

End-Use Level Impacts of the COVID-19 Pandemic on Residential Energy Usage in the Northwest

Hans Lehndorff, Evergreen Economics

Kevin Price, Evergreen Economics

David Clement, Northwest Energy Efficiency Alliance

ABSTRACT

How did the impact of the COVID-19 pandemic affect energy efficiency equipment usage, and how are load profiles shifting back towards normal as pandemic restrictions wane? This paper presents research methods and findings from a large-scale energy monitoring study in the northwest US that can provide insights into the pandemic's effect on energy use at an end-use level. Since 2018, this study has collected one-minute interval data for a range of end uses with a focus on electric HVAC and water heating equipment for over 200 homes across the region.

Since this study began well before the start of the pandemic and data collection is ongoing, it is uniquely positioned to provide end-use level insights into the ultimate non-routine event—the COVID-19 pandemic. To leverage this opportunity, this paper presents analysis completed using study data to examine the impacts of COVID-19 on a set of key end uses: ducted heat pumps, electric resistance storage water heaters, and electric vehicle chargers.

These insights help inform how the usage of key measures (such as heat pumps), key baselines (such as water heaters) and high demand end uses (such as electric vehicles) has been affected by human behavioral changes as a result of the pandemic and, therefore, the extent to which the assumptions that underly savings calculations may have changed. While the implications of these findings vary by application, these results highlight the importance of quantifying the impact of the pandemic on energy usage as those impacts may not always conform to expectation.

Introduction

The COVID-19 pandemic has had wide-reaching impacts on many aspects of daily life. However, quantifying how these impacts have affected residential energy usage at an end-use level can be difficult as few studies have sufficient data from both before and during the pandemic. Data from the Northwest Energy Efficiency Alliance (NEEA) and its funders in the Northwest US are now available from one such study that provides insights into the impacts of the pandemic on residential energy usage.

Leveraging these data requires a method of weather-normalization in order to compare across years. Evergreen Economics' Advanced Metering Infrastructure Customer Segmentation (AMICS) approach is one method of accomplishing this weather normalization through the generation of weather-day-type specific predictions for load. With weather-related changes accounted for by the model, the remaining differences in usage can be attributed to non-weather-related factors such as the non-routine event of the COVID-19 pandemic.

This paper presents a summary of results from the NEEA study and shows how the data and AMICS modeling approach can be used to determine the impacts of the COVID-19 pandemic on the energy usage of three key end uses: electric resistance storage water heaters, ducted heat pumps, and electric vehicle chargers.

NEEA's End Use Load Research Study

NEEA's residential and commercial End Use Load Research (EULR) studies are a key component of a broader regional strategy intended to update end use load research data. As NEEA and its partners identified, existing data were outdated and insufficiently robust to support efforts to meet the region's multitude of clean energy-related goals. The residential study—the Home Energy Metering Study (HEMS)—follows NEEA's Residential Building Stock Assessment (RBSA), which documented detailed characteristics of homes and occupants across the Northwest, including in Oregon, Washington, Montana, and Idaho (NEEA 2019).

The main objective of HEMS is to develop a robust characterization of continuous energy consumption of key heating and cooling measures to support achieving clean energy goals and utility information needs, providing:

- A much more accurate assessment of the contributions of energy efficiency technologies towards reducing peak demand;
- A better understanding of how to integrate renewable energy into the grid, increasing reliability as the deployment of distributed generation and new end use technologies increases over time; and
- Prioritized information needs by end use for use in a range of utility functions including demand response, load forecasting, and resource planning.

The study includes collecting one-minute interval data by circuit and whole house data from over 200 homes across the region. To be a part of the study, homes must have one of six targeted end uses,¹ but other non-targeted loads² are also captured when possible at each site.

This large-scale, high-profile study is on-going and will result in the production of updated and robust load shapes for heating and cooling measures that are critical to maximizing the value of energy efficiency in a rapidly changing utility context. As HEMS will run from 2019 to 2024, much of the analysis from this study is still forthcoming. However, some data from the study are now publicly available.³ The timing of this study also makes it uniquely positioned to provide insights into the impact of the COVID-19 pandemic on residential energy usage as many meters were installed prior to the onset of the pandemic.

Data Collection Processes

Evergreen Economics has developed a streamlined approach to implementing residential metering studies, which was utilized for HEMS (Price, Lehdorff, and Clement 2019). We start broadly by examining the population to develop a sample frame. From there, Evergreen evaluators methodically narrow our frame of reference to drawing the study sample and then to recruited sites and meter installations, which lead to data streams that are uploaded via cellular routers that securely push to the cloud-based database infrastructure.

¹ The targeted end uses are ducted heat pumps, ductless heat pumps, heat pump water heaters, electric forced air furnaces, central air conditioners, and electric baseboard heaters.

² There are many non-targeted loads that are captured including dishwashers, clothes washers, clothes dryers, electric vehicle chargers, non-targeted water heating, cooking appliances, refrigerators, and non-targeted HVAC equipment.

³ See <https://neea.org/data/nw-end-use-load-research-project/energy-metering-study-data> to access data. Data are currently up to date through the first quarter of 2022, and more data will be available soon.

Each data point is a time-stamped reading of energy usage (or temperature for the temperature sensors) over the past one-minute interval for the end-use/circuit.

Once data are uploaded, Evergreen runs a series of computing processes—including significant quality control and quality assurance checks (Lehndorff et al. 2020) that lead to a clean, aggregated dataset. Ultimately, these data will be used to estimate end use load shapes for key equipment types to be used by entities in the study regions.

