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Reducing Gas Consumption in Existing Large Commercial Buildings

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FINAL PROJECT REPORT

Reducing Gas Consumption in Existing Large Commercial Buildings

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ABSTRACT

Natural gas combustion to serve space heating hot water systems causes approximately one third of large commercial building energy use in California. This project evaluated an innovative set of non-proprietary, cost-effective methods to reduce energy consumption and associated emissions from these systems. The project demonstrated 70% natural gas savings and substantial electricity savings in two large office buildings, yielding total utility cost savings of approximately $110,000 (or $0.5/ft²) per year. The project also conducted detailed studies on distribution losses and boiler efficiency in several buildings; measured performance of key components in laboratory tests; gathered and analyzed data from hundreds of buildings to evaluate actual performance of these systems; and provided a public dataset to inform future retrofits, research, and code development. The research also highlighted characteristics that make a building a good candidate for retrofit so these results can be scaled. Market transformation activities included 10 journal and conference publications, policy recommendations and a design guide. Based on these findings and other recent work, the opportunity for similarly large emissions reductions appears to be common within the existing large commercial building stock. The resources provided by this project can aid stakeholders in achieving California's goals to decarbonize buildings.

Keywords: Natural Gas, large commercial buildings, energy efficiency, heating hot water, boiler, reheat, distribution losses, retrofit

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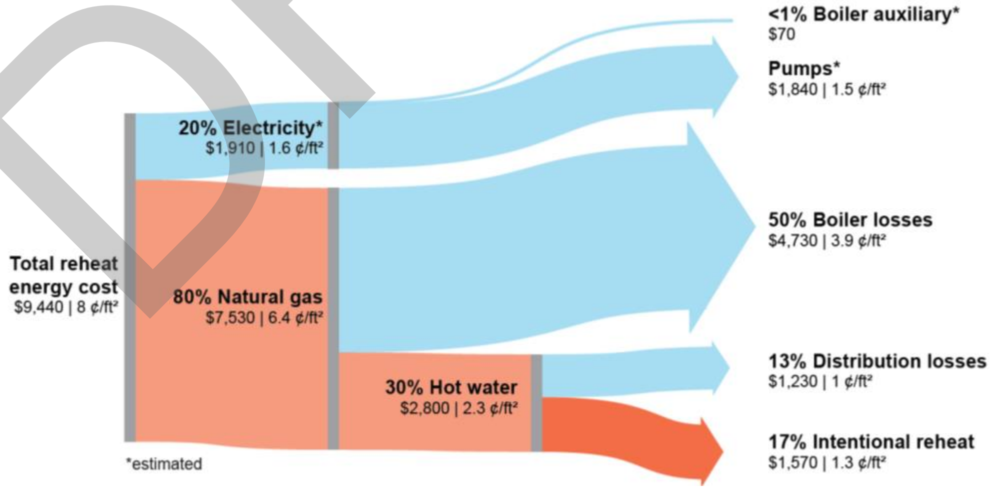
EXECUTIVE SUMMARY

Natural gas-fueled space heating in large commercial buildings represents an enormous opportunity to reduce both energy costs and carbon emissions. This project validated a low-cost Deep Decarbonization re-Design approach in several ways: demonstrated the savings potential in multiple large commercial buildings, conducted detailed studies in several buildings, quantified energy losses and component performance in laboratory tests, analyzed data from hundreds of buildings, and provided market transformation through a design guide, screening method, and ten journal and conference articles.

Background

Natural gas accounts for a third (32%) of all energy consumed by commercial buildings (U.S. Energy Information Administration (EIA), 2012). In California 90% of natural gas consumed in large commercial office buildings provides space and water heating (California Energy Commission (CEC), 2019), representing a third of all energy use in (CEC, 2022). Natural gas-fired boilers constitute the vast majority of space heating systems in large commercial buildings in California; typically these boilers supply hot water to 'reheat' coils at zones and sometimes also at the air handling units. Many of the zones served by these systems have incorrect minimum airflows, wasting reheat energy as well as fan energy to unnecessarily recirculate indoor air within the building. Furthermore, though boilers have high nominal efficiencies (80-90%), many are far less efficient in operation. A recent study that of the total cost for reheat building energy, 83% was lost due to a combination of high distribution losses and poor boiler efficiency (Figure 1).

Figure 1. Annual Energy Costs in a Hot Water Reheat System in a 120,000 Square Foot (ft²) Office Building



Calculated losses per equipment for a large commercial building.

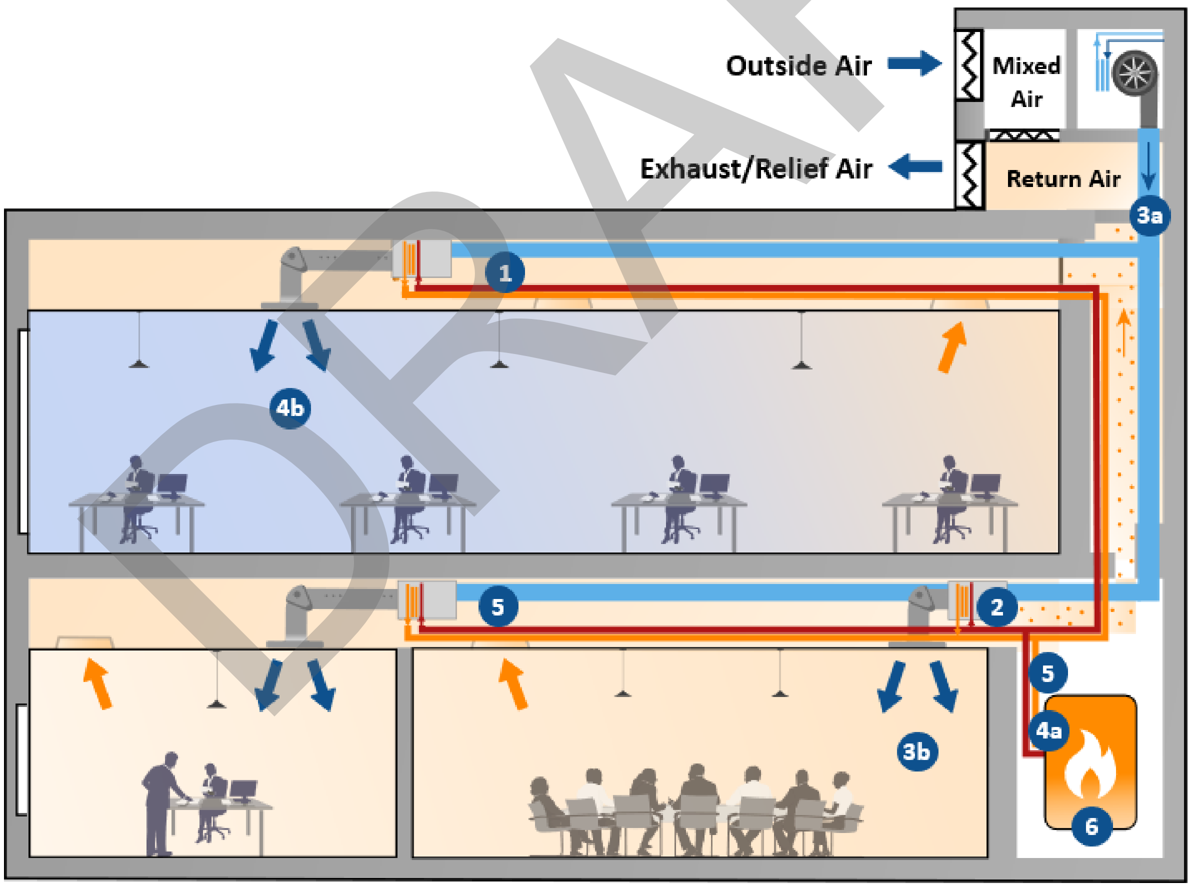
Credit: Paul Raftery, UC Berkeley

Despite heating hot water (HHW) being the predominant system installed in existing large buildings, there are few proposed solutions to fully decarbonize this system without entirely replacing it. Wholesale replacement is typically not economically feasible (even at boiler and/or air handling unit end-of-life) as it often means replacing the entire heating, ventilation and air conditioning (HVAC) system. This includes replacing zone-level reheat coils serving individual rooms which disrupts occupants. However, meeting California's climate goals requires a pathway to cost-effectively reduce the carbon emissions associated with these systems.

Project Purpose and Approach

This project proposed to reduce the carbon intensity of natural gas space heating in existing large buildings in a scalable manner by focusing on deep efficiency measures. The aim is to capture as many savings opportunities as possible within these systems, at zone, air handler, and heating plant levels (Figure 2), so that in aggregate they yield a very substantial reduction.

Figure 2. Opportunities to Reduce Natural Gas Consumption in Large Buildings

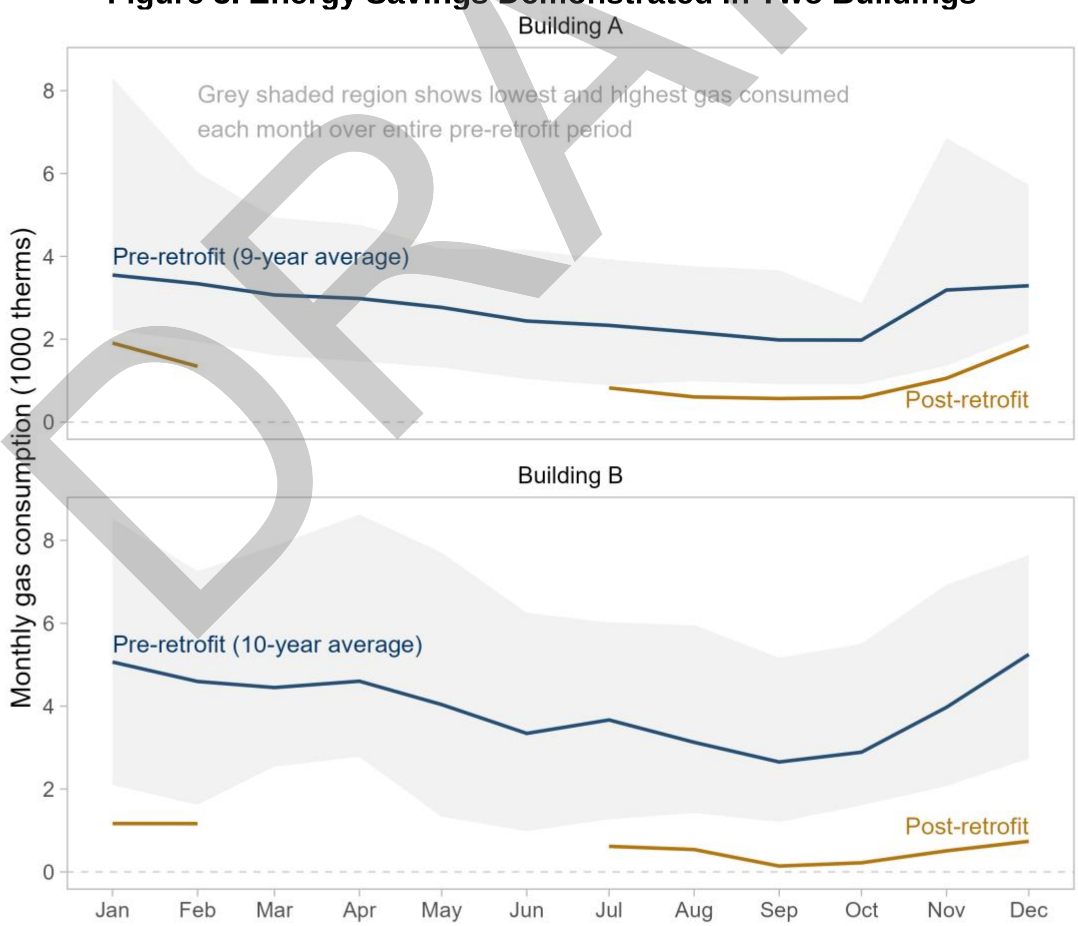


Six ways to reduce gas consumption: 1) correct minimum airflows, 2) fix passing reheat coil valves, 3) correct supply air temperature resets, 4) reduce high hot water temperatures, 5) address branch distribution losses, and 6) improve poor boiler efficiency.

These savings can be achieved—without replacing entire HVAC systems or performing a gut renovation—through a combination of **Deep Decarbonization re-Design** measures. This approach solves the underlying problems by first reducing unnecessary demand for heating and reducing distribution losses through controls measures, and then resolving issues with heating equipment itself. Many of the measures leverage existing automation systems to identify energy savings opportunities and then directly improve controls using recently standardized industry guidance (ASHRAE Guideline 36 2021). Another innovative feature of the proposed approach is novel equipment sizing and control to avoid poor part-load performance, while also reducing first costs. One major competitive advantage is that this approach can be adapted to the variety of conditions found in the existing building stock, whereas many purely equipment-focused retrofits will only apply to a small number of commercial buildings, and will achieve only a fraction of these savings.

In this project, the team demonstrated that capturing these opportunities in two existing office buildings (120 and 110 kft²) reduced annual gas consumption by 70%, as well as substantial electricity savings. When combined, the measures reduced costs by $110,000 per year ($0.5/ft².yr) at current utility rates.

Figure 3. Energy Savings Demonstrated in Two Buildings



The overall project included five technical tasks: Full **Demonstrations** in two existing large office buildings, as well as a secondary 'software-only' demonstration in a third building. This task involved in-depth design, evaluation, and measurement & verification of the Deep Decarb re-Design approach. **Detailed Field Study** to measure HHW system performance in detail in multiple buildings. **Full Scale Laboratory Testing** to evaluate key components of these systems in a controlled environment at Price Industries (HVAC manufacturer and project partner). **Data-Driven Analysis** of measured data consisting of over 120 million data-points from 259 existing buildings which the team gathered from 59 organizations nationwide to assess performance and opportunity for savings at scale. **Market Transformation** activities to provide public resources so that other stakeholders in the building industry can capture these opportunities more easily at scale.

Key Results

- The primary demonstrations reduced annual natural gas consumption by 69% and 71% annually in two large office buildings, and reduced electricity consumption. Demonstration in a third site using ultra low-cost, software-only controls changes in the non-lab portions of the building yielded 22% gas savings.
- Substantial energy, cost, and emissions savings can be achieved in existing buildings by correcting VAV minimum airflows and bringing controls up to ASHRAE Guideline 36.
- Further savings are possible through equipment replacement. Buildings with a heating hot water system served by a single, older, non-condensing gas boiler likely have very poor operational efficiency—far below nominal efficiency—and should be prioritized for retrofit.
- The team acquired and analyzed data from heating hot water systems in 259 buildings nationwide, highlighting that many of the assumptions regarding how these systems operate do not align with real world performance, with these systems operating far more frequently and less efficiently than expected, indicating substantial savings opportunities.
- The team measured heating hot water distribution losses (i.e., standby losses) of 1.2 W/m^2 in 7 buildings, and validated those measurements with newly installed, high-quality instrumentation at both building and branch level in one building. The team also validated the intentional reheat method using that instrumentation and repeated this analysis in a third building.
- The team performed full-scale laboratory testing of HHW system components, including developing and testing a custom coil designed for low water temperature operation suitable for all-electric new construction and existing building electrification retrofits.

Knowledge Transfer and Next Steps

- The team developed a screening method to identify candidates with high savings potential based on monthly gas consumption and minimal building information.
- The researchers released anonymized data consisting of over 100 million measurements from 216 buildings as a public resource for future research.
- Based on laboratory testing, one manufacturer is releasing a single circuit VAV reheat coil option which supports low water temperature designs, improving performance in both new and existing buildings.
- The team published findings in 10 journal and conference articles, a policy recommendations report, and numerous presentations.
- The team released a design guide to aid others in achieving these savings at scale in more buildings.

Conclusion

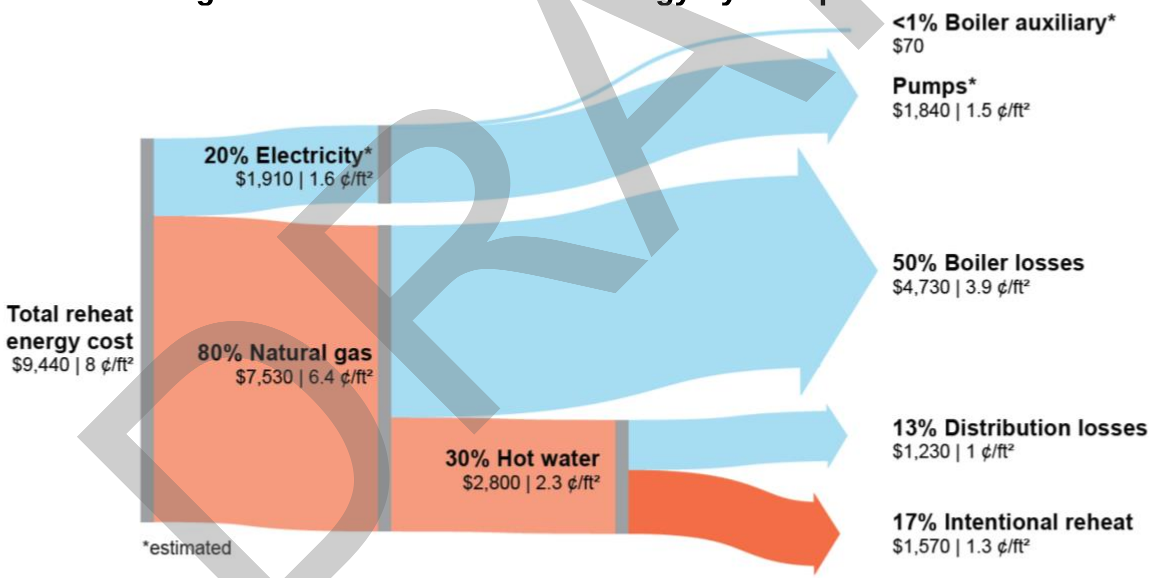
Overall, this project demonstrated substantial cost and carbon savings in existing buildings and provides information regarding the range of actual conditions experienced in these buildings. This information will assist building stakeholders in achieving decarbonization goals. First focusing on efficiency, and then electrifying the remaining loads will always be more feasible and cost-effective, than solely focusing on electrification. Further, the eventual emissions savings will be larger as the loads served by the electric equipment will be reduced, and these reduced electrical loads will also make it more feasible to achieve grid decarbonization goals.

