Are we prioritizing the right thing? Cutting carbon emissions in California's large office buildings before installing a heat pump.

Hwakong Cheng, Taylor Engineers
Paul Raftery, Center for the Built Environment, University of California Berkeley
Patrick Wendler, Taylor Engineers

ABSTRACT

We studied a combination of heating system measures in two large commercial office buildings in San Francisco (110,000 and 120,000 ft^2 respectively) within a project funded by the California Energy Commission. We retrofitted the existing heating plants and updated the HVAC controls to ASHRAE Guideline 36-2021 as closely as possible while retaining the existing controller hardware. These measures decreased annual natural gas consumption by 70 percent while also reducing HVAC electricity consumption. The results reinforce previous work showing significant natural gas reductions in 3 other buildings that underwent full controls retrofits (including controller hardware), and large savings from another 3 buildings that underwent partial controls upgrades. We show that on today's electricity grid, which is carbon intensive during the winter and early morning hours when most heating occurs, the carbon emissions reduction from these measures exceeds the reduction from subsequently electrifying the resulting heating system's load with today's air-to-water heat pumps. More importantly, these solutions are mutually beneficial. Acknowledging that we also need to electrify HVAC loads to meet our climate goals, replacing controls first will reduce the size, weight, first cost, embodied carbon, and ongoing operating cost of the subsequent heat pump installation required to fully electrify, and will make it more feasible to do so. This paper highlights an overlooked opportunity for enormous decarbonization in the existing commercial building stock using a solution that is available, cost effective, and scalable. We should prioritize these measures first, and then electrify, rather than focusing solely on electrification.

Introduction

Interest in building decarbonization has grown rapidly in recent years with a range of related policy directives and organizations independently setting targets. While there are practical all-electric solutions for typical small and medium commercial buildings (e.g., air-to-air heat pumps and variable refrigerant flow systems), these solutions do not scale well for large building applications. Electrifying large commercial buildings can be very challenging, particularly for retrofit applications, because of high first and operating costs, large space requirements, electrical and structural impacts, and compatibility of air-to-water heat pumps (AWHP) with existing hydronic distribution systems (Gill 2021).

Within the building industry, the terms decarbonization and electrification are often used interchangeably but in fact the carbon emissions from building operations can be significantly reduced without electrifying building systems. In many cases, retrofitting buildings with other decarbonization measures can provide as much marginal carbon emissions reductions as electrification projects, and often for much lower first cost.

Opportunities with Airside HVAC Controls

Improving the operation of heating ventilation and air conditioning (HVAC) control systems has long been an opportunity for energy savings and challenge for the building industry to get right. ASHRAE Guideline 36 High Performance Sequences of Operation for HVAC Systems (ASHRAE 2021) was developed to help industry overcome some of the associated barriers by providing a standard set of sequences, or strategies, for how HVAC systems are to be controlled to maximize energy efficiency, while maintaining thermal comfort and indoor air quality. With standardization on Guideline 36, many of the processes involved during design, construction, and operation of HVAC control system software can be streamlined (Cheng, Eubanks, & Singla, 2022), which further offers the potential of simplifying application, reducing implementing cost, and improving quality.

A recently completed demonstration study retrofitted the airside HVAC systems in 6 nonresidential buildings in California to evaluate the energy savings potential with Guideline 36 control sequences (Cheng, Singla and Paliaga 2022). Three of the retrofit projects achieved weather-normalized natural gas reductions of 4 to 18 percent after updating the direct digital control (DDC) programming to follow Guideline 36, while maintaining the existing control system hardware. Three of the sites underwent full control system retrofits in which all of the control hardware, including sensors, devices, and controllers, and software were replaced, achieving natural gas savings of around 50 to 60 percent. As the existing control hardware were fully replaced, some of the energy savings from these sites were attributed to resolving deferred maintenance issues such as failed economizer dampers and control valves, in addition to the high performing control sequences. Among the 5 sites where construction cost data were available, each project was completed with a simple payback of 8 years or less based on energy cost alone, excluding demand savings or carbon savings. A companion simulation study leveraged the cutting-edge Spawn of EnergyPlus simulation tool to explicitly model detailed Guideline 36 control sequences and reported an overall average HVAC energy savings of 31 percent relative to a range of typical baseline conditions for buildings in California (Zhang et al 2022). An earlier field demonstration study, prior to Guideline 36's release, modified a single software variable at each thermal zone (the zone minimum airflow) and reported 4 to 19 percent natural gas savings (overall HVAC savings of 5 to 19 percent) across 5 commercial buildings in California (Arens et al 2015).

Though each of the studies involved different buildings with different existing conditions, the range of savings achieved by Arens et al (2015) corresponds closely with the range achieved in the Guideline 36 programming retrofits by Cheng, Singla and Paliaga (2022), suggesting that correct zone minimum airflows are potentially responsible for a significant portion of the energy savings potential with retrofits using Guideline 36 control sequences. A simulation study that evaluated the impact of a range of control factors for variable air volume (VAV) systems found that zone minimum flows had by far the largest energy impact when varied between poor vs. good practice (Pang, Piette and Zhou 2017). Building energy codes have long limited zone minimum airflows, with current versions mandating them to be no larger than the minimum zone ventilation requirement (ASHRAE 2022; CEC 2022), but many new buildings continue to be designed with unnecessarily high zone minimums that exceed code limits (Singla et al. 2023; Rosenberg et al. 2017) and encounter other operational issues related to key control strategies like supply air temperature and duct static pressure resets (Rosenberg et al. 2017).

