of all heating. With the state-of-the-art EHPs, this figure jumps to 57%. This suggests that heating electrification can already be a cost-effective means of reducing GHG emissions in some locations even with current levels of renewable energy and EHP technology.

Discussion

The computations presented in this report provide an understanding of the current contribution of space heating to residential building GHG emissions. The top line takeaways are clear: (1) Fossil fuel-based heating has lower emissions and energy costs than electric resistance heating, (2) among fossil fuels natural gas is both lower emitting than fuel oil and lower cost than fuel oil or propane, and (3) state-of-the-art electric heat pumps (EHPs) are already the lowest emission and lowest energy cost heating option in more than half of the country, even with current electricity grid emissions (i.e. without additional renewable energy) and prices.

We note again here that we have not considered the capital costs or maintenance costs of any system whether new or replaced, nor have we considered the costs associated with changing any distribution or delivery modalities. In this report, we discuss the several prominent approaches in current use and their associated roles in current emissions and their potential for reducing emissions.

The findings here are not necessarily novel, but based in new computations using recently published methodological advances [2], they do help better understand a context in which deep emissions reductions are needed to the tune of 80% and approaching 100% to mitigate the effects of climate change. This will frame the quantitative analysis of pathways to deep decarbonization of residential space heating that we will investigate in a later report. There are multiple options for this pathway, such as switching from fuel oil to natural gas (and extending gas infrastructure to where it does not yet reach), replacing electric resistance heating with EHPs, and in some prioritized fashion switching from fossil fuels (fuel oil, propane and natural gas) to EHPs. Another option is maintaining fossil fuel equipment in dual source systems in some settings during a transition. These choices come with their own costs to the consumer, potential changes to distribution networks and aggregated societal impact on emissions.

As a flavor of those discussions, consider a switch of fuel oil or propane to natural gas, which has already been under way. Natural gas is frequently proposed as a "bridge fuel" towards an energy system that would eventually no longer rely on fossil fuels, but this often misses the GHG effects of methane leakage during production, transportation and distribution. We estimate that emissions reductions of a shift to natural gas could be significant for current fuel oil users. This may not be an option where oil and propane might be the only fuel choices available. Extending natural gas infrastructure to less dense and rural areas could be extremely costly, so today's low prices may not capture the prices these areas would see. Deploying costly new gas infrastructure only to be abandoned – if it is truly a bridge fuel – could also saddle the users directly or indirectly with high costs. The question may also be largely moot: Because of the methane leakage effects on natural gas emissions and the relatively small residential floor area heated by fuel oil (less than 7%), we compute overall space heating emissions reductions to be only 2% even if all fuel oil homes switched to natural gas

Even with the advent of EHPs, this report highlights continued significant use of electric resistance heat especially in geographies where there is relatively low heating demand (Southeast) or inexpensive low-emission electricity (Northwest). This locational consideration is important for a shift to EHPs. We estimate that if all homes that currently use electric heating (which includes some legacy EHPs) were to shift to state-of-the-art EHP technologies, then the space heating emissions across the electric heating group could be reduced by 70%. The overall residential space heating emissions reduction would be 30% with the current electricity grid. This is certainly significant, in fact more significant than is commonly understood in the context of reducing building-related GHG emissions. However, the much larger emissions reductions needed to mitigate the oncoming effects of climate change motivate identifying other shifts that can occur at scale both within buildings and in broader energy systems, as well as the integrated effects of parallel building- and infrastructure-scale evolutions. We will investigate how this may be achieved, quantify its impact and assess approaches to *transition* away from the current system in a subsequent report.

Additional Resources, Data Sets and Acknowledgements

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[15] Oak Ridge National Laboratory (ORNL), Los Alamos National Laboratory (LANL), Idaho National Laboratory (INL), National Geospatial-Intelligence Agency (NGA) Homeland Security Infrastructure Program (HSIP) Team. [Dataset] North American Electric Reliability Corporation (NERC) Regions and Subregions Shape Files 2019.
[16] De Chalendar JA, Taggart J, Benson SM. Tracking emissions in the US electricity system. Proc Natl Acad Sci 2019;116:25497–502. doi:10.1073/pnas.1912950116.