The metering study data sample is designed to be representative of the study regions, thereby allowing for inferences to be drawn across regions, states, and climate zones.

With an average of 16 metered end uses plus whole home usage and two temperature sensors, the average home in HEMS produces around 10,000,000 minute-level data points each year.

Generating Weather Normalized Load Shapes with AMICS Modeling

Metering data like those collected for HEMS can be used to generate load shapes; however, load shapes vary considerably across homes. Usage also varies across the range of temperatures experienced by an individual home and can change generally over time. To make the insights from metering data actionable, especially when comparing across time periods, metering data and resulting load shapes must be weather normalized.

One method for producing weather-normalized load shapes is to use the AMICS modeling approach to perform weather normalization and conduct load shape analysis across years, regions, and studies. The AMICS model was originally designed by Evergreen for the purpose of creating annualized, weather-normalized load shapes from hourly whole-home energy usage data for Phase I of the AMI Billing Regression Study (Evergreen Economics 2016).⁴ Since the conclusion of the Phase I study, the AMICS approach has been extensively tested on residential customers participating in HVAC programs, smart thermostat optimization, multifamily whole-building retrofits, and home energy report programs (both recipients and controls).

The AMICS approach produces a portfolio of daily energy use load shapes, representing how each customer uses energy across a wide range of different weather conditions. A unique step in the AMICS modeling approach is segmenting the interval data into thousands of distinct segments (bins). Each bin contains interval energy use data for customers with similar energy usage patterns on days with similar weather conditions (e.g., cooling degree-day [CDD], heating degree-day [HDD], weekends vs. weekdays, and season). By binning the data before modeling, the approach limits the amount of variation (across customers and days) for which the model must account, thus increasing model accuracy. To test model accuracy, AMICS modeling includes holdout testing to ensure the appropriateness of the model.

Through extensive testing, we found that for this type of analysis, estimating models for each piece of equipment individually rather than grouping them on the basis of a broader characteristic was the most effective way of accurately predicting energy usage for specific end uses. Segmenting customers individually leverages their unique behaviors and patterns to accurately estimate end use load shapes for each customer under a variety of circumstances. Figure 1 shows a simplified example of how AMICS might be applied to energy monitoring data

⁴ In Phase I, this approach was referred to as the Random Coefficients Model (RCM), named for the specific type of regression. Evergreen has since renamed the model to emphasize segmentation, the step that is unique to this approach.

of electric furnaces in this analysis. In this example, the days at each site have been grouped by coldness (e.g., HDD) and day type (weekday/weekend). “Very cold” is defined as days with average temperatures below 24 degrees Fahrenheit and “mild” as days with average temperatures greater than 60 degrees Fahrenheit, with “cool” and “cold” in between. The lines within each of the charts represents the average hourly usage for that customer on that type of day with the shaded areas representing the 95 percent confidence interval around the estimate. To test this particular model, a random selection of days would be held out to determine the model’s ability to accurately predict the held-out data.

