Using home energy monitoring technology to assess residential air conditioning

Research from Sense Labs

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sense

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Abstract

A new study using detailed home energy data quantifies the extent, and financial and carbon costs, of air conditioning usage. Using anonymized data from approximately 15,000 homes, the study showed that a disproportionate amount of air conditioning use came from a small number of the most inefficient homes. The data was gathered by the Sense Home Energy Monitor, a consumer product that tracks real-time electricity usage in homes and uses machine learning and device disaggregation to identify individual devices by their energy signatures. The study quantified that:

- Optimizing the 20% of homes with highest air conditioning energy usage to match the 20% of homes with lowest air conditioning energy use could save 8% of all US residential electricity;
- Customers in the most inefficient homes spend almost four times as much to cool their homes than customers with the most efficient homes, leading to an average of $882 extra spent on cooling per year;
- Potential savings to U.S. consumers is $15.3 billion annually;
- 115 billion kilowatt hours could be saved annually;
- 52M tons of carbon emissions could be avoided annually if the HVAC inefficiency were addressed; and
- The twenty percent of homes with highest cooling use have a disproportionate impact, accounting for 45% of all cooling consumption nationwide.

Updating 20% of homes could save 8% of US residential electricity usage

Even in a cool weather state like New York, transitioning the 20% of homes with the highest AC usage to equal the most efficient similar homes would reduce the state's residential electricity use by 6%. Some states face a summer peak power problem where air conditioning usage is very high. An analysis in California showed that if the 20% least efficient houses were upgraded to match the most efficient homes, residential electricity usage at peak could be reduced by 13.5%.

Previously, utilities could only estimate the extent of these inefficiencies and their impacts from a 5,000-foot view, using general data like characterization studies.

This new analysis based on real-time home energy data opens the way for economic and environmental relief. Credible, specific data gives customers, utilities, and policymakers confidence that targeted mitigation efforts will deliver results. States with economic pain and aggressive carbon goals may want to consider this traditionally overlooked opportunity to boost jobs and cut carbon. Those working toward electrification can embrace targeted mitigation as a way of getting significant excess energy and demand off the power grid at a time when EVs and other technologies will be increasingly reliant on electricity.

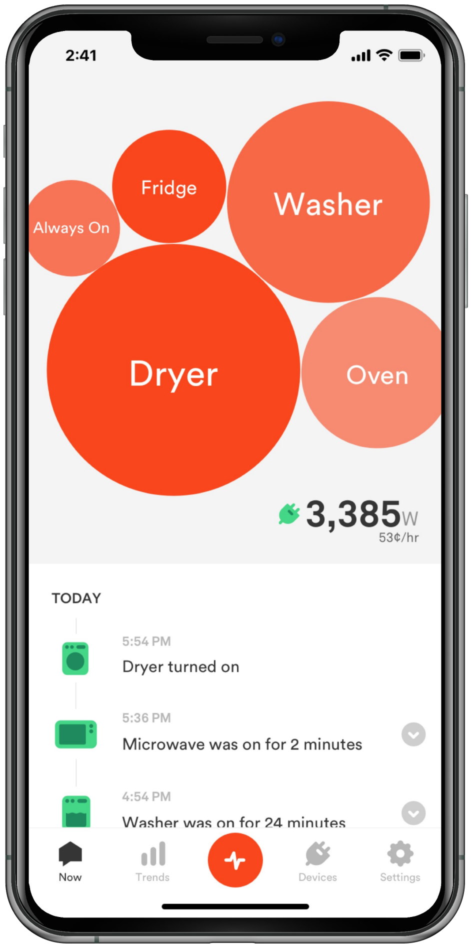
Introduction

The purpose of the study was to identify homes that use significantly more energy for air conditioning than similar homes and could be candidates for remediation. This approach could lead to reduced consumer costs, lower peak demands on utility grids, and more targeted strategies for utilities to reach energy efficiency goals.

According to the EIA[1], more than half (51%) of an average residential household's annual energy consumption was allocated to heating and air conditioning in 2019. The residential sector as a whole accounted for about 21% of total U.S. energy consumption in 2019. Reducing home electricity consumption by addressing inefficient air conditioning could have a significant impact on the country's ability to reach climate change goals.

