PECAN STREET

Cooling a Warming Planet: What Homes in Texas and New York Can Teach Us About Cooling Demand Around the Globe

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Cooling a Warming Planet: What Homes in Texas and New York Can Teach Us About Cooling Demand Around the Globe

Introduction

Space cooling is a primary driver of electricity demand, and it's growing. U.S. electricity demand for residential air conditioning (AC) is expected to grow 59% by 2050, with 86% of the total residential cooling load from single family homes. This growth presents a significant climate challenge as countries are seeking solutions that reduce overall climate emissions. It's an economic challenge, too, especially for low-income families who already spend a disproportionate percentage of their income on basic energy needs. In this paper, Pecan Street draws on our network of volunteer research participants to examine cooling loads in different parts of the United States. Our data shows that cooling loads differ based on location, building characteristics, cooling systems, and human behavior. Understanding how these factors interact will be crucial to managing cooling load growth over the next several decades. With supportive policy and innovative technology, the greenhouse gas emissions from increased cooling can be minimized.

Preparing for Growing Cooling Demand

The United States has been steadily adding air conditioning to homes since the early 1900s. Today, 90% of U.S. homes have some form of air conditioning. Cities on the west coast with traditionally temperate climates are among the last large cities with low AC adoption. But they now regularly reach uncomfortably warm temperatures and are expected to spark the highest AC adoption rates in coming decades. At the same time, homes across the country are cooling more space by upgrading room-based air conditioning (primarily window units) to central air or mini-split systems that cool the entire home. Aside from general grid stability challenges, this trend creates a climate challenge; more demand can result in more carbon emissions.

It will also create cost issues that will affect all customers, but will be particularly challenging for low-income households who already pay a higher portion of their income on basic energy needs. Among all U.S. households, 13% pay more than 10% of their income on energy – a measure referred to as "severely energy burdened." That number is 60% for families living at or under 200% of the federal poverty level. The highest rates of energy burden are found in urban, multi-family, and manufactured housing where buildings are often old and lack investment. Moreover, an estimated 59% of low-income households are renters who have less say than homeowners in energy efficiency decisions that could reduce their energy bill.

Key to this transition will be policies and programs that incentivize high-efficiency, low-emission cooling.

1. Two-way electric heat pumps decrease greenhouse gas emissions over the life of the cooling system. They can not only cool an entire home, they can also replace natural gas furnaces or inefficient electric resistance home heating in most climates.
2. Focus on cooling efficiency, whatever the technology.
3. Improving building envelopes can reduce cooling demand for new and existing housing stock.
4. The combination of renewable energy, storage, and demand response technology can significantly ease grid stress from higher cooling demand, reduce emission increases, and save consumers money.

Cooling Load Analysis in New York and Texas

Pecan Street's volunteer research network began in Austin, Texas, where the majority of our connected homes are located today. In recent years, we have expanded our network into California, Detroit, Puerto Rico, and upstate New York (Ithaca) to diversify the housing stock, climate, and energy profiles represented in our data. Here, we compare the average hourly HVAC electric consumption and temperature for homes in Austin and Ithaca.

Austin has a humid subtropical climate typical in the American South. Approximately 90% of homes in Austin have central air units, and 5% have window air conditioners. Ithaca, New York has a warm summer humid continental climate. An estimated 49% homes have central air, and 36% have window AC units.

Central air units are the most common AC system installed in single family homes in the United States. Figure 1 shows that while almost all homes in the South have been built with central air since the 80s, the number of homes built with central air conditioning has been rapidly increasing over this period. Eventually, almost all U.S. homes will have some air conditioning, with the majority of full home cooling systems being central air systems.

In this analysis, we combine cooling data from a sample of homes with meteorological data, building characteristics, and participant survey data to evaluate cooling load differences normalized for outside air temperature between Austin and Ithaca. First, we isolated HVAC power consumption for a sample of 160 homes in Austin and 27 homes in Ithaca during the calendar years 2020 and 2021. We included hourly HVAC measurements when outside air temperature was above 70 degrees. The size and age of these homes are shown in Figure 2. The sample skews toward newer homes in Austin; Ithaca has a more distributed sample of newer and older homes. Home size is well distributed throughout the sample in both locations.