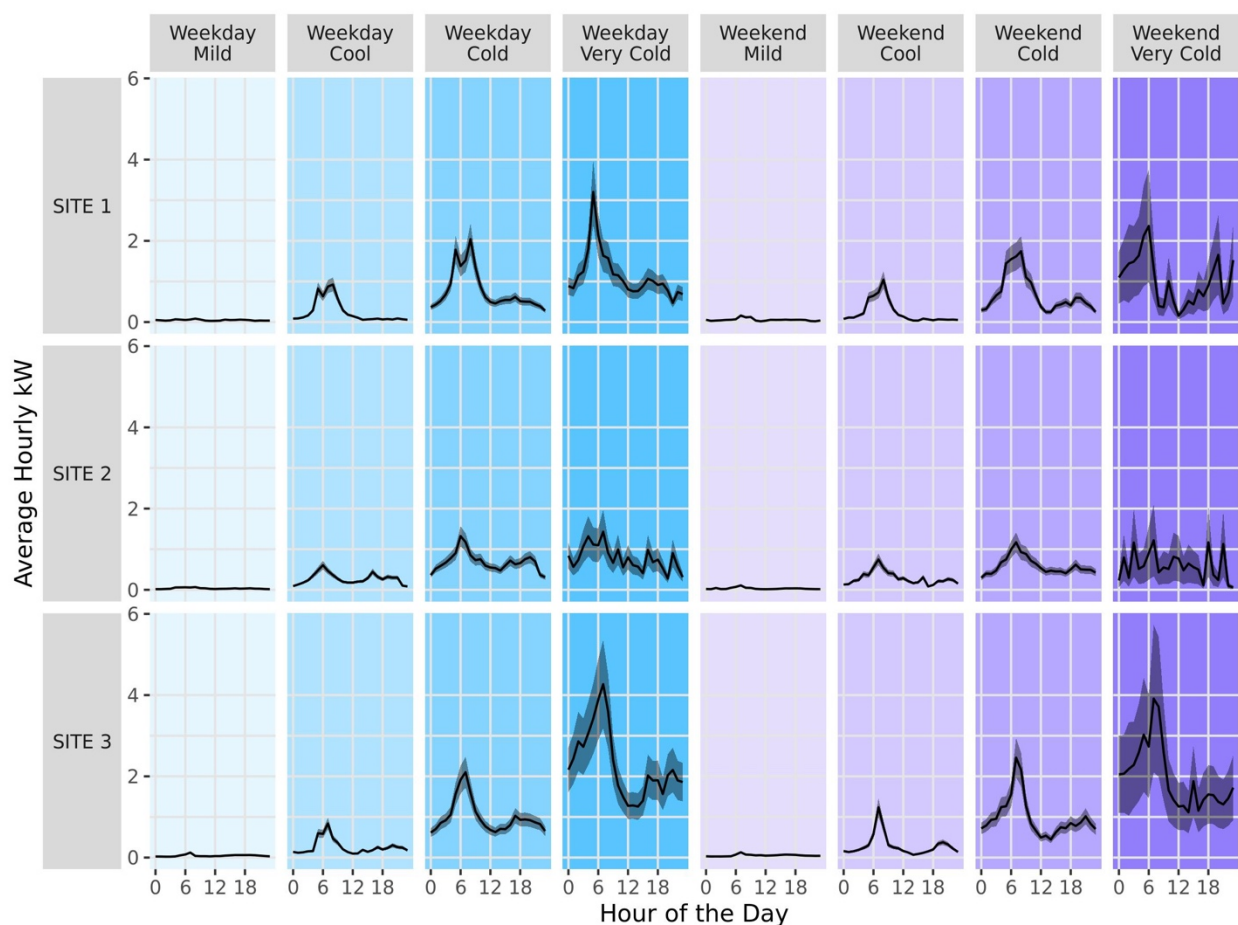


Figure 1. A simplified example of the AMICS approach

To detect changes over time, Evergreen constructs an AMICS model based on the data prior to program (or pandemic) intervention and then compares these predictions against the actual, observed usage. To compare across years (or simulate a theoretical year), a common set of weather observations are applied to the data. For example, if more very cold weekdays were observed at a site prior to the pandemic, the results of the during-pandemic data would be up-weighted to ensure a like-to-like weather comparison. Figure 2 shows an example of how Evergreen uses the electric furnace data for Site 2 shown in Figure 1 to determine the impacts of a theoretical program aimed at reducing electric furnace usage. In this example, furnace usage post-intervention was decreased significantly, especially in the afternoons of cold weekdays.

Also, in this example, no very cold weekdays were observed at this site in the post-period, meaning that those days would be excluded when aggregating up to the site or program level.

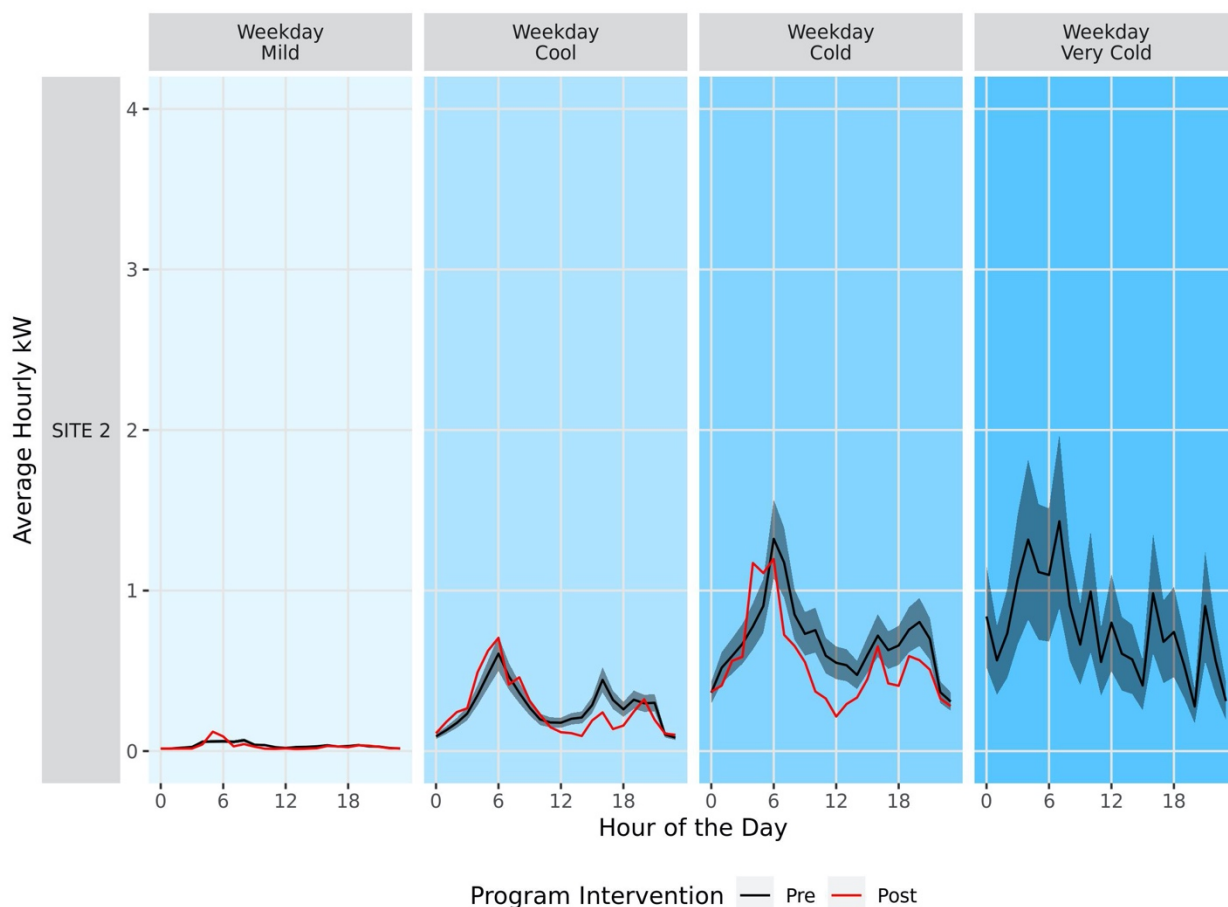


Figure 2. A simplified example of using AMICS to estimate energy impacts

While typically used to evaluate the impact of energy efficiency programs (often at a whole building level), we applied the AMICS approach to determine the impacts of the COVID-19 pandemic on end-use level energy usage data.