Data Collection by the Sense Home Energy Monitor

The study drew on home energy data from 14,948 households across the U.S. that had installed the Sense Home Energy Monitor. Introduced to the consumer market in late 2016, the Sense monitor is a device about the size of a large smartphone that's installed in the home's electrical panel. Two sensors clamp around the service mains to monitor power usage.



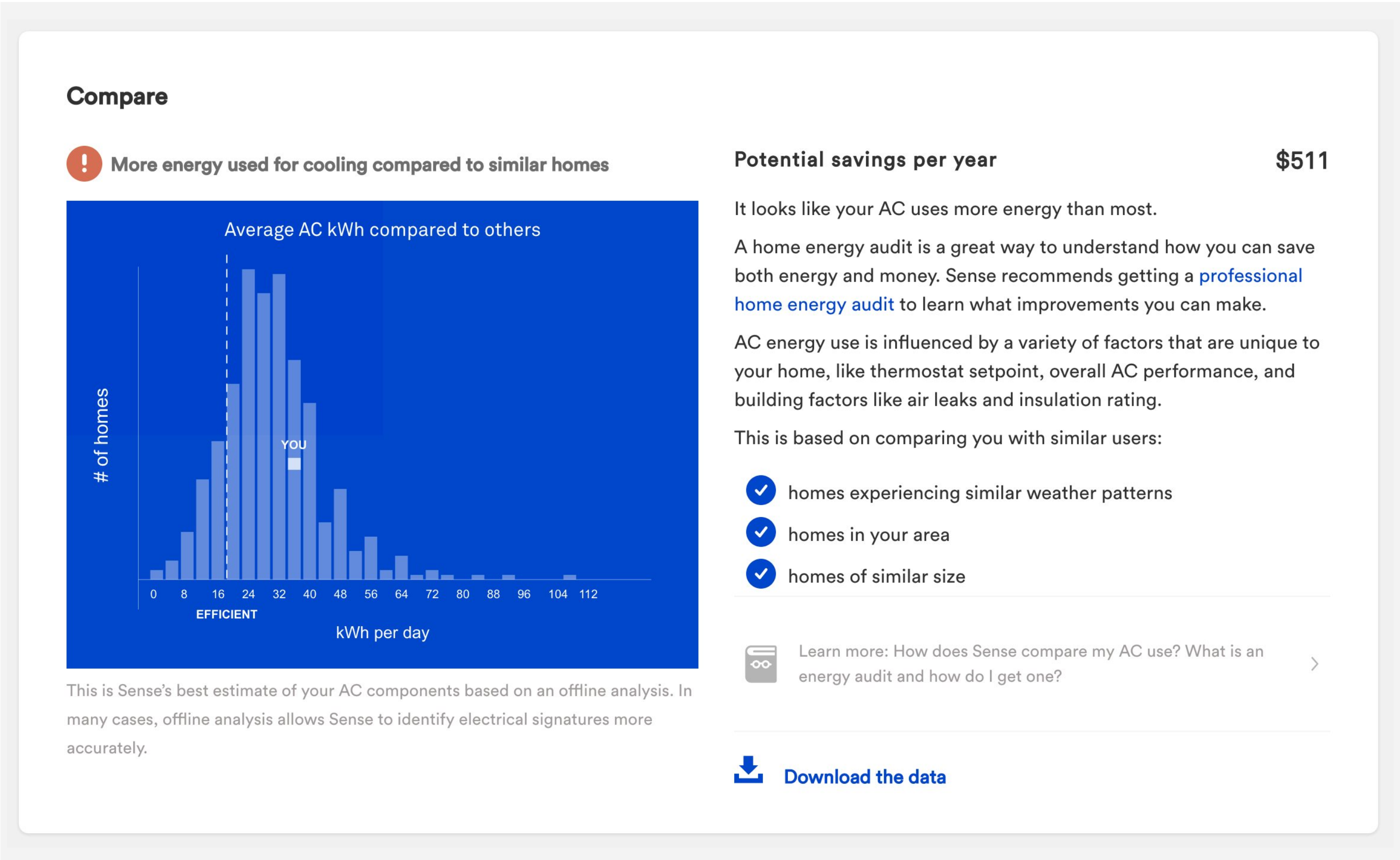
The Sense monitor continuously tracks how much electricity the home is using and can detect energy variations as devices turn on and off. It uses high-resolution waveform monitoring, measuring voltage at 1 million samples per sec and current at 41 thousand samples per second. The data is analyzed using advanced machine learning algorithms that disaggregate the electrical signatures of individual devices in the home. Once individual devices are found, users can name and track them in the Sense app. They can see energy waveforms of their home appliances, real-time views of devices turning on and off, historical data and trends. Users can set goals and get alerts regarding their electricity usage in the Sense app. (More information at sense.com.)