CHAPTER 1: Introduction

Most natural gas consumption in large commercial buildings in the US is for space heating using a hydronic heating system. This heating hot water (HHW) system typically serves all space heating end-uses in the building, both at the air handling unit(s) and at the terminal units in individual thermal zones or rooms. In California, natural gas consumption is responsible approximately one third of site energy consumption in commercial buildings (California Energy Commission (CEC), 2022). Using current annual average electricity grid emissions rates, this also corresponds to approximately one third of site emissions.

Unfortunately, HHW systems often operate inefficiently. Field studies (Raftery et al., 2018) have shown that in some cases these systems may have exceptionally poor overall efficiency—only 17% of energy goes to intentional reheat (Figure 1)—due to a combination of issues.

Figure 1: Losses in Reheat Energy by Component and Cost



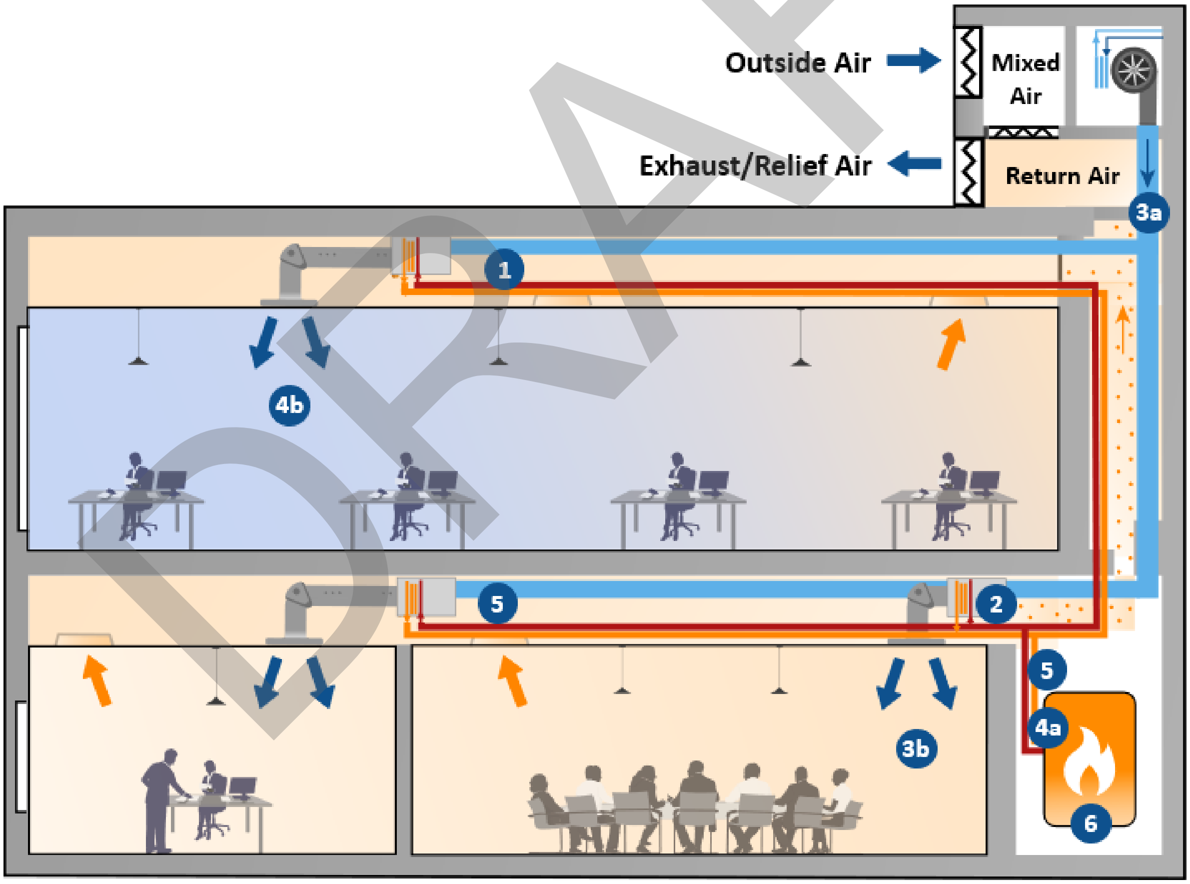
Calculated losses per equipment for a large commercial building: only 17% of the total reheat energy actually goes towards intentional reheat.

Credit: Paul Raftery, UC Berkeley

Figure 2 shows six typical contributors to these losses. Poor building automation system controls represent half of the problem (1, 3, and 4 in Figure 2). At the terminal unit, many HHW systems in the United States serve single-duct Variable Air Volume (VAV) systems with hot water reheat at the zone. While modern, code-compliant buildings can operate efficiently, many existing buildings operate with incorrect (high) minimum airflow rates and single-maximum control logic, which causes substantial and unnecessary reheat energy consumption (S. Taylor et al., 2012), and often will cause zones in a building to unnecessarily demand heat. For example, a study of seven buildings (nearly a million square feet of office space) measured whole building gas consumption savings ranging from 6.1% to 19.3%, along with measurably improved occupant thermal comfort surveys, from simply correcting minimum air flow rates at the terminal units (Arens et al., 2012). Another driver of poor efficiency is passing reheat valves, where a fully closed valve still allows a small amount of water to flow through it and into the heating coil, causing heat to enter the space unintentionally.

At the air handler there are opportunities to correct economizer controls, correcting outside air flow rates to those required by code (e.g. ASHRAE 62.1 (ANSI/ASHRAE, 2022a)), closing outside air dampers during unoccupied morning warmup periods and improving supply air temperature setpoint (Raftery et al., 2018) and duct static pressure reset controls.

Figure 2: Opportunities to Reduce Natural Gas Consumption in Large Buildings



Six main areas to focus on reducing gas consumption energy: 1) correct minimum airflows, 2) fix passing reheat coil valves, 3) correcting supply air temperature resets, 4) reducing high hot water tempertures, 5) addressing branch distribution losses, and 6) improving poor boiler efficiency.

Credit: Paul Raftery and Therese Peffer, UC Berkeley

At the heating equipment, there are often issues with boiler scheduling, staging, tuning, and water temperature controls. For example, (Katipamula et al., 2021) found that over 40% of the 151 buildings evaluated for retro-commissioning measures would benefit from improved hot water plant controls, particular for controlling supply water temperature. ASHRAE Guideline 36 (ASHRAE, 2021) describes these best practice controls strategies, but very few existing buildings currently operate this way. A simulation study estimated that implementing these best practice controls in existing buildings will save 31% of annual HVAC energy consumption (K. Zhang et al., 2022). Demonstrations of these retrofits as part of a previous CEC EPIC research project measured between 53 and 60% gas savings at three sites which underwent a full controls hardware retrofit, and savings between 12 and 23% for an additional three sites that underwent a partial 'software-only' retrofit (Cheng et al., 2022).

Yet another cause is the branch piping distribution system served by the heating equipment loses heat whenever the system operates. These losses are almost always neglected in analysis, simulation, or operation of these systems. For example, the ASHRAE 90.1-2022 standard (ANSI/ASHRAE, 2022b) requires that "piping losses shall not be modeled" when assessing building energy performance. However, the losses are not zero even in idealized, fully insulated conditions, and real buildings often have sections of exposed piping and uninsulated fittings. While these losses may have limited detrimental effect in very cold outdoor conditions as they (mostly) occur within the building envelope, medium and large commercial buildings typically have some demand for hot water year-round. So these losses also occur during the cooling season, placing additional burden on the cooling system to reject the heat which has been added to the building. Several studies have investigated these kinds of losses in other contexts in similar systems, such as (Y. Zhang, 2013) which found that an average of 33% of input natural gas energy was lost annually from Domestic Hot Water (DHW) recirculation piping in 28 multi-family residential buildings and (Hiller, 2006) measuring these losses in laboratory conditions, further highlighting that these losses are not negligible.

Finally, another cause of this poor efficiency is inefficient boilers. Heating equipment is typically oversized in commercial buildings. The seasonal nature of peak heating demand in buildings combined with the need for hot water in many buildings throughout the year exacerbates this, as the annual distribution of heat loads is highly skewed with many operating hours at very low loads that are a small fraction of the heating equipment's maximum capacity. Thus, even when appropriately sized, systems typically spend most of the time operating at very low load conditions, often below the minimum operating output (or 'turndown') of the boiler. This causes the boiler to cycle on and off (or 'short cycle'), which reduces efficiency and equipment life, and increases maintenance (Heselton, 2005; Peterson, 2018; U.S. Department of Energy (US DOE) Advanced Manufacturing Office, 2012). Secondary issues affecting heating equipment efficiency are that they have slightly lower operating efficiency in practice than nominal efficiency, shown both in laboratory tests with larger boilers for commercial buildings (Beliso et al., 2012; B. Taylor et al., 2012) and smaller residential scale boilers (Hayton, 2009). Over time, efficiency also decreases further due to issues such as scaling, poor combustion gas ratios, and poor maintenance.

To meet California's decarbonization commitments—for example, the commitment to carbon neutrality by 2045—we need to reduce natural gas consumption by HHW systems in commercial buildings. However, historically, these systems have received less attention due to the relatively low cost of natural gas compared to electricity. There is limited info available in the public domain about how HHW systems in commercial buildings actually operate. What exists is based on simulation and associated input assumptions, or detailed measurements from a single system (or small set of them), or whole building consumption level data (i.e. utility meter) often at very coarse time resolution (typically annual, rarely even monthly). In contrast, for residential combined space and domestic hot water systems there have been relatively large-scale field and lab studies, as well as broad data collection and analysis efforts (e.g. (Bennett et al., 2019; Rayment, 1995)).

To reduce emissions from existing large commercial heating systems, we need to both demonstrate that it is possible to save energy and quantify that savings potential, better understand these systems, and share these resources with building owners, operators, designers, and policymakers.

CHAPTER 2: Project Approach

The primary aims of this research project are to:

- Demonstrate that substantial energy and emission savings are feasible in existing large commercial buildings through equipment replacement and/or substantial improvement to controls (**Demonstrations**)
- Further measure performance of these systems in the field, validate whether prior methods and findings apply in other buildings, and identify viable strategies for improving performance in both new and existing buildings (**Detailed Field Study**)
- Measure performance in detail in a laboratory setting to better understand operating characteristics and limitations of system components (**Laboratory Study**)
- Acquire data from buildings at scale to report typical operating hours, temperatures, and loads for these systems (**Data-driven Analysis**)
- Identify opportunities to improve codes and standards, and conduct other market transformation activities (**Market Transformation**).

Each approach is described in this chapter. CBE and Taylor Engineers worked on the demonstrations. UC Davis, CBE, TRC, and Taylor Engineers conducted the detailed field studies in several locations. CBE researchers worked on the laboratory study at Price Industries. CBE, TRC, and Taylor Engineers developed the data-driven analysis. CBE, TRC, and Taylor Engineers worked on the market transformation tasks.

2.1 Demonstrations

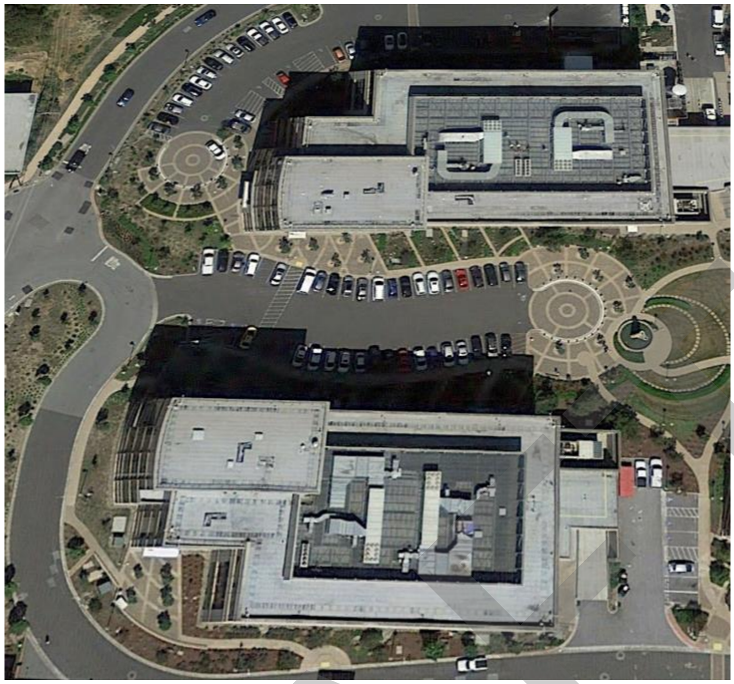
2.1.1 Primary Demonstration Buildings

The demonstration buildings for this project are two large office buildings in the San Francisco Bay Area. These are Building A and B (120,000 ft² and 110,000 ft² respectively). The primary HVAC system in both buildings is a single duct variable air volume system with terminal hot-water reheat. Two air handling units (AHUs) serve each building, and with a gas-fired boiler plant providing HHW and a campus chilled water system providing chilled water.

Overall Project Scope and Schedule

Prior to the start of the research project, there was a retrofit project scheduled to begin in late 2020 for both buildings. The primary aim was to replace the existing single boiler in each building due to end of service life, and to improve the redundancy of the new system by providing two boilers per building instead of one. The demonstration site owner's match funding covered the costs associated with the boiler replacement. The

Figure 3: Satellite Image of the Demonstration Buildings



Top view of Building A (top) and Building B (bottom).
Credit: *Google Earth*

research project then added a broad range of heating plant, air handling unit (AHU), and zone level measures to this scope. The majority of these were to update the existing buildings' controls to match ASHRAE Guideline 36-2021 as closely as possible without replacing the existing physical controller hardware throughout the buildings. The full set of measures implemented were:

Physical retrofit measures

- Right-sized new boilers, substantially smaller than typical
- Condensing boilers with high turndown (10:1), high mass and no minimum flow requirement
- Primary-only variable flow distribution (from primary-secondary)
- Capping bypass on 3-way valves (where feasible) to reduce distribution losses
- Automated detection (using discharge air temperature sensors) and repair of passing reheat valves

New instrumentation

- New flow meters, supply and return water temperature on boiler HW output
- New natural gas meters on boiler input
- New discharge air temperature sensors at each VAV box with a heating coil

Reprogram Building Automation System (BAS)

- Zone measures

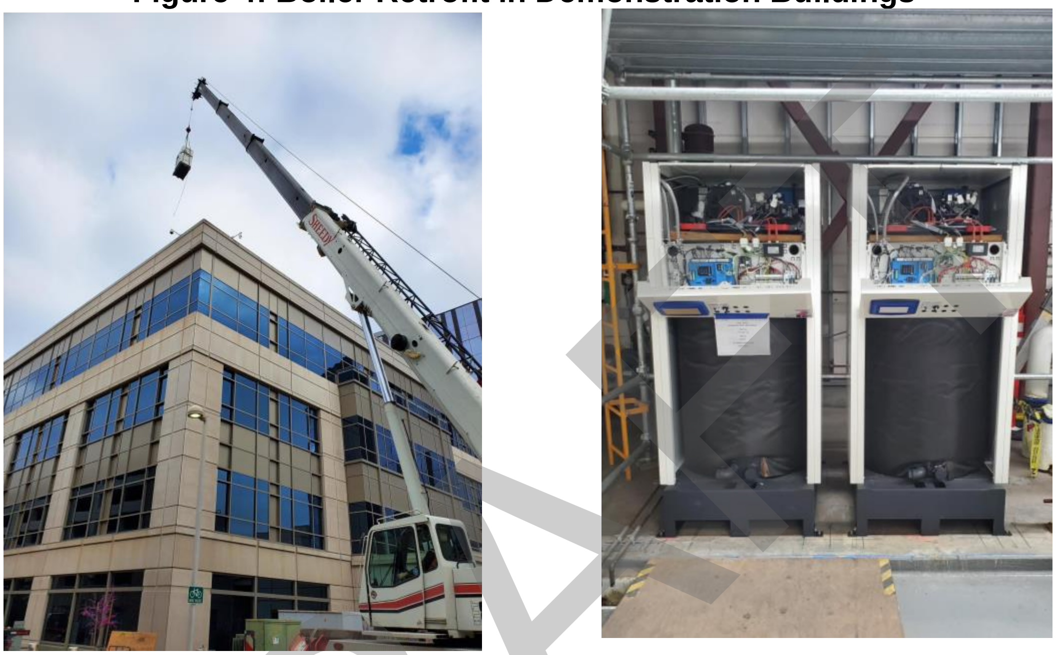
- Correct VAV minimum airflows to ventilation minimum according to ASHRAE Guideline 36 (ASHRAE 2018), Standard 90.1 (ASHRAE 2019) and Title 24 (California Energy Commission 2018)
  - Pseudo dual-maximum VAV logic using existing zone controllers to simultaneously ramp heating airflow and valve position starting at 0% and 50% heating loop output respectively
  - Resetting zone heating and cooling temperature setpoints to standardized values (70 and 74 °F)
  - Detecting rogue zones and addressing the underlying issue, for example, by increasing the cooling or heating maximum air flow rate for the terminal unit serving that zone when doing so would not cause other issues
- Air handling unit measures
  - Demand- and outside-air based supply air temperature reset
  - Added warmup mode (i.e. 100% recirc) during unoccupied periods in cold weather
  - Demand-based duct static pressure reset
- Boiler measures
  - Demand-based hot water plant operation (only when air handlers operate)
  - Demand-based hot water supply temperature (HWST) reset (when required by zone valve feedback)
  - Staging based on HW load measured by newly installed meters

BAS adjustments:
- Releasing long-standing overrides and addressing underlying causes
- Tuning controls parameters based on trend review
- Correcting a range of existing issues in the existing controls system

Table 1 describes the system and equipment both pre- and post- in more detail.

The COVID-19 pandemic caused these buildings to be unoccupied from March 2020, with the HVAC system operating intermittently at most one day per week. This change in operation had numerous impacts, and these affected the feasibility of a traditional measurement and verification (M&V) approach. For example, with these operating conditions and the existing boiler retrofit timeline, it was not possible to obtain pre-retrofit data by installing new meters—the comparison must rely on what was available pre-pandemic for the pre-retrofit dataset. Similarly, there was substantial uncertainty surrounding when the buildings would be back to normal operation throughout the pandemic, and substantial delays to performing the retrofit and subsequent controls work. Even after the buildings re-opened, they initially did so at very reduced occupancy rates and the air handlers were configured to 100% outside air in response to a Cal-OSHA requirement that was only removed in January of 2023. The boilers were replaced in May 2021 and the controls measures were completed by June 2023. The project M&V plan initially aimed to stagger deployment of measures in groups over the course of the project, thus allowing a separate quantification of the savings associated with groups of measures. However, pandemic related impacts meant that it is only possible to compare the combined impact of all measures.