End-Use Level Impacts of the COVID-19 Pandemic

While the AMICS approach has a number of applicable use cases when applied to end use metering data (Lehndorff et al. 2020), Evergreen has recently used it to understand the end-use level energy usage impacts of the COVID-19 pandemic. To do so, Evergreen conducted additional research to better understand the pandemic's impact on residential energy usage.

Defining COVID-19 Pandemic Phases

The COVID-19 pandemic's impact on the behaviors of residents of the Northwest (the study area for HEMS) has changed over time. In order to define the different phases of the pandemic, Evergreen has constructed a timeline of the pandemic on the basis of case counts as

well as state and local executive orders. While the trajectory of the pandemic has varied greatly, not only between states but also within states, general case count trends serve as guides for the time periods included in this analysis. Figure 3 shows the seven-day moving average of new COVID-19 cases in Oregon, Washington, Idaho, and Montana. The colored areas correspond to the various phases of the pandemic. For simplicity, we have also divided the pandemic into two general periods, Year 1 (Lockdown, Restriction Easing, Winter Peak) and Year 2 (Summer Reopening, Delta, and Omicron).

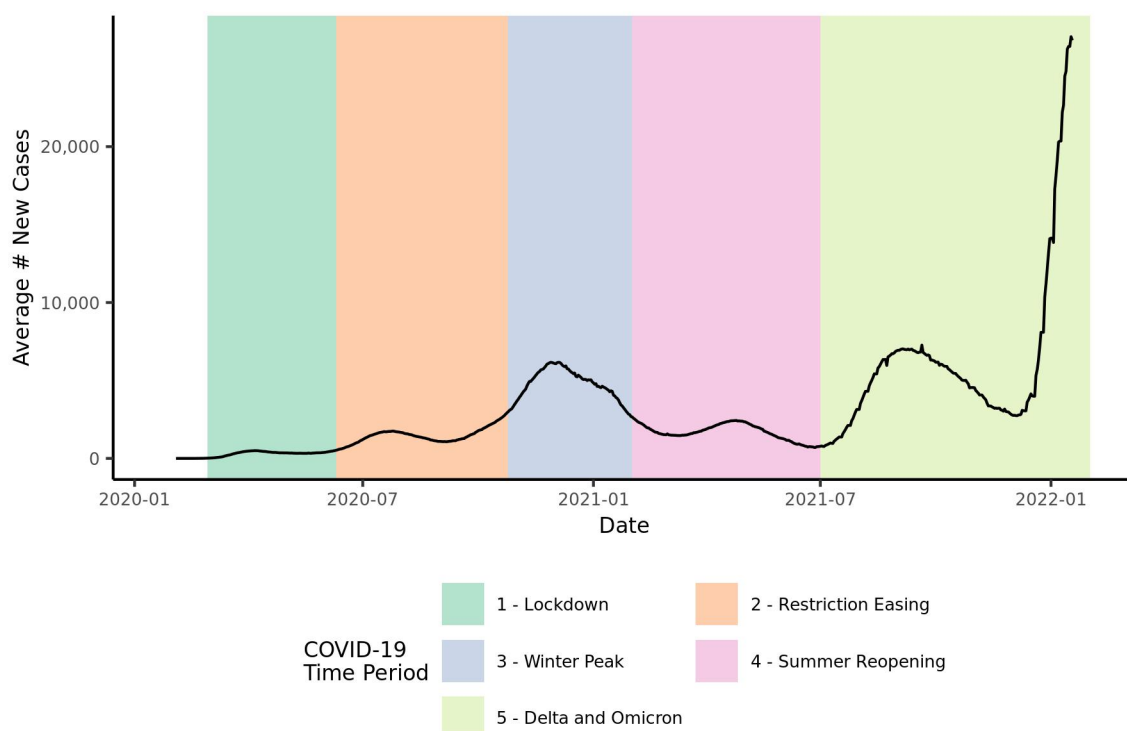


Figure 3. Seven-day moving average of new COVID-19 cases in Oregon, Washington, Idaho, and Montana

End Use Specific Results

To analyze the end-use level impacts on energy usage of the COVID-19 pandemic, we selected three representative end uses: electric resistance storage water heaters, ducted heat pumps, and electric vehicle chargers. We chose these because they represent a key baseline⁵ end use (electric resistance storage water heaters), a key energy efficiency measure⁶ (ducted heat pumps), and a high demand end use (electric vehicle chargers).

For each end use, we calculated actual load shapes during the pandemic as well as predicted load shapes based on pre-pandemic data. Results in this section are split between “Year

⁵ We use baseline in this context to mean an end use that is common and often replaced by a more efficient measure (e.g., heat pump water heaters).

⁶ This analysis describes how ducted heat pump usage has changed, not how it has changed relative to its baseline (e.g., electric furnaces).

1” (March 2020 through January 2021) and “Year 2” (February 2021 through January 2022) of the pandemic.

For this analysis, predicted load shapes are based on AMICS-modeled pre-pandemic energy consumption data for each end use. We have normalized all load shapes to reflect the weather observed *during* the pandemic. As a result, predictions represent the expected load shapes for each end use if the pandemic had not occurred. This analysis includes 95 percent confidence intervals as shaded areas around the predictions, and results have been weighted to represent the population of each targeted end use in the Northwest US.