There are no formal public accuracy standards and comparative testing for disaggregation technology, and measuring real-world accuracy is challenging except in small numbers of homes where there are additional sensors for collecting "ground truth" measurements of appliances. However, a report[2] conducted by Pacific Northwest National Laboratory (PNNL) and the U.S. Energy Information Administration (EIA) describe the results of an analysis they conducted in 2018-2019 “to evaluate the latest load disaggregation or submetering technologies” for residential energy consumption.

PNNL and EIA compared three monitors: the Sense product (Product A), and two other products on the market (not named in the study). “The test results indicated that, of the three products, the Sense monitor “demonstrated strong potential to support EIA, and therefore merits further evaluation.” In particular, Sense “demonstrated better overall accuracy and fewer homeowner obligations than the other two” products. Sense technology has evolved significantly since the original testing more than two years ago.

AC Energy Comparison Project

In 2020, Sense introduced an experimental feature that measures the home’s air conditioning performance and delivers personalized information in the Sense app. The AC Energy Comparison project compares the home’s air conditioning energy usage to similar homes based on state, zip code, local weather and home size. Sense calculates the average AC electricity usage per day (kWh) during the summer months and shows performance relative to other Sense users and potential savings. This comparative information provides insights to help Sense users decide whether they need to weatherize their home or consider HVAC system maintenance, updates or replacement.



The Sense application provides comparative information about AC energy usage to consumers.

After the feature had been introduced, the company enrolled homes in the study to shed light on the impacts of high air conditioning usage on consumers in aggregate.

Financial and Climate Impacts of Inefficient HVAC

Quantifying potential household financial savings, energy waste, and carbon reduction with precision data is important on a few levels. For utility customers without the Sense Home Energy Monitor, a targeted, in person home energy audit is the only way to discover whether their AC is inefficient. An audit can cost hundreds of dollars, which is burdensome for many consumers. Without good information about where energy is potentially being wasted, many consumers cannot make educated decisions about home weatherization and HVAC system maintenance or replacement. With data about their home's AC usage, consumers can understand whether remediation will save them money, and they can make informed decisions about steps they could take to address it.

For utilities, data about AC performance in customers' homes provides specific and credible information to message savings and other benefits they can offer to customers, encouraging them to take part in programs. Studies show that consumers do not believe the generic "save money" messages utilities currently use to market energy efficiency programs (see Shelton Group 2016 Energy Pulse[3]). With no ability to see behind the customer meter, utilities cannot offer the kind of highly personalized suggestions that consumers have become accustomed to from smart home providers such as Google, Amazon, and others. This inability to see how customers and their appliances are using energy use leaves utilities struggling to target specific offerings with the right information to the right customers, which can significantly impact the success of their energy efficiency programs. An analogy could be made to telephone providers

At the policy level, having AC comparison data on a broad scale allows policy makers to appropriately calculate incentives for new efficiency programs. Knowing customer savings and carbon reductions can give policymakers greater confidence in their program designs.

Identifying and targeting the least efficient homes could also support efforts by utilities to reach aggressive climate change goals set by states. As the earth's temperature continues to rise, with longer and more frequent heat waves both in the U.S. and around the globe, residential air conditioning usage will continue to increase, impacting both climate change goals and the ability of the utility grid to address high peak demands. As homes become more electrified with heat pumps and electric vehicles, overall demand for electricity will increase. At the same time, more renewables such as large-scale wind and power have come online and are predicted to increase as a proportion of energy sources for the grid, driven by a combination of the economics of renewable energy and climate change goals at the state and federal levels.

Utilities are challenged with adapting the grid to address these changes. Both at the local and grid level, we can expect that adaptation will be costly. As utilities try to meet carbon emissions goals, reducing overall consumption via energy efficiency measures can ease the transition and buy utilities the time they'll need to adapt their infrastructures, while moderating costs for consumers.

