Reshape the PNW. New load shapes incoming for commercial HVAC

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ABSTRACT

The COMMERCIAL Energy Metering Study (CEMS), led by the Northwest Energy Efficiency Alliance (NEEA), delivers the most granular and representative HVAC end-use load data for commercial buildings in the Northwest in over three decades. Spanning 2020–2025, CEMS collected sub-hourly data from 70 sites across four states, capturing nearly 1,000 circuit-level channels for rooftop units (RTUs), heat pumps (HPs), and electric resistance heating (ERH). Unlike physics-based models such as NREL's ComStock, which simulate load profiles using building prototypes and assumptions, CEMS provides real-world, directly metered data that reflects actual usage patterns, including responses to extreme weather events like the January 2024 cold snap.

This empirical dataset enables energy efficiency program implementers to design more targeted and effective interventions. For example, CEMS data can identify inefficient HVAC control strategies—such as unnecessary backup heater cycling—allowing for retro-commissioning opportunities. Evaluators can use CEMS-derived load shapes to validate savings assumptions and improve the accuracy of forecasting tools. Compared to modeled datasets, CEMS offers higher confidence in time-of-use impacts, peak demand contributions, and regional variability.

Moreover, the integration of CEMS with NEEA's Commercial Building Stock Assessments enhances its scalability across the Northwest. With 15-minute interval data publicly available, CEMS empowers stakeholders nationwide to refine demand response programs, forecast electrification impacts, and pursue decarbonization goals with unprecedented precision.

Introduction

The Pacific Northwest has a long history of using end-use metering and load research to inform regional power planning. Beginning with the End-Use Load and Consumer Assessment Program (ELCAP) in the 1980s, hourly end-use data from about 80 commercial buildings has underpinned many of the region's commercial load shape assumptions for decades.[1] The ELCAP study produced a well-designed and thoroughly vetted dataset, but over time, as building envelopes, technologies, controls, and operating practices have evolved, planners have increasingly supplemented or replaced ELCAP-era shapes with a suite of commercial building simulation models used by the Northwest Power and Conservation Council (the Council) and the Regional Technical Forum (RTF). These models are based on the U.S. Department of Energy's commercial prototype buildings developed by the Pacific Northwest National Laboratory, which provide physics-based representations of office, retail, and other building types across code vintages. The Council and RTF calibrate these prototypes to reflect Pacific Northwest building stock characteristics—including regional codes, construction practices, equipment saturations, and operating schedules—using inputs such as NEEA's Commercial Building Stock Assessment

[1] ELCAP has also been referred to as the End-Use Load and Conservation Assessment Program

(CBSA) data and other data derived from studies sponsored by RTF or other regional stakeholders.

These approaches have supported important planning and evaluation decisions, but they share a growing deficit: they do not reflect how today's commercial HVAC systems actually operate in real buildings under real weather and control conditions. In particular, the region has lacked large-scale, modern, directly metered load data for rooftop units (RTUs), heat pumps (HPs), and electric resistance heating (ERH) in commercial offices and retail buildings.
The Commercial Energy Metering Study (CEMS), conducted under the five-year End-Use Load Research (EULR) initiative and managed by NEEA, shrinks that gap. CEMS monitored 70 office and retail buildings, totaling over 4.4 million square feet of conditioned space, across Idaho, Oregon, Washington, and western Montana. The study deployed circuit-level submetering, indoor ambient and supply air temperature sensors, and, where feasible, collected whole-building and advanced metering infrastructure (AMI) interval data to develop high-resolution, weather-normalized, population-scaled load shapes for RTUs, HPs, and ERH.

CEMS data is intended to renew modeled commercial HVAC end-use load shapes with meter-based sources for the Northwest, while also supporting demand response (DR), retro-commissioning, and electrification planning. This paper describes the CEMS dataset and methods, compares CEMS to legacy ELCAP and prototype-based approaches, presents key findings for RTU, HP, and ERH load shapes, and offers concrete calls to action for technical advisory committees, program administrators, and planners.

