

Boiler Retrofits and Decarbonization in Existing Buildings: HVAC Designer Interviews

Emily Lamon, UC Berkeley, Center for the Built Environment (CBE)
Paul Raftery, UC Berkeley, CBE

ABSTRACT

In this study, we investigate methods to reduce carbon emissions from existing large commercial buildings with central natural gas-fired boilers used for space heating. This research explores opportunities to reduce natural gas use through improved building operations and through building decarbonization. We 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. We 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, we developed five key findings: (1) New boilers are oversized, (2) Actual building load distributions are not available, (3) Heating Hot Water temperatures are too high, (4) Boiler end-of-life is not the best electrification opportunity, (5) Reduce building emissions even if all-electric is infeasible. There are many challenges to reducing carbon emissions from existing buildings, but we conclude there are also many opportunities to make immediate positive change.

Access to the full version of the report: <https://escholarship.org/uc/item/6k4369zv>

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Interviews:

Conducted one-hour **interviews** on **commercial space heating** covering:

1. Professional Background
2. Heating Loads and Boiler Selection
3. Boiler Controls
4. Existing Building Decarbonization

Participants:

Interviewed **17 HVAC Designers**, collectively having over **350 years** of industry experience.

Over 80% of participants had experience at **engineering consulting firms**, while the remainder had experience at **design/build firms**.

Design projects were predominantly located in **mild climate zones** (70% in California), with the rest located in **diverse climate zones** from TX to NY.

Key Findings:



New boilers are oversized

Size to prioritize efficiency at all load conditions in addition to meeting peak loads



Actual building load distributions are not available

Install meters as soon as possible to capture high quality building data



Heating Hot Water temperatures are too high

Operate at design boiler temperatures and introduce effective temperature resets



Boiler end-of-life is not the best electrification opportunity

Focus on other milestones like boiler end-of-life, facade upgrades, and gut renovations



Reduce building emissions even if all-electric is infeasible

Explore partial electrification options when building constraints prevent a full electrification

Summary: There are many opportunities to improve operational efficiency and reduce carbon emissions from existing commercial buildings today, by reducing building loads, right-sizing boiler selections, and pursuing partial or full electrification of building end uses.

Introduction

Commercial and residential buildings account for 37% of global greenhouse gas emissions (UNEP 2021). Although the buildings sector has a large environmental impact, the market for renewable energy generation is growing, awareness of low-carbon building materials is increasing, and the construction industry is moving away from fossil fuels in favor of electrified systems on new construction projects. However, existing buildings are falling behind. In the United States, two-thirds of buildings today will still exist in 2050 (IEA 2020). Natural gas-fired equipment continues to provide domestic hot water and space heating in most commercial and residential buildings, globally generating 24% of all building related emissions (UNEP 2021). The latest climate report released by the International Panel on Climate Change (IPCC) made it clear that transformational change and aggressive carbon emission reductions are required over the next ten years to prevent warming above 1.5°C by the end of the century (IPCC 2021). All sectors of the global economy, including existing buildings, must work to reduce greenhouse gas emissions to prevent the worst effects of climate change.

This study focuses on methods to reduce carbon emissions from space heating systems in existing commercial buildings served by centralized natural gas-fired boilers. This study focuses on space heating systems and does not address domestic hot water systems. This research explores opportunities to reduce natural gas use through improved building operations and through building electrification. Both of these approaches, reducing building loads through energy efficiency measures and ultimately electrifying all end uses within the building, play an important role in decarbonizing the built environment (Leung 2018). With 6 million commercial buildings in the US (US EIA 2021), improving the operational efficiency of existing commercial buildings provides a large opportunity for carbon emission reductions.

Commercial heating, ventilation, and air conditioning (HVAC) systems can be complex. They can include miles of pipework, hundreds of thermal zones, and detailed control sequences to operate the system. System scale and complexity can cause inefficient heating system operation in commercial buildings. In heating hot water (HHW) systems, energy is commonly lost from the system through equipment operation and the distribution system. Equipment losses occur as a byproduct of boiler combustion, standby losses, and purge losses. Distribution losses occur as heating hot water is circulated through the insulated and uninsulated pipework of a building and by passing valves (valves that allow water to move downstream even when commanded “closed”) (Raftery et al. 2018).

Previous research on commercial heating systems has shown that HHW reheat systems often operate inefficiently. One case study of a variable air volume (VAV) reheat system found that only 21% of natural gas energy was converted to heating hot water reheat energy, and 44% of boiler output energy was lost in distribution (Raftery et al. 2018). Studies of domestic hot water (DHW) systems, which are similar to HHW systems, have also found low operational efficiencies. In a study of 28 multifamily buildings located throughout California, only 35% of domestic hot water natural gas consumption was delivered as hot water energy, while 31% was lost to equipment inefficiency and 33% was lost to recirculation losses within the building (Zhang 2013).