Appendix

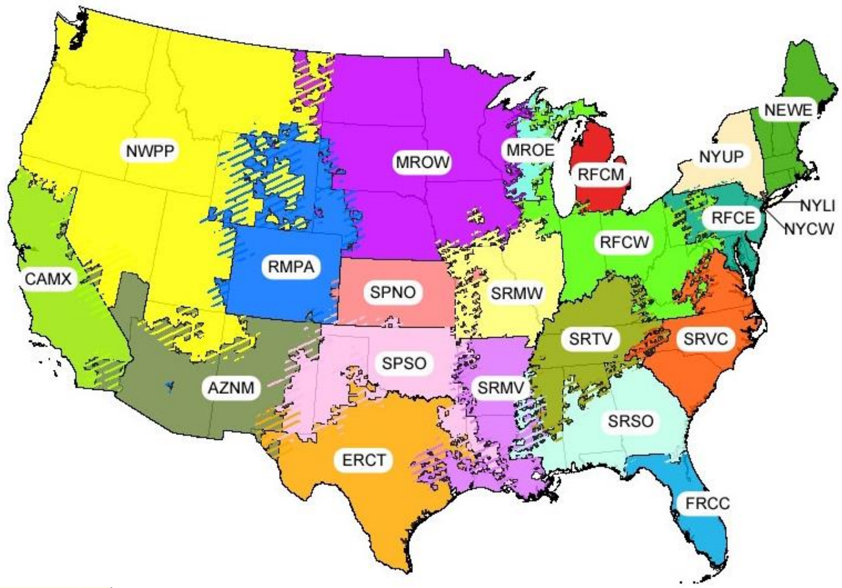

Figure A1 | U.S. Environmental Protection Agency eGRID subregions [11] Note: The boundaries of many subregions can overlap with others. Here we use the boundaries defined by publicly available shape files [15].

Table A1 | Relevant eGRID Subregion-Level Reference Values

Subregion	Grid Emissions Rates (kg/MWh)[1]	Grid Emissions Rates (kg/MWh)[1]	Average 2018 Electricity Price [6]	
	Total	Total	$/kWh	$/MMBtu
AZNM	506.9	506.9	0.1243	36.43
CAMX	265.5	265.5	0.1874	54.92
ERCT	467.3	467.3	0.0984	28.84
FRCC	490.1	490.1	0.1065	31.21
MROE	797.4	797.4	0.1339	39.24
MROW	575.8	575.8	0.1126	33.00
NEWE	284.6	284.6	0.1864	54.63
NWPP	306.8	306.8	0.0992	29.07
NYCW	326.7	326.7	0.2461	72.12
NYLI	637.5	637.5	0.2180	63.89
NYUP	142.0	142.0	0.1239	36.31
RFCE	361.4	361.4	0.1374	40.27
RFCM	630.4	630.4	0.1498	43.90
RFCW	554.1	554.1	0.1321	38.71
RMPA	607.5	607.5	0.1339	39.24
SPNO	545.3	545.3	0.1419	41.59
SPSO	578.3	578.3	0.1013	29.69
SRMV	441.9	441.9	0.1013	29.69
SRMW	771.0	771.0	0.1268	37.16
SRSO	518.1	518.1	0.1225	35.90
SRTV	497.6	497.6	0.1007	29.51
SRVC	373.4	373.4	0.1136	33.29
US	465.3	465.3	0.1250	36.63

[1]Values as reported by EPA eGRID 2018 [11] and adjusted to reflect methane leakage in natural gas production, processing and transportation [9] and the most recent IPCC-published global warming potential of methane [12].