Fig. 1 — Percentage of New U.S. Homes Built with Central AC

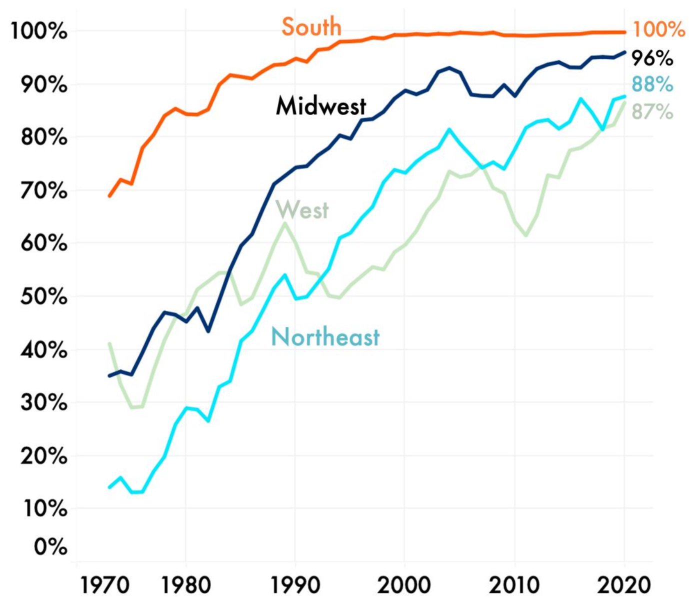


Fig. 2 — Sample Home Size vs. Age

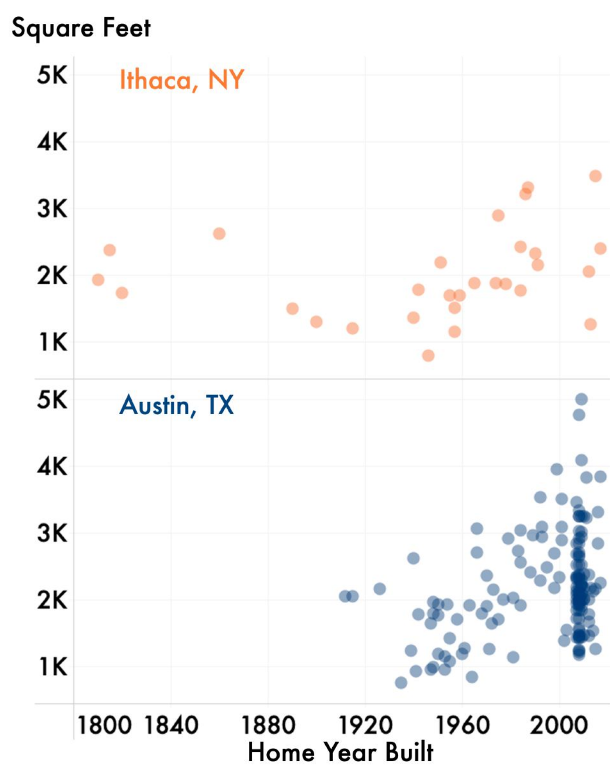
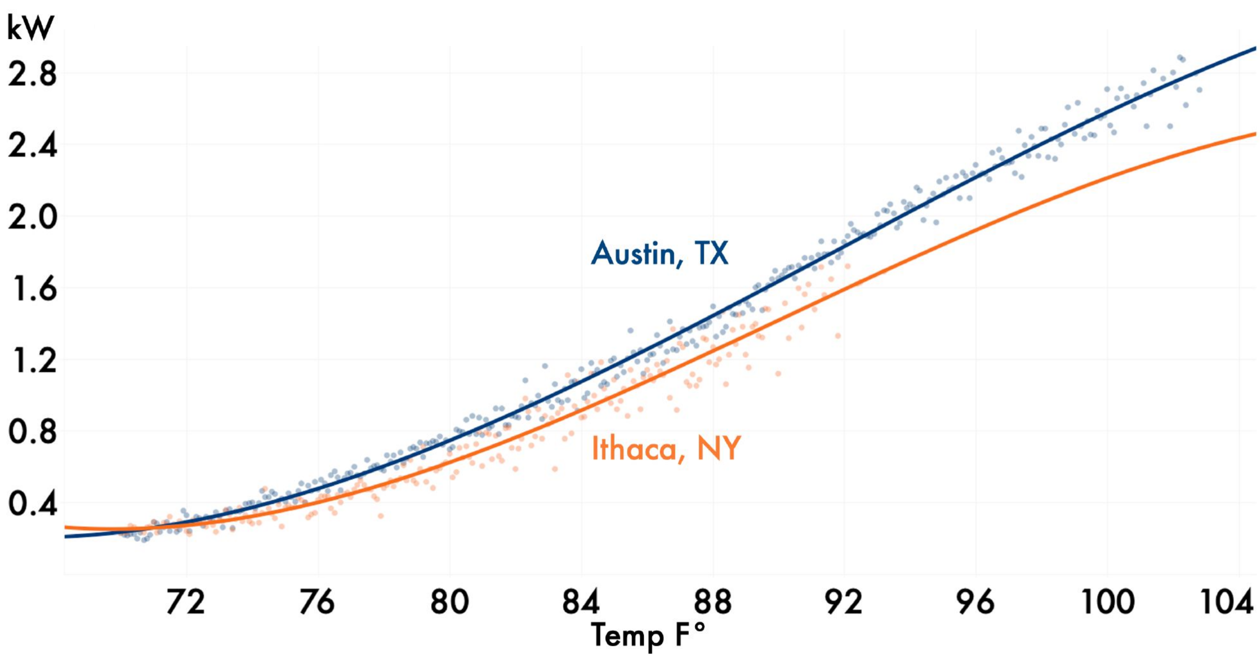