Methodology

Data and study design

To understand the impact of inefficient ACs, we selected Sense customers that had installed the Sense Energy Monitor prior to August 2019, had an AC reliably detected by Sense and had completed an in-app questionnaire about their home's location (zip code),

Policymakers can use AC comparison data to target efficiency programs house size (in 500 sq. ft. increments), age (year built), and type of house (single-family, multi-family, etc).

There were 14,968 households that satisfied the above criteria and were included in the study using anonymized data. For those households, we recorded AC consumption for the period of May 1st to August 31st 2020.

Our analysis consisted of three steps:

Step 1: Validation of AC consumption estimates
Establish the validity of the AC consumption estimates that the Sense app is providing. Here we demonstrated that the Sense daily estimates have a very high correlation with true AC consumption, and that on the aggregate across a 2+ month period, the Sense mean estimate of AC consumption was 95% of true consumption.

Step 2: Accounting for differences in weather and house size
We analyze the factors that impact AC consumption and we identified that weather, size of house and thermostat setpoint are the primary factors that affect AC consumption. To make comparisons between homes meaningful, we developed cohorts of similar homes, grouping by geo location and local weather and then normalizing AC energy use according to square footage.

Step 3. Putting it all together: empirical savings estimates
For each house and cohort, we estimate an empirical histogram of AC consumption. We then identify the inefficient houses (defined as similar houses that fell in the 80+%-percentile of higher consumption), compare them to the efficient houses (defined as similar houses that fell in the 20-% percentile of lower consumption) and estimate the potential cost savings (defined as current kWh minus kWh of efficient houses times the billing rate).

By aggregating the potential savings on a per cohort, state or US basis we estimate potential savings for making inefficient AC houses efficient.

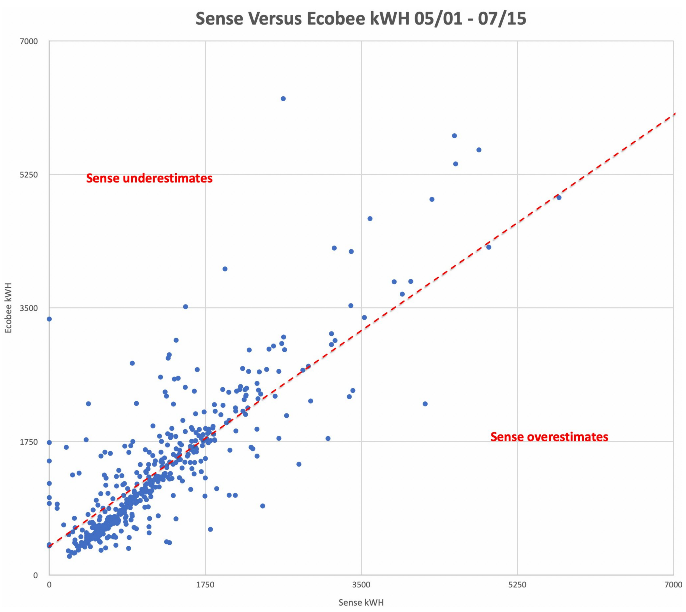
Validation of the AC consumption estimates

The Sense app allows consumers whose houses are equipped with Ecobee thermostats to enable integration of the thermostat with Sense. For these houses Ecobee provides AC condenser motor and blower fan runtimes, as well as indoor and outdoor temperature and thermostat setpoint in 5 minute increments. We selected 1263 such houses and manually curated an estimate of steady state AC consumption. By multiplying the Ecobee provided runtime with the manually curated wattage estimate we obtain an accurate estimate of kWh consumption which we can use as ground truth.

The next graph shows a scatter plot of the Sense kWh estimate compared to the Ecobee derived kWh for the period of 05/01/2020 to 07/15/200.

With the exception of a few outliers, the agreement is very good. The average correlation is 71%. There is a small bias for Sense to underestimate consumption. Manual inspection revealed that the cause is interference from other electrical devices in the house obscuring the condenser electrical signature and making detection harder. On the other hand, Sense kWH was occasionally higher than Ecobee kWh due to either an inaccurate wattage estimate by Sense, or by artifacts in ground truth (for example, there were a few houses with multiple AC units but only a subset of them connected to the smart thermostat).