Table A2 | Relevant State-Level Reference Values

State Name	State Abbreviation	Average 2018 Fuel Price ($/MMBtu)			Heating Temp-Dependence (Btu/1000sf-°F) [2]
		Natural Gas [4]	Fuel Oil [5]	Propane [5]	
Alabama	AL	14.69	20.98[1]	28.09	329.3
Arizona	AZ	14.82	23.56[2]	26.47[2]	304.7
Arkansas	AR	11.36	20.98[1]	23.89	289.6
California	CA	11.87	23.56[2]	26.47[2]	327.2
Colorado	CO	7.45	23.56[2]	23.15	272.2
Connecticut	CT	13.44	24.12	32.58	379.2
Delaware	DE	12.16	22.76	34.44	255.2
District of Columbia	DC	11.37	29.42	35.20[1]	396.2
Florida	FL	20.60	20.98[1]	52.31	275.6
Georgia	GA	13.49	20.98[1]	25.40	355.2
Idaho	ID	6.86	23.56[2]	26.91	275.8
Illinois	IL	7.87	19.36[1]	17.88	340.0
Indiana	IN	8.42	20.04	22.39	313.8
Iowa	IA	8.63	17.85	14.54	258.7
Kansas	KS	9.83	19.36[1]	16.87	324.1
Kentucky	KY	10.19	19.40	24.34	318.9
Louisiana	LA	11.25	20.98[1]	26.78[1]	381.2
Maine	ME	15.75	21.93	32.79	234.8
Maryland	MD	11.38	23.53	35.81	314.2
Massachusetts	MA	14.93	23.79	34.28	327.0
Michigan	MI	7.91	19.53	22.06	288.1
Minnesota	MN	8.39	19.38	17.73	221.5
Mississippi	MS	10.02	20.98[1]	27.66	352.9
Missouri	MO	10.00	19.36[1]	19.36	314.0
Montana	MT	7.07	23.56[2]	20.71	262.6
Nebraska	NE	8.24	18.40	14.68	262.5
Nevada	NV	8.92	23.56[2]	26.47[2]	276.6
New Hampshire	NH	14.82	22.67	35.90	234.0
New Jersey	NJ	8.77	24.02	42.07	357.1
New Mexico	NM	7.62	23.56[2]	26.47[2]	266.3
New York	NY	11.94	25.76	35.78	339.9
North Carolina	NC	11.69	21.01	30.89	343.1
North Dakota	ND	6.95	19.36[1]	15.57	253.2
Ohio	OH	8.78	19.57	29.22	306.8
Oklahoma	OK	8.93	19.36[1]	20.93	309.2
Oregon	OR	10.28	23.56[2]	26.47[2]	304.6
Pennsylvania	PA	10.86	20.90	33.20	338.1
Rhode Island	RI	15.11	24.43	38.74	378.0
South Carolina	SC	13.06	20.98[1]	35.30[1]	370.6
South Dakota	SD	7.39	19.36[1]	16.23	219.4
Tennessee	TN	9.14	19.36[1]	33.00	369.0
Texas	TX	11.02	20.98[1]	26.65	370.0
Utah	UT	8.73	23.56[2]	27.84	246.1
Vermont	VT	13.18	20.80	37.88	251.2
Virginia	VA	11.30	20.96[1]	33.90	330.2
Washington	WA	9.92	23.56[2]	26.47[2]	327.6
West Virginia	WV	9.50	20.98	35.15[1]	278.0
Wisconsin	WI	7.76	19.59	17.20	239.6
Wyoming	WY	8.30	23.56[2]	23.73[1]	261.0
U.S. Average	*US*	*10.14*	*23.56*	*26.47*	*N/A*

[1]PADD or PADD subregion value (state-level data unavailable)
[2]U.S. average value (PADD or PADD subregion value unavailable)
[3]Temperature dependence is relative to a reference temperature of 65°F

Table A3 | State-Level Computations: Residential Areas Heated by Each Fuel

State Name	State Abbreviation	Residential Area (Million sq ft)	Percentage Residential Area Heated by…			
			Natural Gas	Fuel Oil	Propane	Electricity