Electric Resistance Storage Water Heaters

A total of 131 electric resistance storage water heaters had sufficient data to analyze the impacts of the pandemic. Figure 4 shows how observed usage in year 1 and year 2 of the pandemic compares to predicted usage based on pre-pandemic data. Results are weighted to represent the weather observed during year 2 and include a 95 percent confidence interval around the predictions. Overall, we observed a slight, 0.2 percent increase in electric resistance storage water heaters usage in year 1 and a 7.5 percent decrease in year 2 with significant decreases in the morning and evening hours for both years. While year 2 shows a decrease in usage across all hours, usage in year 1 actually increased between the hours of 8:00 a.m. and 7:00 p.m. by 6.6 percent.

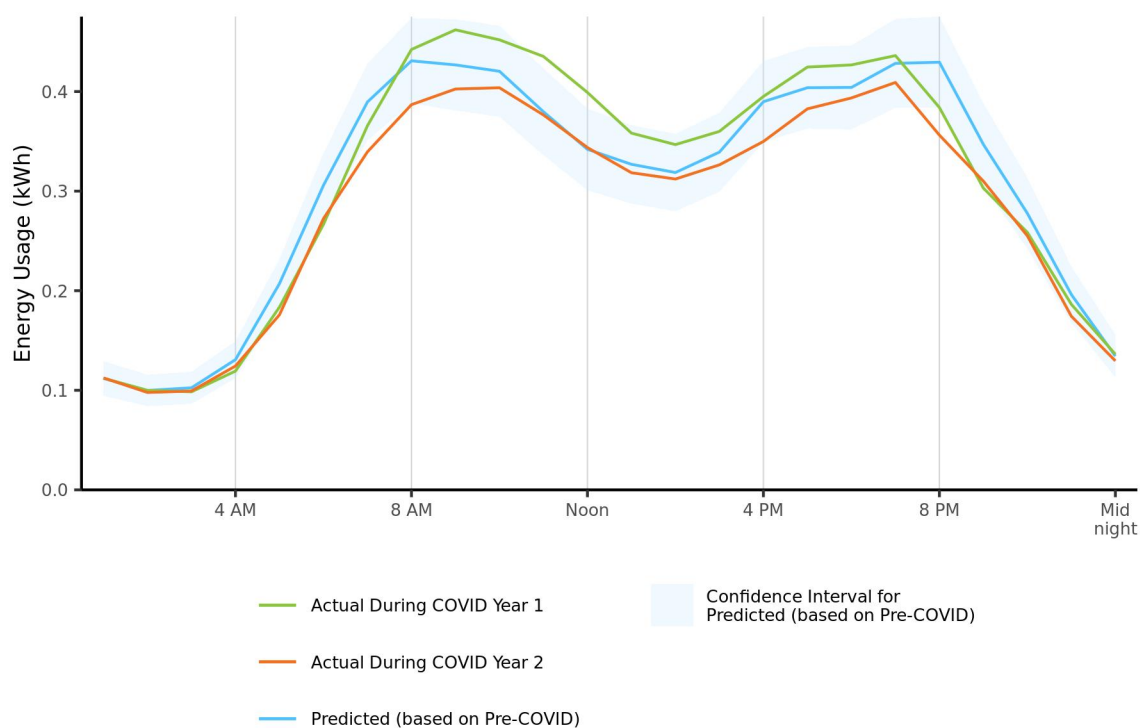


Figure 4. The impact of the COVID-19 pandemic on electric resistance storage water heater usage

To further highlight how electric resistance storage water heater energy usage changed over time, we also analyzed the change in energy usage on a daily basis, as shown in Figure 5.

For this analysis, we first calculated the average electric resistance storage water heater usage predicted by our model for each day and compared it to the average actual usage. For observations prior to the pandemic, the differences between actual usage and predicted usage reflect the relative accuracy of the model (i.e., model error). For observations during the pandemic, these differences represent the average estimated impact of the pandemic on energy usage on that day. To aid in identifying general trends, a 30-day retrospective moving average was applied to the impact estimates and provides monthly trends. From this view, several patterns in usage emerge.

First, there clearly are seasonal usage patterns that the model is not properly accounting for as evidenced by the consistent drop observed prior to the end of each year. While this suggests some model error, these are accounted for in Figure 4, and significant changes in energy usage are still observed, suggesting that general trends are reliable. Among these, we see a large usage increase for electric resistance storage water heaters that occurred during the first few months of the pandemic when the strongest restrictions were in place. At its peak, electric resistance storage water heater usage had increased by more than 0.9 kWh per water heater per day. As restrictions eased in the summer of 2020, electric resistance storage water heater usage returned toward normal, eventually showing decreases relative to pre-pandemic values.

Similarly, during the rise in cases in the winter of 2020, and during the peak of the omicron wave, electric resistance storage water heater usage trended in an increasing direction, and during the relatively open summer of 2021, peak usage decreased. The one break from this pattern was the rapid decrease in energy usage observed during the rise of Delta-variant cases in the summer and fall of 2021.

Overall, outside of the usage increases at the very onset of the pandemic, electric resistance storage water heater usage has trended downward throughout the pandemic with periods of increasing case counts somewhat countering this trend.