Figure 4: Boiler Retrofit in Demonstration Buildings



Photograph of boiler crane pick, and subsequent install.

Pre- and Post-intervention Datasets

The research team collected monthly gas and electricity utility data for both buildings from 2010 to 2024[1]. The pre- and post-pandemic gas consumption data is reasonably comparable, but given the other changes in occupancy and associated impacts on electricity consumption, it is not reasonable to estimate electricity savings from the whole building electricity meter. Higher resolution daily gas data is available from 2018, and mid 2019 for Building A and B respectively, and the team relied primarily on this for the pre- and post-intervention comparison.

Heating hot water flow meter data was not available in either building pre-retrofit. However, the team installed gas submeters and new HHW flow meters as part of the retrofit, which were used to compare performance of measures that either were alternated on a fixed schedule, or that occurred after the submeters were installed and calibrated. Regarding utility costs, both buildings currently are billed under the G-NR1

1 Data from 2010 to 2018 because a new building was constructed in 2019 beside Building A, and receives gas from Building A. The new building has a separate gas submeter, and once calibrated, used to account for the new building consumption on the Building A utility meter.

"Gas Service To Small Commercial Customers" tariff structure; for electricity Building A and B are under A-10 and A-6 respectively (see

Table 2)

Table 1: Building Equipment Descriptions, with Post-retrofit in Parentheses.

	Building A	***Building B***
Boiler model	1 x Laars Mighty Therm HH 2000 (2 x Cleaver Brooks CFC- E 1000)	1 x Laars Mighty Therm HH 2450 (2 x Cleaver Brooks CFC- E 1000)
Boiler input size [kBTU/hr]	1 x 2,000 (2 x 1000)	1 x 2,450 (2 x1000)
Nominal efficiency	80% (90%)	
Minimum turn-down	30% (10%)	
HWST reset strategy	Constant, 180 °F (Demand-based, 140 - 90 °F)	
Pumping strategy	Constant speed primary, variable speed secondary (Variable speed primary)	
Building automation system	Siemens Apogee Insight (predominantly ATEC zone controllers)	
# VAV zones	222	196
Mean zone heat & cool stpt. [°F]	70.8 & 73.0 with wide variation throughout building (70 & 74)	69.5 & 73.1 with wide variation throughout building (70 & 74)
# VAV zones with reheat coils	120	119
VAV reheat strategy	Simultaneously ramp valve position and airflow linearly from 0 to 100% heating loop output (Delay start of flow ramp to 50% heating loop output)	
# of reheat coils with 3-way valves	16	23 (15)
Total VAV box min airflow [cfm]	36,000 (20,000)	37,000 (20,000)
Total VAV box max airflow [cfm]	144,000	122,000
AHU hot water heating coil	None	
AHU duct static pressure reset	Zone demand based with limited setpoint range (1" – 1.9") (Widened range to 0.3" – 1.9")	
AHU supply air temperature reset	Frequent operator overrides to constant SAT, typically ~62°F (Zone demand and outside air-based SAT reset 55-68 °F, re-mapped zones correctly to associated air handlers)	
AHU warmup/recirculation mode	None (Warmup mode – 100% recirc prior to occupancy on cold days, length of warm-up increases with colder outdoor temperatures)	

Source: UC Berkeley and Taylor Engineers

Table 2: Utility Rates (2024)

Building	*Energy use*	*Summer*	*Winter*
Building A	Gas [$/therm]	1.426	1.533
	Electricity [$/kWh]	0.260	0.222
	Electricity demand ($/kW)	21.80	21.80
Building B	Gas [$/therm]	1.468	1.567
	Electricity, part-peak [$/kWh] (peak, off-peak)	0.404 (0.446, 0.352)	0.342 (0.351, 0.341)

Source: PG&E

2.1.2 Secondary Demonstration Building

The team conducted additional field demonstration and testing at the Brentwood Education Center at Contra Costa Community College in northern California (CA climate zone 12) in the spring of 2023. Constructed in 2020, the single story, 55,000 ft² facility houses classrooms, laboratories, faculty offices, and a student center. Each of the four wings is conditioned by a separate VAV reheat system with airside economizers, with hot water generated by two condensing boilers. The laboratory HVAC system operates 24/7 with 100% outdoor air. The facility HVAC systems are controlled with an Automated Logic Corporation (ALC) building automation system (BAS).

Figure 5: Image of the Brentwood Demonstration Building

View of the Brentwood Education Center, part of Los Medanos College.
Credit: *Los Medanos College*

Project Scope

The demonstration at the Brentwood Education Center was divided into two phases: A pilot study to evaluate the impact of morning warmup operation on peak hot water loads, and then a demonstration of simple HVAC control changes to improve energy efficiency and system performance.

The warmup pilot study took place in March and April 2023. Conventional morning warmup strategies aim to recover as fast as possible, yielding unnecessarily high peak heating loads and potentially lower system efficiencies. The pilot study aimed to modify warmup strategies to show that peak heating loads could be effectively reduced while still recovering to comfortable temperatures on time (Cheng et. al., in press, 2024).

The team applied control measures in June 2023, with the post-retrofit monitoring period extending through March 2024. Most changes were simple setpoint or parameter changes that the researchers could implement through the BAS interface. The team also applied three minor programming changes that were programmed by the team and installed in the system by the building's BAS service contractor during one of their scheduled monthly visits. The measures included:

1. Released an incorrectly set limit in the programming for Air Handling Unit 3 (AHU-3) to allow it to recirculate and modulate outdoor airflow for economizing, instead of unnecessarily running at 100% Outside Air.
2. Adjusted a setting to change AHU-3 duct static pressure setpoint control from fixed to trim-and-respond reset based on zone demand.
3. Adjusted minimum duct static pressure limit from 0.5 to 0.1 inWC for AHU-1, -3, and -4.
4. Revised reheat valve control in non-lab zones to control the discharge air temperature (DAT) setpoint in warmup mode, instead of driving the valves to 100%, and reduced the max DAT from 115 to 95 °F. The programming was also revised to allow the AHU-3 HW valve to control to setpoint during warmup.
5. Increased the warmup period for non-lab zones from 1.5 to 3 hours, and adjusted the tuning to allow the logic to leverage the longer warmup period.
6. Reduced maximum HWST from 170 °F to the design of 135 °F.
7. Reduced the HW minimum bypass flow setpoint from 55 gpm to 40 gpm, still conservatively above the boiler's requirement for a minimum flow of 30 gpm.
8. Adjusted a setting to change the HW pressure setpoint control from a fixed setpoint of 10 psi to reset based on valve demand.
9. Increased the number of ignores in the HWST setpoint reset logic from 2 to 5.
10. Adjusted zone minimum airflows to the higher of the ventilation minimum or controllable minimum. The minimums were reduced to an average 13% of maximum, compared to the 22% that they were found at.
11. Adjusted occupancy scheduling to begin at 7 am instead of 6 am.
12. Revised programming for SAT reset logic for AHU-1, -3, and -4 to evaluate cooling requests instead of heating requests.

13. Revised programming of boiler staging to stage based on load instead of flow to reduce cycling.

2.2 Detailed Field Study

The team conducted four separate studies of detailed measurements at several sites. Three studies focused on measuring losses to better quantify and understand them, such as building-level heating hot water distribution losses in seven buildings, measuring distribution losses using newly installed instrumentation at the building and branch level at UC Davis' Ghausi Hall, and conducting detailed analysis of intentional reheat at CSU Dominguez Hills. One study also measured boiler efficiency (LA Metro).

2.2.1 Field Measurements of Distribution Losses in Seven Buildings

The research team measured HHW distribution losses in seven large commercial buildings at five different organizations in California climate zones 3B and 3C.

Figure 6: Pictures of Three of the Seven Buildings With Measured Standby HHW Losses.

Typical office buildings in which to study HHW losses

For each building, the team commanded the valves closed on heating hot water end-use components and shut down the air handlers. Researchers operated the heating hot water system to maintain a constant flow and a constant hot water supply temperature setpoint typical for each building. The team then measured the steady-state heating power required to maintain that setpoint.

2.2.2 UC Davis (Ghausi Hall)

This study (Vernon et al., 2024) measured HHW distribution losses in detail in a 66,000 ft² (6,200 m²) office and lab building, Ghausi Hall, built in 2000 in Davis, California (CA climate zone 12). Five air handler units serve single duct distribution systems with terminal units serving thermal zones throughout the building. For the whole building, the researchers used newly installed water flow meter and matched pair HHW supply and return temperature sensors. They used typical HHW setpoints with all air handlers turned off (no intentional air flow, and measured the steady-state unintentional heat loss when all VAV terminal unit HHW valves were commanded shut (so that the only HHW heat loss is unintentional heat loss). They also repeated this with one HHW valve was commanded open. The team further measured HHW distribution losses in greater detail on the single HHW distribution branch.

For the detailed heat loss measurements, one HHW branch on the top floor was selected that feeds nine VAV terminal units that serve private offices, computer labs, and a section of hallways, with a total floor area of 355 m² (3,855 ft²).The researchers estimated the intentional reheat energy use and unintentional heat loss during normal building operation over a two-month period in the heating season by performing both a water side heat balance and an air side heat balance. The team used methods adapted from (Raftery et al., 2018) to calculate the HHW distribution losses from Building Automation System (BAS) measured data, and then from separately installed calibrated temperature sensors and water flow rate sensors and further corrected air flow rates with passive flow hood single point calibration of BAS reported flow rates.

2.2.3 Cal State University Dominguez Hills (CSUDH) LaCorte Hall

The intentional reheat energy analysis conducted in this section intended to calculate the efficiency of the reheat system, i.e., how much of heat energy provided to the hot water is transferred to zones during times when reheat is required, for LaCorte Hall, a classroom and office building on California State University, Dominguez Hills' campus.

Constructed in 1978, LaCorte Hall is a three-story 67,800 ft² (55,000 ft² conditioned) classroom and office building on the CSU Dominguez Hills campus in Carson, California (CA climate zone 6). The lower two above-grade levels contain classrooms, workshops, music rooms, offices, a gallery, and an auditorium. The third story houses faculty offices and additional classrooms.

A single VAV air handler with fan walls on both the supply and return serves 97 VAV boxes. An airside economizer and chilled water coil fed by the campus chiller loop provide cooling. Heating is provided by zone hot water reheat coils served by the campus boiler plant.

Data Collection and Processing

LaCorte Hall's HVAC system is monitored and controlled by a Johnson Controls Metasys building automation system (BAS). The project team downloaded the monitored data through a SkySpark data analytics platform connected to the BAS. Data used for the analysis include zone-level variable air volume (VAV) box flow rate, discharge air temperature (DAT), heating valve position, damper position, air handler unit (AHU) supply air temperature (SAT), supply fan speeds, and campus hot water supply and return temperatures and flow rate for the building. The data collection time interval was 10 minutes and the analysis period was from January 1, 2022 to December 31, 2022.

The team pre-processed the downloaded data in csv format to filter in time periods where intentional reheat energy was transferred to zones and to address data quality issues. Table 3 summarizes these issues and how they were treated. In addition, the team analyzed the measurement statistics to identify potential erroneous data such as unusually high airflows compared to design max airflows from mechanical schedules.

Table 3: Data Quality Issues, Scale, and Resolution

Data Quality Issue	Scale of Issue	Resolution
Zone trends with more than 15% of data missing	6 zones, 25% to 100% missing data	Remove these zones from the reheat energy use analysis. Add estimated reheat energy use from these zones back in based on the average from other zones.
Zones with Erroneous /mislabeled data	2 zones	Re-label correctly or remove these zones from the reheat energy use analysis. Add reheat energy use from these zones back in based on the average from other zones.
Zone data gaps	3.9% 10-min timestamps	Filled in gaps less than 1-hour using available before and after value average, removed the time periods from entire analysis (zones and hot water) for longer gaps.

Analysis

The team followed the method in Raftery et al. (2018) to calculate zone reheat energy during intentional reheat time periods using the discharge air flow rate, specific heat capacity of air, density of air, and air temperature difference at 10-minute intervals. Researchers calculated the air temperature difference using AHU supply air temperature (SAT), VAV discharge air temperature (DAT) and the long-term temperature difference. The long-term temperature difference represents the heating gains along the ducts between the AHU supply and VAV box and is calculated as the median difference between DAT and SAT for the annual data when the VAV heating valve is closed, and the airflow is above a minimum threshold. The team filtered time periods with intentional reheat using occupied times (excluding weekends, nights, and holidays), discharge air flow rate, VAV damper position, heating valve position, and steady state condition. The team summed the calculated zone reheat energy for all zones in the building to get the total intentional reheat energy. As Table 3 highlights, the team accounted for the small number of zones that were removed from the analysis due to data quality issues by estimating them using average reheat energy in other zones.

The researchers separately calculated the energy supplied to the hot water system using hot water supply and return temperatures, flow rate, water density and specific heat capacity. Time periods used for this calculation included times when the hot water flow rate is above a minimum threshold (1 gpm) to account for sensor errors. The ratio between cumulative zone reheat energy and energy supplied by the heating hot water system is the reheat efficiency. The difference between them is the heat lost from the distribution system.

2.2.4 LA Metro Efficiency Measurement for an Existing Non-Condensing Boiler

As part of the broad data collection effort and the demonstration site instrumentation, the team was able to collect field performance data for relatively new boilers and quantify the boiler efficiency for those boilers. However, most boilers in operation are significantly older than these. The U.S. Department of Energy's 2020 Energy Conservation Standards for Commercial Packaged Boilers Rulemaking found a wide range of boiler lifetimes and assumed a typical boiler lifetime of 24.8 years. Though the team was able to collect some data, functioning input gas meter and output hot water BTU meters were exceptionally rare on older systems. Given the prevalence of older boilers, the team was interested in installing metering to collect data to fill this gap for one building. The team identified a site on the Los Angeles County Metropolitan Transportation Authority, Division 9 Transportation Building to monitor and analyze.

This 41,500 ft^2 office building was built in 2006 and uses a single duct VAV system with terminal hot-water reheat. Two packaged DX units serve the building, with a gas-fired boiler providing HHW. The original boiler served the building from initial construction until it failed and was replaced in November 2023. The original single boiler plant used a single Raypak Hi Delta H3-0752A with an input rating of 750,000 Btu/h, output of 630,000 Btu/h, and 2:1 turndown. In November 2023 when the original boiler unexpectedly failed, it was replaced by a single Lochinvar Copper-Fin II CHN062 boiler, with an input rating of 650,000 Btu/h, output of 553,000 Btu/h, and 4:1 turndown.

Meter Installation and Data Collection

The team installed metering to capture measure boiler efficiency, which then captured the performance of both the original boiler and the new boiler. The team and LA Metro staff installed an Onicon F-5500 Insertion Gas Meter on the gas input to the boiler, and an Onicon System-20 BTU Meter with a F-3500 Insertion Magnetic Flow meter to measure the boiler hot water output. The original boiler data collection period was 52 days in the shoulder (nonprimary heating) season. The new boiler data collection period started in late November 2023 and continued for 103 days until mid-March 2024.

Table 4. Original and New Boiler Data Collection Periods

1 minute interval data	Original Boiler	New Boiler
Data Collection Period Start	8/31/2023	11/30/2023
Data Collection Period End	10/22/2023	3/11/2024
Number of Days Data Collected	52 days	103 days

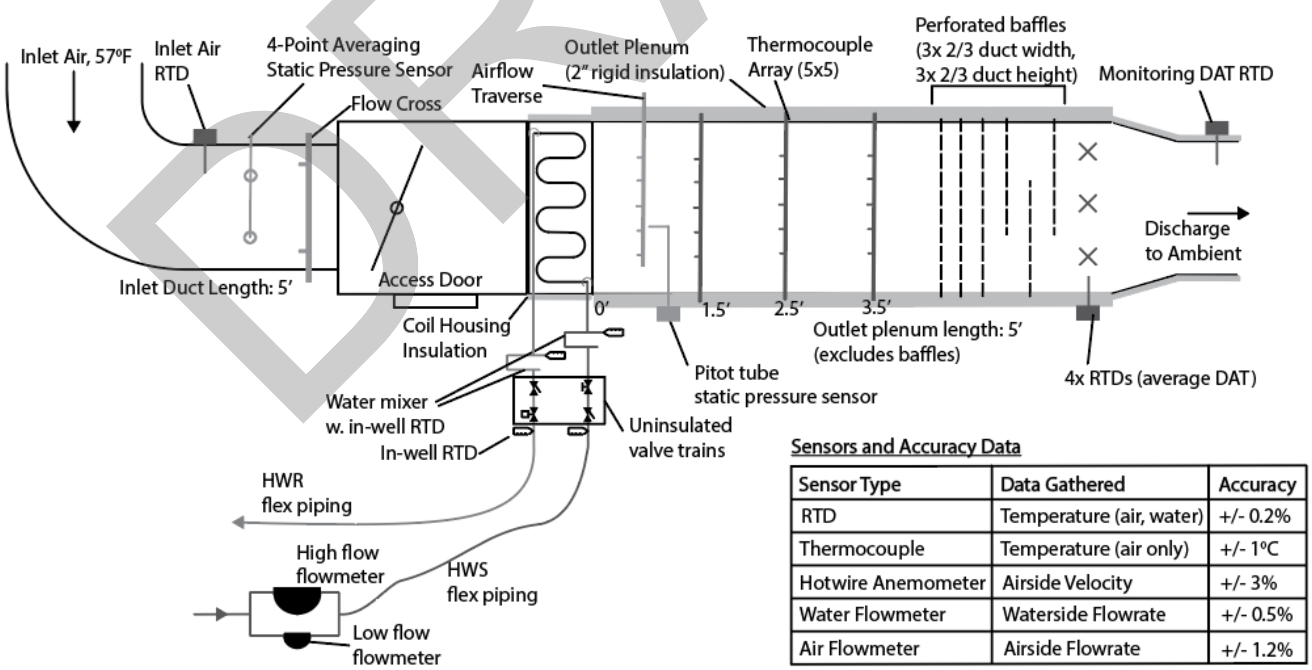
2.3 Laboratory Testing

The performance of conventional variable air volume hot water reheat systems is impacted by losses in the distribution system, temperature stratification downstream of the reheat coil, and the impact of damper position on coil capacity. Researchers conducted a lab experiment at Price Industries Laboratory in 2022 to gather data on these factors and investigate their impact on the performance of VAV hot water reheat systems. Based on results, the team recommended several improvements to the design, control, and installation practices of VAV reheat systems that address the performance issues realized by the data gathered. The background, methods, findings, and recommendations of this experiment are presented in more detail in the report (Wendler et al., 2023) with a summary in ASHRAE Transactions (Wendler et al., 2023).