Legacy Load Data and Modeling in the Northwest

The ELCAP dataset has informed commercial end-use shapes used in long-term forecasting tools, RTF methodologies for conservation potential, and resource planning and cost-effectiveness analyses (RTF 2013). However, ELCAP's commercial dataset is now nearly four decades old. The buildings, HVAC equipment, and controls it captured all reflect an era before many building energy efficiency and electrification initiatives were adopted across the region. The Northwest climate has also significantly warmed since the ELCAP study was conducted, influencing the frequency of heat waves and other climatological events that directly affect HVAC responses and shapes (USDA, NOAA/NCEI 2022). ELCAP's hourly resolution and circuit grouping approach, while a necessary metering restriction 40 years ago, is ill-suited for modeling today's diverse HVAC technologies, advanced controls, and real-world operations.[2]

The region's commercial building simulation models used by the Council and the RTF are invaluable for exploring what-if scenarios (for example, converting a share of gas-fired RTUs to high-efficiency HPs), power capacity and generation resource planning, and for filling data gaps where no metered data exist, such as emerging technologies or under-studied building types and end-uses. But some of the models' HVAC inputs are ultimately assumptions about how buildings and technologies behave rather than direct observations, especially at higher resolutions (e.g., 1-minute, 15-minute). These assumptions cannot fully capture how HVAC systems actually run under non-ideal controls, misconfiguration, or degraded equipment; the

[2] The "circuit grouping approach" that the ELCAP metering methodology used appears to have been limited to metering groups of similar circuits (e.g., if there were three 3-phase rooftop air conditioning circuits, the metering protocol would allow grouping those three similar circuits together). The ELCAP metering protocol appears to have restricted metering in aggregate circuits of different end uses, except for cases where metering individually would have prevented them being metered at all.

extreme responses seen in real cold snaps or heat waves; or the distribution of responses across a heterogeneous stock of buildings and operators.

When planners use vintage, outdated shapes or purely model-based profiles for ubiquitous HVAC technologies, they risk assuming that old equipment and control practices approximate today's stock; that prototype schedules and thermostat settings chosen to simulate code design approximate actual operation; and that HVAC capacity responds to extreme climate events as modeled. These assumptions affect DR potential estimates and the timing and pricing of dispatch, the estimated peak contribution of space heating electrification, and the time-varying avoided costs and cost-effectiveness of HVAC programs. CEMS is designed to materially reduce these uncertainties by providing directly metered, temperature-conditioned, and population-scaled HVAC load shapes for office and retail buildings in the region.

CEMS Design, Methodology, and Dataset Overview

EULR Context and Objectives

CEMS is part of the End-Use Load Research (EULR) project, a five-year, $12.5 million effort co-funded by Northwest utilities and federal partners. EULR comprises two major studies: the Home Energy Metering Study (HEMS) for residential loads and the CEMS for commercial loads. NEEA managed both CEMS and HEMS, and DNV was the lead implementer for CEMS.[3] The main objective for CEMS was to develop representative high-frequency energy and temperature data that characterize three key commercial HVAC technologies in office and retail buildings: RTUs, HPs, and ERH. Metering was intentionally planned to last five years to capture a wider range of extreme weather events, enabling increased understanding of HVAC equipment performance. The intent of the EULR was to support decarbonization, energy efficiency, demand response, and load forecasting across the Northwest.

Sample, population, and HVAC technology frame

The CEMS sample consists of 70 commercial buildings: 43 office buildings and 27 retail buildings. These range from a 3,400 square foot mattress store to a 1.1 million square foot, 56-story office tower, and the sample totals over 4.4 million square feet of conditioned space. Within each sector, sites are stratified by building size. Study sites were primarily drawn from NEEA's CBSA participants willing to host meters, with additional recruits agreeing to participate in both CEMS and CBSA. This design ensured each CEMS site has rich CBSA building data (for example, floor area classification, envelope characteristics, and end-use inventory) and facilitates population expansion.

To scale site-level results to the regional population, the study used the 2019 CBSA as the population frame. The CBSA indicates that, across the Northwest, offices and retail buildings with RTUs, HPs, or ERH represent hundreds of millions of square feet of conditioned floor area, a significant percentage of the 3.4 billion square feet of the total commercial floor space in the Northwest. These CBSA counts and floor areas are critical for expanding CEMS site-level data to population-representative technology load shapes and sector totals. Table 1 and Table 2 present stratification and case weights for the office sector and retail sector, respectively.