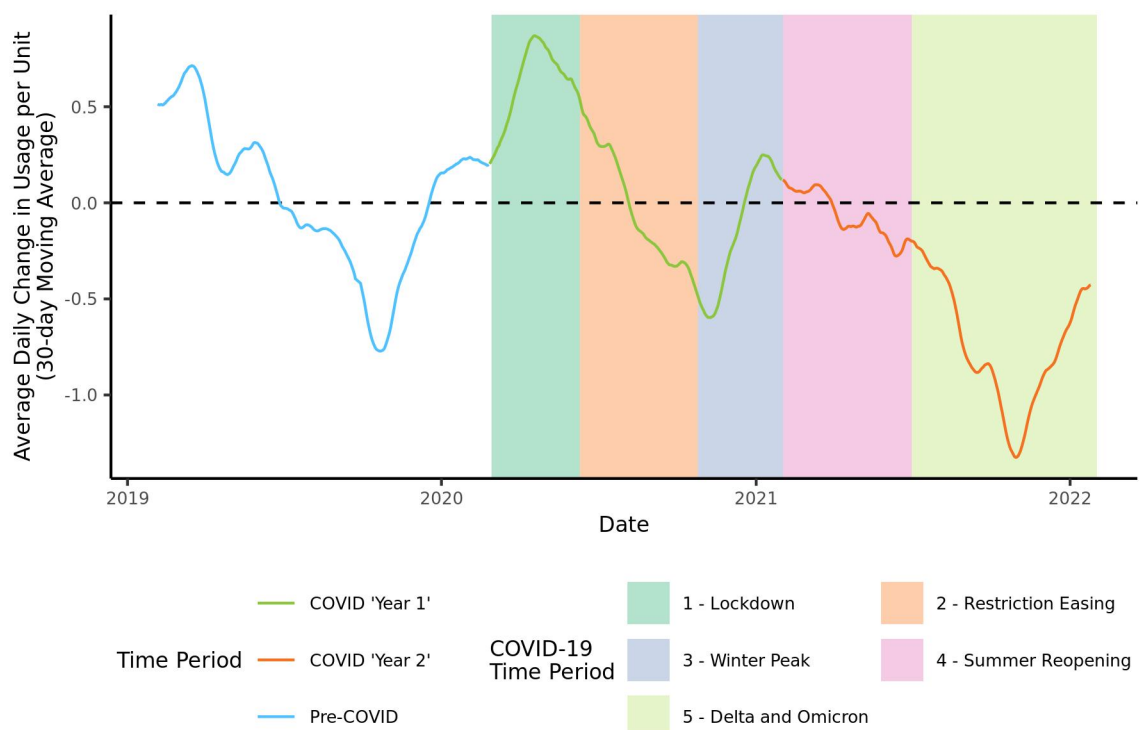


Figure 5. The impact of the COVID-19 pandemic on electric resistance storage water heater usage over time

Combined, these findings suggest that while net electric resistance storage water heater usage may have shown little change throughout the first year of the pandemic, usage actually increased at certain times and decreased at others during this time period. During year 2, electric resistance storage water heater shows a consistent downward trend, and further research with updated data will be required to determine the extent to which usage of this key baseline end use may have permanently shifted downward.

Electric Vehicle Chargers

A total of five electric vehicle chargers had sufficient data to support analysis of the impacts of the pandemic on EV charging. Figure 6 shows how observed usage in year 1 and year 2 of the pandemic compares to predicted usage based on pre-pandemic data. Results are weighted to represent the weather observed during year 2 and include a 95 percent confidence interval around the predictions. Because of the limited sample of electric vehicle chargers and the underlying variation of usage, some observed changes are not statistically significant; however, we observed an overall decrease of 42.6 percent in electric vehicle charger usage in year 1 and a 12.4 percent decrease in year 2 (relative to pre-pandemic usage) with the majority of this change occurring during the evening when peak charging typically occurs at these five homes. While these results are based on a small sample and may not be representative of the population at large, they do represent actual electric vehicle charging and conform to expected changes in usage patterns during the pandemic time period when commuting decreased.