Opportunities with Hot Water Boiler Plants

Each of the studies described above focused on the impact and potential with improving the control of airside HVAC systems. Other recent efforts have also highlighted the opportunity for significant natural gas savings at the hot water boiler plants. Hot water boilers generally have rated, full-load thermal efficiencies of around 80 percent for non-condensing and above 90 percent for condensing boilers. However, Raftery et al (2018) reported a measured annual thermal efficiency of merely 33 percent for a non-condensing boiler plant during normal operating hours. Several other non-condensing boiler plants have been reported with measured efficiencies of 50 percent or less, including one plant with a newly installed boiler (Raftery et al. 2024a; Raftery et al. 2024b). The very low efficiencies found in these non-condensing boilers is largely the result of very low part load profiles for typical building heating hot water systems and consistent boiler oversizing relative to peak loads (Raftery et al. 2024b). Paired with limited turndown capabilities (e.g., often only 4:1 or less), many non-condensing boilers frequently operate at low loads that force them to short-cycle, where losses from standby and pre/post-cycle purges can result in actual thermal efficiencies drastically lower than when rated at full-load operation. By contrast, condensing boilers generally have much better turndown capability (e.g., 10:1 or 20:1) and are less prone to short-cycling. Measured thermal efficiencies of condensing boilers have approached their rated values in some buildings. However, in a study of hundreds of operating boiler plants, a large fraction of condensing boilers was found to seldom operate at condensing return water temperature conditions, indicating a consistent opportunity to improve operating efficiencies and reduce natural gas consumption in commercial buildings (Raftery et al. 2024b).

Here we describe the results from field demonstrations of building retrofits that aimed to significantly reduce natural gas consumption using available strategies to overcome common inefficiencies in existing buildings, but notably without shifting the space heating loads to electricity.

Field Demonstrations

Building Description

We retrofitted two buildings in the California Bay Area, both large office buildings comprising 120,000 ft^2 and 110,000 ft^2. The primary HVAC system in both buildings is a single duct variable air volume air handling unit (AHU) system with hot-water reheat terminals. Each building is served by two AHUs, with a gas-fired boiler plant providing heating hot water and a campus chilled water system providing chilled water.

Retrofit

Each building's hot water plant was originally planned for retrofit projects in late 2020 to replace the existing single boiler in each building to address end-of-service-life and to improve redundancy by providing two boilers per building instead of one. Our research effort supported the boiler plant retrofit design and added a broad range of heating plant, AHU, and zone level measures to the project scope. The majority of these measures were to update the existing building controls to match sequences of operation in Guideline 36 as closely as possible without replacing the existing physical controller hardware throughout the buildings. A summary of the building equipment descriptions, including changes as part of the retrofit, is provided in Table 1.

The retrofits were largely divided into two phases with the first phase focusing on measures applied to the hot water plant and distribution:

- Right-sized new boilers, substantially smaller than typical for redundancy applications with each boiler targeted to meet 75 percent of the estimated peak load.
- Condensing boilers with high turndown, high mass and no minimum flow requirement. The existing boiler in each building was non-condensing with 30 percent turndown capability.
- Primary-only variable flow distribution. The flow distribution was converted from the existing primary-secondary distribution. Bypass flow must be minimized to ensure low boiler entering water temperatures (EWT) required for condensing, whereas the existing primary-secondary flow distribution generally blends secondary return flows with the primary supply under most conditions, unnecessarily elevating EWTs and preventing condensing.
- Capping bypass on 3-way valves where feasible. 3-way valves are often installed at end-of-line coils to ensure that piping branches remain hot and that heat is instantly available when valves open, but space heating demands can generally tolerate small delays in heat availability. Unnecessary bypass flow negatively impacts condensing efficiency and increases pipe distribution losses (Raftery 2023).
- Installing all new hot water plant controls, including new hot water flow meters, supply and return temperature sensors, and natural gas flow meters.
- Revising hot water plant operation so that it is only enabled when an air handler is operating, and with boilers staged based on measured hot water load according to Guideline 36. The boilers often ran continuously in the existing condition.
- Reducing the maximum hot water supply temperature (HWST) from 180 to 140 °F, and implementing demand-based reset based on zone valve demand down to a HWST of 90 °F.
- Implementing warmup mode (i.e., 100 percent recirculation) during unoccupied periods at the AHUs. This change to prevent unnecessarily ventilating the building during unoccupied recovery periods required re-programming but was a necessity to reduce heating demand during peak warmup periods and allow for aggressive boiler "right-sizing."

In the second phase of work, controls only (i.e., software only) adjustments were made to the Building Automation System (BAS) to reduce heating demand and improve boiler plant efficiency. Control programming was largely left unchanged, partly by necessity because the zone controllers were not capable of being programmed (configurable-only) and partly out of practicality at the AHUs to minimize project scope. BAS changes included:

- Adjusting VAV minimum airflows to ventilation minimum according to Guideline 36 (ASHRAE 2021), Standard 90.1 (ASHRAE 2022) and Title 24 (CEC 2022). The existing condition was relatively high minimum flows.
- Applying pseudo dual-maximum VAV logic using existing zone controllers to delay the ramp of heating airflow from newly determined minimums to heating maximum until the heating loop output (and reheat valve position) were at 50%. The existing condition simultaneously ramped airflow and valve position.
- Resetting zone heating and cooling temperature setpoints to standardized values (70 and 74 °F)
- Detecting rogue zones and addressing the underlying issue where feasible, for example, by increasing the cooling or heating maximum air flow rate for the terminal unit serving the rogue zone when doing so would not cause other issues.
- Implementing demand- and outside-air based supply air temperature (SAT) reset at each AHU based on Guideline 36. This was existing logic that failed to function effectively because the zones were incorrectly mapped to each AHU. Instead, the systems were operated with fixed SAT setpoints that were manually adjusted as needed.
- Implementing demand-based duct static pressure reset based on zone damper demand at each AHU based on Guideline 36. This was existing logic that failed to function effectively because the zones were incorrectly mapped to each AHU.
- Other adjustments: Releasing long-standing operator overrides, addressing underlying causes (where feasible), and tuning control parameters based on detailed trend review

Table 1. Building equipment descriptions, with post-retrofit descriptions in parentheses where changed.