3 DNV. https://www.dnv.com/about/

Table 1. Office sector stratified population, sample, and case weights

Population bin	Sites w/ RTU	Sites w/ ERH	Sites w/ HP	Total sites
Office sector – population counts				
<10,000 Sq. ft.	18,843	10,948	11,088	26,924
10,001 - 20,000 Sq. ft.	3,518	462	3,575	5,535
20,001 - 100,000 Sq. ft.	2,268	244	1,650	2,474
>100,000 Sq. ft.	209	35	64	336
Office Sector – sample counts				
<10,000 Sq. ft.	2	2	6	7
10,001 - 20,000 Sq. ft.	5	7	7	10
20,001 - 100,000 Sq. ft.	13	16	10	18
>100,000 Sq. ft.	3	7	4	8
Office sector – case weights				
<10,000 Sq. ft.	9,422	5,474	1,848	3,846
10,001 - 20,000 Sq. ft.	704	66	511	553
20,001 - 100,000 Sq. ft.	174	15	165	137
>100,000 Sq. ft.	70	5	16	42

Table 2. Retail sector stratified population, sample, and case weights

Population bin	Sites w/ RTU	Sites w/ ERH	Sites w/ HP	Total sites
Retail sector – population counts				
<10,000 Sq. ft.	40,788	40,242	-	59,874
10,001 - 20,000 Sq. ft.	7,534	3,876	2,971	8,412
20,001 - 100,000 Sq. ft.	4,875	4,350	1,572	4,875
>100,000 Sq. ft.	759	-	-	759
Retail sector – sample counts				
<10,000 Sq. ft.	3	2	-	4
10,001 - 20,000 Sq. ft.	6	6	7	10
20,001 - 100,000 Sq. ft.	10	6	2	11
>100,000 Sq. ft.	2	-	-	2
Retail sector – case weights				
<10,000 Sq. ft.	13,596	20,121	-	14,968
10,001 - 20,000 Sq. ft.	1,256	646	424	841
20,001 - 100,000 Sq. ft.	488	725	786	443
>100,000 Sq. ft.	379	-	-	379

While the CEMS metering plan prioritized three HVAC technologies (RTU, HP, and ERH), the study also metered other HVAC loads such as energy recovery ventilators, chilled water plants, and air handling units, as well as non-HVAC loads, including domestic hot water, lighting, and plug loads. Whenever possible and available, whole-building loads were collected via DNV-installed meters or utility AMI data. Across the 70 buildings, CEMS sub-metered nearly three-quarters of all targeted HVAC loads and metered or collected 55 whole building loads.

Data Collection and Quality Assurance

Metering commercial buildings at the circuit level is inherently complex and hazardous. The CEMS team encountered highly variable electrical infrastructure—multiple panels and subpanels spread across large building footprints, often with incomplete or inaccurate labels; constrained space in panels that made installing current transducers (CTs) on main feeders difficult or unsafe; unexpected panel configurations, such as "orphaned" energized breakers that were not connected to loads or three-phase circuit breakers feeding three independent single-phase loads; communication challenges in mechanical rooms and basements with weak Wi-Fi or cellular signals; and operational changes, such as tenant turnover or equipment replacements during the multi-year metering period. These realities required careful recruitment, pre-installation site visits, flexible metering plans, and continuous data quality assurance.

To ensure data quality, DNV developed detailed field procedures and applied quality assurance and quality control (QA/QC) at multiple stages. Field staff conducted pre-installation site visits to map panels, assess communication options, and draft metering plans; cross-checked panel schedules against actual breaker locations, ampacities, and observed loads; selected CT sizes based on breaker rating and wire gauge; verified voltage configuration and phasing; used handheld meters for spot checks of power and current readings; and carefully labeled CTs at both ends to maintain the integrity of circuit-to-channel mapping.

QA/QC was structured in three broad stages: pre-installation and installation (plan validation, CT selection, phasing, spot checks); post-installation events (flagging periods with meter clock issues, power outages, or anomalous readings); and contextual checks (comparing measured power ranges against expected ranges based on breaker size and nameplate capacity). The metering platform synchronized clocks via time servers, and alerts were triggered when a meter's clock drift exceeded a threshold. Affected periods were flagged as bad data when time errors could not be ruled out.

CEMS provides several data streams: one-minute circuit-level data (for study funders); 15-minute circuit data hosted by NEEA; whole-building power for a subset of sites from DNV meters (1-minute or 15-minute) or utility AMI (ranges between 15-minute and 1-hour); temperature data for indoor spaces and HP supply air; and weather data (NOAA actuals and TMYx normals) from each site's assigned weather station.[4] These streams are organized into a relational schema comprising tables describing site-level characteristics—like building type, square footage, total HVAC capacity—down to circuit-level and time-series information like circuit load designation (RTU, HP, ERH, Other, NonHVAC, WB), detailed equipment type, system grouping identifiers, capacity estimates, and data quality flags.