Alabama	AL	3040	32.4%	0.3%	9.2%	56.6%
Arizona	AZ	3835	42.1%	0.2%	9.9%	42.4%
Arkansas	AR	2002	37.1%	0.1%	3.7%	55.5%
California	CA	19,486	68.3%	0.4%	3.9%	22.3%
Colorado	CO	3075	74.2%	0.1%	6.3%	15.9%
Connecticut	CT	2014	29.4%	51.2%	2.9%	14.0%
Delaware	DE	638	65.6%	3.5%	1.1%	28.6%
District of Columbia	DC	375	37.2%	18.0%	12.7%	30.4%
Florida	FL	12,740	5.0%	0.3%	1.5%	91.4%
Georgia	GA	6130	44.6%	0.3%	7.1%	46.7%
Idaho	ID	905	64.9%	1.2%	14.9%	15.9%
Illinois	IL	7111	49.8%	2.9%	6.6%	31.1%
Indiana	IN	3765	81.5%	0.3%	4.5%	12.5%
Iowa	IA	1824	63.2%	1.4%	8.3%	24.3%
Kansas	KS	1689	70.1%	0.1%	8.8%	18.5%
Kentucky	KY	2678	41.0%	1.5%	7.7%	46.3%
Louisiana	LA	2982	39.2%	0.1%	3.5%	56.0%
Maine	ME	910	46.4%	36.1%	3.0%	12.3%
Maryland	MD	3890	43.9%	13.0%	3.6%	37.5%
Massachusetts	MA	3661	3.2%	73.4%	6.7%	4.5%
Michigan	MI	6123	76.1%	2.3%	10.7%	6.7%
Minnesota	MN	3241	65.5%	4.1%	12.1%	13.6%
Mississippi	MS	1738	53.1%	0.4%	11.5%	30.6%
Missouri	MO	3627	33.2%	0.2%	15.3%	49.3%
Montana	MT	636	53.2%	2.0%	15.0%	18.6%
Nebraska	NE	1078	25.3%	6.4%	10.4%	55.2%
Nevada	NV	1579	40.2%	6.1%	16.0%	34.5%
New Hampshire	NH	817	63.9%	0.8%	9.0%	23.3%
New Jersey	NJ	4842	17.2%	53.5%	13.8%	7.1%
New Mexico	NM	1176	72.8%	14.1%	2.1%	10.1%
New York	NY	9872	66.1%	0.2%	11.8%	13.4%
North Carolina	NC	6368	66.1%	0.9%	3.6%	27.5%
North Dakota	ND	409	52.7%	31.6%	3.6%	8.5%
Ohio	OH	6881	68.2%	3.4%	5.9%	19.6%
Oklahoma	OK	2622	57.0%	0.1%	8.9%	30.7%
Oregon	OR	2316	38.8%	4.0%	2.0%	46.7%
Pennsylvania	PA	7285	50.3%	22.0%	4.0%	19.0%
Rhode Island	RI	599	46.4%	41.1%	2.4%	8.1%
South Carolina	SC	3064	24.4%	2.1%	5.5%	66.4%
South Dakota	SD	478	47.8%	4.0%	19.5%	24.4%
Tennessee	TN	3979	36.7%	0.8%	5.4%	54.8%
Texas	TX	15,704	40.4%	0.1%	4.5%	53.9%
Utah	UT	1384	85.1%	0.3%	3.1%	9.3%
Vermont	VT	416	35.1%	8.4%	5.3%	47.9%
Virginia	VA	5330	12.5%	51.8%	15.7%	4.1%
Washington	WA	4100	36.1%	3.5%	4.0%	50.4%
West Virginia	WV	1267	63.8%	4.5%	13.2%	12.3%
Wisconsin	WI	3522	42.5%	4.9%	5.3%	38.8%
Wyoming	WY	355	58.1%	0.5%	12.7%	20.7%
United States	*US*	*183,557*	*49.1%*	*6.7%*	*5.9%*	*35.0%*

Table A4 | State-Level Computations: Residential Heating Energy from Each Fuel

State Name	State Abbreviation	Annual Residential Heating Energy (Million MMBtu)	Percentage Residential Heating Energy by…			
			Natural Gas	Fuel Oil	Propane	Electricity
Alabama	AL	64.7	32.1%	0.3%	9.8%	56.3%