Figure 7: Photograph of an example laboratory test

Source: Patrick Wendler, UC Berkeley

Figure 8: Schematic of Sensors in the Test VAV Box in the Lab



Sensors and Accuracy Data

Sensor Type	Data Gathered	Accuracy
RTD	Temperature (air, water)	+/- 0.2%
Thermocouple	Temperature (air only)	+/- 1ºC
Hotwire Anemometer	Airside Velocity	+/- 3%
Water Flowmeter	Waterside Flowrate	+/- 0.5%
Air Flowmeter	Airside Flowrate	+/- 1.2%

Source: Patrick Wendler, UC Berkeley

2.4 Data-Driven Analysis

Throughout this multi-year project the research team reached out to a broad network of contacts to gain access to as much data from heating hot water systems as possible. This included a wide range of stakeholder organizations in the building industry, from individual building and portfolio building owners, to manufacturers, designers, and their clients and past contacts. The team reviewed information from thousands of buildings to identify those that have sufficient building automation system data to warrant inclusion in the analysis. The primary focus was searching for buildings with measure hot water loads, flows, and supply and return temperatures over at least a year. Researchers gathered data, standardized them into a common format, analyzed for patterns and relevant insights. After removing clearly erroneous data and outlier buildings from this dataset, there were over 120 million datapoints from 259 building across 56 different organizations throughout the United States. The team analyzed the data to share insights regarding how these systems operate in real buildings versus assumed performance. The team released as much of the dataset as possible given data sharing agreements as an open dataset for future research; a total of 216 buildings (Raftery et. al., in press).

2.5 Market Transformation

The team worked on several aspects of market transformation and outreach activities to disseminate the findings to the broader commercial building market for maximum effectiveness. The list includes:

- Interviews of HVAC designers
- Recommendations of campus measures
- Rapid retrofit screening tool
- Hot water heating design and retrofit guide
- Policy recommendations
- Code change proposals for Title 24 CASE efforts for 2025

CHAPTER 3: Results

3.1 Demonstration Results

3.1.1 Primary Demonstration Buildings

The results show substantial natural gas reductions in both buildings. The team first identified the most appropriate baseline and post-intervention period given the available information and challenges posed by the pandemic. The team then fit a linear model to predict daily gas consumption based on daily average outside air temperature for business days, and another for days that were either a weekend or a state/federal holiday. This model is valid for the range of outdoor temperatures spanned by both periods, daily average outside air temperatures from 45 to 76 °F; which includes 98% of the actual weather from 2018 to Feb 2024. **The estimated annual gas savings are 71%** (22,000 therms/yr, \$32k/year, 110 tonsCO_2e/yr) **in Building B and 69%** (29,000 therms/yr, \$43k/year, 150 tonsCO_2e/yr) **in Building A**. The heating plant in both buildings typically operated while unoccupied on holidays and weekends during the baseline period. This issue was largely resolved (almost entirely in Building B) by the new controls measures, and thus savings are larger on these days and smaller on weekdays. For context, non-holiday weekday savings were 65% in Building B. The following figures show the data used in the analysis and notes relevant. In each, the grey-shaded region indicates temperature range spanned by both baseline and post-intervention periods and faded triangular datapoints indicate a weekend or holiday.

Figure 9: Building B Utility Gas Meter Consumption Data

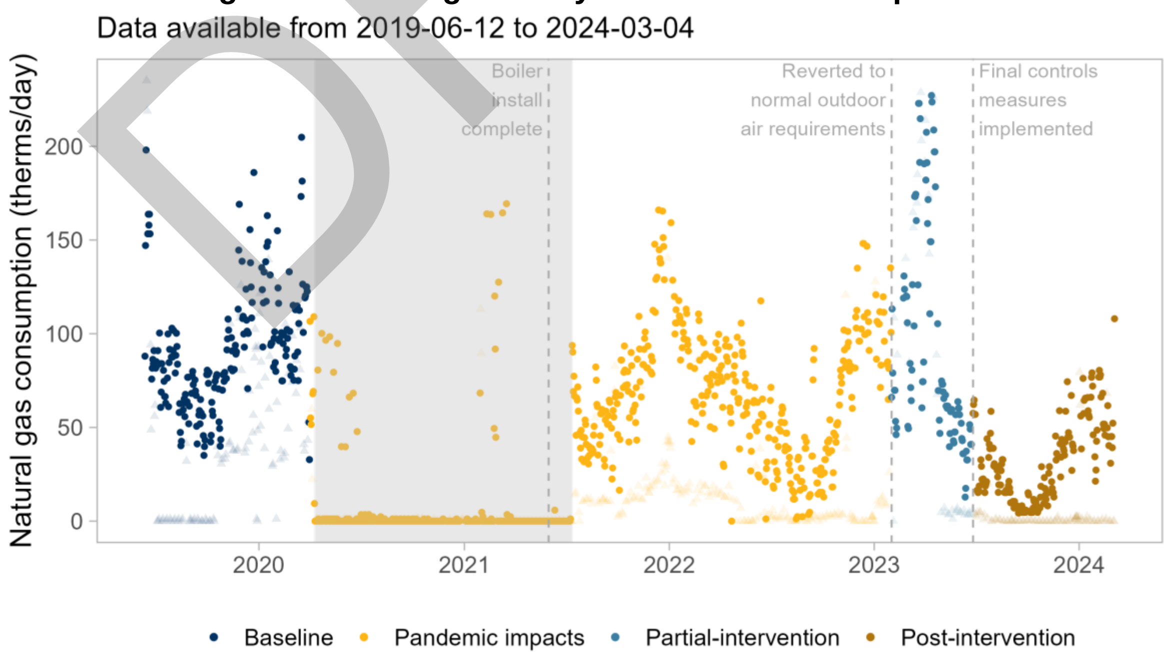


Figure 10: Building B Natural Gas Consumption by Outdoor Temperature

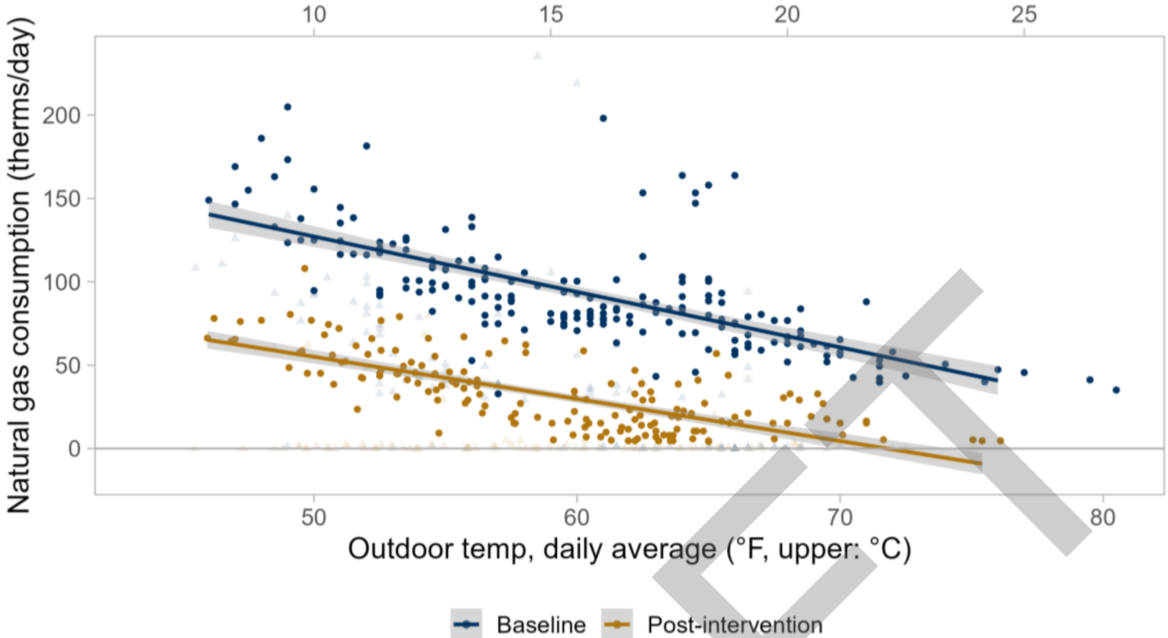


Figure 11: Building A Utility Gas Meter Consumption Data

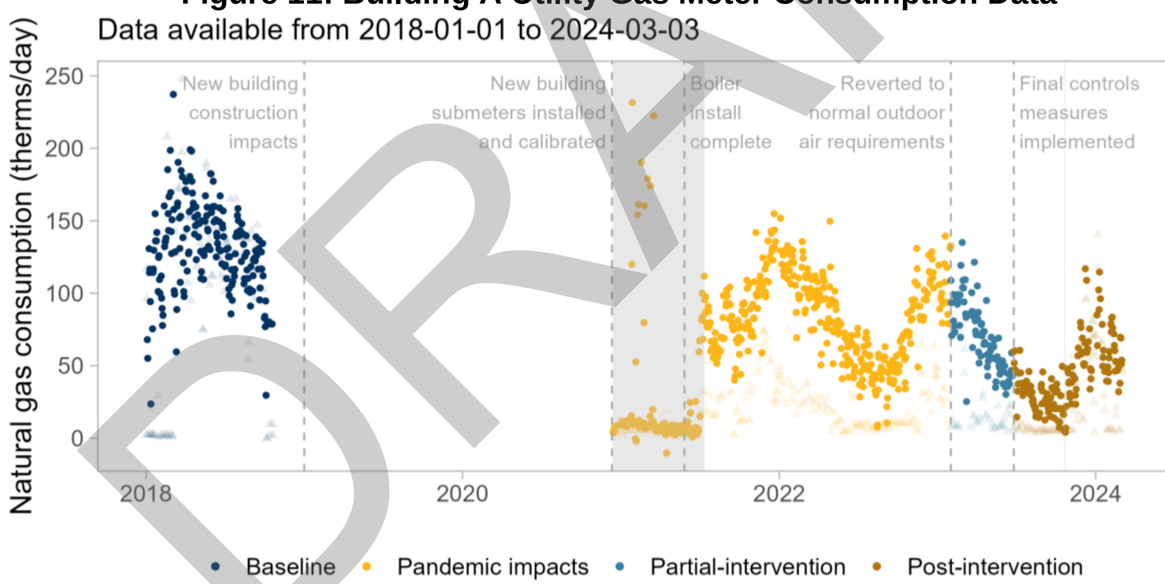
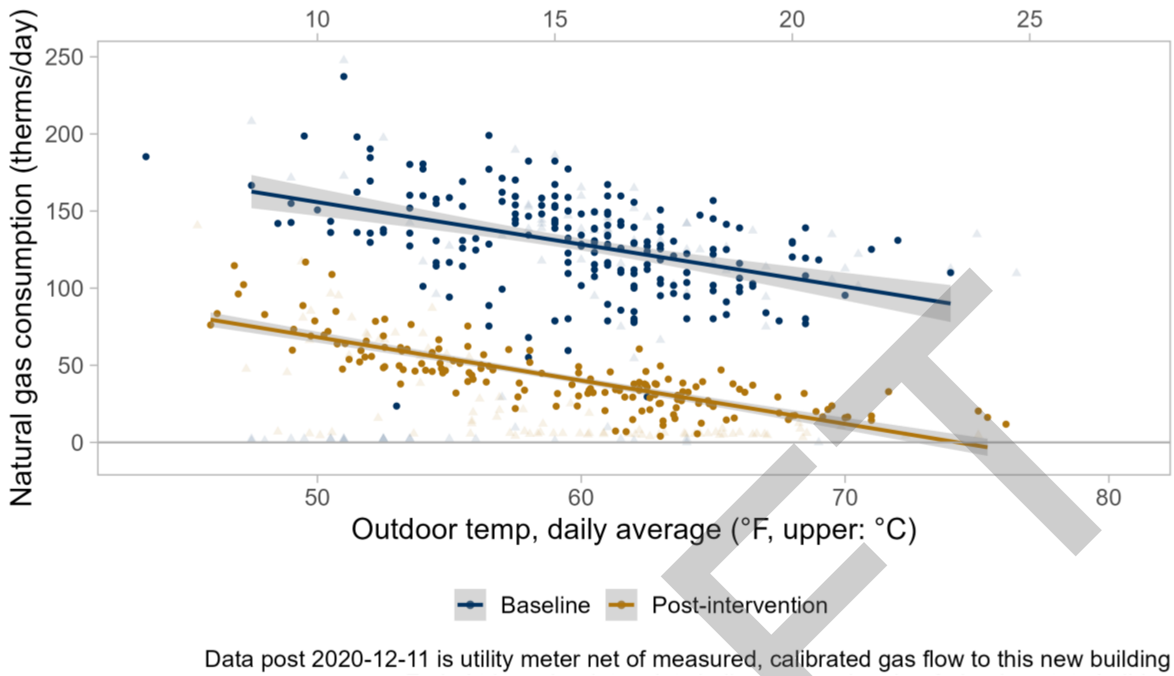


Figure 12: Building A Natural Gas Consumption by Outdoor Temperature



For context, the team also obtained long term monthly utility bill data to highlight the effectiveness of this retrofit. Using the average consumption for these buildings over long term (approximately the last decade) would yield an even higher savings estimate, particularly for Building B (see Figure 13).

Last, the research team also analyzed the impact of the measures using submeter data to estimate the impact on HVAC electricity use. However, the dataset is more limited as it relies on submeter data that was only available after the pandemic began. The utility electricity data is not comparable pre- and post-pandemic due to substantial non-HVAC end uses served by those meters. To span warmer weather, the baseline comparison data period by necessity must also span a period after the boiler was replaced and building re-occupied but before the pandemic ventilation requirement was lifted (reverting to normal in Jan 2023). This requirement was for 100% outside air up within the range of outdoor air temperatures of 57 - 80 °F (instead of typical economizer controls, which includes an upper limit of 75 °F). This has a substantial negative impact on natural gas consumption and a lesser negative impact on HVAC electricity use, each of which is difficult to quantify with much certainty. With that limitation in mind, comparing all weekdays within the same months each year (Jul 2022 to Feb 2023 against Jul 2023 to Feb 2024) showed that measured chilled water load decreased 40% in B44 (120 tons/day average)[2]; total fan power (supply and return fan VFD power

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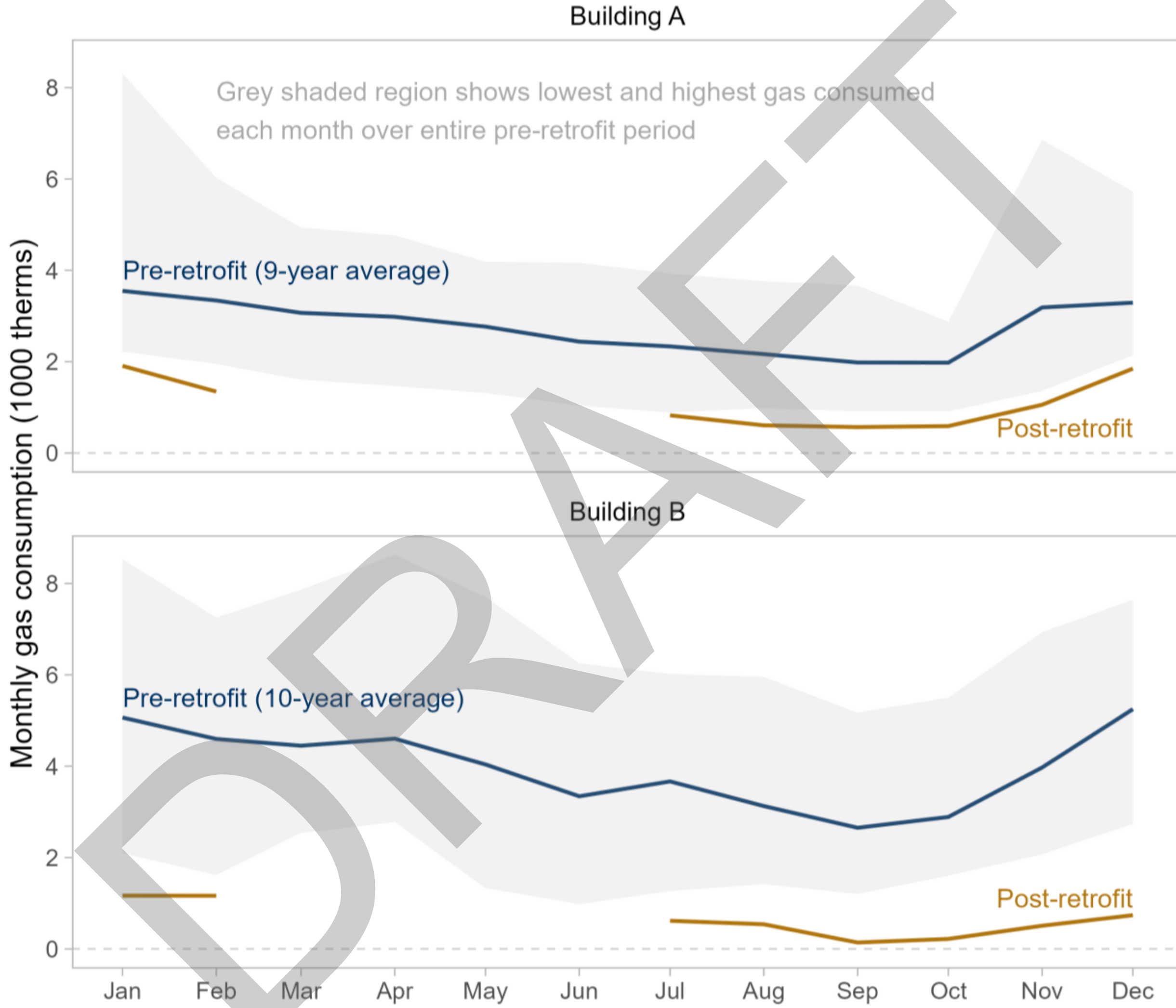
2 The chilled water flow meter failed in Building B during this period, so a comparison cannot be made for the second building.

outputs for each air handler) decreased by 25% for Building A and 20% for Building B (130 and 70 kWh/day respectively), and gas use measured by the boiler gas submeters decreased 55% in Building A and 50% in Building B (27 and 28 therms/day respectively). Assuming similar chilled water savings for Building B as Building A, the combined utility cost savings of the full set of measures for both buildings is approximately $110,000 per year, or $0.5/ft².yr.