Deriving Representative HVAC Load Shapes

A critical step in CEMS was assigning each circuit to an HVAC technology and, where appropriate, assigning heating and cooling capacities. The study used a consistent set of rules and

[4] "NOAA actuals" are meteorological data from weather stations or datasets administered by the National Oceanic and Atmospheric Administration. The data coincides with the metering period. "TMYx" data is Typical Meteorological Year weather data derived from data more recent than the "TMY3" version. The TMYx version chosen was derived from 2004 – 2018 weather data.

component types to categorize each metered circuit. Capacity was assigned using another set of rules to each circuit, where applicable. Capacity assignment allows estimation of each HVAC system and the total (electric) heating and cooling capacity captured through sub-metering. For heat pumps, CEMS employed several algorithms to distinguish heating versus cooling modes based on combinations of power data, supply-air temperatures, and outdoor air temperatures. The algorithms separated HP heating and cooling load shapes. This circuit-level capacity data was later used to allocate square footage served by each technology, assuming floor area served is proportional to total capacity by technology in each building.

Circuit-level data was aggregated to system-level profiles (for example, all separately circuited components of a HP system), technology-level profiles (all HP circuits in a building), and sample-level aggregates (all HPs across the 70-building sample). An example of circuit-level data, averaged by weekday, is illustrated in Figure 1.

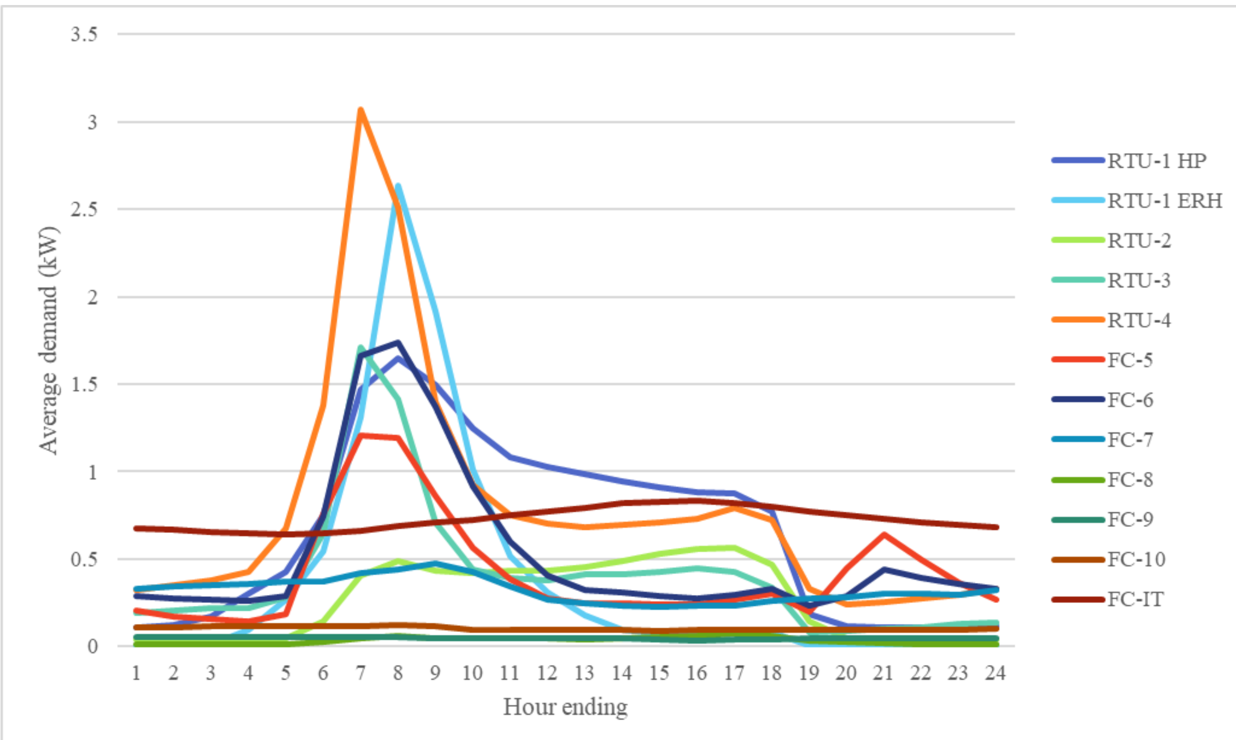

Figure 1: Individual HVAC loads at a small office, average weekday

To create normalized annual load shapes, CEMS fit time–temperature regression models for each HVAC technology, building type, and sometimes size segment. Models incorporated hour of day and day of week and use heating and cooling degree-days with optimized base temperatures. Regression models were evaluated based on mean squared error, and the best model in each cell was used to generate 1×8,760 hourly profiles using TMYx weather data for each site, then aggregated and weighted to create sector-level normalized shapes.

