Title

Boiler Retrofits and Decarbonization in Existing Buildings: HVAC Designer Interviews

Authors
Lamon, Emily
Raftery, Paul
Schiavon, Stefano

Publication Date
2022-08-01

Boiler Retrofits and Decarbonization in Existing Buildings: HVAC Designer Interviews

Authors

Emily Lamon

Paul Raftery

Stefano Schiavon

Project Lead

Center for the Built Environment (CBE)

University of California, Berkeley

Prepared for

California Energy Commission (CEC)

March 2022

CENTER FOR THE BUILT ENVIRONMENT

ACEEE Summer Study on Energy Efficiency in Buildings,
August 2022

https://escholarship.org/uc/item/6k4369zv

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.

Acknowledgments

We wish to sincerely thank the participants for volunteering their time and for sharing their valuable insights and project experiences. Thanks also to Lindsay Graham of the CBE, Gwelen Paliaga and Rupam Singla of TRC, and Hwakong Cheng of Taylor Engineers for their early guidance and support on interview format and question development, and valuable technical contributions and review. The Center for the Built Environment (CBE) at the University of California, Berkeley and the California Energy Commission Public Interest Energy Research (PIER) Project funded this work. Components of this project related to building electrification were funded by the CBE. This work was conceptualized and initiated as part of a California Energy Commission (CEC) project entitled "Getting Out of Hot Water" (contract number PIR-19-013).

Emily Lamon: Conceptualization, Methodology, Investigation, Writing - Original draft preparation. **Paul Raftery:** Conceptualization, Methodology, Investigation, Resources, Writing - Reviewing and Editing. **Stefano Schiavon:** Supervision, Writing - Reviewing and Editing.

Key Words

Boiler Retrofits, Existing Buildings, Building Decarbonization, Electrification, Commercial Buildings, Boiler Oversizing, Designer Interviews

For more information regarding this study contact Emily Lamon at emily_lamon@berkeley.edu and Paul Raftery at p.raftery@berkeley.edu.

Table of Contents

Boiler Retrofits and Decarbonization in Existing Buildings: HVAC Designer Interviews

Executive Summary

Transformational change and aggressive carbon emissions 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. In the United States, two-thirds of buildings today will still exist in 2050 (IEA, 2020). Therefore, a strong push is needed to retrofit existing buildings to improve their operational performance and to replace natural gas systems with lower carbon emission alternatives to meet climate goals.

This study focuses on methods to reduce carbon emissions from existing large commercial office 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. Building decarbonization refers to the process of reducing building loads through energy efficiency measures and ultimately electrifying all end uses within the building (Leung, 2018). Interviews with mechanical design professionals provide insight into current industry practices and we develop recommendations for direct application in industry by mechanical designers and building owners.

Boiler Retrofits and Decarbonization in Existing Buildings: HVAC Designer Interviews

CENTER FOR THE BUILT ENVIRONMENT

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 low 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 or design at lower temperatures and introduce effective temperature resets

Boiler end-of-life is not the best electrification opportunity
Focus on other milestones like chiller 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 all-electric design

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

We conducted one-hour interviews with 17 participants between May 2021 and December 2021. Interview questions fell into four categories: General Background, Peak Heating Load and Boiler Selection, Boiler Controls, and Existing Building Decarbonization. The interviews provided guidance on current industry trends and insights into key considerations including 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 decarbonization of existing commercial buildings.

There are many challenges in decarbonizing existing buildings. The challenges mentioned by participants with the highest frequency were the additional equipment space requirements of electrified heating systems, the lower Heating Hot Water (HHW) operating temperatures, and the cost increase of heat pump equipment compared to natural gas alternatives. The most commonly mentioned decarbonization design considerations were the evaluation of every electric heating option in addition to air source heat pumps, to reduce peak heating loads, and to consider partial electrification of the system.

From the interviews, we established five key findings and subsequent recommendations for direct application in industry by mechanical designers and building owners.

1. **New boilers are oversized**

    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.

2. **Actual building load distributions are not available**

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

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

3. Heading Hot Water temperatures are too high

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.

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

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.

5. Reduce building emissions even if all-electric is infeasible

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.

Our interviews with industry experts reveal the many challenges of existing building decarbonization. They also highlight opportunities for immediate impact and positive change in the industry.

1. 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 will focus on methods to reduce carbon emissions from existing commercial buildings served by centralized natural gas-fired boilers providing space heating. This research explores opportunities to reduce natural gas use through improved building operations and through building decarbonization. Building decarbonization refers to the process of reducing building loads through energy efficiency measures and ultimately electrifying all end uses within the building (Leung, 2018). Although direct emissions from commercial buildings are responsible for only 3% of global emissions, compared to direct emissions from the residential sector at 6% (UNEP, 2021), commercial buildings produce more emissions on average per building. 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 (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 water heating equipment efficiency and 33% was lost to hot water recirculation losses within the building (Zhang, 2013).