	Building 1	Building 2
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/h)	1 x 2,000 (2 x 1000)	1 x 2,450 (2 x1000)
Nominal efficiency	80% (90%)	
Minimum turndown	30% (10%)	
HWST reset strategy	Constant, 180 °F (Demand-based, 140 - 90 °F)	
Flow distribution and pumping	Constant flow/speed primary, variable flow/speed secondary (Variable flow/speed primary)	
Building automation system	Siemens Apogee Insight with predominantly ATEC zone controllers	
Number of VAV zones	222	196

	Building 1	Building 2
Mean zone heat & cool setpoint [°F]	70.8 & 73.0 with wide variation throughout building (70 & 74)	69.5 & 73.1 with wide variation throughout building (70 & 74)
Number of VAV zones with reheat coils	120	119
VAV reheat strategy	Pseudo dual maximum with reheat valve and airflow ramping together in heating (Reduced minimum airflows, delayed start of airflow ramp to 50% heating loop output)	
Number of reheat coils with 3-way valves	16	23 (15)
Total VAV box minimum airflow (cfm)	36,000 (20,000)	37,000 (20,000)
AHU hot water heating coil	None	
AHU duct static pressure reset	Zone demand based with very limited range (Zone demand based with expanded range)	
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% recirculation prior to occupancy on cold days, length of warm-up increases with colder outdoor temperatures)	

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 has had numerous impacts, and these affect 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 generally provide 100 percent outside air in response to public health guidance that was only removed in January of 2023. The boilers were replaced in May 2021, and the entire set of controls measures, including reverting to code-required ventilation rates, was completed by June 2023. Though the project M&V plan aimed to stagger the deployment of measures in groups over the course of the project, thus allowing us to separately quantify the savings associated with those groups, the effects of the pandemic meant that it was only possible to compare the combined impact of all measures.

Results

We collected monthly gas and electricity utility data for both buildings from 2010 to 2024. 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 bill data is available from 2018 for one building, and mid 2019 for the other, and we rely primarily on this for the pre- and post-intervention comparison.

The results show substantial natural gas reductions in both buildings. We first identified the most appropriate baseline and post-intervention period given the challenges posed by the pandemic. Daily natural gas consumption for one building is shown in Figure 1 over the course of the project, depicting the overall timeline and major milestones, and selected periods for measurement and verification. We 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 holiday (Figure 2). The pre- and post-retrofit monitoring periods are both sufficiently long such that the range of ambient temperature conditions are comparable and representative of typical weather years (evaluated but not shown here for brevity) to provide robust savings estimates. The measured monthly natural gas consumption before and after the retrofit in Figure 3 shows the exceptional reduction in natural gas consumption at one of the study buildings.

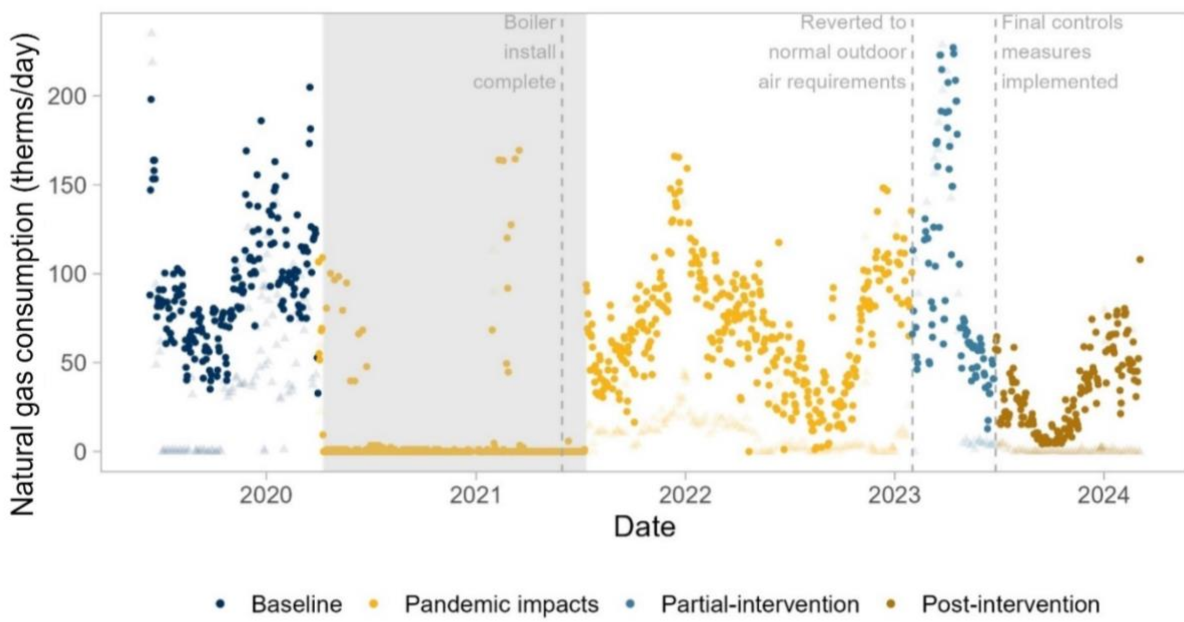

Figure 1. Natural gas consumption over time at one of the study buildings. Grey shaded region indicates intermittent pandemic shutdown periods. Faded triangular datapoints indicate a weekend or holiday.