Initial Insights

Commercial HVAC Load Shape Insights

Electric resistance heat (ERH) causes the most extreme peak electrical demand of the three technologies and is a major driver of winter system peaks. For example, average facility-level ERH load increases by roughly 150% at the coldest temperature bins, as shown in Figure 2.

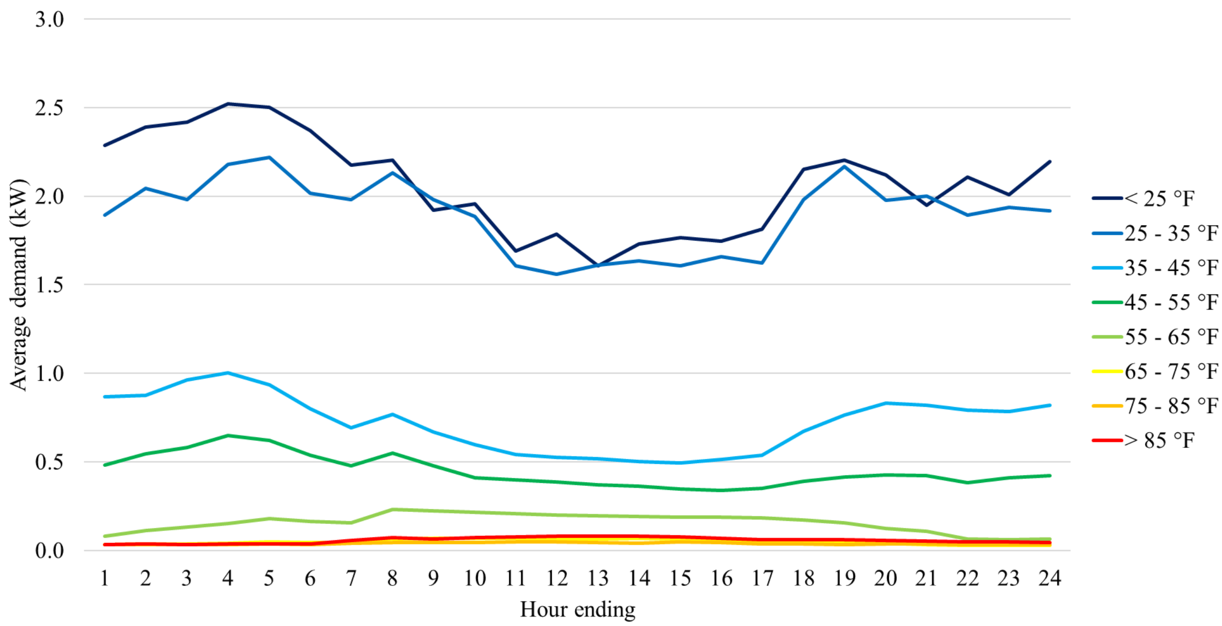

Figure 2: ERH load sensitivity to outdoor temperature (bins 10 °F temperature gradients, and < 25 °F and 85 °F), facility-level (average load per facility in the office + retail population)

Heat pumps also exhibit strong winter sensitivity but obviously carry a high summer demand when used for cooling. Office heat pumps, for example, show peak demands above 50 MW on the coldest January mornings, roughly five times greater than the annual average demand.[5] Retail heat pumps cause similarly high peaks, with winter peak demand nearly six times greater than the annual average. Figure 3 illustrates for the average load per facility that HP winter peak is one-third greater than the respective peak for ERH but occurs several hours later than ERH, suggesting different control strategies and heating priorities.

[5] The peak demand values are expanded actuals observed in 2023/24 observation period.