Raftery et al. (2018) and Zhang (2013) found the field operating efficiencies of HHW systems to be much lower than is often assumed by mechanical designers working with these systems. Typically, designers would assume the boiler nameplate thermal efficiency as the overall system efficiency. For a condensing boiler, the nameplate thermal efficiency is often

above 90%. Using the boiler nameplate efficiency, instead of representing the average HHW system efficiency, can cause designers to greatly overestimate the efficiency of HHW systems. Boiler nameplate thermal efficiency values exclude system inefficiencies related to distribution losses, boiler short cycling at low load conditions, and condensing boilers operating in non-condensing mode due to high return water temperatures. These factors are multiplicative, and overall can substantially reduce system efficiency compared to nameplate efficiencies.

Large reductions in natural gas use and greenhouse gas emissions can be realized by improving the operational efficiency of commercial HHW systems and by pursuing the electrification of these systems, particularly as adoption of renewables continues to increase. Given the low operating efficiencies and the high first costs associated with HHW systems, electrification presents a unique opportunity to improve system efficiency, reduce emissions, and meet global climate goals.

This research explores opportunities to reduce natural gas use in commercial buildings through the implementation of improved building operations and through heating electrification. In the methodology section, we describe our interview design and delivery approach, and in the results section we synthesize interview responses and identify common themes. We conclude with recommendations for direct application in industry by mechanical designers and building owners.

Methodology

The study presented here is part of a larger [Center for the Built Environment \(CBE\)](#) project on HHW systems in existing large commercial buildings. The project includes site demonstrations, analysis of operational data from hundreds of heating hot water systems in commercial buildings, lab testing of VAV box reheat coil performance, and the designer interviews presented in this report. As part of this study, we conducted remote video interviews with design professionals from the heating, ventilation, and air conditioning (HVAC) industry. The objective of the interviews was to understand how existing buildings can reduce natural gas use, whether by implementing more efficient boiler operations or by electrifying building space heating.

We contacted 24 mechanical designers and ultimately interviewed 17 volunteer participants. We conducted interviews between May 2021 and December 2021, each interview lasting between 60 and 90 minutes. The interviews included a mix of quantitative and qualitative open-ended questions. The project team collaboratively developed the interview questions, and shared them for outside review by experts in qualitative research and the Institutional Review Board of UC Berkeley.

Interview questions fell into four categories: General Background, Peak Heating Load and Boiler Selection, Boiler Controls, and Existing Building Decarbonization. Table 1 provides a summary of the most relevant interview questions. Not all interview questions yielded meaningful results and therefore the project team omitted some topics from this report. For some questions, participant answers fell into multiple categories. We counted these responses across all relevant categories, resulting in more responses than the total number of participants for some questions. Questions were asked specifically for commercial office buildings with VAV reheat systems, but participant responses include other system types, and many responses can also be applied to other systems, so the following results are generalized.

The project team identified interview participants through the CBE network of Industry Partners, personal professional connections, and targeted outreach to design engineers active in

the energy efficient building design and building decarbonization fields. We purposefully sought designers with varied professional experiences, including diversity in types of firms, project locations, years in industry, and their current role. We conducted all interviews remotely on Zoom, where we recorded the conversations and produced transcripts to ensure accurate capture of quotations and interpretation of responses.

The project team reviewed the interview recordings, took extensive notes, and identified key ideas and themes. The obtained results provide insight into the cause of boiler replacements, designer preferences for determining peak heating load and boiler equipment selections, designer preferences around boiler controls, and designer experiences with existing building decarbonization.

Limitations of our methodology include the reliance on our personal networks in seeking participants, resulting in a strong bias towards design engineers with project experience in California and with professional experience at engineering consulting firms. Additionally, our process could have been limited by conducting verbal interviews with participants without sharing the questions in advance. Participants answered questions on the spot, and perhaps some responses would have been altered if participants had more time to consider the question or had access to the questions in advance of the interview.