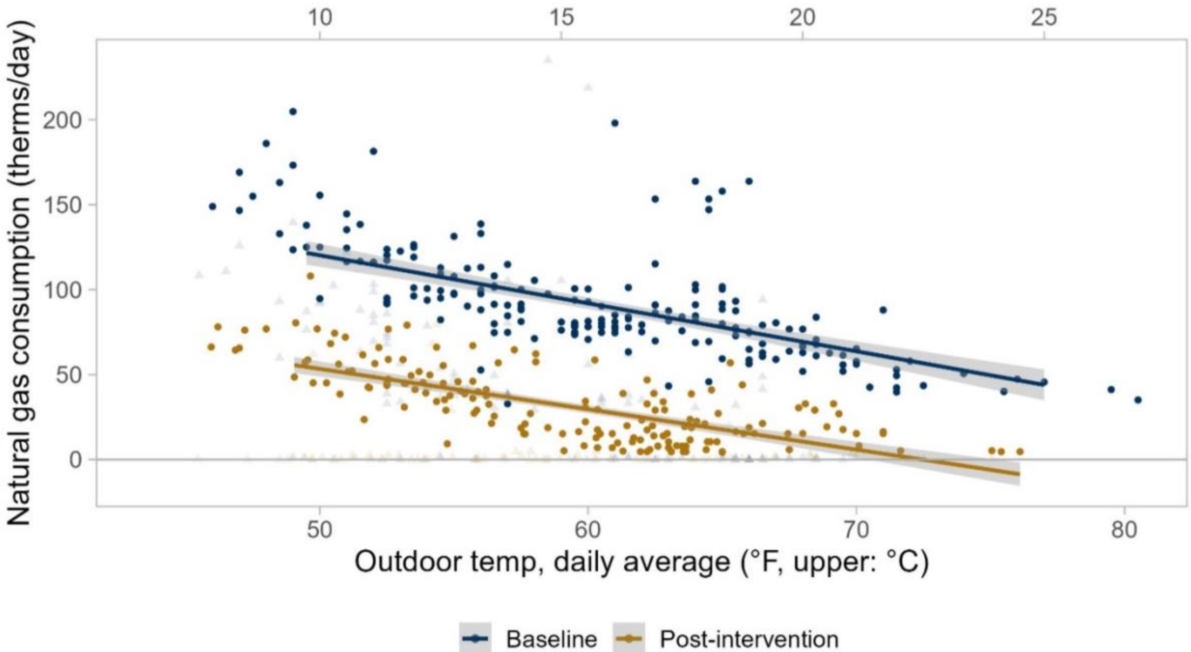

Figure 2. Natural gas consumption by outdoor air temperature at one of the study buildings. Faded triangular datapoints indicate a weekend or holiday. Linear fits use only unfaded datapoints over the range of temperatures spanned by both periods.

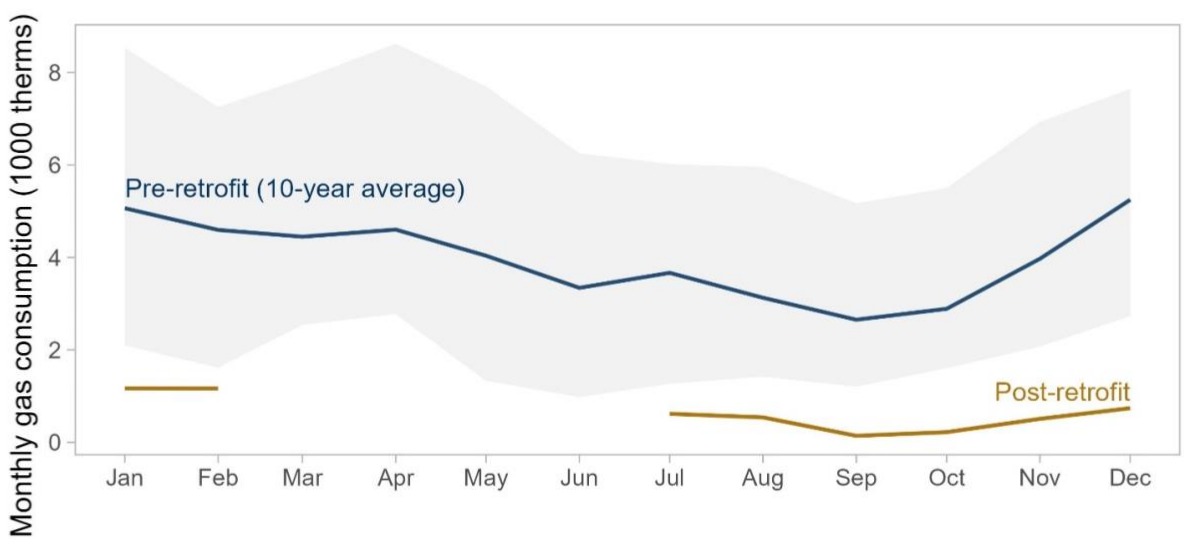

Figure 3. Measured pre- vs. post-retrofit natural gas consumption at one of the study buildings. Pre-retrofit, pre-pandemic data spans 2010-2019 with average shown in blue and range shown shaded in gray. Post-retrofit, post-pandemic data starts July 2023. One outlier not shown (Jan 2017, 17,451 therms).