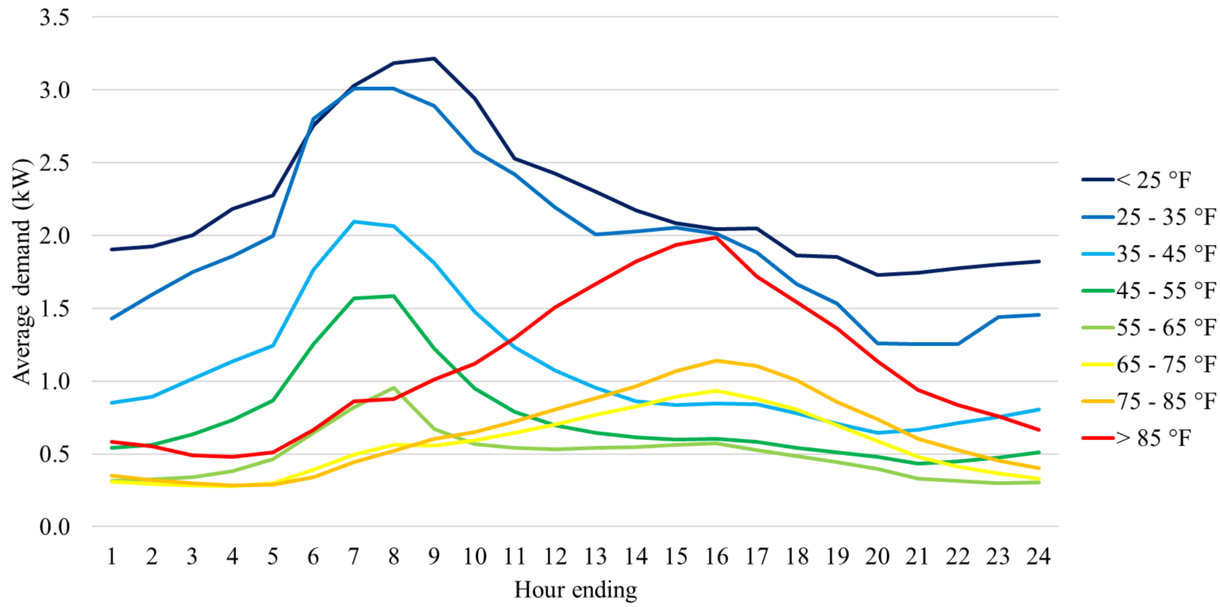

Figure 3: HP load sensitivity to outdoor temperature (bins 10 °F temperature gradients, and < 25 °F and 85 °F), facility-level (average load per facility in the office + retail population)

RTUs remain the workhorse cooling technology in Northwest offices and retail. Total retail and office RTU peaks occur in August and exceed 450 MW for the population, with the retail RTU peak (317 MW) more than double the office RTU peak (143 MW). RTU load factors (ratio of average demand and peak demand over the period) are higher in winter, when gas-heating units demand are dependent on schedule and ventilation demand rather than weather. Figure 4 shows average per-facility load and the relatively low demand during winter temperatures (no to low mechanical cooling) relative to the summer demand driven by hotter temperature. The RTUs metered in the study are gas-fired which offers stakeholders the ability to investigate potential electric impacts from fuel substitution scenarios for existing RTUs.