Figure 3 shows a cubic trend line of the average home HVAC load vs. temperature rounded to the tenth decimal place) observed in our sample. For example in Austin, when the temperature was 85.5F, the average HVAC load in our sample was 1.3 kW, which is represented by a single blue dot. The linear regression model output for the Austin and Ithaca samples (see Appendix A) show that both regressions have a statistically significant positive relationship; as outside air temperature increases so does the average HVAC load. Furthermore, the R-squared statistics for Austin and Ithaca are 0.99 and 0.95, respectively, which means that in both locations, changes in the temperature accounts for the majority of variance in the sample average HVAC load.

The Figure 3 trend line is steeper for Austin than Ithaca, which means that, on average, homes in Austin use more electricity for cooling than the homes in New York when the outside temperature in both places is the same; the Austin temperature normalized cooling load is, on average, 15% higher than the Ithaca sample.

As temperatures get hotter, the absolute difference between the cooling load trend line in Austin and Ithaca increases. This disparity is likely driven by building characteristics, cooling systems, thermostat setpoint preferences, and climate differences like irradiance and humidity. The rest of this paper explores the potential causes of this difference and what implications these factors have on the growing AC load in the United States.

Figure 3 — Temperature (F°) vs. Average Home HVAC (kW)



Building Characteristics

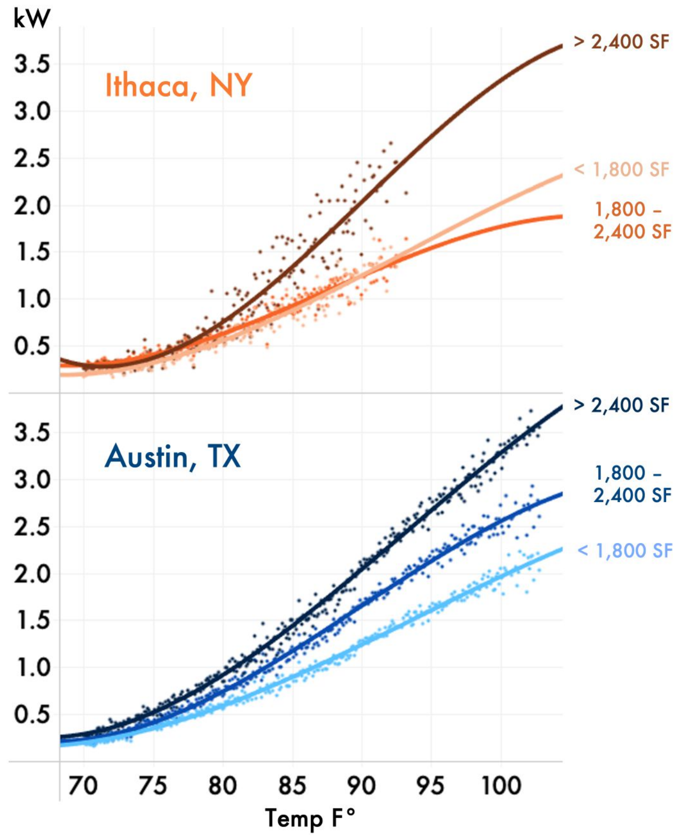
Home Size and Age

Cooling load generally increases as building size increases. Linear regression showed that sample homes in Austin have a statistically significant positive linear relationship with home size, but homes in Ithaca do not. Both locations have low R-squared values, which means most of the variance in HVAC load is not explained by home size (see Appendix A). The significance of the Austin home sample is likely because almost all of the homes have central air conditioning. When an entire home is air conditioned, the positive relationship between home size and average HVAC load is strongest. Conversely, the Ithaca sample's lack of a significance of home square footage is likely because only 49% of the homes in this region are fully air conditioned. When a home has only partial air conditioning, the average cooling load will be more dependent on the conditioned square footage of the home rather than the total square footage.

Another way to visually evaluate the relationship between home size and average HVAC load is to group the samples into roughly equal subsamples based on home size and observe their polynomial trend lines (Figure 4).