Table 2 shows overall average weather-normalized natural gas consumption data, with both buildings achieving around 70 percent reductions from the baseline condition. Associated reductions in carbon emissions are also shown in pounds per hour (averaged over entire post-retrofit period) of CO_2 equivalent emissions (CO_2e). The measured savings represent a combination of the impact of the boiler plant upgrades as well as the airside control measures, but insufficient data are available to confidently parse the savings associated with each measure due to pandemic-related impacts. The controls measures also generally reduced fan energy and chilled water use but there were insufficient data to confidently quantify those savings.

Table 2. Overall natural gas consumption and avoided emissions results

	Building 1	Building 2
Baseline (therms/day)	120	83
Post-retrofit (therms/day)	37	24
Reduction (therms/day)	81	59
Reduction (%)	69%	71%
Avoided emissions (lbs/hr CO_2e)	40	29

Discussion

Key Control Retrofit Measures

Across the two sites in this study, as well as previous control retrofit studies, there are some commonalities among the existing HVAC control parameters that may help indicate the opportunity for energy savings potential in other buildings. Table 3 shows a summary of key control attributes for the sites in this study as well as several other buildings from other past studies. All of the sites listed had relatively high zone minimum airflow setpoints. This is a very common condition in existing buildings, even among recent construction (Singla et al. 2023; Rosenberg et al. 2017) and has been previously identified as having a large impact on energy consumption (Cheng, Eubanks and Singla 2022; Pang, Piette and Zhou 2017). Recent efforts have developed strategies and tools for screening buildings for high VAV minimums (Thawer and Raftery 2024) and evaluating new ventilation minimums (Cheng, Wendler and Raftery 2024). Across the various sites with pre- and post-retrofit minimum airflow data available, post-retrofit minimums were reduced by a factor of 2 to 4, on average. Though implementing low minimum airflows in retrofits sometimes requires re-programming of zone controllers to use dual maximum VAV logic, only a simple parameter adjustment was required at the two buildings in this study to largely achieve the strategy described in Guideline 36. Most of the study sites featured in Table 3 also had fixed setpoints or only limited reset capability for duct static pressure and supply air temperature at the AHUs.

Most of the retrofits shown in Table 3 from past studies reported simple paybacks of less than 10 years. Though detailed first cost data were not available for the controls retrofit work for the two sites in this study, we expect the control changes to have been very cost effective given that they generally did not require physical hardware replacement, as they were mostly adjustments to configurations, setpoints, and programming. With estimated annual utility cost savings of $110,000, the project was estimated to have a simple payback of less than 5 years (omitting the cost of the boiler replacement as this was largely an end-of-service-life project, though the incremental efficiency costs associated with the condensing boiler and piping changes were not insignificant).

Table 3. Existing (and new) conditions for key control parameters in retrofit demonstrations

Attribute	This study		Cheng, Singla and Paliaga 2022						Arens et al. 2015
	Bldg. 1	Bldg. 2	Bldg. 1	Bldg. 2	Bldg. 3	Bldg. 4	Bldg. 5	Bldg. 6	5 bldgs.
VAV control logic	Simultaneous ramp (Pseudo-dual max.)		Single maximum (dual maximum)						
Average VAV minimum airflow	33% (18%)	30% (16%)	44% (14%)	unkn. (12%)	30% (9%)	36% (15%)	28% (7%)	unkn.	30% (14%)
Zone control type	DDC (DDC)		Pneumatic (DDC)		DDC (DDC)				
Duct static pressure control	Limited reset (Reset)		Fixed setpoint (Reset)						n/a
Supply air temperature control	Fixed, manual adjustment (Reset)		Limited reset (Reset)					Fixed setpoint (Reset)	n/a

Impact of Boiler Sizing and Turndown Capability

In new construction, heating equipment are generally sized based on load calculations with conservative assumptions to ensure adequate capacity. Oversized boilers with limited turndown capability are likely to short-cycle frequently, with potentially disastrous impact on overall efficiency. This risk is particularly high for single boiler plants compared to multiple boiler plants where equipment staging allows for better overall turndown capability. For boiler retrofit projects, there is potentially the opportunity to directly measure heating loads to evaluate actual peak conditions, instead of relying on load calculations and conservative assumptions. For these demonstration buildings, hot water load data unfortunately was not available pre-retrofit so we evaluated measured peak heating loads from a similar neighboring building to estimate expected peak loads for these two buildings. The resulting peaks were significantly lower than the design output of the existing boilers. The final boiler sizing selections were further reduced based on predicted reductions in peak heating loads associated with revised AHU morning warmup controls. A common strategy for recovering from night setbacks is to simply start the HVAC systems in occupied mode a few hours prior to expected occupancy. However, this approach increases heating demand during recovery because cold ventilation air is unnecessarily introduced when not needed during non-occupied recovery periods. We revised the control to implement a proper warmup mode with the AHUs operating in full recirculation mode during the recovery period, according to Guideline 36.