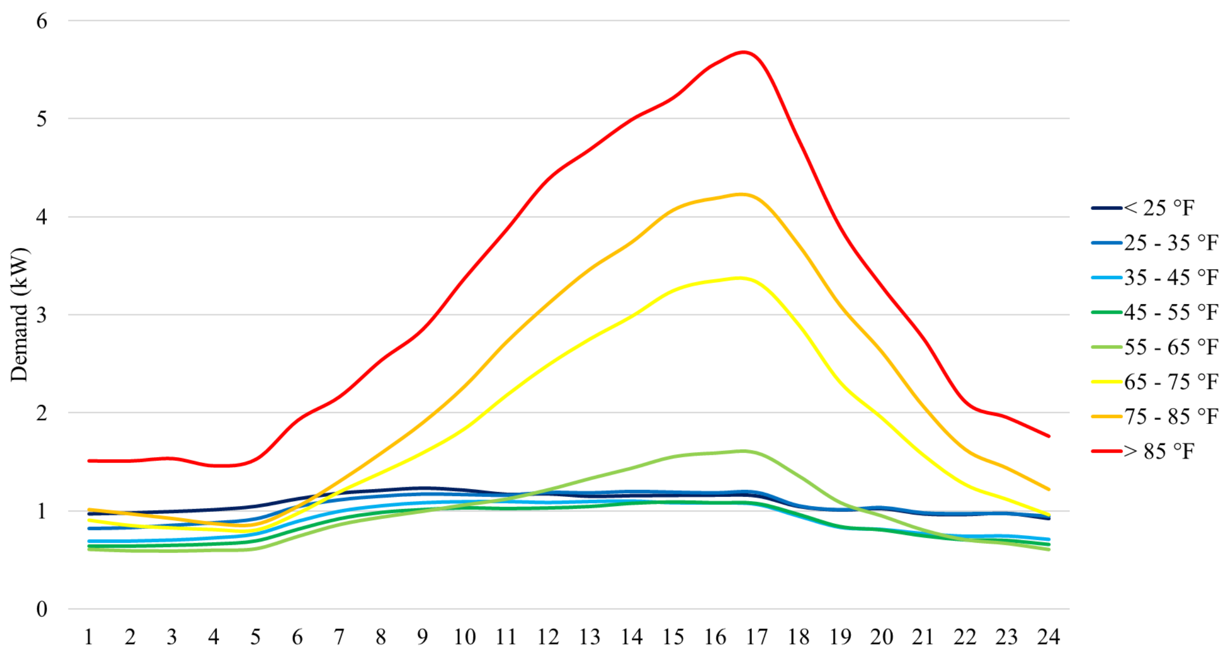

Figure 4: RTU load sensitivity to outdoor temperature (bins 10 °F temperature gradients, and < 25 °F and 85 °F), facility-level (average load per facility in the office + retail population)

Operational and Commissioning Insights

Beyond population-level shapes, CEMS circuit-level granularity exposes operational patterns that are vital for retro-commissioning, controls optimization, and fault detection and diagnostics. While CEMS did not perform concentrated analyses for these insights, there were multiple systems where ERH circuits operated under conditions indicating non-ideal control—for example, auxiliary strip heat for HPs energized at mild outdoor temperatures (more than 40 ˚F) where heat pumps could handle the load, or systems' load profiles maintaining occupied-level operation well into unoccupied hours, suggesting poor thermostat scheduling or controls. Because CEMS tracks individual HP circuits (and, if circuited separately, their associated auxiliary ERH circuits), analysts can disaggregate total heating load into HP versus ERH contributions and quantify how much ERH use occurred at temperatures where HP operation could have sufficed.

Common patterns across CEMS sites suggest a potential taxonomy of commissioning findings specific to RTU, HP, and ERH systems, such as backup ERH operating above intended lockout temperatures, RTUs with fans running 24/7, or compressor behavior indicating frequent short cycling or staging issues. Such a taxonomy could be incorporated into machine-learning algorithms with access to utility AMI data to identify potential participants for regional retro-commissioning programs.

Applications for Program Design, Demand Response, and Electrification

For **energy efficiency and commissioning programs**, CEMS offers regional utilities granular insights on specific HVAC technology load shapes, reducing reliance on ELCAP-era derived shapes or unsubstantiated modeling assumptions. Demand reduction estimates become more accurate as impacts can be mapped to specific hours of the day and year, and segment-specific targeting becomes easier as shapes reveal which building size bands have particularly high peak contributions. Program administrators can also use CEMS to quantify peak and fuel-substitution impacts, such as winter peak reduction stemming from better control of auxiliary ERH lockouts or improved summer demand profiles driven by the replacement of old vintage RTU ACs with high-efficiency heat pumps. In addition, metered sites where ERH is the primary heating source can be used to "ground truth" algorithms that infer the presence of ERH from customer AMI data—an area where stakeholders have reported limited visibility into the HVAC system types serving their small and medium commercial customers. By comparing AMI-based signatures to CEMS-derived ERH load shapes, utilities can identify prime candidates for ERH-to-HP conversions within their portfolios and better prioritize outreach to customers with the highest potential peak and emissions benefits.

For **DR programs**, CEMS provides data needed to define event windows and control strategies. Fifteen-minute and hourly shapes reveal when HP and ERH loads are most responsive to temperature and schedule, allowing DR events to target peak-dense hours.[6] The data can also improve our understanding and modeling of the relationship between HVAC response to weather events and equipment scheduling. For example, buildings that open at 9:00 a.m. or are closed on weekends can have very different peak reduction potentials than those with earlier or seven-day operations. These scheduling-informed patterns can improve the predictive models that identify which buildings are most suitable for DR participation and for how long they can sustain load reductions without compromising comfort or operations. Normalized shapes allow planners to understand typical DR potential, while actual-weather shapes show the magnitude of extreme-event DR opportunity, such as the January 2024 cold snap. A relatively small percentage of hours—winter mornings and summer afternoons—account for a large share of HVAC peak demand, indicating a sizeable slice of controllable load in the top 1 percent of hours that could be targeted for short-duration DR events.