In both locations, average HVAC load increases as home size increases. This progression is more uniform in Austin likely due to more homes being fully air conditioned. This also drives Austin homes to have higher average HVAC usage than Ithaca homes at each home size grouping. When comparing home size between locations, the average HVAC trend lines are most similar for homes under 1,800 square feet. This suggests that in smaller homes, the factors that differentiate the cooling load in both locations are less pronounced. One possible explanation is that small homes in Ithaca with partial air conditioning have a load that is much closer to smaller central air units that serve small homes in Austin. The largest difference in cooling load between the two locations is in the

Fig. 4 — Temperature vs. Average Home HVAC Grouped by Square Footage



1,800-2,400 square-feet group, but the gap between them narrows in the over 2,400 square-feet group.

Linear regression did not show a significant relationship between the year a home was built and the average HVAC load. This could be the result of renovations to older homes in our sample and the energy efficiency standards and appliance technologies that are also found in newer homes. Older, un-renovated homes could yield a stronger relationship between year built and cooling load, but both of these samples contain a majority of homes with whole home cooling.

Thermal Envelope

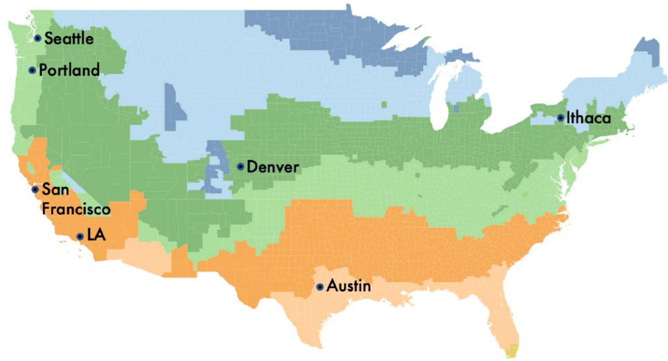
Homes in the northern United States are generally better insulated and have stricter building regulations than homes in the southern and western United States. Since heating a home in an Ithaca winter has a larger indoor vs. outdoor temperature delta than cooling a home in Austin, there are more incentives for the building envelope to be thermally insulated. For example, homes in Ithaca often see winter night time temperatures in the teens, which requires approximately 60 degrees of heating for the indoors to be comfortable. An Austin summer high-temperature of 100 would only need 30 degrees of cooling for the same level of comfort. Austin homes generally have less insulation, less efficient windows, and less weatherstripping than homes in Ithaca. Thus, in general, it is likely that a home in Austin requires more power to cool at the same temperature as an Ithaca home.

Insulation requirements also vary broadly by climate region. Figure 5 shows Department of Energy recommendations for homes in climate zones across the country. Northern states like New York have the insulation recommendations with the highest R-values to overcome the sizable indoor-outdoor temperature gaps during cold winters. As cooling demand grows in these areas, the ample insulation should outperform milder climates like the west coast or even hot climates like Austin. This thermal envelope difference is probably underrepresented in our sample, since many of the homes in our Austin sample were certified through the Austin Energy green building program which goes beyond local energy code standards for sustainability. A completely random sampling of regional homes in Austin would likely illustrate this disparity more dramatically.