Table 1. Summary of most relevant interview questions

Topic	Questions
General Background	Can you please tell us a bit about your professional background, the company you work for, and the typical kinds of projects that you work on? In your experience with large commercial VAV buildings, typically what prompted the replacement of the boiler?
Peak Heating Load and Boiler Selections	Can you walk us through your typical design process on a heating hot water boiler retrofit project in a large commercial VAV building? Do you conduct any tests of the systems to understand performance / load / operating temps / capacities? Do you include any safety factors in your design loads? If a client does (or were to) request redundancy, how do you size each boiler?
Boiler Controls	For a commercial office retrofit, do you typically prefer to use the manufacturer's boiler staging controls or do you prefer to self-program through the BAS? What heating hot water supply temperature reset strategies do you typically use? Have you ever considered changing the HHW pumping strategy during a commercial office retrofit? Why or why not? Have you worked on a commercial office building retrofit project that has a boiler which operates 24/7?
Existing Building Decarbonization	What challenges did you come up against, and how were they resolved? Have you had experience working on the full or partial electrification of HHW systems in existing commercial office buildings?

Results

Participant Overview

As detailed in Table 2, the majority of participants are currently working as HVAC designers and serving as Engineers of Record on new construction and retrofit projects. The remainder of participants previously worked as HVAC designers but are currently holding professional roles in HVAC controls and commissioning, early-stage design ideation, learning and development, energy audits, and building decarbonization policy. The majority of participants gained HVAC design experience at engineering consulting firms, while a few have experience with design/build firms. Most participants have either 10-19 years of experience or 20-29 years of experience. A majority of participants have conducted most of their project work in California.

Table 2. Overview of participant professional experience (n=17)

Parameter	Values
Engineer of Record*	Yes (11), No (6)
Current Role	HVAC Designer (11), Controls/Commissioning (2), Early-Stage Design Consulting (1), Learning and Development (1), Energy Audits (1), Building Decarbonization Policy (1)
Type of Firm Experience	Engineering Consulting Firm (14), Design/Build Firm (3)
Years of Experience	10-19 years (7), 20-29 years (6), 30-39 years (2), 40+ years (2)
Project Locations**	California (12), New York (2), Texas (2), Alaska (1), United Kingdom (2), Canada (1)

* Engineer of Record in current role. All participants have professional experience as the HVAC design engineer of record. **Multiple participants have extensive experience in multiple locations.

Interview Results

For the purposes of this report, we omitted a detailed description of individual interview question results in order to highlight key interview findings and recommendations. Table 3 and Table 4 are included below as examples of the result format. A full report of detailed interview results can be accessed here: <https://escholarship.org/uc/item/6k4369zv>.

Table 3 shows designer preferences on equipment redundancy. Once designers determine the peak heating load of a building, including safety factors if applicable, designers need to decide how to distribute the heating load over physical pieces of equipment. Plant design strategies are a balance of equipment redundancy in the event of unit failure, upfront cost of plant equipment, and boiler operational efficiency at low load conditions.

Designers expressed a range of preferences related to plant design, including Traditional, Redundant, Unequal, and Modular approaches. The highest number of participants (10 of 15) use a Traditional plant design approach of 2 boilers, each sized between 50% and 66% of the peak heating load. The second highest number of participants (5 of 15) use a Redundant approach, favoring plant designs with 3 or 4 boilers, to maintain a higher percentage of peak heating capacity in the event of one boiler going down. Next is the Unequal approach (4 of 15), in which designers prefer to break up the heating load into a base load, covered by a small pony boiler

sized at about 30% of the peak load, and a peak load, covered by a primary boiler sized to meet the remaining 70% of the building heating load. The Modular approach (2 of 15) includes boilers composed of multiple modules which can fire up separately, allowing the boilers to turn down to very low percentages of total plant capacity to increase operational efficiency.

Table 3. Designer preference on equipment redundancy (n=15)

Category (# designers / total)	Plant Design	Quotes
Traditional (10/15)	2 boilers @ 50-66%	<i>"I feel that this is the typical 'standard of care' for commercial buildings."</i> <i>"Trying to balance efficiency and redundancy."</i> <i>"This is a good place to start but would need to check the efficiency at part load operation."</i>
Redundant (5/15)	4 boilers @ 30-33% or 3 boilers @ 50%	<i>"If you lose one boiler, you can still really maintain all demand."</i> <i>"With new boilers, they all have electronic components in them that are only available from the manufacturer. It can take weeks for the part to arrive on site."</i>
Unequal (4/15)	Primary and Pony Boiler	<i>"Very rarely is the peak load divided by how many boilers you want the correct answer [when you're thinking about typical load profiles of a building]."</i> <i>"You will see improved efficiency [with unequally sized boilers], as long as everything is working correctly."</i>
Modular (2/15)	1 boiler, 3 modules @ 33%	<i>"An advantage to using a modular boiler plant design is to allow for really low turndowns compared to total building load."</i> <i>"The traditional sizing method [of 2 boilers at 66%] now is changing. We tend to go for more modular boilers now... They provide a large amount of heating for a small amount of floor space."</i> <i>"20-years ago we would have used very large boilers, two of them or three of them. Very inefficient and very wasteful.... The approach we have today is modular boilers."</i>

On the topic of electrification, we asked participants to describe some of the main challenges with electrification retrofits in existing buildings. We received a wide range of responses across many categories, including heat pump equipment requirements, heat pump cost, heat pump construction, electrical requirements, existing conditions, information and awareness, and electric resistance coils and electric boilers. Specific responses are summarized in Table 4.