Figure 13: Long Term Monthly Utility Bill Data for Both Buildings



Pre-retrofit (2010 - Mar 2020). Pandemic data omitted. Post-retrofit (Jul 2023- Feb 2024).
2019 removed for Building A due to addition of new building served by same gas meter that year.
Submeter installed and calibrated during pandemic, Building B post-retrofit data is bill minus submeter.
One outlier not shown (Jan 2017, Building B 17451 therms)

Additional Measures

The team also configured the HHW plants to operate differently in both buildings to leverage this research project to assess and improve upon ASHRAE Guideline 36 sequences. In Building A, boiler 1 had 5:1 turndown while boiler 2 had 10:1 turndown, lead/lag boiler alternating daily. In Building B, both boilers had 10:1 turndown and lead/lag alternating weekly with the boiler stage up criteria alternating in tandem with lead/lag switchover. The plant stages up at 80% of load (boiler 1 lead, so boiler 2 benefits from reduced stage up cycles) one week, and the plant stages up at 40% of load (boiler 2 lead, so boiler 1 cycles more)[3] the next week.

This causes both buildings to switch between control strategies frequently throughout the entire measurement period and removes the potential for unrelated changes in building operation to affect one strategy more than the other. The results are clear that - as expected - higher turndown capability and higher stage up thresholds reduce cycling. In 2023, the 5:1 turndown boiler in Building A cycled 1095 vs 944 times, and the 80% stage-up condition boiler in Building B cycled 553 vs 414 times (so the lag boiler for the 80% stage up condition staged up less). The net efficiency impact between these two strategies is difficult to measure given the small effect size and all the other factors that impact this. However, in Building A, days when the plant operates with the 10:1 boiler as lead show a mean improvement in efficiency of 0.76% (95% confidence interval: -0.55%, 2.1%). In Building B, days when the plant operates with a higher stage up threshold show a mean efficiency improvement of 1.2% (-0.01%, 2.4%). The results and confidence intervals are skewed in the direction of indicating that higher turndown capability and higher stage up thresholds improve efficiency. However, these efficiency results are small and relatively uncertain given the effect size, and there is potential for bias associated with the gas meter measuring consumption of each boiler as well as potentially differences between the physical boilers themselves.

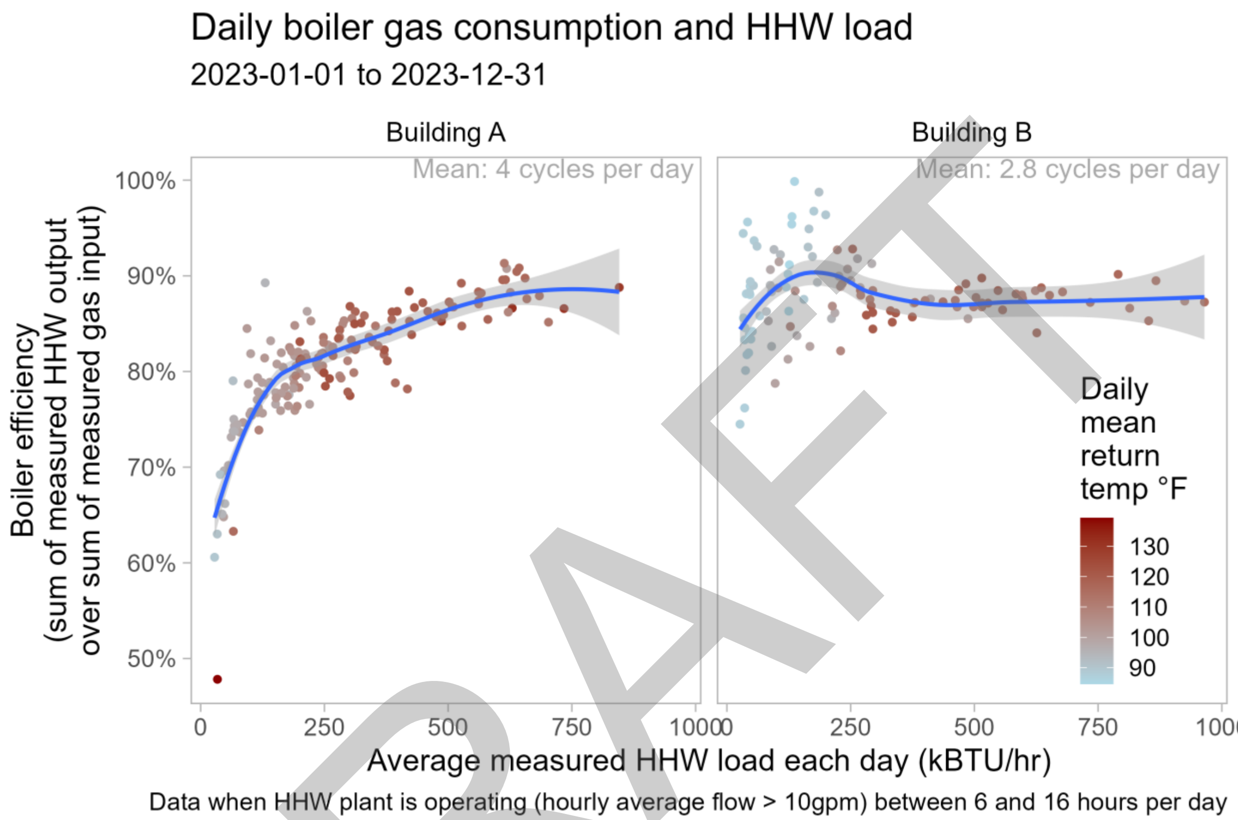
Boiler Efficiency

The annual average input efficiency for the new boilers over a 1-year period (2023) was 82% and 88% at mean return temperatures of 113 and 103 °F, for Building A and B respectively. Adjusting for the natural gas heating value (ranging from 1.01 - 1.04 at this site according to the utility provider) would further decrease these efficiencies. These are both below the nominal efficiency expected at these return temperatures and part loads, presumably due to the effects of cycling behavior and heat losses that occur after a boiler shuts down (e.g. at the end of the day, or after staging down for the last time each day), as well as other real world conditions that are not reflected by laboratory test conditions used to determine nominal efficiency. Comparing the two buildings to each other, note that Building A has a lower stage up criteria and higher stage down criteria than Building B. This is due to the effect that the 5:1 boiler's higher minimum turndown load has on the stage up and down loads. In Building A, the plant stages up at 528 kBTU/hr and stages down at 387 kBTU/hr; a relatively narrow range of loads. In contrast, Building B stages up at either 704 kTBU/hr or 352 kTBU/hr (depending on which equipment is lead, corresponding to 80% or 40%), and stages

3 Note however that on most days, the boilers stage up based on criteria other than load, typically a failsafe criteria that stages up the boiler plant when the difference between HWS setpoint and measured temperature exceeds 15°F, which often occurs shortly during morning warmup as the HWST is increasing in response to building loads.

down at 194 kBTU/hr. Though clearly the buildings and associated loads and return temperatures are different, Building A has a higher cycle count and operates at lower efficiency.

Figure 14: Boiler Efficiency in Both Buildings

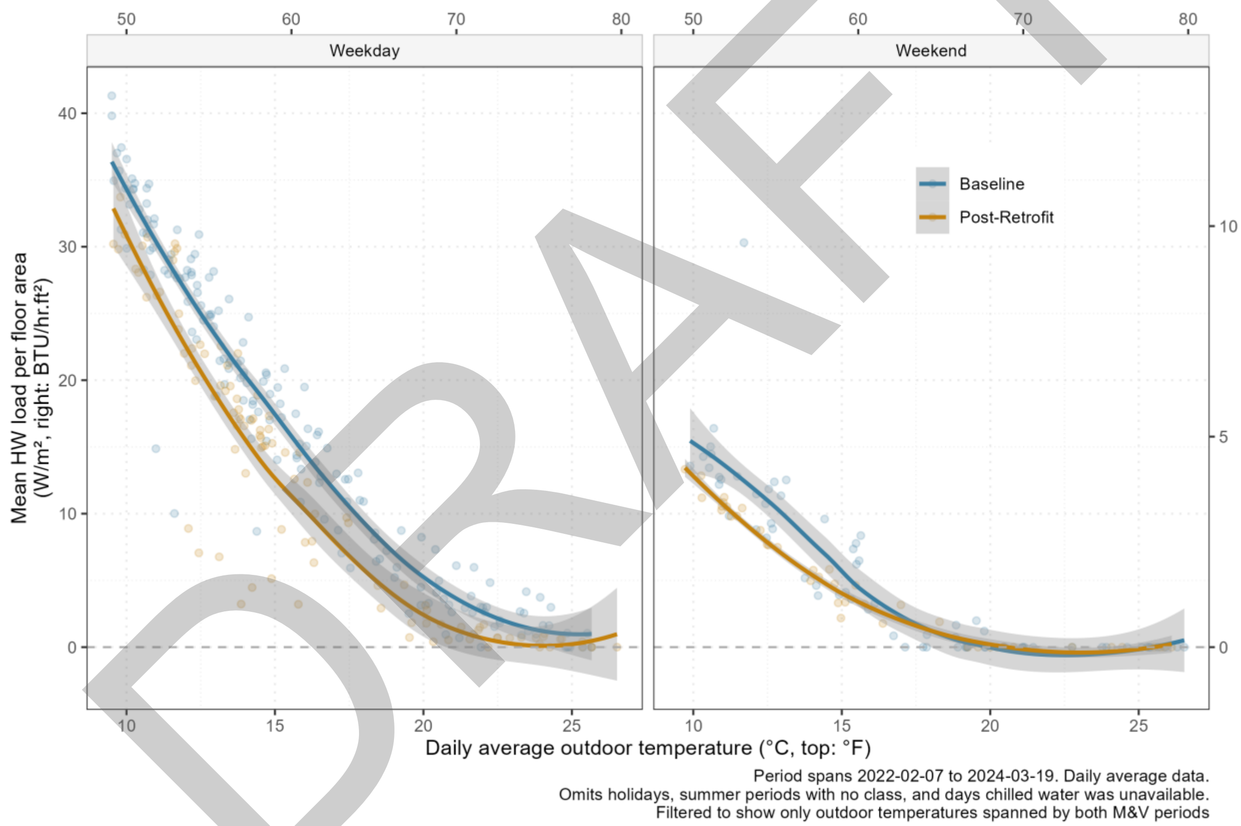


3.1.2: Secondary Demonstration Building

To understand the impact of the controls measures, the team downloaded timeseries data from the BAS system in the Brentwood Education Center dating back to early 2022. This data included boiler load, flow, supply and return temperatures, fan power, and chiller power consumption. The team processed the data to identify and filter out periods where the building was unoccupied or had atypical occupancy and operation hours, such as holidays, weekends, and summer months. Unfortunately, the site's chiller failed at the end of August 2023 and a temporary chiller was installed to meet the building's cooling needs until January 2024. Given the limited amount of data acquired since the controls intervention, particularly over summer months when students are mostly not on campus, that leaves insufficient data to determine the impact of the measures on chilled water consumption. However, gas consumption did substantially decrease post-retrofit. Using a linear model fitting daily average HHW load against daily average outdoor air temperature, separately for both weekdays and weekends, shows savings of 22% annually (1 BTU/hr.ft², or 1.3 BTU/hr.ft² normalized to just the non-lab area that was affected by the measures, or approximately

$8000/year after accounting for boiler efficiency). The team also monitored fan power for all of the supply and return fans for the three air handlers serving the unaffected non-lab areas of the building (as the lab areas were not affected by the controls changes). In aggregate, there was an increase in fan electricity consumption (24kWh/day, $3,500/year), partially offsetting the natural gas savings. Supply air temperatures were slightly higher on average (1-2 °F) post-retrofit which could be partly causing this increase. Similarly, differing occupancy levels post pandemic may have influenced these results, but no data is available to assess that. Lastly, this fan electricity increase would likely be offset by chiller energy savings, but due to the chiller failure the chilled water meter was not functional while the temporary chiller was operating and thus there is insufficient data to assess net impact on HVAC electricity.

Figure 15: Measured Heating Hot Water Load at the Brentwood Site

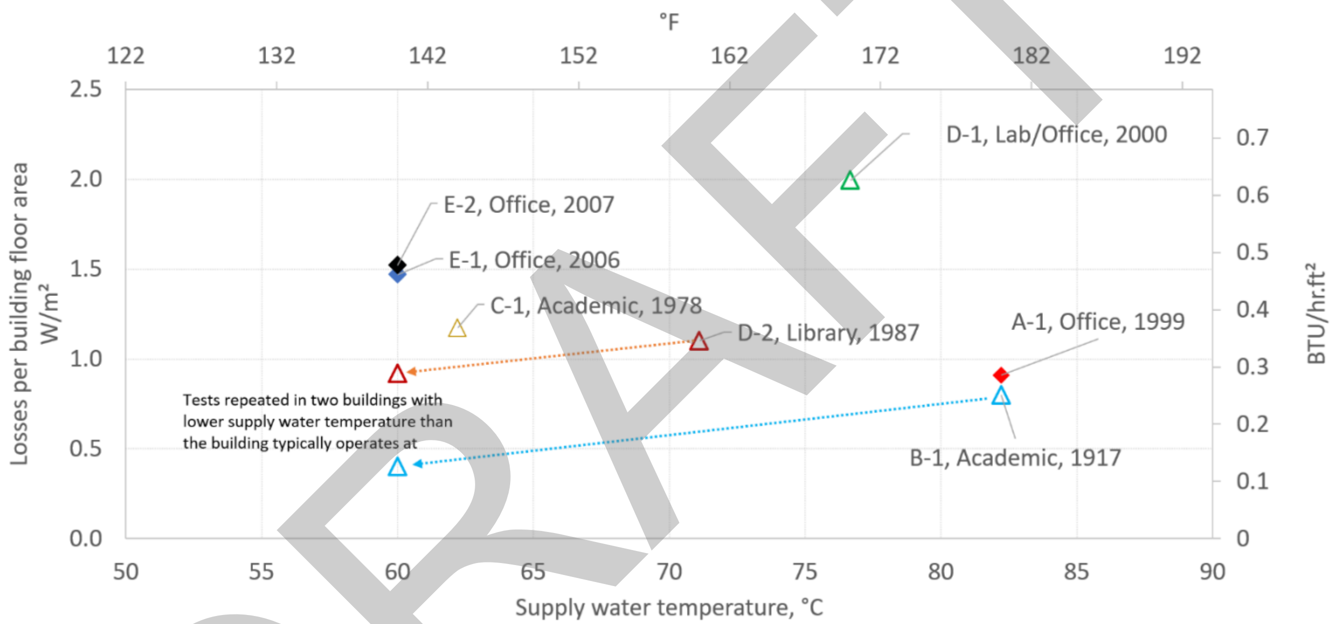


3.2 Detailed Field Study Results

3.2.1 Field Measurements of HHW Distribution Losses in Seven Buildings

Building characteristics varied widely in terms of size (5,100-15,000 m² or 55,000-160,000 ft²), type (e.g., city administrative office, college lab and classroom), HVAC design (VAV reheat or dual duct systems), and year of construction (1917-2000). Despite this, the results were reasonably consistent when normalized to building conditioned floor area. The median loss rate was 1.2 W/m² (0.37 BTU/hr.ft²) with a min/max range of 0.8 - 2 W/m² (0.25 – 0.63 BTU/hr.ft²) across all buildings at typical supply temperatures for each building. For comparison, this is roughly a third of average office plug loads, and though it is low on a conditioned floor area basis, it ranged from 6% to 60% of the annual HHW energy consumption for the five buildings for which the team had long term data. In two of the buildings, the research team also repeated the test at a different hot water supply temperature, demonstrating that the losses decrease with lower water temperature, as expected. The team discusses the methods, buildings, and results in more depth in a conference paper, as well as the opportunities for improving system design and operation (Raftery et. al., 2023).

Figure 16: Measured Hot Water Distribution Losses in 7 Buildings



Filled, diamond shapes indicate relatively new, high-quality instrumentation; unfilled triangular shapes indicate existing instrumentation.

3.2.2 UC Davis Ghausi Hall Results

For the whole building, using a newly installed water flow meter and matched pair HHW supply and return temperature sensors, typical HHW setpoints, with all air handlers turned off, the steady-state unintentional heat loss was 4.4 W/m² (1.4 Btu/h.ft²) when all VAV terminal unit HHW valves were commanded shut, and 3.2 W/m² (1.0 Btu/h.ft²) when one HHW valve was commanded open.

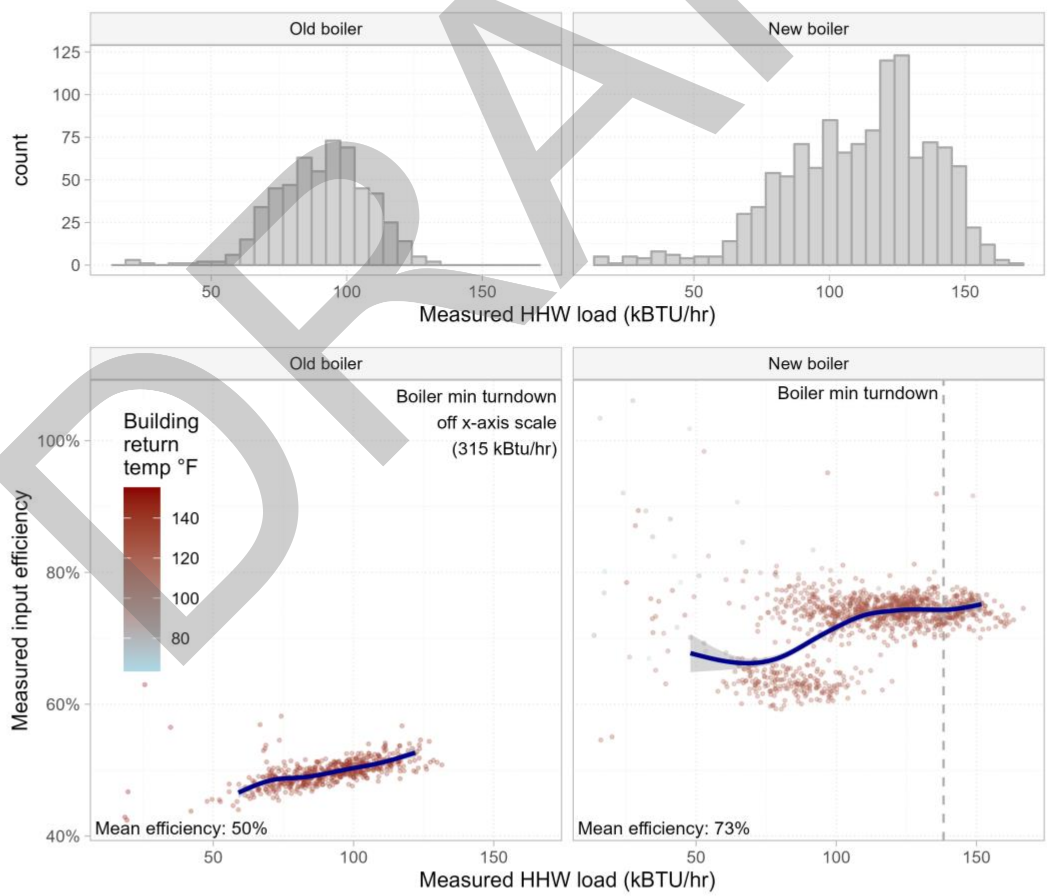
For the single HHW branch, during normal building operation over a two-month period in the heating season, the researchers used BAS readings for air flow rate, supply air temperature, and discharge air temperature and measured a distribution heat loss of 2.86 W/m² (0.91 Btu/h.ft²) and 40% HHW distribution efficiency. Using separately installed, calibrated temperature sensors yielded a similar result (2.43 W/m² (0.77 Btu/h.ft²), 49%), and further correcting air flow rates with passive flow hood single point calibration of BAS reported flow rates also yielded a similar result (2.76 W/m² (0.87 Btu/h.ft²), 42%). The close agreement between the results using BAS and calibrated sensors suggests that intentional reheat and distribution losses can be reliably estimated using only BAS data.