Customer Behavior

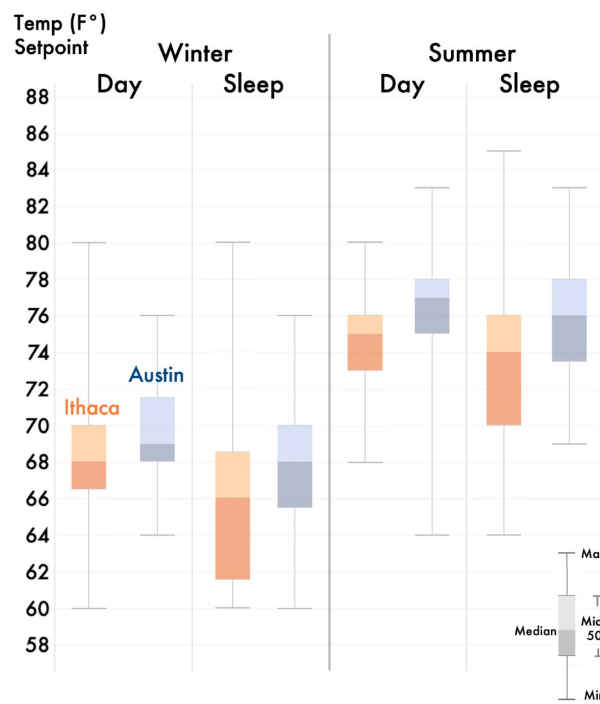
A home's building characteristics and energy efficiency affect energy consumption, but the way residents operate these systems also plays a large role. Thermostat temperature setpoints, in particular, are a major influence on how and when a home gets heated and cooled, but they vary significantly from person to person. Data from Pecan Street's participant survey (Figure 6) illustrates how

Fig. 5 — ENERGY STAR Recommended Insulation Levels



Climate Zone	Attic	Floors	Crawl Spaces	2x4 Walls	2x6 Walls
7	R49 - R60	R25 - R30	R25 - R30		
6					
5	R38 - R60	R25 - R30	R25 - R30	R13 - R15	R19 - R21
4					
3	R30 - R60	R25	R19 - R25		
2	R30 - R49	R13	R13 - R19		
1			R13		

Figure 6 — Thermostat Setting by Location
Pecan Street Participant Survey Data



these behavioral differences vary. Austin participants have a higher median setpoint and tighter range in the summer than the Ithaca participants. During winter, the roles are reversed; Ithaca homes have lower temperature setpoints and a tighter range. Put another way, our Ithaca participants are willing to keep their homes cooler in the winter; Austin participants are willing to keep their homes warmer in the summer. There are several explanations for this beyond simply getting used to the current climate. For example in Austin, electricity rates are higher in the summer, and natural gas (heating) rates often have low fuel costs with high fixed charges. For homes with gas furnaces, these rate structures incentivize energy conservation in the summer more than in the winter.

Survey responses for thermostat settings were more consistent during the day than at night, which can be seen by the smaller interquartile range (total size of each box) for daytime settings. Median nighttime temperature settings were lower than daytime settings in both the summer and winter in both locations.

Thermostat flexibility observed in our participant survey cannot be directly measured in our cooling load analysis. However, it shows the potential for demand response to offset cooling load increases in the future. Setpoints across all times of day and season averaged a 12.8 degree range from the highest to lowest setting in each category. In many scenarios, adjusting thermostats just a few degrees over many houses can provide demand relief for a utility. Cooling load will continue to increase due to rising temperatures while new and existing homes add AC capacity. This will put pressure on electric grids everywhere, but especially in summer peak regions. Demand response programs can help relieve grid stress by coordinating home thermostat setpoints and lower the grid impact of cooling load. R&D efforts like Pecan Street's ARPA-E funded collaboration with the University of Michigan, University of California, Berkeley, and Los Alamos National Lab show promise to coordinate short interruptions of HVAC cycles to manage load without causing resident discomfort.

Cooling Systems

The main cooling systems in homes today are window units, ducted central air systems, and ductless mini split systems. They all use heat pump technology to move hot air from the inside to outside of the home, but they vary in cost, cooling capacity, and energy efficiency Window units are less energy efficient than central air systems, but they use less electricity overall since they normally condition only a portion of the home. The two main drivers of increasing cooling load nationwide are upgrading partial to full home cooling and adding new cooling systems to homes that previously had no cooling.