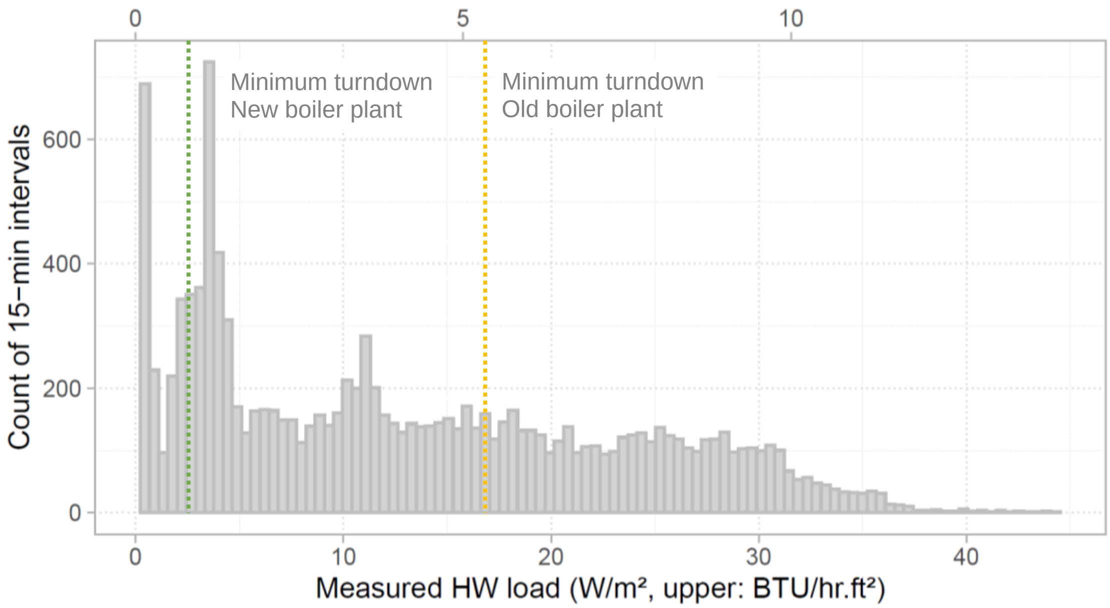

Figure 4. Building hot water load distribution for 2023 with turndown capability of original (orange line) and new (green line) boiler plants.

Figure 4 shows the measured hot water load distribution for the year of 2023 normalized to building area, which captures operation before and after the control measures were implemented. The minimum turndown capabilities are shown by the green dashed line at 0.82 Btu/h-ft^2 for the new boiler and orange dashed line at 5.3 Btu/h-ft^2 for the original boiler plant. If the original single boiler plant were serving this load profile, the loads would be below the minimum turndown capability more than half the time, with significant reductions in boiler efficiency due to short cycling. In contrast, the new two boiler plant, each with 10:1 turndown, has greatly improved turndown capability such that the vast majority of operating hours are at loads above this limit.

Aggressive right-sizing of boilers is uncommon in industry because of the fear of liability among designers and because the first cost and size impacts of oversizing boilers are minor. For end-of-service-life boiler replacements, new awareness of potentially very low boiler efficiencies warrants attention to the part load operating conditions to improve system performance and longevity. The calculus may also be different for all-electric heating plants where the cost, size, and weight impacts of heat pumps are much more pronounced, and where the physical constraints are often prohibitive in retrofit projects.

Carbon Emissions

The overall carbon emissions reductions from the efficiency retrofits at these two sites averaged 39.6 and 28.7 lbs/hr, assuming 11.7 pounds of CO2e per therm, representing more than 70 percent reductions at each site (Figure 5). These efficiency projects eliminated most of the site carbon emissions without shifting the heating source to electricity. We also evaluated the emissions reductions of these efficiency retrofits against estimates of additional hypothetical electrification projects based on the measured heating hot water loads, a basic model of air-to-water heat pump efficiency, and 5-minute interval marginal carbon emissions data for the current northern California utility grid (WattTime 2024). The coefficient of performance (COP) and capacity for a heat pump are modeled to vary as a function of outdoor air temperature based on reported performance data for 122 °F supply water temperatures for a leading manufacturer (Aermec n.d.). In practice, the heating coils served would typically require higher temperature water at design conditions than the modeled heat pump can achieve. As COP decreases significantly for higher water temperatures, this simplification underestimates the heat pump emissions and overlooks a major barrier to electrification. Estimated emissions for the same electrification scenarios are also shown for comparison based on a future zero emissions grid.