Table 4. Challenges of electrification (n=16)

Category	Challenge	Frequency*
Heat Pump Equipment Requirements	Additional equipment space requirement	Very High
	Change of HHW operating temperatures and resulting impacts on pumps, pipework, and terminal coil sizing	Very High
	Potential structural impact of larger/heavier HVAC equipment	High

Category	Challenge	Frequency*
	Challenges with heat pump controls	Moderate
	Need to locate plant outdoors / change in plant equipment locations	Moderate
	Finding heat pump in correct size to match building loads	Moderate
	Heat pump reliability / maintenance	Moderate
	Heat pump operations at low outdoor temperatures	Low
	Heat pump compressor noise rating	Low
Heat Pump Cost	Heat pump equipment cost increase	Very High
	Heat pump operational cost increase	Moderate
Heat Pump Construction	Contractors are less familiar with heat pump technologies	Low
	Heat pumps require two contractors (mechanical, electrical) to install compared to boilers which only require mechanical contractor	Low
Electrical Requirements	Need for increased electrical service to the building	High
	Substantial electrical rework within the building	High
Existing Conditions	Thermal performance of existing facade	Moderate
	Piping de-rates in tall buildings	Low
Information / Awareness	Lack of electrification retrofit case studies and examples	Moderate
	Familiarity of owner / tenant with electrified systems	Low
Electric Resistance / Electric Boilers	Electric resistance / electric boiler operational cost increase	Moderate
	Technical performance issues with electric resistance	Low
	Historically challenging for designs with electric heat to comply with Title 24 requirements	Low

* Frequency of this electrification challenge mentioned across all interviews. Very High Frequency (10 or more mentions), High Frequency (6-9 mentions), Moderate Frequency (3-5 mentions), and Low Frequency (1-2 mentions).

Discussion

In this section, we highlight the results of the interviews and provide recommendations for mechanical designers and building owners for direct application in industry. Recommendations are intended to improve the operation of existing commercial buildings, to prepare buildings for future electrification projects, and reduce existing building carbon emissions.

New boilers are oversized

Natural gas boilers installed as part of retrofit projects are likely oversized. Through participant interviews, it became apparent that many factors influence the size of the boiler, and all factors result in an increase to the final installed equipment capacity. To improve the selection of new boilers, building loads need to be fully understood and boilers need to be selected to perform efficiently at anticipated low load conditions as well as meet peak heating loads. To improve boiler operational efficiency, the project team recommends:

Designer Recommendation: Determine actual building peak load through building trend data or develop best approximation through energy modeling. Evaluate the impact of number of boilers installed, level of equipment redundancy, and equipment turndown on boiler performance and efficiency.

Owner Recommendation: Add scope to boiler retrofit projects to understand building heating load and fine tune new boiler equipment selection at existing equipment end-of-life, communicating the priority for operational efficiency to the designer.

Many technical resources are available to HVAC design professionals which outline best practices for building heating load calculations, the most popular of which for the U.S. is the ASHRAE Fundamentals Handbook (ASHRAE 2021). Per the guideline, the building is assumed to have no benefit of solar heat gain, and no benefit from internal loads such as people, lighting, or equipment (simulating a nighttime, off condition). This set of assumptions does not represent a real-world heating condition, therefore resulting in heating systems that are very conservative and often oversized for the actual heating demand of the building.

The boiler selection is determined by either energy modeling heat load calculations or by the capacity of the boiler that was previously installed (like-for-like replacement). Since the original boiler was installed, the building could have undergone an envelope upgrade, the building use type could have changed, or it's likely that the original boiler was oversized, all making it a potentially poor indicator of current building heating loads.

In performing load calculations for larger retrofit projects, most designers apply safety factors to the peak heating load (most commonly 10-20% is added to the calculated peak load). Designers also need to consider equipment redundancy (most commonly installing 2 boilers at 50-66% of peak heating load), and then the load is rounded up to the next available equipment size. These design elements compound and result in the installation of what are often oversized boilers. Ultimately, the majority of participants tend to install boiler plants with greater than 100% of the calculated heat load for the building, which already includes conservative energy model assumptions and safety factors.