Existing Window Unit to Central Air / Mini Split / Additional Window Units

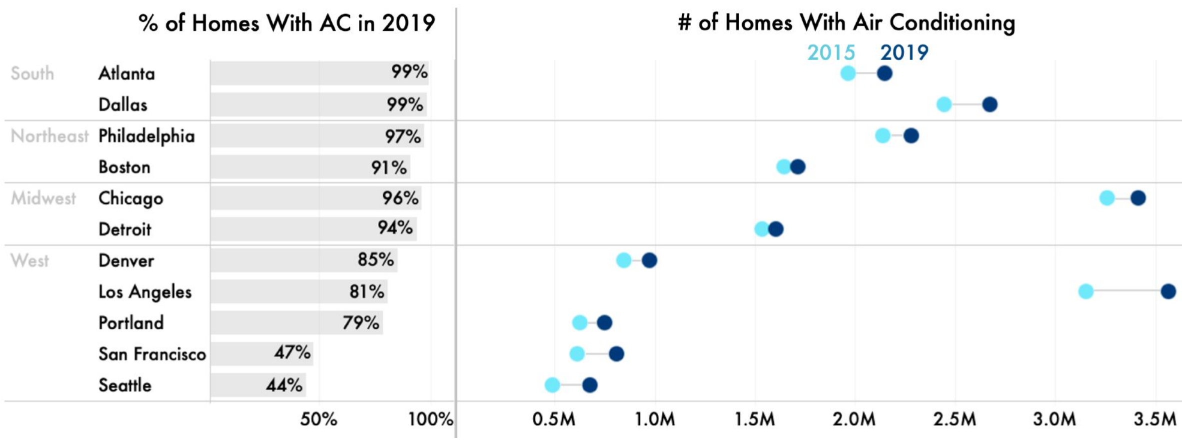
As cities in the Northeast and Midwest transition from partial cooling to full home cooling, they will likely be adding window units or upgrading to full home cooling via central air or mini split systems. These cities will likely have a similar cooling trend to our Ithaca sample because their thermal envelopes are built for cold winters which make air conditioning more efficient as well.

No Cooling to Central Air / Mini Split / Window Unit

Homes in coastal western cities that are adopting cooling for the first time will likely fall somewhere in between the Texas trend and the Ithaca trend. Homes on the west coast are generally more energy efficient than most other cities and smaller than those in Austin and Ithaca. California, in particular, has the strictest energy code in the country, so it's likely that the cooling demand for cities on the west coast will be more similar to Ithaca than Austin.

Since 90% of American homes already have some form of cooling, the majority of the countrywide transition will be from partial- to full-home cooling. Moreover, more than 90% of homes that are built today have central air conditioning systems. As the climate warms, many homeowners in western coastal cities who haven't needed air conditioning will switch. These "cooling holdouts" will end up being a significant, though delayed, driver of cooling demand growth. West coast cities have the low-

Fig. 7 — Number and Percent of Homes with Air Conditioning in U.S. Cities



est percentages of homes with air conditioning, but have had large gains recently. New construction in Southern cities like Dallas and Atlanta will increase overall cooling load. Northeast and Midwest cities are not adding as many new homes, but homes in this region are transitioning from partial to central air conditioning, which will result in a net increase in cooling demand.

This transition of cooling systems has huge implications for home electrification and greenhouse gas emission trends over the next 50 years. Central air systems are expensive and last approximately 15 years. When homes in western coastal cities add an electric heat pump and possibly ducting for cooling, it is essential that they install a two-way electric heat pump which can heat the home as well. Pairing gas furnaces (heating) with electric heat pumps (cooling) locks in fossil fuel technology and consumption for the lifetime of the central air system. At a time when we must be transitioning en masse to all electric HVAC systems across the country, there's a strong chance that swaths of homes on the west coast could be adding more natural gas infrastructure and prolonging the consumption of residential natural gas consumption for decades to come.

Summary

Our Ithaca sample is a good proxy for temperature normalized cooling load in the Midwest and Northeast. The combination of efficient thermal envelopes and more full-home cooling systems will produce modest increases in overall cooling demand.

Texas homes are larger, less insulated and have more cooling square footage than most regions. Because 55% of the Austin sample was built to Austin Energy's green building standards, these homes represent a highly efficient cooling load. Generally, however, homes in Texas and the south are likely the top end of temperature normalized cooling load in the country.