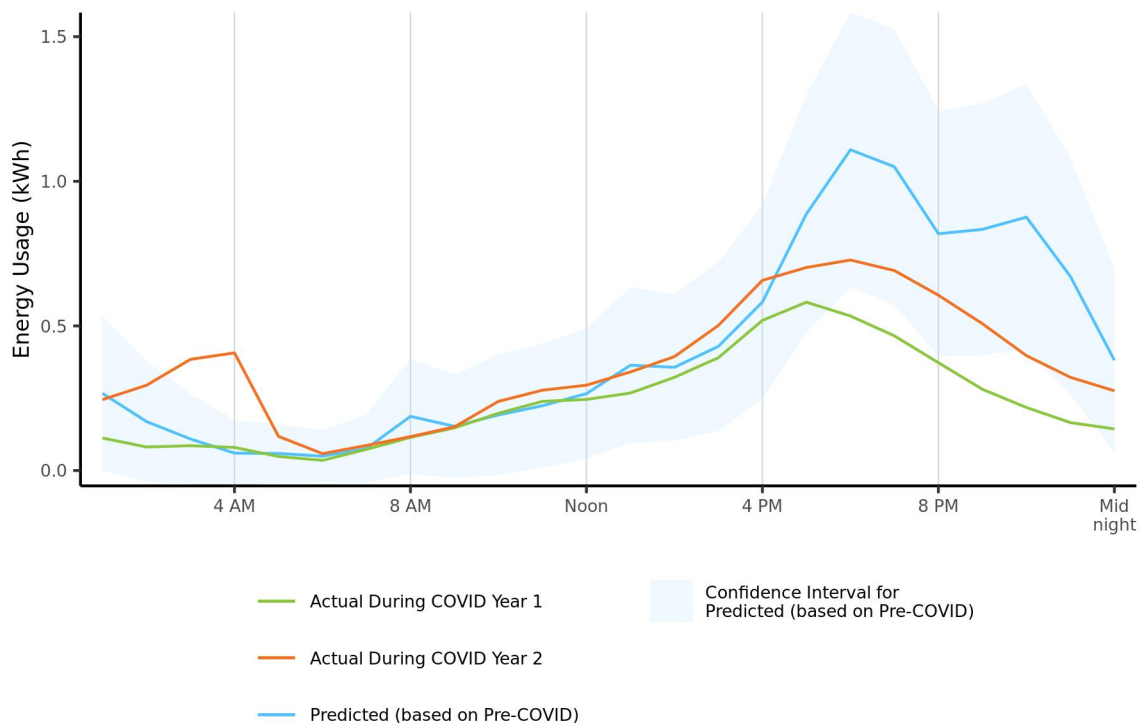


Figure 6. The impact of the COVID-19 pandemic on electric vehicle charger usage

As with electric resistance storage water heaters, we can analyze how this impact has changed over time. Figure 7 show a 30-day moving average of the difference between predicted and observed electric vehicle charger usage. Similar to electric resistance storage water heaters, the most dramatic changes in usage occurred during the lockdown time period when average electric vehicle charging fell by as much as 7.4 kWh per day per charger in our sample. Unlike electric resistance storage water heaters however, electric vehicle charger usage has steadily increased since this time. In fact, in recent months, despite the rise in cases as a result of the Delta and Omicron variants, electric vehicle charger usage has returned to pre-pandemic levels.

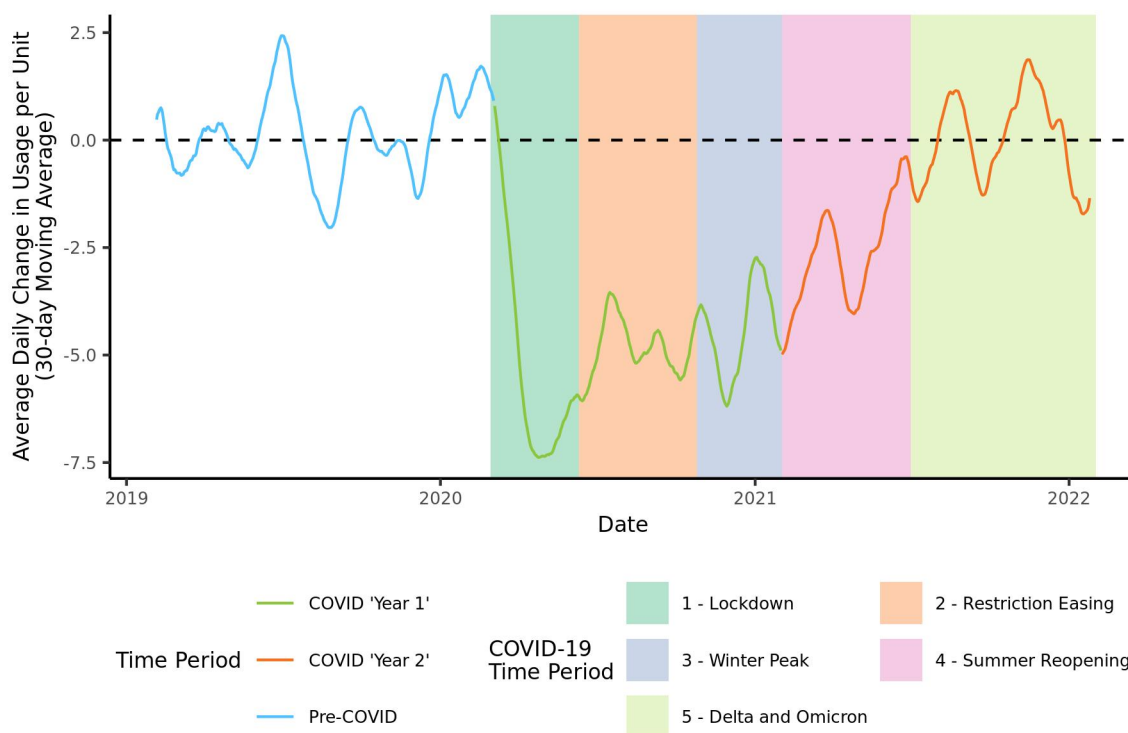


Figure 7. The impact of the COVID-19 pandemic on electric vehicle charger usage over time

Given that electric vehicle charger usage appears to have reached pre-pandemic levels, this analysis suggests that the decreases observed at the beginning of the pandemic were large but temporary. Like electric resistance storage water heaters, additional data will help determine the extent to which the return to normalcy currently observed in electric vehicle charger usage continues.

Ducted Heat Pumps

A total of 44 ducted heat pumps had sufficient data to analyze the impacts of the pandemic. Figure 8 shows how observed usage in year 1 and year 2 of the pandemic compares to predicted usage based on pre-pandemic data. Results are weighted to represent the weather observed during year 2 and include a 95 percent confidence interval around the predictions. Overall, we observed a 1.6 percent decrease in ducted heat pump usage in year 1 and a 1.2 percent decrease in year 2 (relative to pre-pandemic usage). However, at 95 percent confidence, only one hour in year 1 shows a significant change in usage (6:00 p.m.) and only three hours

show a significant change in year 2 (7:00 a.m., 8:00 p.m., 9:00 p.m.). Changes in ducted heat pump usage over time corroborate these findings, suggesting that ducted heat pump usage was largely unaffected by the behavior changes associated with the pandemic.