Participants did not think of plant design in terms of percent chance of failure, percent downtime, or percent of annual heating hours. Framing plant design in terms of peak heating load obscures the fact that the average heating load of a building is going to be much less than peak load, resulting in boilers operating in low load conditions, often below minimum turndown, for the majority of hours of the year. McGowan (2021) suggests that it's common for boilers to operate between 5% and 50% for the majority of the year. In essence, the percentage chance of an equipment failure that will substantially impact comfort in the building is far lower than it appears when focusing on the percentage of peak capacity that remains operational after that failure: 50% of peak heating capacity will meet the building load far more than 50% of annual hours because buildings spend relatively few days operating at high capacity. Thinking about boilers in terms of peak load, instead of considering the distribution of loads over the entire year, can often lead to oversizing and low efficiency performance at part load conditions.

Previous research has also found that residential and commercial heating systems are commonly oversized. Among 60 boilers installed in UK homes, there did not appear to be any correlation between the heating load experienced in the home and the size of the boiler that was installed (Burton, Lelyveld, and Orr 2009). In another study of 221 UK residential boilers, it was found that boilers are commonly oversized and therefore cycle on and off much more frequently than the assumed typical system operation. Frequent boiler cycling causes a large increase in natural gas emissions associated with the system (Bennett, Elwell, and Oreszczyn 2018). In one case study example, the boiler plant for a large commercial building was found to operate at only about 50% capacity during heating design day weather conditions (Raftery et al. 2018).

Interview participants did not express much concern about installing an oversized boiler. The physical size and the upfront cost are similar between two adjacent boiler models, and designers will experience lower risk and will not get a callback for installing too much heating capacity. Multiple participants also expressed the notion that right-sizing a boiler would not produce significant energy savings. However, this reflects a reliance on boiler nameplate efficiencies of over 90% as substitutes for the overall system efficiency, when research has shown system efficiencies to be as low as 21-35% (Raftery et al. 2018; Zhang 2013). The large difference in performance can be attributed to system inefficiencies due to poor low part load performance. This highlights the importance of installing a right-sized boiler on all projects to improve system efficiency at low load conditions.

One efficiency penalty experienced by oversized boilers is short cycling. Short cycling, turning on and off repeatedly over a short period of time, occurs when boilers need tuning and are firing from 0% to 100%, or when boilers are operating under low load conditions. Short cycling causes undue wear on the boiler, significantly decreases system efficiency, and wastes a significant portion of boiler energy due to the pre-firing purge cycle. The purge cycle draws air through the boiler as a precaution to remove any potentially flammable gasses from the system, but this mechanism also causes the system to cool down, reducing efficiency.

Another efficiency penalty experienced by oversized boilers is the likely discrepancy between boiler minimum turndown and building low load conditions. As a designer moves through the design process, they perform conservative load calculations, apply a safety factor, design a plant with 120% to 150% of calculated capacity needs to provide equipment redundancy, and perhaps also round up to the next largest boiler size. There is a lot of extra capacity included in the system. In many scenarios, a boiler is not able to turndown to a sufficiently low level to operate continuously at the low loads typically experienced by the building, resulting in boiler short cycling, very poor efficiency, and equipment deterioration.

Another factor impacting plant design, and ultimately boiler efficiency, is upfront equipment cost. Boiler equipment costs do not scale linearly with equipment capacity, so a larger capacity boiler can be installed at limited increase in equipment cost, and limited increase in physical equipment size. This is a very different relationship compared to chillers, where installing additional equipment capacity will come at a significant cost increase, and compared to heat pumps, where installing additional capacity will come at a significant cost and physical equipment size penalty. Although designers may be in favor of installing a system with 3 or 4 smaller boilers for increased redundancy and improved turndown performance, the upfront equipment cost may be beyond what is achievable for a given project.

Actual building load distributions are not available

We found that most designers do not have access to actual building load distributions, or they have low confidence in using the data as an integral part of their capacity determination. To increase availability and fidelity of operational heating plant data, the project team recommends:

Designer Recommendation: Include metering on projects to allow for system adaptation in the future.

Owner Recommendation: Verify data from your meters is accessible and retained for an appropriate duration. Add temporary meters as soon as possible if considering a retrofit project.