For **resource planners**, CEMS provides baseline HVAC load shapes for the current stock of RTU, HP, and ERH systems by building type and size and a foundation from which to analyze electrification scenarios, such as converting gas-heated RTUs to high-efficiency HPs or replacing zonal ERH with HPs. By applying scenario assumptions to CEMS load shapes, planners can estimate changes in annual kWh and winter versus summer peaks, shifts in time-of-day peak profiles, and implications for resource adequacy and infrastructure planning. Because the shapes are meter-based and weather-normalized, they can also serve as calibration points for the Council's suite of commercial building models, improving confidence that those planning tools reflect actual Northwest building operation.

Limitations and cautionary notes

CEMS has limitations that users should consider, and those that the authors believe are notable are listed below. Despite these caveats, CEMS remains overwhelmingly more modern and granular than ELCAP and provides a much stronger empirical basis for many commercial HVAC segments.

- The sample is opportunistic, not strictly statistically representative, and focuses on buildings with RTU, HP, or ERH that agreed to participate. Statistical error bounds, though calculated, still reflect non-random sampling and should be interpreted in context.

[6] Study funders have access to 1-minute data and shapes, which allow for even greater sensitivity and insight into responsiveness and staging of technologies

- Not all HVAC capacity in each building could be metered, and some targeted technologies were intentionally metered in groups or in mixed aggregate if sub-metering them individually would have precluded metering at all.[7]
- Some non-routine events during the study period significantly affected the HVAC load, either by occupancy or equipment alterations. These events were noted and are available to consider but were not explicitly accounted for during load shape development.
- COVID "effects" were not statistically measured or accounted for in the load shapes. Metering began in November 2019, about five months before Northwest states issued statewide stay-at-home orders forcing commercial shutdowns, and only eight of the 70 sites were installed before those shutdowns. Recruitment and new metering did not resume until June 2021. We did perform nonstatistical, site-specific analyses comparing pre- and post-COVID periods, which found a mix of buildings with acute (and temporary) COVID effects and those with little to no apparent change.

Because each CEMS site has an expansion weight, a heavily weighted site can noticeably influence the population-scaled load shape. It was the intent of the CEMS contractor to document periods that were and were not included in the load shape development so users may assess themselves the impact that non-routine events had on the buildings' load shapes. The CEMS dataset and accompanying methodology documentation should allow analysts to modify data inclusion flags, population, and sample weights.

Conclusions and Calls to Action

CEMS provides the most granular and contemporary metered dataset of commercial HVAC technology loads in the Northwest in more than 30 years. It offers population-scaled, weather-normalized load shapes for RTUs, HPs, and ERH in office and retail buildings in the Pacific Northwest. These load shapes are based on actual loads experienced by 70 buildings over at least two years, with some building loads represented by over five years of data.

The RTF and Council should formally review and compare CEMS-based load shapes for office and retail RTU, HP, and ERH technologies to the disaggregated end-uses estimated in their existing commercial building simulation models. To compare, the CEMS technology-specific load shapes must first be disaggregated into their constituent heating, cooling, ventilation, and auxiliary end-use energies. For example, packaged "rooftop" heat pumps measured at the circuit level are aggregates of the packaged HP components: compressors, condenser fans, air handlers, auxiliary strip heat, etc.[8]

Utilities, program administrators, and demand response planners should pursue developing segment-specific load shape and scenario analyses from CEMS—by climate zone, size band, technology configuration, or control strategy—to directly support demand response program design, time-of-use rate design, and integrated resource planning. Regional funders should also treat CEMS as a template for future end-use load research, expanding meter-based

[7] Approximately 4% of metered circuits in CEMS were mixed aggregate circuits (i.e., a sub-panel was metered which fed multiple end-uses including HVAC), and 1% of metered circuits were grouped circuits by technology (i.e., all the sub-circuits in the aggregate were the same end-use technology).
[8] While the CEMS dataset does disaggregate HP heating and HP cooling, the disaggregation methodologies do not disaggregate ventilation or auxiliary loads from the HP heating or HP cooling.

load shapes to additional commercial segments and critical end-uses so that regional planning datasets evolve in step with the building stock and electrification trends.

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AI Disclosure

AI-assisted tools used: Microsoft Co-pilot.
Used for: Co-pilot was used to draft the conference paper. Co-pilot was given specific prompt in the form of guidelines and inputs for the draft, limited to the sources referenced in this draft paper. The primary source was the NEEA report *End-Use Load Research Commercial Energy*

Metering Study – Final Report. Using the referenced sources, the AI tool drafted the paper outline and text.
Extent: Drafting outline and text; summarizing
Human review: The authors reviewed and performed heavy draft editing on all sections of the paper.