Our survey data suggests that Texas customers are more willing to operate cooling systems at higher setpoints than Ithaca customers. Developing thermostat setpoint control as demand response can help assuage electrical grid peaks due to cooling load.

Our analysis shows there are important and significant differences in temperature normalized cooling load in different areas of the country. The main factors driving these differences relate to building characteristics, human behavior, and the cooling system used in a home. Other factors, such as humidity and solar irradiance, likely impact cooling load and are ripe for further analysis. An electric heating load comparison with a similar sample is another possible extension of this analysis. This would be especially useful to evaluate future impacts of two way heat pumps.

Recommendations

Increased cooling demand caused by a warming climate and higher living standards are inevitable. However, the increased power demand and greenhouse gas emissions that will accompany the growth in cooling is yet to be determined. The following actions can optimize the increase in global cooling demand:

#1: Install Two-Way Electric Heat Pumps to Reduce Greenhouse Gas (GHG) Emissions

When HVAC systems are installed, their energy efficiency and power demand are locked in for the life of the system — approximately 15 years. Thus, if a new central air system is paired with a natural gas furnace, the natural gas use and GHG emissions associated with that system are locked in for decades. Two-way heat pumps have a distinct advantage over natural gas furnaces in both energy efficiency and GHG emissions. First, they are the most energy-efficient heating method in almost all climate zones, and they outcompete gas furnaces on a BTU per unit energy basis. Second, since climate emissions from electricity generation continue to decline, so too will the carbon footprint of heat pumps. Conversely, burning a therm of natural gas will have the same climate warming effect in 20 years as it does today.

#2: Install the most efficient air conditioning units possible.

Installing the most efficient cooling systems and methods available will reduce demand spikes. Ducted central air systems, ductless mini split systems, and window units all use the same heat pump technology, but there are varying levels of efficiency and sizing that significantly affect cooling load. High SEER ratings and units with the DOE's EnergyStar label should be prioritized to maximize cooling efficiency. Professionally installed central air systems are sized better to the space and layout of a home than window units, and variable speed models can increase efficiency and lower cooling load by running at different power levels to best match the cooling demand.

#3: Improve thermal building envelope with better insulation, energy efficient windows and less solar heat gain.

Generally speaking, the tighter a home's thermal envelope is, the lower its heating and cooling needs will be. Energy efficiency advocates have argued for years that the cheapest (and cleanest) kilowatt is the one you never have to use. As more homes add cooling, state and local building codes should increase the value of efficiency measures, from increasing insulation in attics and walls to installing high-efficiency windows. Importantly, additional research is needed to understand and account for the indoor air quality impacts of tighter building envelopes.

#4: Investigate residential demand response programs and renewable electricity generation to reduce emissions and ease grid strains caused by increased cooling load.

Small changes in a home's thermostat setpoint can contribute meaningful demand response at peak grid demand. Utilities should develop and scale these programs to maximize their potential to offset cooling load growth. Residential solar panels produce power during peak cooling hours and can offset much of a home's cooling load. Residential solar production is also synergistic with thermal envelope improvements and thermostat-based demand response programs that can pre-cool a home while the sun is out and minimize power consumption after the solar panels stop producing. Solar power's concurrent timing with daily peak cooling load also make it a strong candidate to offset this demand at the utility scale, particularly when paired with short-term energy storage.

Appendix A — Regression Model Output

Figure 3 Polynomial Regression

Model formula:	Mailing State*(Temperature^3 + Temperature^2 + Temperature + intercept)
Number of modeled observations:	534
Number of filtered observations:	0
Model degrees of freedom:	8
Residual degrees of freedom (DF):	526
SSE (sum squared error):	2.63328
MSE (mean squared error):	0.0050062
R-Squared:	0.990516
Standard error:	0.0707548
p-value (significance):	< 0.0001

Analysis of Variance:

Field	DF	SSE	MSE	F	p-value
Mailing State	4	2.3936	0.5984	119.531	< 0.0001

Individual trend lines:

Panes		Color	Line		Coefficients				
Row	Column	Mailing State	p-value	DF	Term	Value	StdErr	t-value	p-value
Hvac Use	Temperature	Texas	< 0.0001	316	Temperature^3	-5.412e-05	5.138e-06	-10.5323	< 0.0001
					Temperature^2	0.0148826	0.0013291	11.1976	< 0.0001
					Temperature	-1.26681	0.113907	-11.1214	< 0.0001
					intercept	34.5492	3.23412	10.6827	< 0.0001
Hvac Use	Temperature	New York	< 0.0001	210	Temperature^3	-7.017e-05	2.644e-05	-2.6543	0.0085559
					Temperature^2	0.0189505	0.0064325	2.94606	0.0035817
					Temperature	-1.61954	0.520057	-3.11417	0.0021019
					intercept	44.8322	13.9706	3.20905	0.0015404

Linear Regression Model for Home Size and Age with Avg HVAC kW

A linear trend model is computed for average of Hvac Use given House Construction Year. The model may be significant at p <= 0.05. The factor Mailing State may be significant at p <= 0.05.

Model formula:	Mailing State*(House Construction Year + intercept)
Number of modeled observations:	182
Number of filtered observations:	5
Model degrees of freedom:	4
Residual degrees of freedom (DF):	178
SSE (sum squared error):	26.9557
MSE (mean squared error):	0.151437
R-Squared:	0.0979684
Standard error:	0.389149
p-value (significance):	0.0003631

Analysis of Variance:

Field	DF	SSE	MSE	F	p-value
Mailing State	2	1.8961089	0.948054	6.2604	0.0023578

A linear trend model is computed for average of Hvac Use given Total Square Footage. The model may be significant at p <= 0.05. The factor Mailing State may be significant at p <= 0.05.

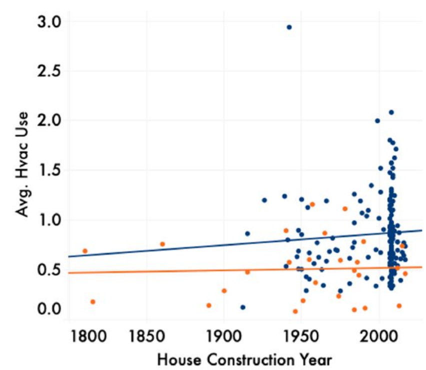
Model formula:	Mailing State*(Total Square Footage + intercept)
Number of modeled observations:	184
Number of filtered observations:	3
Model degrees of freedom:	4
Residual degrees of freedom (DF):	180
SSE (sum squared error):	22.7783
MSE (mean squared error):	0.126546
R-Squared:	0.241755
Standard error:	0.355734
p-value (significance):	< 0.0001

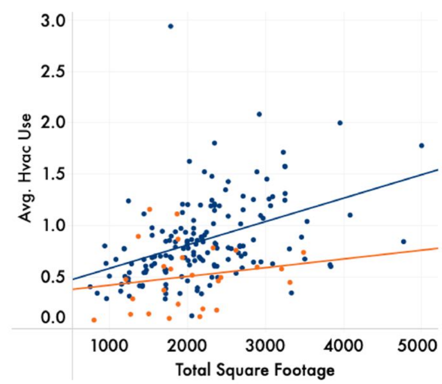
Analysis of Variance:

Field	DF	SSE	MSE	F	p-value
Mailing State	2	2.4449864	1.22249	9.66044	0.0001035

Individual trend lines:

Panes		Color	Line		Coefficients				
Row	Column	Mailing State	p-value	DF	Term	Value	StdErr	t-value	p-value
Hvac Use	Total Square Footage	Texas	< 0.0001	155	Total Square Footage	0.0002274	3.929e-05	5.78755	< 0.0001
					intercept	0.353626	0.0909183	3.88949	0.0001487
Hvac Use	Total Square Footage	New York	0.357458	25	Total Square Footage	8.499e-05	9.065e-05	0.937526	0.357458
					intercept	0.333074	0.193498	1.72133	0.0975454
Hvac Use	House Construction Year	Texas	0.404519	153	House Construction Year	0.0011479	0.0013733	0.835892	0.404519
					intercept	-1.43496	2.74023	-0.523664	0.60127
Hvac Use	House Construction Year	New York	0.825548	25	House Construction Year	0.0002454	0.001102	0.222739	0.825548
					intercept	0.0266143	2.15214	0.0123664	0.990231





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*Author Note: AHS Heating and Air Conditioning figures for Rochester were used to represent Ithaca because of their similar location and climate

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