Most designers have low confidence in monitored BAS data and are not comfortable using monitored operational performance to determine peak heating load and installed equipment capacity. Only about 30% of participants were confident in monitored building data and would rely on it in determining peak loads and equipment sizing. The majority of participants expressed that they would reference the data if it was available, but ultimately, they would perform a load calculation to determine the heating load, if possible, but most likely they would install a like-for-like boiler. Most participants reported that building data was often not available on their projects or it wasn't available to a sufficient granularity to be useful in determining peak heating load. Access to high quality operational data would provide designers with an accurate understanding of building peak heating load and base heating load for direct application in equipment selections and plant design.

Access to high quality building operational data will become even more important as electrification retrofits become more common. There is a large cost penalty for installing heat pump capacity in excess of what is required to meet the building heating load, unlike with natural gas boilers where similar sizes will not see a large difference in equipment. With electrification, it will be even more important to understand in detail how existing buildings are operating in order to execute efficient electrification retrofits and to minimize project costs.

Heating Hot Water temperatures are too high

We found that many systems are designed at 180°F (82°C), when likely the building could meet heating loads at a lower HHW supply temperature. To reduce distribution losses and to smooth the transition to future heating electrification, the project team recommends:

Designer Recommendation: Design all-electric or use lower HHW supply temperatures (120°F/50°C) to ease the transition to future electrification, improve equipment efficiency, and reduce distribution piping losses.

Owner Recommendation: Try lowering HHW supply temperatures in existing buildings, evaluate energy and cost savings, and locally address zones which require supplementary heating capacity.

Many participants believe that most buildings in mild climates, like the San Francisco Bay Area, can meet their heating loads using HHW temperatures lower than 180°F (82°C). McGowan (2021) suggests that reheat systems can often meet heating loads at 100°F (38°C). Participants shared that many terminal unit coils are oversized due to the nature of box selections, and that existing equipment could likely meet building heating load at lower temperatures, perhaps also in combination with faster flow through the system.

Lowering HHW temperatures will reduce distribution losses within the system. Research has shown that intentional reheat energy was only 17% of the total cost of energy to operate the boilers of a large commercial building (Raftery et al. 2018). A large portion of HHW system energy and operating expenses are lost due to distribution losses, which increase in direct proportion to water temperature. High volumes of HHW which recirculate from the supply pipework to the return pipework through bypasses or 3-way valves without going through an AHU coil or a terminal unit coil will increase return water temperature. This reduces heating equipment efficiency and can prevent the boiler from condensing. Further, 3-way valves at

terminal units ensure that the entire distribution piping is hot (both supply and return branches to that terminal unit) whenever the system is operating. This directly increases piping distribution losses.

As hot water piping is often located in the return air plenum, the heat lost from the distribution piping is rejected into the building's relief air whenever the air handling unit is not operating in heating mode. Thus, for much of the year, this piping heat loss is of no benefit in heating the building, even though the losses occur within the building's envelope. Worse, under warm outdoor conditions (above economizer lockout temperature), the piping heat loss increases the building's cooling load, further penalizing overall HVAC system energy performance.

This issue of excess HHW recirculation through bypasses or 3-way valves can be addressed in some existing buildings relatively easily, as there is sometimes a shutoff or balancing valve on the bypass of 3-way valves serving terminal units. This can be closed by maintenance staff at minimal cost. Where this is not possible, the bypass can be capped (with or without replacing the 3-way valve with a new 2-way valve), though this has a higher cost and is more disruptive.

Multiple participants suggested that existing buildings could lower their HHW temperatures, or introduce lower HHW reset temperatures, without any other system changes. Running a test in which building operators lower the HHW supply setpoint incrementally down to 120°F (50°C) and monitor if building zones are able to maintain the heating setpoint. This test will inform the building of which zones may need additional heating capacity to be installed at the zonal level, such as a larger reheat coil in the terminal unit, a wall-mounted electric resistance heater, or a small electric heat pump (e.g., a retrofit wall-mounted packaged heat pump, or a ductless mini-split). Some participants advocated for a cascade heat pump approach in which a water-to-water heat pump would boost HHW temperature, but most participants declined to use this strategy due to low system COP in favor of leaving the central system as is and installing intermittently operated zonal equipment to make up any required heating load.

One challenge to reducing HHW temperature in existing buildings is the potential impact on pipework sizing. Using lower temperature heating hot water to meet the same heating load will result in increased HHW flow, possibly requiring increased size of pipework. This could be a barrier to adopting significantly lower HHW temperatures in existing building retrofits and could also result in increased first costs for gut renovation projects.