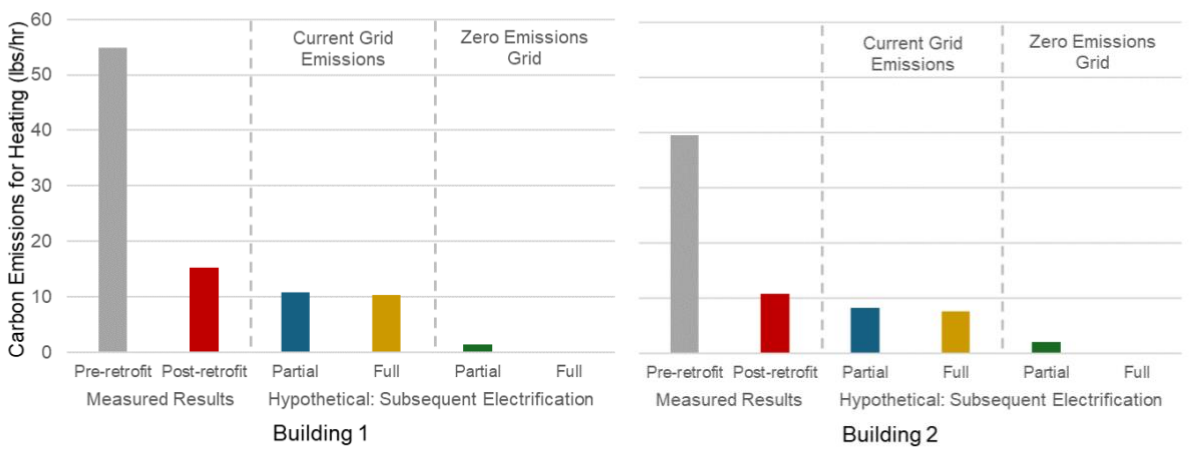

Figure 5. Carbon emissions associated with space heating for the retrofits at two demonstration buildings, as well as estimated emissions if further applying partial and full electrification to hot water plant. Full electrification assumes hot water loads served by an AWHP with efficiency and capacity varying with outdoor air temperature based on manufacturer's data, and WattTime's marginal emissions rates for the current grid. Partial electrification is the same but with AWHP capacity capped at 2 Btu/h-ft^2 at heating design day conditions, (14% the heating capacity of the boiler/full electrification cases) assuming unmet load served by gas with same measured boiler efficiency (~85 percent). The full and partial electrification scenarios are also shown for a zero emissions grid scenario.

If the condensing boiler plants were to subsequently be fully replaced with AWHPs, carbon emissions would be further reduced by an estimated 5.0 and 3.2 lbs/hr at the two buildings on today's grid. These reductions would be significantly smaller than for the efficiency upgrades, but might yet incur much higher cost, disruption, and technical barriers. The incremental emissions reduction from electrification is smaller because a large portion of the heating energy consumption is during winter and early morning hours when the marginal emissions from the utility grid are relatively high, and the heat pump COP is relatively low due to low ambient temperatures. Figure 6 shows the marginal emissions rates (a) for example summer and winter days for the northern California utility grid (WattTime 2024), and one of the building's space heating emissions rate (b) for the measured post-retrofit operation and two theoretical electrification scenarios. In the hours around midday there is typically a large reduction in the grid's marginal emissions rate due to solar power generation. However, natural gas power plants are typically on the margin at other times and during those hours grid emissions are generally 900-1000 lbs of CO_2 equivalent per MWh. For most days, the morning warmup heating load is before solar generation is available, so electric-based heat would occur at the higher marginal emissions rates. In winter, the marginal emissions rate often remains high even during the day so much more of the electric heating would be at high marginal emissions rates. Electrifying the heating plant offers minor emissions reductions under these conditions. California's marginal emissions rates are relatively low; in many other states the overall emissions reduction from electrification would be even lower due to high marginal emissions rates and lower AWHP efficiencies at colder temperatures.

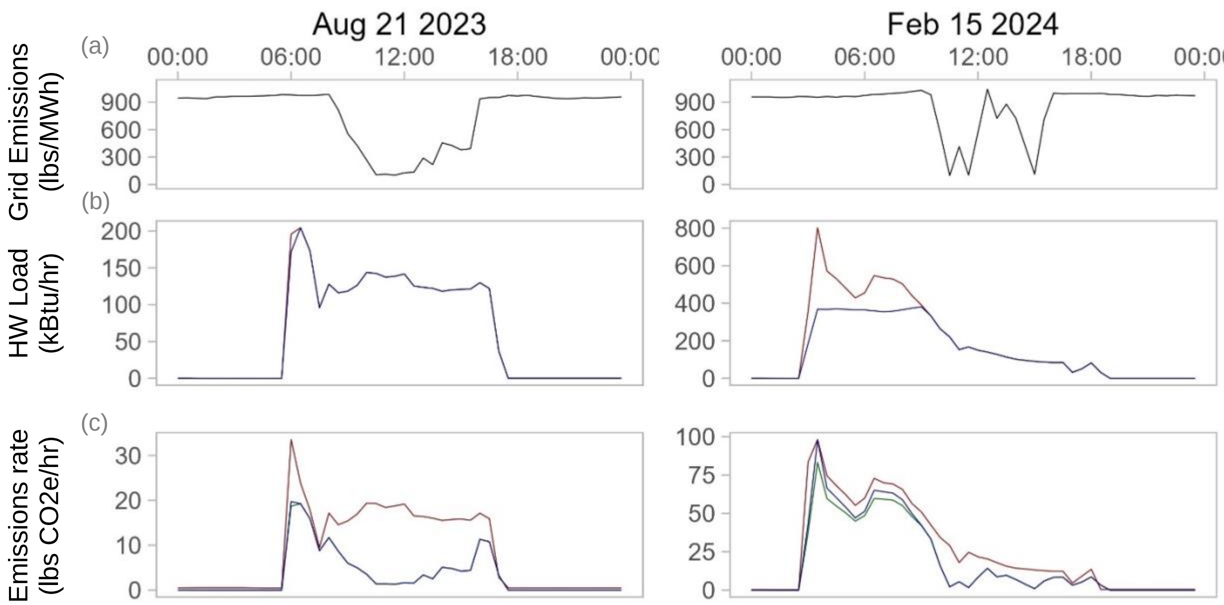

Figure 6. Top (a), marginal emissions rates for the northern California utility grid for example summer and winter days (WattTime 2024). Middle (b), heating hot water load from one building for these same days. Bottom (c), associated carbon emissions for three scenarios for these same days. Red: measured gas consumption from actual condensing boilers, converted to CO_2e assuming 11.7 lbs/therm. Green: measured heating hot water load converted to emissions assuming loads are entirely served by an air-to-water heat pump and WattTime's marginal emissions rate (5-minute interval). Blue: same as green but with heat pump capacity capped at 2 Btu/h-ft^2 at heating design day temperature, assuming unmet load served by gas with same measured boiler efficiency (~85 percent). The days shown are generally typical for these seasons, though there is wide variability depending on availability of solar generation and grid demand.