Arizona	AZ	52.3	41.6%	0.2%	10.4%	42.2%
Arkansas	AR	48.0	38.6%	0.1%	6.2%	47.6%
California	CA	376.4	66.8%	0.6%	5.0%	21.8%
Colorado	CO	136.1	72.9%	0.2%	6.9%	16.2%
Connecticut	CT	103.1	28.8%	51.6%	2.9%	14.1%
Delaware	DE	17.5	65.6%	3.5%	1.1%	28.6%
District of Columbia	DC	14.4	38.1%	18.1%	12.2%	30.0%
Florida	FL	59.3	6.6%	0.4%	2.4%	89.3%
Georgia	GA	144.8	46.7%	0.3%	7.4%	44.2%
Idaho	ID	39.7	64.8%	1.2%	15.1%	15.8%
Illinois	IL	347.2	48.2%	3.0%	7.2%	31.5%
Indiana	IN	157.7	82.3%	0.3%	4.3%	12.1%
Iowa	IA	75.9	64.0%	1.4%	8.3%	23.5%
Kansas	KS	65.2	70.0%	0.1%	8.9%	18.5%
Kentucky	KY	91.7	40.7%	1.5%	7.7%	46.5%
Louisiana	LA	47.4	38.9%	0.1%	4.0%	55.6%
Maine	ME	38.2	46.0%	36.4%	3.0%	12.2%
Maryland	MD	128.4	43.4%	13.2%	3.7%	37.7%
Massachusetts	MA	174.8	3.0%	73.4%	6.6%	4.5%
Michigan	MI	281.4	74.8%	2.4%	11.4%	6.7%
Minnesota	MN	137.4	63.7%	4.5%	12.8%	14.0%
Mississippi	MS	37.1	53.1%	0.4%	11.6%	30.5%
Missouri	MO	128.9	34.4%	0.2%	16.4%	46.8%
Montana	MT	32.2	52.5%	2.1%	15.2%	18.7%
Nebraska	NE	42.9	25.1%	7.3%	10.4%	54.2%
Nevada	NV	37.0	39.8%	6.2%	16.2%	34.6%
New Hampshire	NH	31.9	63.5%	0.9%	9.3%	23.4%
New Jersey	NJ	204.9	16.3%	54.1%	13.8%	7.0%
New Mexico	NM	36.0	72.4%	14.4%	2.2%	10.1%
New York	NY	448.0	65.7%	0.2%	12.0%	12.3%
North Carolina	NC	180.8	65.8%	1.8%	5.7%	23.5%
North Dakota	ND	22.3	52.3%	30.6%	4.1%	8.8%
Ohio	OH	286.7	68.5%	3.4%	5.9%	19.3%
Oklahoma	OK	70.6	57.3%	0.1%	8.9%	30.4%
Oregon	OR	86.7	38.2%	4.1%	2.1%	46.6%
Pennsylvania	PA	322.4	49.6%	22.2%	4.1%	18.9%
Rhode Island	RI	31.1	46.4%	41.2%	2.4%	8.1%
South Carolina	SC	70.6	25.7%	2.4%	5.7%	64.7%
South Dakota	SD	19.4	47.5%	4.1%	19.6%	24.5%
Tennessee	TN	133.3	35.7%	0.8%	5.5%	55.5%
Texas	TX	274.1	41.8%	0.2%	4.7%	52.2%
Utah	UT	48.5	85.1%	0.3%	3.4%	8.8%
Vermont	VT	18.6	34.8%	8.5%	5.5%	47.6%
Virginia	VA	172.7	11.9%	52.1%	15.8%	4.0%
Washington	WA	171.6	35.5%	3.4%	4.1%	50.6%
West Virginia	WV	42.8	62.6%	4.6%	14.0%	12.2%
Wisconsin	WI	150.6	42.4%	5.1%	5.5%	38.2%
Wyoming	WY	18.0	56.6%	0.5%	12.9%	21.5%
United States	*US*	*5721*	*53.4%*	*9.3%*	*6.6%*	*26.8%*

Table A5 | State-Level Computations: Residential Space Heating GHG Emissions

State Name	State Abbrev.	Annual Residential GHG Emissions (MMtCO2e)	Annual Residential Heating Emissions (MMtCO2e)	Percentage of Total Residential Emissions from Heating	Percentage Residential Heating Emissions from…			
					Natural Gas	Fuel Oil	Propane	Electricity
Alabama	AL	19.0	9.3	48.9%	18.8%	0.2%	5.5%	75.5%