The magnitude of the HHW losses are small compared to design day loads, but they occur for a large number of hours so reducing these losses can save substantial energy. Further, during the cooling season the losses both waste heat and increase cooling loads. Paths forward include adopting aggressive heating hot water supply temperature resets, reducing unnecessary reheat operation, improving HHW pipe insulation practices, and/or changing design strategies to seasonal switchover or electrically driven distributed systems such as electric resistance or terminal unit heat pump equipment. See (Vernon et. al., 2024) for more detailed measurements and analysis.

3.2.3 LA Metro Results

Figure 17 shows the boiler part load against the input efficiency for the original and new boilers, respectively.

Figure 16: Old and New Boiler Load Distribution and Efficiency



During the monitored period of the original boiler, which was during the shoulder season, the hourly average boiler load generally ranged between 60 and 125 kBTU/hr, well below the boiler’s capacity 630 kBTU/hr. With only 2:1 turndown capability, the result is that the boiler cycled to meet these low part load conditions. The median original boiler efficiency is 50% over the time period measured, much lower than the rated 84% efficiency, which is consistent with data from other boilers operating well below their turndown limits. During the monitored period of the new boiler, which covered most of the winter, the boiler load was higher, generally ranging from 75 to 150 kBTU/hr, still well below the new boiler’s slightly smaller capacity of 553 kBTU/hr. With 4:1 turndown, it still spends the majority of time short-cycling to meet the load. The mean efficiency for the newly installed, non-condensing boiler is 73% over the time period measured, which is lower than the rated 85% efficiency.

3.2.4 CSUDH – LaCorte Hall

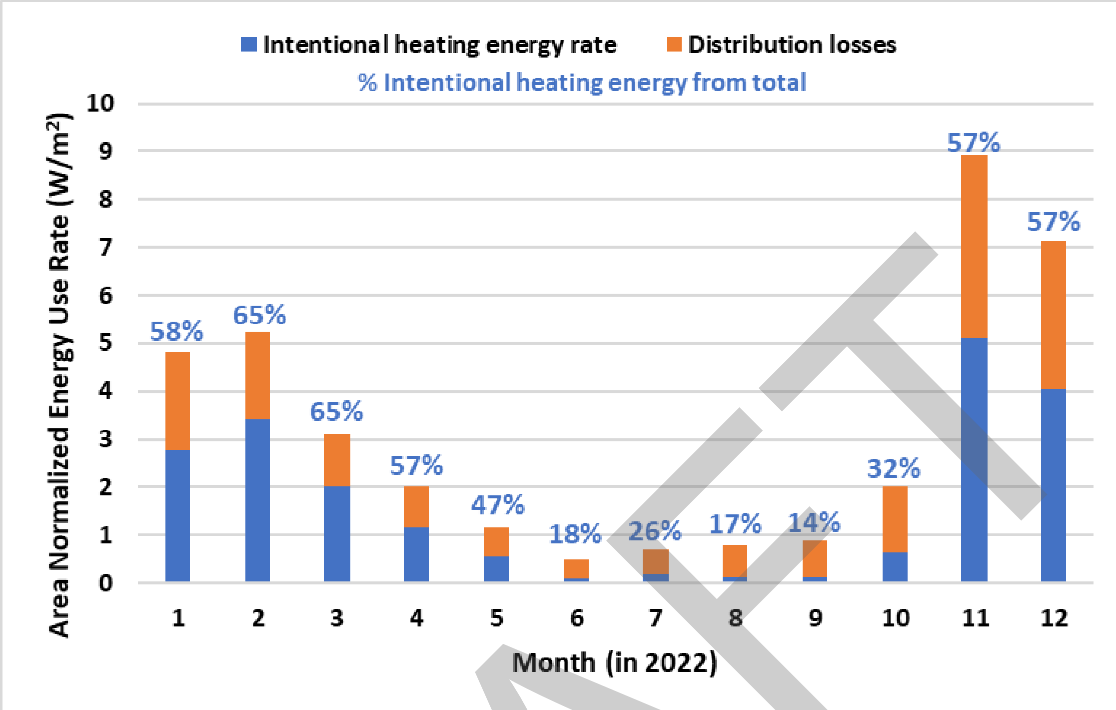
Annual cumulative zone intentional reheat energy transfer rate was 1.72 W/m^2 while the annual hot water system energy transfer rate was 3.06 W/m^2 giving an annual intentional reheat efficiency of 56.1% and an average energy loss of energy loss rate of 1.35 W/m^2. Table 4 summarizes the annual energy and energy rate of hot water system energy, intentional reheat energy and distribution losses.

Table 4: Summary of Whole Building Annual Hot Water Energy and Power Consumption

	Total system heat energy	**Intentional reheat energy**	**Distribution losses**
Annual heating energy	137,000 kWh/yr (468,000 kBtu/yr)	76,800 kWh/yr (262,000 kBtu/yr)	60,200 kWh/yr (206,000 kBtu/yr)
Area normalized annual heating energy	26.8 kWh/yr.m^2 (8.5 kBtu/yr.ft^2)	15.0 kWh/yr.m^2 (4.77 kBtu/yr.ft^2)	11.8 kWh/yr.m2 (3.74 kBtu/yr.ft^2)
Area normalized annual average power	3.06 W/m^2 (0.97 Btu/hr.ft^2)	1.72 W/m^2 (0.54 Btu/hr.ft^2)	1.34 W/m^2 (0.43 Btu/hr.ft^2)

Figure 17 compares the monthly cumulative zone intentional reheat energy and hot water system energy rate with the percentage values representing the reheat efficiency. Monthly reheat efficiency ranges from 14% to 65%, where winter months have higher energy use rates as well as higher reheat efficiency, and also have higher supply water temperatures.

Figure 17: Monthly Normalized Cumulative Zone Reheat Energy Rate and Hot Water Energy Input Rate Comparison



Hot water supply temperature also varies depending on the heating requirement as seen in Figure 18 where winter months have higher daily average hot water supply temperatures to allow for providing more heating energy to the building. Lower hot water supply temperatures in the summer likely contribute to reduced distribution losses, and reduced cooling loads to reject the associated heat emitted into the building. The 2017 analysis (Raftery et al., 2018) conducted in a 118,000 ft² office building in the California Bay Area found a reheat efficiency of 56% between energy supplied to hot water with annual average distribution losses of 0.3 Btu/hr.ft^2. The seven buildings in which the team measured distribution losses by shutting off HHW end-use components (described in Section 3.2.1, Raftery et. al. 2023) included LaCorte Hall. The losses measured at LaCorte Hall under that study were 0.37 Btu/hr.ft^2, which align with the results from this study. The losses at LaCorte Hall were towards the lower end of the distribution losses range from that study (0.25 and 0.63 Btu/hr.ft^2).

The difference between the energy input to hot water and reheat energy received by building zones can be attributed to distribution losses. Figure 19 shows that this building has far lower hot water supply temperatures in the summer compared to the winter. This indicates that the lower absolute energy losses in warmer months correlate with lower water temperatures, as expected, highlighting the importance of a well-functioning hot water supply temperature (HWST) reset to reduce losses. Figure 19 shows distribution losses against outside air temperature (OAT) in this building. These distribution losses may or may not be truly wasted depending on the real time building load conditions and system design. For an example, during cold weather, distribution losses may not be truly wasted heat if piping heating losses are heating parts of the building that require heating. Also, during cold weather, some of the heat lost to the return air will be recirculated to the building as the air handler will be recirculating as much as possible while still providing required outside air for ventilation.

Figure 18. Daily Average Hot Water Supply Temperature Distribution for Different Months of the Year

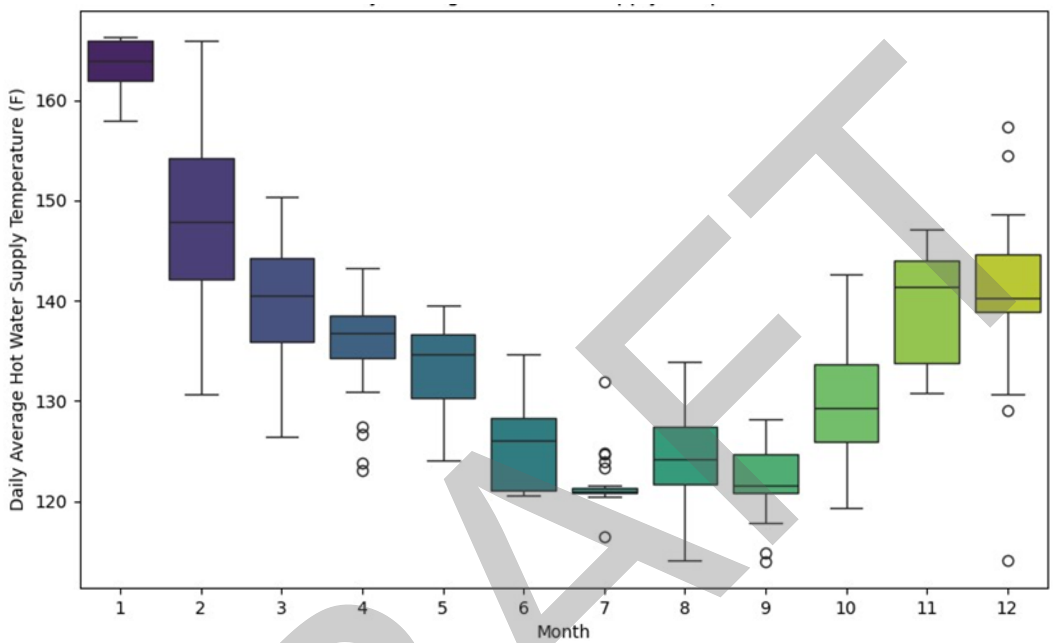
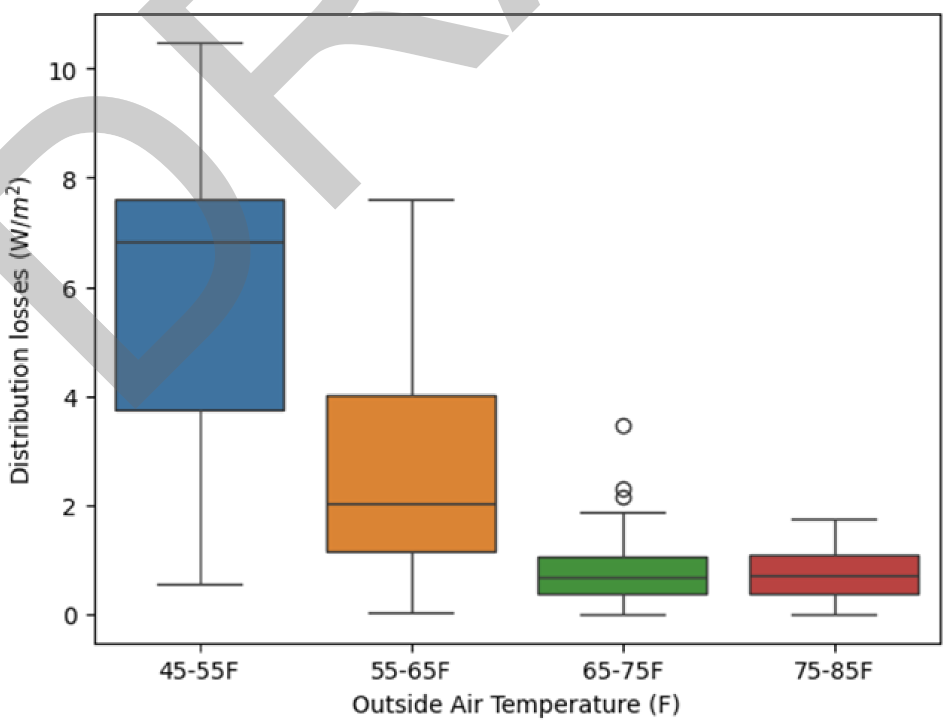
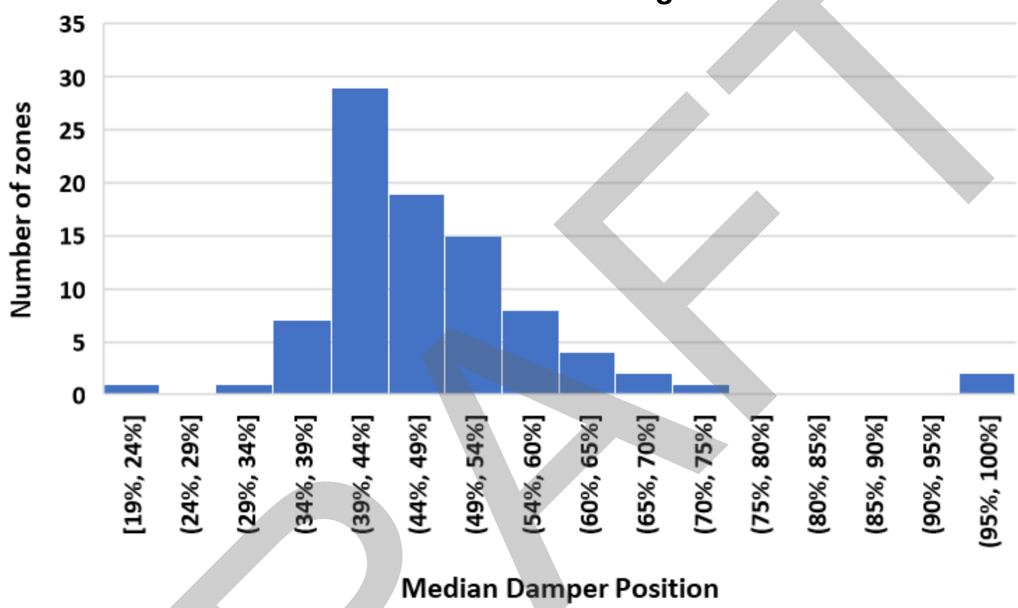


Figure 19. Heating Power Distribution Losses Against Outside Air Temperature



In addition to the intentional reheat energy usage, the team also evaluated the median damper position of each VAV box during heating mode. Figure 20 shows a histogram of median damper positions in all VAV boxes of the building during heating. About half the VAV boxes (48) have median damper positions between 39-49%. This highlights that during heating, VAV box dampers typically operate at a position that will cause significant temperature stratification, reduced heating coil capacity, and unnecessary fan energy use compared to more open dampers (Wendler et al., 2023).

Figure 20. Histogram of Median Damper Position for All VAV boxes During Intentional Reheating

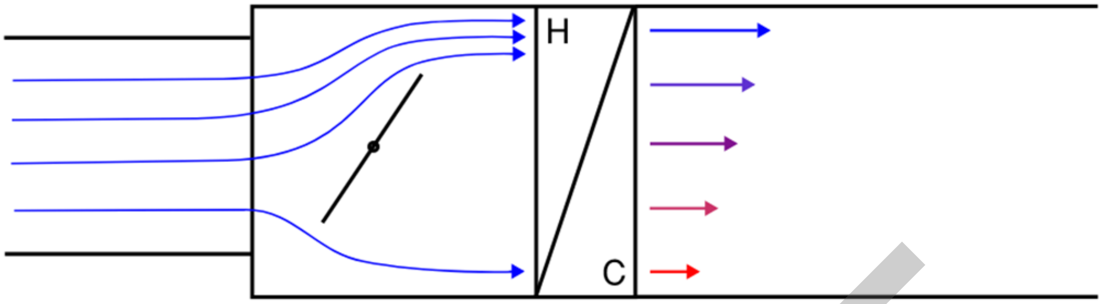


3.3 Laboratory Testing Results

The background, methods, findings, and recommendations of the lab experiment at Price Industries are presented in more detail in the report (Wendler et al., 2023).

One key finding of this experiment was that as the damper in a VAV reheat terminal modulates, velocity becomes higher at the top of the duct than at the bottom. The velocity stratification in turn causes the discharge air temperature off the heating coil to be colder at the top of the duct than at the bottom (see Figure 22). This stratification effect can lead to less accurate temperature measurements in the duct, which makes the controls of VAV reheat systems less effective at saving energy and maintaining comfortable space conditions. Another major finding of our experiment was that as the stratification depicted in Figure 22 worsens as the damper closes, the capacity of the heating coil also decreases. This causes more energy to be spent on making up the lost capacity to maintain comfortable space conditions (see Figure 23).

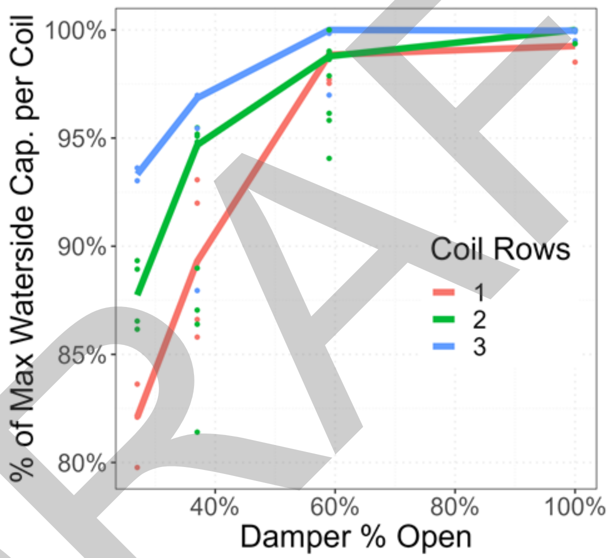
Figure 22: Damper Impact on Air Velocity and Temperature Stratification



Cross-section of a VAV reheat box and outlet duct, showing air deflecting off the top of the damper blade as it closes, causing velocity and temperature stratification to the right of the heating coil.