On the aggregate, overestimates and underestimates nearly canceled - across all those 1263 houses, the Sense kWh estimate was 95% of the Ecobee kWh estimate.

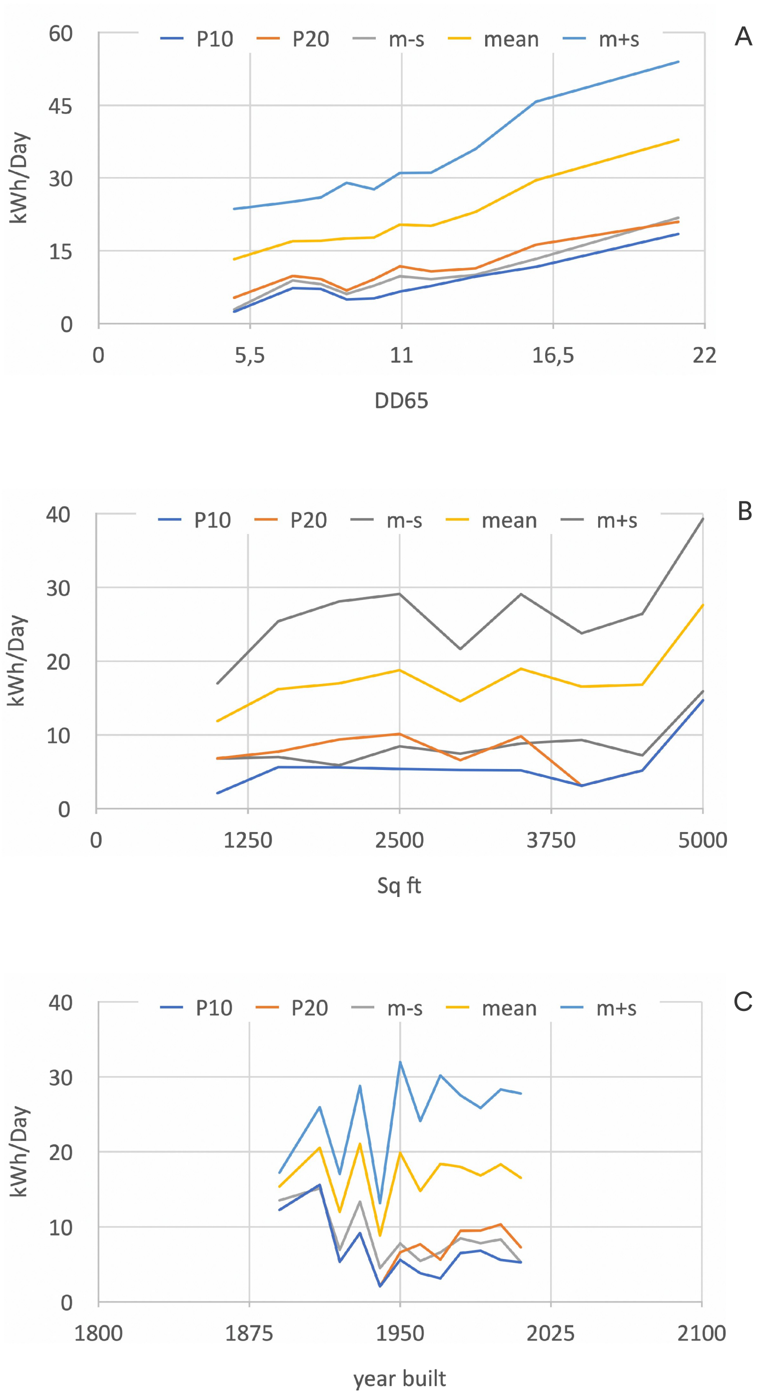


Accounting for differences in weather and house size

In order to understand which factors affect AC power consumption we selected 710 of the Sense/Ecobee homes for further study. We limited the study to the houses where the Sense and Ecobee estimates were most accurate, and to houses where we have available home demographic information - location (zip code), house size (in 500 sq. ft. increments) and house age (year-built).