Figure 5 and 6 also illustrate the emissions impact of a partial electrification scenario. This dual-fuel scenario represents the addition of an AWHP sized nominally for about 15 percent of the hot water plant capacity (about 2 Btu/h-ft^2 at design condition of 32 °F), with the condensing boiler plant meeting the remaining heating load at the averaged measured efficiency of 85 percent. The partial electrification scenario achieves 80 to 90 percent of the emissions reduction of the full electrification scenario. The heating load profile at these buildings, like most commercial buildings, is heavily skewed with the vast majority of operating hours at low part loads. Further, as heat pump capacity increases with increasing outdoor temperature, at milder conditions the small heat pump can meet even more of the heating load. A hybrid heating plant, where feasible, offers the potential for meeting most of a building's annual heating load with the electric source, but at lower first cost and reduced electrical, space, and structural requirements.

During the less frequent peak conditions, the AWHP would be supplemented by boilers but the associated emissions impact is small on an annual basis. In Figure 6(c) the emissions rates from the partial and full electrification scenarios are nearly indistinguishable for the days shown except during periods of higher load.

If we had fully electrified the building heating loads with an AWHP without doing the controls efficiency work, we estimate the resulting emissions would be 20-28 lbs/hr and 15-21 lbs/hr in Building 1 and 2 respectively on the current grid. These are approximate ranges as we only have daily measured natural gas data prior to the retrofit so we must assume both a pre-retrofit boiler efficiency and a pre-retrofit hourly load shape in order to calculate emissions for this hypothetical scenario[1]. However, even the low bound of these ranges is notably higher in both buildings than the actual measured post-retrofit emissions rate after performing the combined boiler plant and controls efficiency measures. This highlights that it is key to improve efficiency first - as that is what yields the largest emissions reduction - and then electrify the remaining loads.

Conclusions

Fully decarbonizing the building sector requires that space heating systems shift away from fossil fuel sources and rely on electricity instead. However, retrofitting existing buildings to convert space heating systems to be all-electric can be very challenging, particularly for large commercial buildings. Even when fully electrified, most buildings will continue to have non-negligible carbon emissions associated with electricity generation. Even in California, where renewables make up a relatively high fraction of utility grid's generation compared to the rest of the U.S., much of a typical building's heating load occurs during periods where marginal emissions rates are high. Retrofitting hydronic space heating systems in large commercial buildings to be all-electric will generally have high implementation costs, increase utility costs, and have a very high overall cost per ton of avoided carbon emissions.

Our study applied a number of relatively simple energy efficiency strategies that are readily available today and reduced natural gas consumption by 70 percent in two large commercial office buildings. Boiler plant efficiency was significantly increased in each building by replacing a single oversized non-condensing boiler with two right-sized, high turndown condensing boilers to avoid excessive short-cycling, and improved demand-based controls. Heating hot water loads were further reduced by applying a series of controls (i.e., software only) changes to the BAS, consistent with building energy codes and ASHRAE Guideline 36. These combined strategies reduced carbon emissions at the buildings by 39.6 and 28.7 lbs/hr, over 70 percent reductions. Past studies involving similar controls energy efficiency measures have been cost effective with reported paybacks of less than 10 years, and the controls measures in this study were estimated to have paybacks of less than 5 years.

Subsequently electrifying the heating plants would only provide an estimated further reduction of 5.0 and 3.2 lbs/hr, but at much greater project cost and complexity. The measured emissions reductions from the actual efficiency project were also greater than the estimated

[1] The pre-retrofit efficiency estimate is informed by the measured load data acquired during the staged retrofit (which unfortunately largely also coincided with pandemic effects), and a comparison against overall pre- and post-retrofit gas savings.

reductions if the original buildings' hot water plants were retrofitted with AWHPs instead of undergoing the efficiency project, based on the current grid's marginal emissions rates. This highlights that the efficiency work was responsible for the majority of the emissions reduction potential in these buildings.

Where electrification is pursued and full electrification is infeasible, projects should consider partial electrification with hybrid heating plants. Typical building heating load profiles are skewed toward low part loads such that heat pumps sized for only a small fraction of the peak load offer the potential to meet a high percentage of the annual heating demand. Hybrid plants may also be much more practical to build, particularly in retrofit projects, because of reduced infrastructure requirements and costs.

To address the urgent need for immediately decarbonizing the existing building stock, we should prioritize efficiency strategies that provide practical and economical reductions in carbon emissions, rather than focus narrowly on full electrification. Alternative decarbonization strategies that focus on energy efficiency first offer the potential for retrofits with much lower implementation costs, decreased utility costs, the possibility of cost effective retrofits, deeper emissions reductions in the long run, and lower cost per ton of avoided carbon emissions, compared to electrifying as a first step. Importantly, these energy efficiency strategies are not mutually exclusive to electrification. Rather, many of the control strategies applied may make electrification projects more effective at reducing overall carbon emissions, and perhaps even more practically achievable, by allowing for smaller equipment through reduced peaks, and by improving compatibility with temperature constraints of air-to-water heat pumps. With the limited time and resources available today, we should prioritize decarbonization of the existing building stock through cost effective and practical energy efficiency measures first, and then tackle the bigger challenge of full electrification.

CRediT authorship contribution statement

Hwakong Cheng: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review and editing. **Paul Raftery:** Conceptualization, Data Curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Visualization, Writing – review and editing. **Patrick Wendler:** Data Curation, Formal analysis, Writing – review and editing.

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