Source: Taylor Engineers

Figure 23: Damper Position vs. Coil Capacity

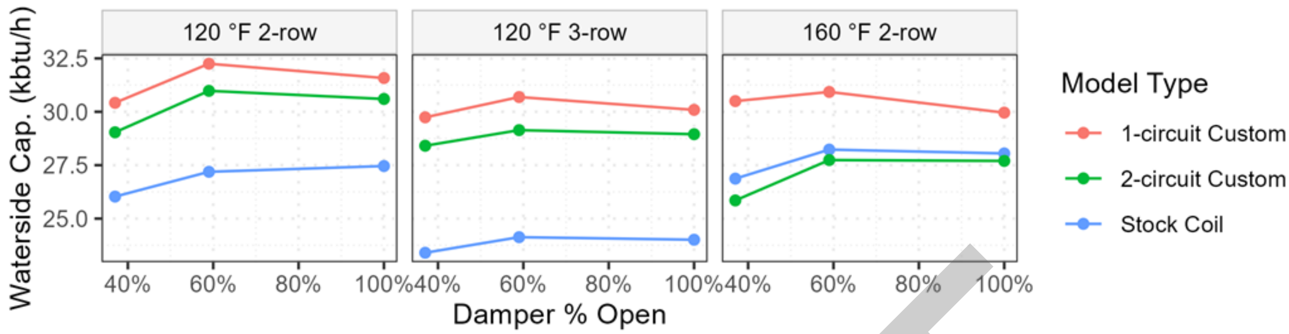


Line graph showing coil capacity being highest at full open damper positions and decreasing as the damper closes, with the effect being more extreme for lower coil row counts.

Source: Taylor Engineering

A key challenge of reducing emissions from these systems, whether through heat pump electrification or condensing gas boilers, is using heating hot water supply temperatures (HWST) that are lower than conventional heating systems. Since lowering HWST yields a lower temperature drop across the coils (ΔT), additional cost must be incurred by increasing the size of other components of the heating system to make up for the lower ΔT. The researchers tested means by which to increase ΔT for low-HWST systems by creating several custom coil designs whose circuiting (i.e. tubing arrangement) was changed relative to the standard coils used in the rest of the experiment. With this coil design, the researchers increased the ΔT (and thereby increase the capacity) of the low-HWST coils over 20% over standard coils (Result 6). See Figure 24 for results.

Figure 24: Custom Coil Performance Over Standard



Line graph showing higher heat capacity of custom coil designs over standard coils. For low-HWST coils, the 1-circuit custom design has a higher capacity than the 2-circuit custom design, which has a higher capacity than the standard design.

Source: Taylor Engineers

In other tests, the team measured distribution losses from the uninsulated coil housing, piping, and valves. The team found that the losses from these uninsulated components represents about 5% of the coil capacity. In a real building, while there is a chance that these losses may serve to eventually heat spaces that require heat during some part of the year, they will also increase cooling loads during other parts of the year when this heat is added to the air returning to the air handler to be cooled.

Given these results, the team made the following recommendations:

1. Designers should ensure static pressure reset sequences are implemented and operating well in VAV reheat systems to minimize heating capacity losses at more closed damper positions.
2. Designers should mount single-point DAT sensors as close to the centerline of the duct as possible, as far from the coil as possible. If budget permits, rigid averaging sensors should be selected for superior accuracy.
3. Designers and builders in new construction projects should insulate all valves, pipes, coil components and housing, while in retrofits, these should be insulated at the same time as other VAV box measures.
4. Coil manufacturers should allocate additional resources to re-designing typical coil circuiting for increased performance and ease of installation.

After the team published our results in early 2023, Price Industries followed Recommendation 4 and ran more complete and varied tests on the 2-row 1-circuit custom coil design and observed increases in capacity over their standard 2-row coil design, similar to the original results the researchers obtained. Given these promising results, they have since planned to further develop and test this coil design, aiming to bring it to market as a new selection option in 2024.

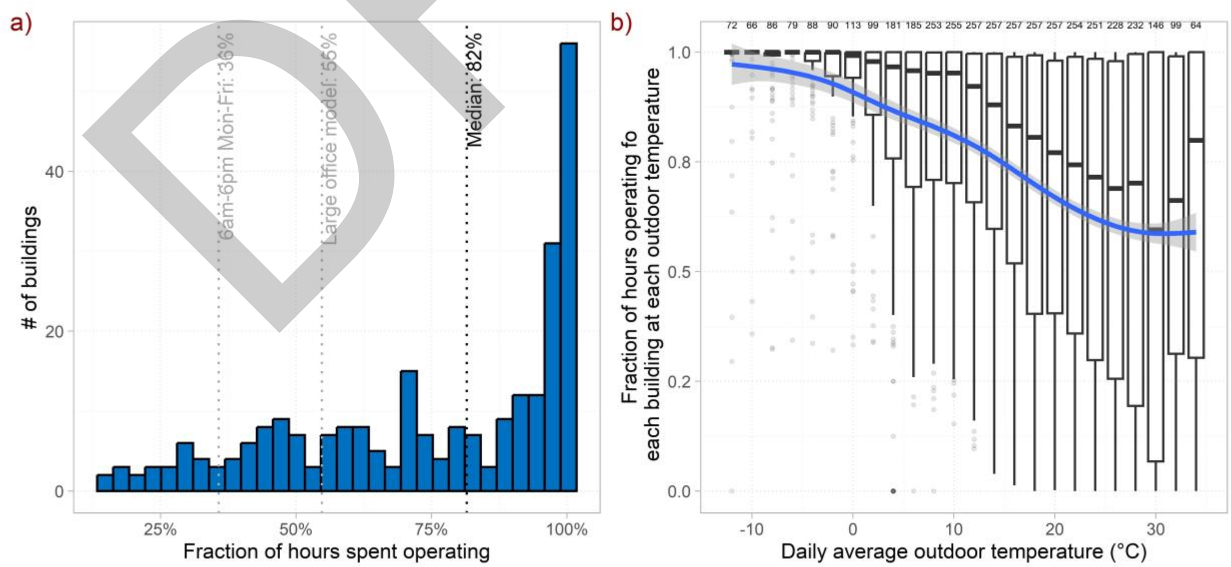
3.4 Data-Driven Analysis Results

As part of this research project, the team gathered data space heating hot water systems in 259 buildings across 56 organizations throughout the USA (Raftery et. al., in press, 2024). The dataset comprises 120 million measurements gathered by building automation systems from 2014-2024. The typical building's dataset contains measured supply and return water temperature, flow rate, output power, system state and outdoor temperature spanning 2.2 years (15-minute interval). Pump and boiler level data are available for smaller subsets of buildings.

The data indicates that many of the assumptions about how these systems operate do not match the findings from the measured data. There are substantial energy savings and first cost savings potential from better understanding how these systems actually operate in practice and modifying design and operation practice accordingly. The main findings are:

1) These systems operate far more frequently than expected, with the typical building operating 81% of the hours of the year. Many systems operate almost continuously throughout the year, including during summer periods and during unoccupied hours at night and weekends, and in many cases for building types that are unlikely to be occupied during those times (i.e. offices and libraries), causing a substantial energy penalty. For context, commercial building reference models (US Department of Energy 2021) commonly used for assessing changes to building codes in the United States assume an operating fraction of 55%.

Figure 25: Actual Fraction of Time Spent Operating of HHW systems in 259 Buildings



2) HHW loads are much lower than expected and the annual load distribution for each building are typically highly skewed towards very low part loads. This highlights the need to design systems that perform well at low part loads (Peterson 2018), and that there is more resilience to failure in systems with two or more pieces of heating equipment than would typically be assumed. It further highlights that a substantial fraction of the total annual heating load can be served by a small piece of equipment, such as a small heat pump.

3) HHW systems are oversized for the loads encountered at design day conditions, by approximately a factor of two, even after accounting for redundancy requirements for the design (when known).

4) Most systems do not modify supply water temperatures downwards with decreasing loads or increasing outdoor temperatures, at all, or if they do, it is over a relatively small range of temperatures. This indicates substantial energy savings potential for a relatively minor change to control strategy.

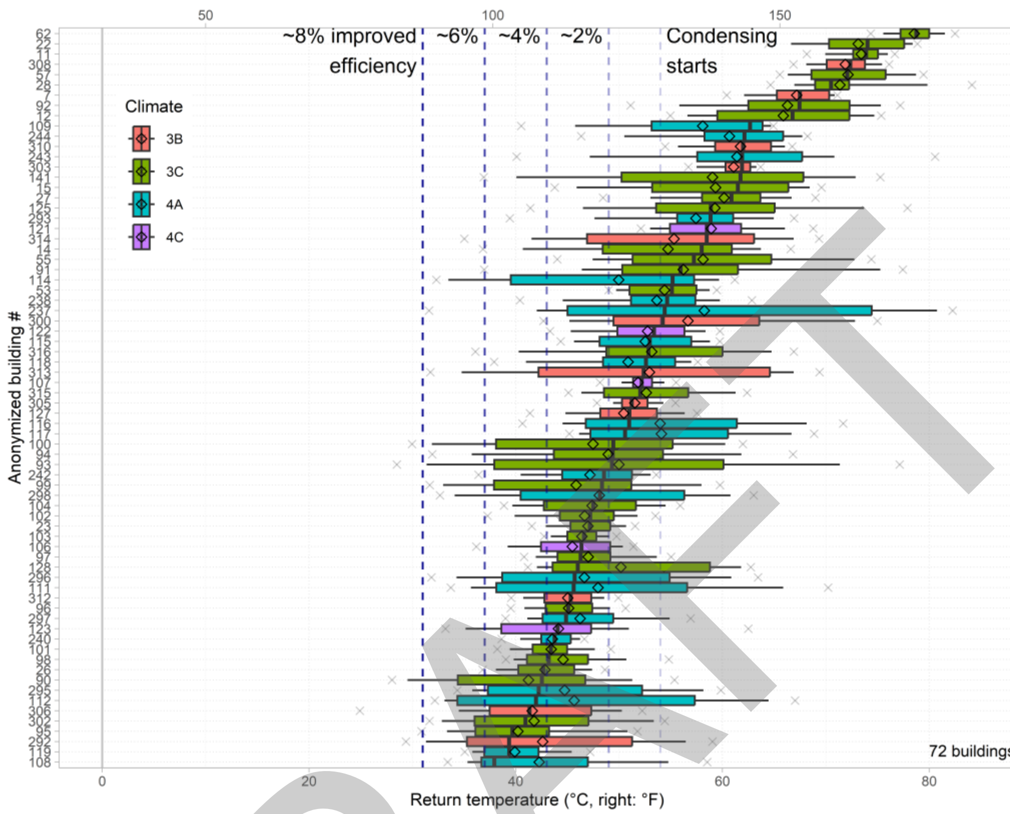
5) For key system operating parameters, such as supply water temperature setpoint, many buildings show evidence of manual overrides that persist for months or years and have a negative impact on performance.

6) Condensing boilers typically operate with high return temperatures, yielding relatively little efficiency gains from condensing operation in practice. Combined with other data on load distribution and measured gas consumption, this indicates that these systems operate below nominal efficiency in practice (see Figure 26).

7) During the data acquisition, screening, and cleaning process it was clear that the quality of data available from most buildings was low. Failed or erroneous sensor data was common even for sensors measuring key system performance metrics, as were long time spans of missing data. This indicates substantial room for improvement in instrumentation quality, failure detection, and maintenance.

In aggregate, these findings indicate potential for substantial energy savings opportunities from resolving the issues identified, many of which are controls related and are relatively low cost compared to replacing equipment. The team also published an open-access dataset consisting of over 100 million measurements from 216 buildings for future use.

Figure 26: Actual Return Water Temperature Distributions for Buildings Using Condensing Boilers



3.5 Market Transformation Results

3.5.1 Interviews with HVAC Designers

The researcher investigated current practice to reduce emissions from existing large commercial buildings by conducted one-hour interviews with 17 mechanical HVAC designers, together having over 350 years of industry experience, professional tenures at engineering consulting firms and design/build firms, and project work in California, New York, Texas, Alaska, the United Kingdom, and Canada. The interviews asked a mix of quantitative and qualitative questions, covering four topic areas: general background, peak heating load and boiler selection, boiler controls, and existing building decarbonization. The interviews yielded insight into industry practices, including determining peak heating load, equipment redundancy, boiler staging controls, heating hot water temperature resets, challenges of building electrification, and design considerations for building decarbonization. From the interview results, the team developed five key findings:

(1) existing and new boilers are commonly oversized,

(2) actual building load distributions are not available,

(3) hot water temperatures are too high,

(4) boiler end-of-life is not the best electrification opportunity,

(5) substantial reductions in emissions are feasible even if all- or part-electrification of heating is infeasible.

The full report of these interviews are published in (Lamon et al., 2022).

3.5.2 Campus Measure Recommendations

The research team prepared a memo containing high level recommendations for a portfolio building owner based on this research project, including specific recommendations for the campuses that researchers worked closely with during this project. See Appendix A for a generic version of the memo.

3.5.3 Rapid Retrofit Screening Method

The team developed and demonstrated a simple screening method to help owners and operators assess extensive or small-scale building portfolios, using easily accessible data encompassing building type, age, size, and monthly gas consumption. The method (Thawer & Raftery, 2024) entails applying a series of filters to a list of potential buildings to identify those that should be prioritized for further investigation. The main filter highlights office buildings with elevated summertime gas consumption, as well-functioning systems lacking a major gas end-user should exhibit minimal gas usage during the cooling season. This filter uses a threshold for summer gas consumption calculated based on standard design parameters, assumptions, and case studies to serve as a benchmark and pinpoint problematic buildings.

The researchers applied this filter, among others, to over a decade of gas consumption data for 22 buildings at California State Polytechnic University, Humboldt. Collaborating with operators enabled us to identify high priority buildings from the data set and then validate the filtering process by cross-referencing floor plans and schedules to verify that these issues do in fact exist. Additionally, the team applied this method to monthly gas data for 3318 buildings in Washington, DC to gauge its applicability on a larger scale. This prioritized 30 buildings as candidates to significantly reduce emissions, elevate thermal comfort, and reduce gas consumption through economical retrofits.

While the screening method does not identify all buildings needing heating system upgrades, the results demonstrate how effective it is at highlighting buildings which should be prioritized to see the largest savings from low-cost interventions.

3.5.4 Hot Water Heating Design and Retrofit Guide

The research team produced a publicly available *Hot Water Heating Design and Retrofit Guide* (Cheng et al., 2023) intended for designers, energy analysts, installers, commissioning providers, and building operators as well as building owners and property managers. This guide describes key design issues, then provides information on strategies to reduce hot water loads and improve heating system efficiency. The guide draws from the findings from various parts of the overall research project, as well as recent past studies, and distills the key findings to help users improve heating system performance. Key design issues include boiler run time, boiler sizing, condensing boilers and distribution losses. Strategies include reducing hot water loads and improving plant and distribution efficiency through controls, configuration, sizing, selection, and commissioning. A spreadsheet tool to help determine zone ventilation requirements in retrofit applications, which was a key energy measure in the demonstration studies, is provided with the Guide. The Guide also lists training and other references.

3.5.5 Policy Recommendations

Two of the primary pathways to meet the project goals and to drive adoption of measures are through codes and standards enhancements and utility programs offerings. The team's objective with respect to codes and standards is to examine current building energy code requirements to identify feasibility, impediments, and opportunities for code enhancement involving hot water control solutions based on project findings. The team focused on code change opportunities in the California Building Energy Efficiency Standards (Title 24) and ASHRAE Guideline 36. The team's objective with respect to utility programs is to identify opportunities within California utility program offerings to improve performance of heating hot water systems. The team identified opportunities for program delivery platforms and measure offerings. See full report for more detail (Singla et al., 2023).

Opportunities for Codes and Standards Changes

The main codes and standards with heating hot water control scope in California are California Title 24 and ASHRAE Guideline 36. The team identified new change opportunities and discussed the steps needed to provide more effective enforcement of the control requirements for both new construction and alterations. The following are the proposed measures:

- Title 24: Reduce Design Maximum Hot Water Supply Temperature. This measure limits the design space heating hot water supply temperatures to 130 °F for new construction, additions, and alterations. This measure was included in the Express Terms draft of the 2025 version of Title 24.
- Title 24: Hot Water Supply Temperature (HWST) Reset: Require chilled water and hot water systems that use variable flow to have temperature reset controls.
- Title 24: HHW Plant Capacity Turndown: Requires that the boiler plant minimum operating load be ≤ 5% of the boiler plant full capacity.
- ASHRAE Guideline 36: Improve Setpoint Reset Effectiveness: Revise the trim and respond resets to direct the designer on how to set the default number of ignored requests for each application, rather than provide a fixed value that will not be appropriate for many applications. This measure was adopted as an addendum to Guideline 36-2021.

Opportunities for Utility Programs

The team provides recommendations on how California's utility program offerings can support improved performance of natural-gas fired boiler fed hot water reheat systems. CPUC program policies and platform guidelines dictate what and how programs and measures are implemented. The team identified the following measure offerings: Lower VAV box minimums, Prevent excess boiler operation, and Reduce piping distribution losses. The recommended measures can be taken to market through one or more of the following Resource Acquisition program platforms: Deemed, Custom, NMEC, On-Bill Financing and Hybrid.

Additional Measure Opportunities

There are other potential measures that came out of the research that the research team is not currently recommending for implementation in codes, standards, or programs, but that could be incorporated in the future. These measures require more research, have lower or uncertain energy savings potential, require additional data, are not mature enough yet, or do not have a clear path for implementation.

3.5.6 Additional Market Transformation Outcomes

Leveraging the information gained in the laboratory testing (Wendler et. al. 2023), Price Industries expects to release a single circuit reheat coil option for VAV reheat terminals in 2024. This new product option is a direct result from the custom single circuit coil that was developed and tested in the laboratory study. The new coil provides increased heating capacity and waterside temperature difference at no additional cost compared to standard options, and will support low water temperature designs for all-electric heating systems as well as improve efficiency for condensing boiler systems.