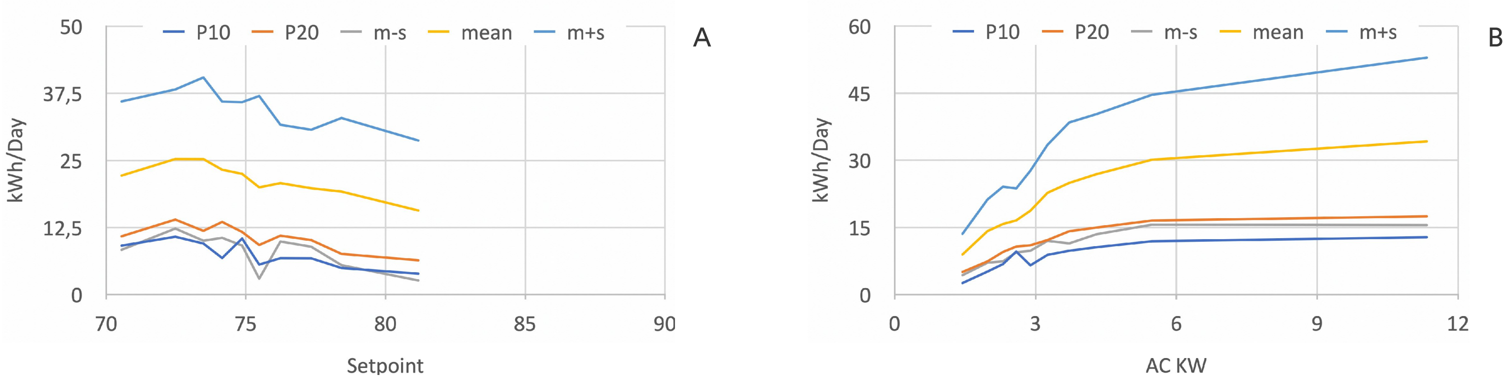
First we compared versus home and weather. The figures on the right plot kWh/by day against weather (degree-days 65, "DD65") house size ("Sq. ft.") and year built. For each variable we show average dependency ("mean"), the one sigma bands ("m+s", "m-s") and behavior of the 10-% and 20-^ percentiles of most efficient houses.

There was a strong, almost linear relationship with temperature; a small correlation with house size - more evident at small (1000sqft) and very large (5000 sqft) houses; and no clear pattern for consumption versus year built.



Relationships between energy consumption and climate (a), house size (b) and year the house was built (c)

What explains the differences between the mean, and the most efficient 10- or 20- percentiles? To understand, we plot daily consumption versus thermostat setpoint, and AC Wattage. As expected, we see reasonable savings at higher setpoints, and a very strong dependency of consumption on AC wattage. Possible causes for this dependency are older, less efficient ACs that need to use more power for same cooling, or ACs that had to be sized larger due to weather, home size or insulation.



Relationships between daily energy consumption and thermostat setpoint (a) and AC wattage (b)

Cohort selection and normalization

Based on the analysis above, comparison of AC consumption between households is more relevant when the households are similar in size, and have similar weather. To normalize for weather, we defined cohorts of similar houses based on the following algorithm:

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Step 1: If a zip code has > 200 houses, all houses in this zip code are defined as a cohort.

Step 2: If a zip-code has <200 houses, then consider all zip codes in a 200-mile radius and sort them by weather
similarity.  Weather similarity between two zip codes is defined as the percentage difference in the time that heat
index exceeds 70.  Only zip codes that are within 5% difference can be grouped in the same cohort.