Another challenge to reducing HHW temperature in existing buildings is the risk of leaks from the HHW pipework couplings, as the seals can become brittle or fail over time. This effect is exacerbated by expansion due to temperature changes. We heard this was a concern of some building operators, and during the interviews a majority of participants confirmed they are aware of this occurring at existing buildings. Participants also confirmed that many boiler plants are purposefully operated 24/7 in order to reduce the risk of system leaks, incurring a large energy penalty to the building. The system leaks as described by participants were not caused by lowering HHW temperatures to 120°F (50°C), but by HHW system temperatures decaying down closer to ambient temperatures (e.g., <100°F/38°C) due to system maintenance, equipment failure, or a power outage. At low temperatures, some pipework couplings may contract and result in leaks from the HHW system.

The concern about system leaks is keeping HHW temperatures high and preventing effective HHW temperature resets to be adopted in many buildings. We encourage designers to address this with their clients and encourage them to conduct the test described above to see how their system performs at lower temperatures. Eventually the building will experience system

maintenance, equipment failure, or a power outage which could put them at risk of system leaks. Instead of risking leaks during an unexpected event, the building could check its system and address any issues encountered as part of a controlled test.

In the event that any system leaks are discovered, fixing them will likely have a very fast payback period. Building operational savings can be very large from introducing a plant schedule, instead of operating the system 24/7, and adopting an effective HHW reset strategy. Savings from these control changes could be used to replace problematic fittings or couplings. One participant described a project where they replaced pipework fittings and they saw a payback period of one year. However, the cost effectiveness of replacement depends heavily on the number of couplings and where they are located in the building. If couplings are located in shafts or above hard ceilings it may be cost prohibitive to replace them, and such a project may only be possible during a gut renovation of the building.

Boiler end-of-life is not the best electrification opportunity

We found that many project teams consider electrification at boiler end-of-life, when counterintuitively, it may make more sense to consider electrification at other building milestones, such as central cooling equipment end-of-life. Central cooling equipment, especially air-cooled chillers, and air source heat pumps (ASHPs) have a lot in common including high equipment cost, large physical footprints, and large electrical loads. Other building milestones such as gut renovations, building change of use, facade upgrades, replacement of rooftop packaged units, and installation of solar PV also provide good opportunities to pursue electrification. To increase the adoption of existing building electrification, the project team recommends:

Designer Recommendation: Prioritize buildings with clear decarbonization opportunities, such as central cooling equipment end-of-life, gut renovations, building change of use, facade upgrades, rooftop packaged unit replacements, and installation of solar PV.

Owner Recommendation: Include energy efficiency and electrification in future capital planning cycles to align with chiller end-of-life and other synergistic building updates.

Participants expressed the challenges of pursuing space heating electrification at boiler end-of-life. Building owners allocate funds for a boiler replacement project sometimes years in advance as part of the capital planning process, and the HVAC equipment alone for space heating electrification could cost as much as 5 times that of a replacement boiler. Often buildings are not prepared for such an expenditure and are not able to pursue an electrification project at that time. Building owners have a sense of what a boiler retrofit project should cost and it's hard to add scope or move cost around in such a project.

Given the high equipment costs and large electrical load, central cooling equipment replacement projects are well suited as electrification projects. Chiller replacement projects tend to include a larger scope of work and larger project budgets. Replacing a chiller with heat pumps that can provide both heating and cooling will reduce the risk of needing to update the main building electrical connection by reassigning the electrical capacity from the chiller to the heat pumps. This could also minimize electrical rework within the building if there are already rooftop air-cooled chillers or rooftop DX units with comparable electrical loads.

There is also a strong opportunity for electrification during gut renovations, building change of use (office to lab, retail to office), envelope upgrades (increased insulation, window replacements, air sealing), or installation of solar PV. Research has shown electrification retrofits are cost effective for most medium office buildings in California when combined with the installation of solar PV (TRC and P2S Engineers 2022). These projects tend to be of a whole-building approach and tend to have much larger scopes of work.

Lastly, there is a unique opportunity to pursue electrification at the replacement of rooftop packaged units. Multiple participants mentioned packaged rooftop unit replacements as a relatively low touch opportunity to electrify space heating in commercial buildings that have these systems (predominantly smaller commercial buildings). Packaged units with natural gas heating can be replaced at end-of-life with a heat pump or VRF packaged unit and should not require any rework to the electrical connection as the compressor serving the cooling side draws the dominant electrical load. Nadel and Perry (2020) conduct a detailed cost effectiveness analysis of rooftop packaged unit replacements for different building use types, and they found that electrifying rooftop packaged units with payback periods of 15-years or less will reduce carbon emissions in most U.S. climate zones.