Arizona	AZ	19.6	7.4	37.6%	23.1%	0.1%	3.6%	73.3%
Arkansas	AR	11.3	5.3	46.9%	31.7%	0.2%	7.6%	60.5%
California	CA	57.0	32.2	56.5%	65.9%	0.7%	4.8%	28.7%
Colorado	CO	20.6	12.6	60.9%	66.7%	0.2%	6.1%	27.1%
Connecticut	CT	13.1	9.5	72.0%	26.4%	53.5%	2.6%	17.5%
Delaware	DE	2.8	1.7	61.3%	32.4%	17.3%	10.0%	40.3%
District of Col.	DC	1.7	1.2	70.0%	65.9%	3.9%	1.0%	29.1%
Florida	FL	58.4	7.0	12.0%	4.7%	0.4%	1.6%	93.3%
Georgia	GA	37.1	16.8	45.3%	34.0%	0.3%	5.1%	60.6%
Idaho	ID	4.6	3.6	79.7%	44.3%	3.1%	6.4%	46.2%
Illinois	IL	59.4	36.0	60.6%	66.9%	0.3%	3.3%	29.5%
Indiana	IN	28.8	19.5	67.6%	43.7%	1.1%	5.4%	49.9%
Iowa	IA	13.9	8.2	59.1%	50.6%	1.1%	11.3%	37.0%
Kansas	KS	12.4	7.8	62.9%	49.2%	0.1%	6.0%	44.6%
Kentucky	KY	17.4	11.9	68.3%	26.5%	1.1%	4.8%	67.6%
Louisiana	LA	17.1	5.3	30.7%	29.7%	0.1%	2.9%	67.3%
Maine	ME	4.6	3.5	76.4%	2.8%	75.5%	5.8%	15.9%
Maryland	MD	18.9	12.1	64.4%	38.7%	13.2%	3.2%	44.9%
Massachusetts	MA	23.1	15.7	67.8%	43.2%	38.6%	2.7%	15.4%
Michigan	MI	45.7	27.9	61.2%	63.5%	2.3%	9.3%	24.9%
Minnesota	MN	23.4	13.4	57.1%	55.3%	4.4%	10.7%	29.7%
Mississippi	MS	10.8	4.6	42.3%	23.5%	0.1%	10.8%	65.6%
Missouri	MO	32.2	17.3	53.7%	33.3%	0.3%	7.0%	59.4%
Montana	MT	3.5	2.8	80.4%	51.3%	2.3%	14.3%	32.2%
Nebraska	NE	8.9	5.1	57.0%	45.2%	0.7%	6.3%	47.7%
Nevada	NV	8.1	4.0	49.6%	51.2%	1.5%	4.3%	43.0%
New Hamp.	NH	4.0	3.0	73.2%	14.9%	55.7%	12.1%	17.4%
New Jersey	NJ	28.7	19.2	66.8%	65.3%	14.7%	1.9%	18.1%
New Mexico	NM	6.4	3.6	56.2%	55.4%	0.2%	9.7%	34.7%
New York	NY	56.4	38.6	68.4%	51.2%	33.8%	3.8%	11.1%
North Carolina	NC	27.7	19.3	69.5%	19.9%	6.5%	7.9%	65.8%
North Dakota	ND	3.8	2.5	67.2%	29.5%	5.2%	11.5%	53.8%
Ohio	OH	49.8	33.9	68.0%	48.9%	2.7%	4.1%	44.3%
Oklahoma	OK	17.8	9.0	50.6%	37.9%	0.1%	5.6%	56.4%
Oregon	OR	9.3	7.6	81.9%	36.6%	4.4%	1.9%	57.1%
Pennsylvania	PA	45.8	32.1	70.0%	42.1%	21.2%	3.3%	33.3%
Rhode Island	RI	3.7	2.8	74.4%	44.1%	44.1%	2.2%	9.7%
South Carolina	SC	13.4	7.7	57.3%	19.9%	2.1%	4.2%	73.8%
South Dakota	SD	3.9	2.3	58.5%	33.9%	3.3%	13.4%	49.3%
Tennessee	TN	25.8	14.5	56.3%	27.6%	0.7%	4.1%	67.6%
Texas	TX	78.4	28.4	36.2%	34.0%	0.2%	3.7%	62.2%
Utah	UT	7.2	4.5	62.8%	76.4%	0.3%	2.9%	20.3%
Vermont	VT	2.2	1.6	74.4%	11.5%	57.1%	14.7%	16.6%
Virginia	VA	26.0	19.8	76.1%	25.6%	7.1%	3.9%	63.4%
Washington	WA	17.3	13.4	77.5%	38.4%	4.2%	4.3%	53.2%
West Virginia	WV	8.4	6.6	78.4%	23.2%	3.1%	2.9%	70.7%
Wisconsin	WI	25.7	14.9	57.9%	53.4%	4.4%	11.5%	30.8%
Wyoming	WY	2.3	1.8	80.9%	47.0%	0.5%	10.3%	42.2%
United States	*US*	*1037.5*	*588.7*	*56.7%*	*43.8%*	*8.6%*	*5.2%*	*42.4%*