Step 3: While step 2 still yields less than 200 houses, double the radius and repeat.
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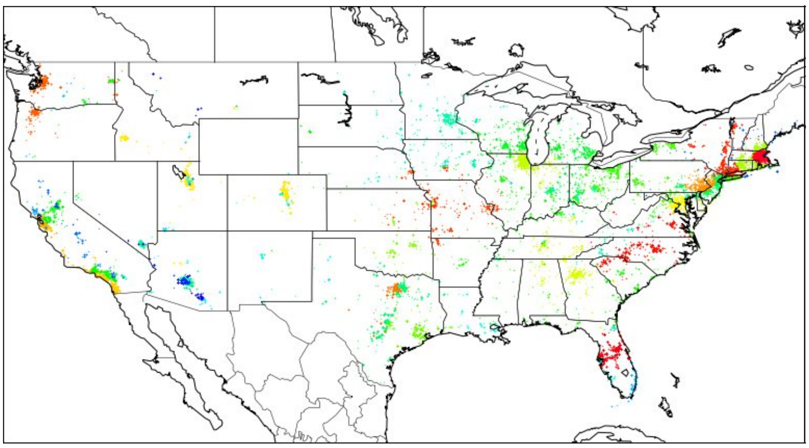
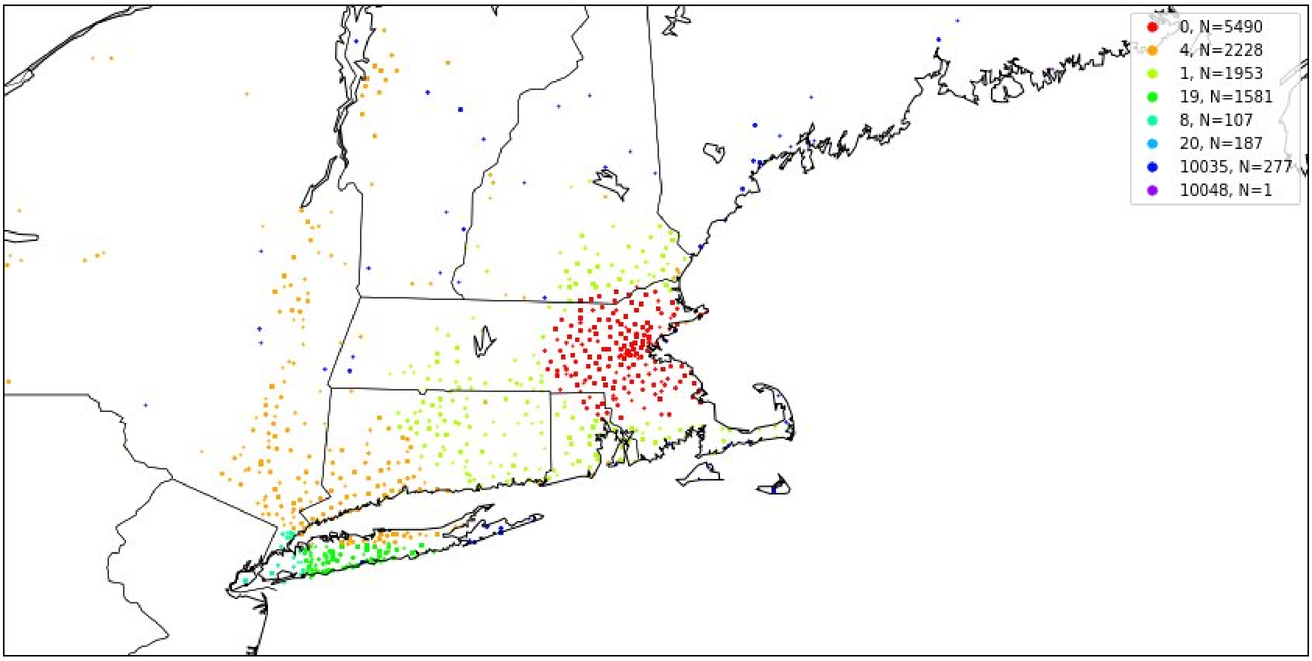
The figure on the right shows the selected cohorts across the US. There are a total of 42 cohorts depicted.



The figure below shows the cohorts selected by our algorithm for the New York and New England region. Note that the clusters delineate different climates. Coastal New England and Long Island (green markers on the plot), which typically have cooler summers, belong to a different cohort than inland Massachusetts (red markers) and the Hudson Valley (orange markers). Further, regions with milder summers, like upstate New York, Vermont, and Maine, belong to a third cluster (blue markers).

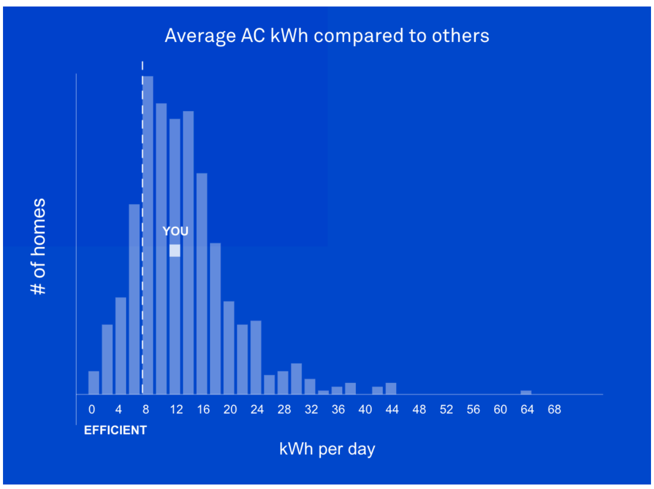


Cohort selections in New York and New England show climate clusters.