CHAPTER 4: Conclusion

Discussion

Through full-building demonstrations, detailed field study of distribution losses and boiler efficiency, laboratory analysis, and analysis of data from hundreds of buildings, this project showed the benefit of the **Deep Decarbonization re-Design.** This approach involves cost-effective controls measures and can also include equipment measures. Low-cost software control measures, such as basic system scheduling, correcting zone minimum airflow rates, outside air controls, and setpoint resets using ASHRAE Guideline 36 sequences can save 50% or more of natural gas consumption in existing large commercial buildings. Adding equipment measures (replacing boiler with correctly sized and efficient unit) can increase the savings another 25% or more depending on the building.

However, these measures can be harder to understand and to fund than equipment replacements, require engineering knowledge and attention to detail, and results vary widely based on the initial condition of the building and the quality and extent of implementation. In addition, operator and facilities constraints include:

- Time: Facilities departments are commonly under-staffed and operators have many priorities other than reducing energy consumption.
- Training: Operators typically lack formal training regarding HVAC system operation, and often resort to overriding a setpoint to address an issue as quickly as possible rather than fixing the underlying issue and implementing a more nuanced but far more efficient solution. These manual overrides often unintentionally persist for months or even years.
- Reverse incentives: There are many reverse incentives at issue too, with operators seeking to avoid any complaints, leaks, or potential disruption.
- Lack of positive incentives: In most organizations, there is little direct incentive to operators to reduce energy consumption of the buildings that they operate.

Specifically, this project identified enormous untapped potential for emissions and cost savings in buildings. This is particularly the case for buildings that have direct digital controls (DDC) controls to the zone level, have high summer gas consumption (and have limited or no non-HVAC gas end-uses), or have a single existing non-condensing gas boiler. Based on the findings in this study and other recent work, the opportunity for large natural gas savings from these measures appears to be common within the large commercial building stock.

Synergies with Existing Building Electrification

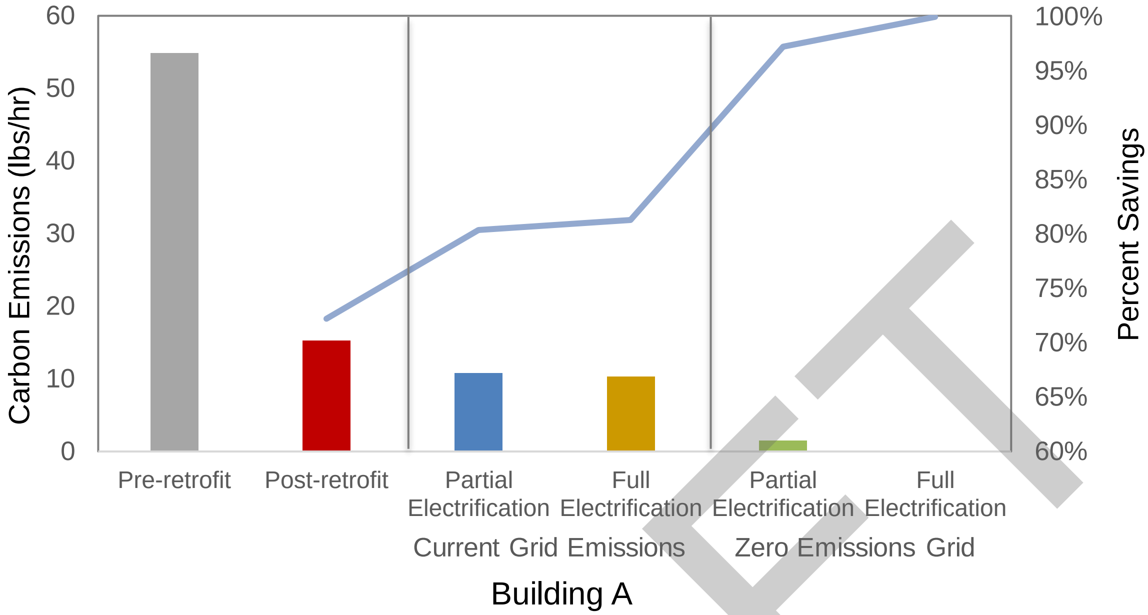
Using the Deep Decarbonization redesign approach will reduce emissions by a similar amount as electrifying them, make existing buildings cheaper and more feasible to electrify, and put less stress on grid infrastructure after electrification. Other findings from this project also apply to all-electric new construction, where the lessons learned can reduce first cost and improve performance.

While this project has demonstrated the feasibility of reducing site emissions by 70% in existing buildings, reducing emissions further requires electrification of heating using heat pumps[4]. Many of the issues the team investigated in this project are relevant to heat pump electrification. For example, heat pumps are more efficient when supplying lower temperature water, and all heat pump equipment has an upper limit beyond which it cannot supply warmer water. A typical air-to-water heat pump system for commercial buildings cannot supply water much above 55 °C (131 °F). This poses a particularly challenging problem for many existing buildings where the terminal equipment was typically sized for water temperatures of 70 or 80 °C (160 or 180 °F) at the design condition. Operating at much lower water temperatures can reduce heating capacity in the zones below what they require near heating design conditions. Similarly, the first cost, physical size, weight, and electrical service requirements of heat pump equipment all increase in direct correlation with equipment heating capacity and those aspects affect project cost and feasibility. Given the highly skewed distribution of loads seen in measured data from hundreds of buildings (Raftery et. al., in press, 2024), with most energy consumption occurring at low part loads, it is possible to achieve the vast majority of the total possible carbon savings from full electrification through partial electrification with a relatively small heat pump (Cheng et. al. in press, 2024).

Further, because air-source heat pump heating capacity decreases with decreasing outdoor temperature, sizing this equipment to fully electrify all heating loads at cold design day temperature conditions will mean that the equipment is very oversized at all other times. At best this excess capacity will be under-utilized, and at worst, it will cause cycling and related performance issues for the new heat pump equipment, affecting both efficiency and durability.

4 Electrifying with an electric resistance boiler has a lower first cost and is more feasible in terms of equipment dimensions, weight, and location constraints than a heat pump. However, it substantially increases operating costs and may be prohibitive due to electrical service capacity constraints and Title 24 requirements. More importantly, given both current and long run marginal carbon emissions for grid electricity, switching from gas to electric resistance boilers will actually increase overall carbon emissions in most cases, defeating the purpose of electrifying.

Figure 26: Reduction in Site Emissions at One of the Demonstration Sites, Actual vs Various Future Electrification Scenarios



Summary

Overall, this project demonstrated substantial (70%) site emissions savings in existing large commercial buildings, and provided information regarding the range of actual conditions experienced in a wide range of other buildings. Both will assist stakeholders in achieving electrification and decarbonization goals at scale. It will always be more feasible and cost-effective to first focus on efficiency, and then electrify the remaining loads, rather than to solely focus on electrification. Further, the eventual emissions savings will be larger as the loads served by the electric equipment will be lower, and these lower electrical loads will also make it more feasible to achieve grid decarbonization goals.

Lessons Learned

Regarding Controls Related Measures

The difficulty and degree of success in implementing G36 *without* replacing the controller hardware highly depends on existing conditions. It is very challenging to assess this up-front without expending substantial effort and associated cost. Both full and software-only retrofits often uncover unexpected issues during the controls upgrade. However, particularly in the case of software-only retrofits, there may not be a clear party assigned (or associated budget) to resolve these unexpected issues, but nonetheless they must be resolved to maximize savings. Further, for software-only retrofits it is often not possible to implement ASHRAE G36 exactly due to limitations of the existing installed hardware, which require customized solutions to capture similar functionality. This process is potentially error prone, and often will require iteration and additional commissioning.

For buildings with controllers that are approaching (or past) end-of-service-life, providers should focus on the synergy of fully replacing the building automation system and upgrading the using G36 control sequences at the same time, preferably from an existing G36 programming library. Where only software upgrades are feasible, focusing on very effective measures that have been rarely implemented to date—correcting zone minimum airflow rates to current code requirements—may yield the most scalable savings. This measure is cost effective, relatively straightforward to implement, does not have a strong interaction between the savings achieved and other potential controls issues in the building, and is far less likely to be overridden by building operators than higher level setpoint resets at air handlers and plant equipment.

Regarding Heating Equipment Replacement

Though based on limited data, it seems likely that existing non-condensing boilers have exceptionally poor operating efficiency due to their age, limited turndown capabilities, and likely oversizing. In the three sites where the team has high quality measured data, researchers saw 30-50% efficiency compared to an 80% nominal rating. This issue is likely prevalent for heating plants that have only one boiler, as the associated oversizing (compared to a plant with two or more boilers) will yield even more short cycling and associated efficiency impacts. Replacing these with appropriately sized condensing boilers with good turndown could reduce gas consumption by 30-50% alone. It also indicates that the actual savings that would be achieved by electrifying these loads with a heat pump would reduce emissions by more than expected if assuming typical boiler nominal efficiency. Thus, end-of-service-life projects should carefully evaluate actual needs, rather than simply replace like-for-like. Further, measures to shut-down these systems if they are operating continuously will yield substantial savings as nighttime and other unoccupied periods are those that have the lowest loads, and yield short cycling operation.

For existing buildings without substantial non-HVAC gas end-uses, daily natural gas consumption data can be a reasonable means of assessing actual building loads when replacing equipment if measured loads or other trend data is unavailable. This daily gas consumption data is typically available from utility providers in California. For example, designers can assess actual peak loads by selecting days that approach the heating design day temperature, assuming that the new heating plant would operate continuously for 18-24 hours on that day to serve that measured gas load, and using engineering judgement to assess how much larger than this the new equipment must be to meet more transient hourly loads on that day. This approach is only feasible if the existing equipment is not grossly oversized to the point that actual input efficiency is very uncertain. Further, it is key that designers size and select equipment to ensure that it can operate efficiently at low part loads without short-cycling. For office buildings, in the absence of measured load data, the heating plant should be designed to efficiently serve loads of 1 BTU/hr.ft² or lower.

Next Steps

The team recommends identifying other opportunities to perform controls retrofits at scale, further demonstrating this substantial energy and emissions savings opportunity and highlighting the results to a broader audience. To that end, the team proposed controls retrofits as a market transformation idea to the California Market Transformation Advisory Board (CalMTA). Their initial review results (Nov 2023) selected it as an idea to investigate further in the first phase. If successful, a program at that scale could potentially identify the key characteristics that correspond with higher/lower net savings, and further share these results with the public. Last, the team recommends further research to continue to evaluate synergies between the findings of this research and electrification of heating systems in new and existing buildings. To that end, the team recently proposed research to the CEC EPIC program (and have received a notice of proposed award) to decarbonize existing large commercial buildings through electrification of heating using ultra-low global warming potential refrigerant heat pumps, allowing us to continue this work.

Conclusion

- The primary demonstrations reduced annual natural gas consumption by 69% and 71% annually in two large office buildings, as well as substantial HVAC electricity savings. A third demonstration site, a recently constructed building in which the team made ultra low-cost, software-only controls changes in the non-lab portions of the building, yielded natural gas savings of 22%.
- Substantial energy, cost, and emissions savings potential may be achieved in existing buildings by correcting VAV minimum airflows and bringing controls up to ASHRAE Guideline 36.
- The team identified that buildings with a heating hot water system served by a single, older, non-condensing gas boiler likely have very poor operational efficiency—far below nominal efficiency—and should be prioritized for retrofit.
- The team acquired and analyzed data heating hot water systems in 259 buildings nationwide, highlighting that many of the assumptions regarding how these systems operate do not align with real world performance, with these systems operating far more frequently and less efficiently than expected, indicating substantial savings opportunities. The team released an open-access dataset of over 100 million measurements from 216 buildings nationwide.
- The team measured heating hot water distribution losses (i.e., standby losses) of 1.2 W/m² in 7 buildings, and validated those measurements with newly installed, high-quality instrumentation at both building and branch level in one building. The team also validated the intentional reheat method using that instrumentation, and repeated this analysis in a third building.

- The team developed a screening method to identify candidates with high savings potential based on monthly gas consumption and minimal building information.
- The team performed full-scale laboratory testing of HHW system components, including developing and testing a custom coil designed for low water temperature operation suitable for all-electric new construction and existing building electrification retrofits.
- The team published findings in a policy recommendations report, design guide, 10 journal and conference articles, as well as numerous presentations.

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Project Deliverables

List of Presentations

- Four presentations at the ASHRAE conferences correspomnding with the papers published below
- Seven presentations (including two scheduled for April and October 2024) to a broad range of stakeholders in the building industry at CBE Industry Advisory Board meetings.
- Three presentations (including one pending for August 2024) at ACEEE conferences
- One presentation at the demonstration site
- One presentation (scheduled for April 2024) at the local ASHRAE Golden Gate chapter
- One seminar (scheduled for May 2024) facilitated by PG&E

List of Journal and Conference Papers

Cheng, H., Raftery, P., Wendler, P. (2024). Are we prioritizing the right thing? Cutting carbon emissions in California's large office buildings before installing a heat pump. *2024 ACEEE Summer Study on Energy Efficiency in Buildings* (accepted, in press). https://escholarship.org/uc/item/9cd4c4zt

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Wendler, P., Raftery, P., Cheng, H., (2024). Rethinking VAV HW Terminal Unit Design and Performance: Results from Lab Testing. *ASHRAE Journal* (accepted, in press)

List of Reports

- Singla, R., LaPalme, G., & Chappell, C. (2024). *Heating Hot Water Policy Recommendations*. https://escholarship.org/uc/item/7sf76298

List of Other Deliverables

- Cheng, H., Wendler, P., & Raftery, P. (2023). *Hot Water Heating Design and Retrofit Guide*. https://escholarship.org/uc/item/8m88d92j

Project website

- Reducing Gas Consumption in Existing Large Commercial Buildings, https://cbe.berkeley.edu/research/reducing-gas-consumption/

APPENDIX A: Campus Recommendations Memo

To whom it may concern:

As part of a project funded by the California Energy Commission's Public Interest Efficiency Research Program (PIR-19-013), the Center for the Built Environment (CBE) at UC Berkeley, Taylor Engineers, TRC, and the Western Cooling Efficiency Center at UC Davis performed a research and demonstration project focused on reducing natural gas consumption of heating hot water (HHW) systems in existing large commercial buildings. The purpose of this memo is to highlight the most relevant findings for campus (or any portfolio) building owners and operators.

First, we developed a simple screening method that identifies good candidates for heating hot water related energy efficiency measures within a large portfolio of commercial buildings using readily accessible building characteristics and monthly utility bill data. In brief, if a building has no large gas user (e.g. a commercial kitchen, swimming pool, or gas process load) other than the HVAC system, but has gas consumption above 700 BTU/month·ft^2 during summer months, it is likely a good candidate for the measures below.[i]

The first measure is to reduce heat losses from HHW distribution piping systems. We measured this in 7 buildings in California and found average losses of ~1.2 W/m^2 [ii], for context, this is approximately the same heat as half of the average plug loads in an office. Reducing hot water supply temperature (HWST) will reduce heating energy consumption, particularly in warmer months when it will also reduce cooling and fan energy use in the building. We also studied data from hundreds of buildings nation-wide and found that HHW systems operate almost continuously, with the typical HHW system operating 81% of hours of the year (including at night, over weekends, and throughout the summer)[iii]. We also found that the majority of these buildings show little sign of a functional or effective hot water supply temperature (HWST) reset, and typically operate at much higher HWST than necessary to meet the buildings' heating loads. From among this data set, we also found that a large fraction of condensing boiler plants operate at return water temperatures above the condensing threshold, likely in part due to higher HWSTs. These findings highlight a substantial energy and carbon savings opportunity by reducing hot water supply temperatures and correcting the operating hours of these systems. Further, reducing HWST will make it more feasible to decarbonize the building's heating system through electrification, as the temperatures are more likely to be within the operating range of currently available heat pump systems, and the annual heating load will be lower[iv].

We also demonstrated that performing an in-depth retrofit to bring a building's HVAC controls up to ASHRAE Guideline 36 reduces natural gas consumption in large commercial buildings, in some cases by 50% or more[v]. When an in-depth controls retrofit is infeasible due to capital or other constraints, then individual very low-cost measures have substantial cost-effective savings even when applied stand-alone. Likely the best individual measure is to correct zone minimum airflow rates in existing VAV reheat systems to those in codes for current new construction, however, this measure is not common knowledge and thus is rarely performed as part of typical retro-commissioning and efficiency efforts today. We have developed guidance on the workflow for evaluating zone ventilation requirements and a spreadsheet calculation tool to help streamline this process in existing buildings[vi]. Based on the study, it is likely that most commercial buildings have similar characteristics and issues as those described above and that highly cost-effective energy and carbon reductions are feasible by applying these measures. As part of this current CEC funded research project, we demonstrated that performing a deep efficiency retrofit that updated controls to ASHRAE Guideline 36 and replaced end-of-service life boiler with small, efficient new condensing boilers reduced measured annual natural gas consumption by 70% in two large office buildings[vi].

Last, we have developed a Design and Retrofit Guide which presents overviews of the common design and operating issues and provides recommendations for reducing hot water loads and improving heating system efficiency[iv].

We hope you find this information useful and actionable, and are happy to discuss, share more information or answer questions you may have about any of these topics and savings opportunities.

Sincerely,

Paul Raftery, Ph.D.,
Professional Researcher, Center for the Built Environment

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[i] Thawer, M., & Raftery, P. (2024). Screening Method to Identify High VAV Minimum Airflow Rates and Retrofit Opportunities. ASHRAE Transactions, Proceedings from the ASHRAE Winter Conference, Chicago, 130(Part 1). https://escholarship.org/uc/item/6gz10718

[ii] Raftery, P., Vernon, D., Singla, R., & Nakajima, M. (2023). Measured Space Heating Hot Water Distribution Losses in Large Commercial Buildings. ASHRAE Orlando https://escholarship.org/uc/item/46h4h28q; Vernon, D., McMurry, R., & Raftery, P. (2024). Heating Hot Water Distribution Heat Losses - Detailed Measurement. ASHRAE Transactions, Proceedings from the ASHRAE Winter Conference, Chicago, 130(Part 1). https://escholarship.org/uc/item/7n6893n6

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[v] Final report; CEC-EPIC Best In Class - Project Brief (2021), https://tayloreng.egnyte.com/dl/fzlRmpRUWI/CEC_Best_in_Class_-_Project_Brief.pdf_

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