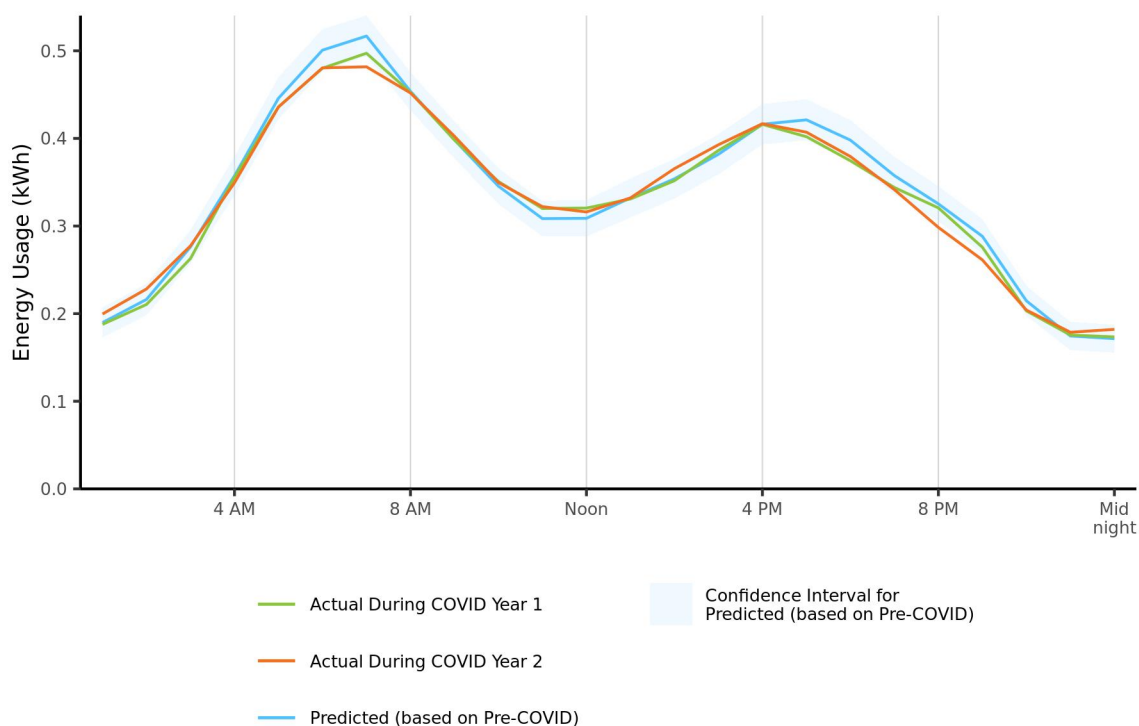


Figure 8. The impact of the COVID-19 pandemic on ducted heat pump usage

Unlike electric resistance storage water heaters and electric vehicle chargers, which saw dramatic shifts in usage during the pandemic, this analysis suggests that ducted heat pump usage was largely unchanged. While this analysis does not address changes that may have occurred in baseline measures, usage for this key energy efficiency measure appears to have not changed significantly at most times of the day.

Conclusions

The COVID-19 pandemic has profoundly impacted daily life, and residential energy usage was not immune to this impact. The publicly available data that are collected as part of HEMS represent one potential avenue for understanding the detailed impacts of the pandemic, as the study was initiated well before the onset of the pandemic.

Leveraging these data requires a method of weather-normalizing metering data in order to compare across years of the pandemic. Evergreen Economics' AMICS approach is one method of accomplishing this weather normalization through generation of weather-day-type specific predictions for load. With weather-related changes accounted for by the model, the remaining differences in usage can be attributed to non-weather-related factors such as the pandemic.

As part of this analysis, Evergreen analyzed the metering data of three end uses using AMICS to determine the pandemic-related changes for each end use. In the case of electric resistance storage water heaters, a common energy efficiency baseline, we observed a shift

toward midday usage and away from morning and evening usage in the first year of the pandemic, but a consistent and sustained decrease in usage since then. For electric vehicle chargers, a high demand end use, we observed a dramatic decrease in usage at the onset of the pandemic followed by a steady return to pre-pandemic usage levels over the subsequent 18 months. Finally, for ducted heat pumps, a common energy efficiency measure, we observed very little in terms of significant energy usage change during any of the pandemic phases.

The implications of these findings vary by application, whether for program planners and implementers or utility resource planners and load forecasters. However, these results highlight the importance of quantifying the impact of the pandemic on energy usage as those impacts may be temporary (as in the case of electric vehicle chargers), potentially lasting (as with electric resistance storage water heaters) or virtually non-existent (as with ducted heat pumps). Above all, these results show that the impacts of the pandemic on energy usage may not always conform to expectation, but that a robust end-use level metering dataset is a key tool in understanding these impacts.

References

- Evergreen Economics. 2016. *AMI Billing Regression Study Final Report*. Prepared for Southern California Edison. http://www.calmac.org/publications/AMI_Report_Volume_1_FINAL.pdf
- Lehndorff, H., K. Price, M. Anderson, and D. Clement. 2020. *From Beginning to End-Use: Analysis Approaches from Two West Coast Residential Energy Monitoring Studies*. ACEEE Summer Study on Energy Efficiency in Buildings.
- NEEA (Northwest Energy Efficiency Alliance). Updated April 2019. *Residential Building Stock Assessment*. <https://neea.org/data/residential-building-stock-assessment>
- Price, K., H. Lehndorff, and D. Clement. 2019. “A New Data Resource for a Changing Energy Landscape.” International Energy Program Evaluation Conference (IEPEC). <https://www.iepec.org/wp-content/uploads/2020/03/Price-Kevin-A-New-Data-Resource-for-a-Changing-Energy-Landscape.pdf>