Reduce building emissions even if all-electric is infeasible

Many participants expressed the challenges of designing all-electric due to high equipment costs and large physical equipment size. To overcome these challenges and other project constraints, participants expressed the opportunity to electrify part of the building load. Partial electrification still results in significant carbon emission reductions with lower equipment costs and reduced physical space requirements. To reduce carbon emissions within project constraints, the project team recommends:

Designer Recommendation: Consider partial electrification, where the base load is covered with electrified heating equipment and the remainder is met with natural gas equipment, as an opportunity to reduce carbon emissions within project constraints.

Owner Recommendation: Consider partial electrification as a first step towards a phased, multi-year decarbonization strategy.

Half of the participants have used or are considering partial electrification on their projects. Participants described many system combinations including ASHPs and natural gas boilers, geothermal loops and natural gas boilers, and natural gas packaged rooftop units with electric resistance reheat coils at the terminal units. The electrified equipment is sized to meet the base building heating load (e.g., approximately 30% of peak load) and the natural gas boilers are sized to cover the remainder of the heating load on cold days. One participant estimated that the base load heat pump equipment would be able to cover 60% of annual hours, significantly reducing the carbon emissions of the system. Nadel and Perry (2020) also highlight partial electrification as an important transition step for existing buildings towards all-electric end uses.

Multiple participants discussed the idea of beneficial electrification and designing buildings for overall carbon emission reductions, emphasizing the importance of understanding the energy mix on the grid at the project location. Participants expressed concern about designing all-electric or partially electric building systems in regions where electricity is predominantly generated from coal. However, it is important to include realistic HHW system efficiencies into

these analyses. Previous research has found that intentional reheat energy was only 17% of the total cost of energy to operate the boilers of a large commercial building (Raftery et al. 2018), making system electrification likely the lowest carbon option.

It is also important to note that the penetration of renewables on the grid is quickly increasing. Recent analysis has shown that a building located in almost every U.S. city would see a carbon benefit from electrification of end uses (Rumsey, Le Garrec, and Levasseur 2021). We recommend designers consider project-specific grid emissions projections when proposing HVAC strategies for new construction and retrofit projects. Over the 15- to 30-year lifetime of a piece of HVAC equipment, electricity carbon emissions are projected to drop across all geographies.

Participants have also recommended partial electrification to their clients as part of a 10- or 15-year building plan to move towards electrification, most commonly for commercial or multifamily high-rise buildings. Participants are recommending that central plant equipment is slowly built up over time and that zonal equipment is replaced with tenant turnover.

However, if the built environment is targeting net zero carbon by 2050, the adoption of dual-fuel systems may prolong the use of fossil fuels in buildings for the lifetime of the HVAC equipment (15-30 years). If a building aims to reach net zero carbon by 2050, partial electrification will cease to be an option 15-30 years before that deadline (2020-2035), unless the building plans for the equipment to be prematurely replaced. Most buildings only have one equipment end-of-life opportunity between now and 2050 to select system electrification.

Conclusions

The mechanical designer interviews described in this paper reveal that the industry is at the very beginning of the process to electrify existing large commercial buildings. Some technological and financial elements of electrification retrofits remain unknown, particularly for large commercial buildings, but these interviews have revealed the innovations that designers are pursuing today on their projects to turn electrification retrofits into common practice.

Through these interviews, participants requested access to example case studies and electrification design tools to help in this transition. Free resources have started to become available to provide retrofit recommendations, such as the Building Efficiency Targeting Tool for Energy Retrofits (BETTER) provided by the U.S. Department of Energy (US DOE 2022), but it's clear that many more tools will be needed to assist in the transition to all-electric designs.

Many utility, state, city, and community choice aggregators provide incentive programs to motivate buildings to adopt electrified systems. However, “the existing electrification programs are by and large aimed at residential and small commercial buildings” (Cohn and Efram 2022). Included in the few programs that address commercial buildings were Sacramento Municipal Utility Department (SMUD) Commercial electrification program (SMUD 2022), offering incentives to small and medium commercial buildings for energy upgrades and larger retrofits. More opportunities need to be provided for large commercial buildings to overcome the unique challenge of custom-built, complex heating and cooling systems as well as larger building heating and cooling loads. This makes electrification of these systems among the most challenging in the built environment.

Through the recommendations put forward in this paper, we hope that mechanical designers and building owners will make changes in their buildings today to reduce operational energy use and to prepare for system electrification in the future. With commercial HVAC

equipment having useful lives of 20 years or more, most buildings only have one equipment end-of-life opportunity between now and 2050 to select system electrification.

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