Putting it all together: empirical savings estimate

For each user, we present a cohort histogram that is consistent with the size of the user's house. In order to build this histogram, we normalize using a linear-regression based model. The normalization process is as follows:

- For the data within the cohort, we fit a linear regression model that relates the average daily usage to the square footage of houses in each cohort.
- Using this model, we transform the histogram to represent the statistics of houses with the same floor area as the user.



Lexington house AC comparison in the Sense app.

The image to the left shows the resulting comparison for a 4,000 square foot house owned by a Sense employee in Lexington MA. This house consumed 1318 kWH for AC for the period May 9th to Sep 4th, for an average of 11.55 kWH daily. Compared to similar homes, this consumption was close to the average. However, the square-foot adjusted average of the 20% most efficient houses was 6.53 kWh. The billing rate for Lexington, MA, is 0.22 per kWh. Therefore this house spent 5.02 kWh/day * $0.22 * 122 days = $134 more than a similar, efficient house.

Study results

The analysis demonstrated that 20% of homes with highest cooling energy use have a big impact on the nation's energy picture, accounting for 45% of all cooling consumption nationwide. Incentive programs from utilities that target and update these least efficient homes could save 8% of US residential electricity usage overall and have a significant impact on U.S. climate change goals by eliminating nearly 52M tons of CO2 emissions annually and reducing annual electricity usage by 115 billion kWh. By comparison, in 2019 the U.S. generated 107 billion kWh from solar and 300 billion kWh from wind. At the same time, updating and weatherizing the least efficient homes in the country could save consumers $15.3B per year.

> *Incentive programs could eliminate nearly 52M tons of CO2 emissions annually*

Many states have committed to ambitious goals to decarbonize their energy systems, and energy efficiency is a key part of those goals. For instance, New York has adopted aggressive targets to decarbonize the power sector by 2040 and reach net-zero economy-wide by 2050. The Climate Leadership and Community Protection Act (CLCPA)[4] set a 2025 statewide energy efficiency target that will deliver nearly one-third of its greenhouse gas emissions goal of a 40% reduction by 2030. The state has called upon its utilities to achieve significantly more, in both scale and innovation, in their energy efficiency activities.

Being able to identify and target homes with inefficient HVAC systems could help utilities reach those goals faster and at lower cost. In New York, Sense data shows that transitioning the 20% of homes with the highest AC usage to equal the 20% lowest AC usage similar homes would reduce New York state's residential electricity use by 6%. Homes with the highest 20% AC energy consumption have an outsize impact on the state's energy footprint, accounting for 40% of all residential cooling consumption. Residents in homes with the highest AC energy use pay a higher price, too, spending $782 more annually compared to the most efficient homes.

> *Upgrading the least efficient houses could reduce usage at peak by 13.5%*

The study also examined impacts on peak energy consumption. In California, the demands on the grid from millions of homes running air conditioning during peak evening hours (from 6 to 8 pm) prompted rolling blackouts in summer 2020. Sense's data shows that if the 20% least efficient houses in California were upgraded to match the most efficient homes, peak AC consumption would drop by 27.5%, reducing overall residential electricity usage at peak by 13.5%. Reducing peak loads so substantially would make the transition to low carbon energy a more realistic and achievable goal for policymakers and utilities, and reduce the current reliance on peak energy from carbon sources like natural gas - or expensive battery storage.

Conclusion

The study demonstrated the feasibility of using consumer technology to analyze electricity usage at the level of individual homes in order to identify the most effective ways to reduce energy usage. It showed that significant impacts could be made by targeting the houses with highest AC usage for utility incentives to improve their overall energy efficiency. Utilities could take advantage of this detailed home energy data in the following ways:

- Improve customer segmentation to increase participation in energy efficiency programs that include measures such as home assessments, HVAC upgrade rebates, or incentives to install heat pumps
- Enable cost-effective behavior change programs
- Increase meaningful participation in demand response events

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