Raftery et al. (2018) and Zhang (2013) have found field operating efficiencies of HHW systems to be much lower than are 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 high quality condensing boiler, the nameplate thermal efficiency is often above 90%. Using the boiler nominal 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. 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 will explore opportunities to reduce natural gas use in commercial office buildings through the implementation of improved building operations and through heating electrification. Interviews with mechanical design professionals will provide insight into current industry practices, and we will synthesize interview discussions to form recommendations for direct application in industry by mechanical designers and building owners.

2. Methodology

The study presented here is part of a larger Center for the Built Environment (CBE) project on heating hot water 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 interview is 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 participants. We conducted interviews between May 2021 and December 2021, each interview lasting between 60 minutes and 90 minutes. The interviews included a mix of quantitative and qualitative open-ended questions. The project team collaboratively developed the interview questions, then shared the questions 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 votes than the total number of participants for some questions. Questions were asked specifically for commercial buildings with VAV reheat systems, but participant responses include other system types or responses can be applied to other systems, so the results have been generalized. Appendix A contains the full list of interview questions.

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 (Section 3.2), designer preferences for determining peak heating load and boiler equipment selections (Section 3.3), designer preferences around boiler controls (Section 3.4), and designer experiences with existing building decarbonization (Section 3.5).

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?

3. Results

3.1 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.

3.2 Cause of Boiler Replacement

Table 3 provides a summary of common causes of boiler replacements in existing buildings. The most common response, given with a very high level of frequency, was boiler end-of-life. The second most common response, given with a high level of frequency, was a gut renovation of the building. Responses given with a moderate level of frequency include new tenant fit-outs or new building owners, and the building owner's specific interest in pursuing electrification to align with larger Environmental Social Governance (ESG) goals.

Some causes for boiler replacements are location specific, such as the Bay Area Air Quality Management District emissions standards for Northern California and Local Law 97 emissions limits for New York City, and were mentioned with a low frequency.

Table 3: Cause of boiler replacement (n=16)

Category	Cause	Frequency*
Building Rehabilitation	Boiler is at end-of-life	Very High
	Gut renovation of entire building (can involve premature boiler retirement)	High
	New tenant fit-out or new building owner	Moderate
	Building owner ESG Goals or interest in electrification	Moderate
	Building change of use (office to lab, retail to office)	Low
	Conversion from steam heating to hydronic heating system	Low
Regulation	Bay Area Air Quality Management District Emissions Standards	Low
	Planning for future New York City Local Law 97 Requirements	Low
	Building required seismic upgrades, triggering broader building upgrades	Low

*Frequency of this cause of boiler replacement 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).

3.3 Determining Peak Heating Load and Boiler Selections

Peak Heating Load

The majority of interview participants use energy modeling software to determine peak heating loads for new construction projects. Existing building heating systems, however, are different. Existing building retrofits often include constraints such as limited project scope, limited budget, and tight schedule which alter the heating load calculation process as compared to new construction projects. From the interview responses, most designers share the same general process for existing buildings. If the retrofit is part of a large gut renovation in which the building use is changing, or if the building has undergone a facade update since the previous boiler was installed, then a new construction heating load calculation process is followed. If the building is not changing uses, then most designers compare the current heating capacity installed in the building to a heating rule of thumb for that region and ask the building engineer if they have any trouble with cold calls. For the San Francisco Bay Area, designers (n=6) agreed on the rule of thumb they use, citing between 20-25 BTU/sf to calculate building peak heating loads for older buildings and between 10-15 BTU/sf for newer buildings. If a project has additional budget or a more extended schedule, designers may ask the building for heating system trend data from the building automation system (BAS) or may build an energy model to calculate the heating load. However, it is very likely that the new boiler ultimately installed on the project will be like-for-like, equivalent to the capacity of the previous boiler in the building.

Participants agreed that most boiler retrofits were like-for-like projects. Participants felt that changing boiler sizing could expose them to additional risk and liability for the performance of the system. Most participants also did not perceive much benefit from installing a smaller capacity boiler, as there is little immediate cost penalty in installing larger sizes.

Designers often installed like-for-like boilers instead of relying on real heating system trend data from the Building Automation System (BAS). BAS trend data should benefit retrofit projects by giving designers visibility into how the building is currently operating, without relying on the many assumptions that are inherent in the energy modeling process. However, designers did not view BAS trend data this way. Table 4 summarizes participant perspectives on using existing building BAS trend data to determine the building peak heating load.

A majority of participants (11 of 14) would reference building trend data if it was available, but they would not use it in isolation to influence their heating system design. The second most common response (9 of 14) was that most buildings do not have this data available. Most buildings do not have sufficient metering in place to be used to determine peak heating load, or the instrumentation was installed but is not maintained or trended, or the data that is available is not sufficiently granular to be used (e.g., gas meter providing only daily gas use). A smaller group of participants (5 of 14) felt confident in using building operational data to determine building peak heating capacity, however they would often recommend that a monitoring period take place before the retrofit project began for additional metering to be installed on site to increase access to high quality building operational data. Lastly, a few participants (2 of 14) would not consider operational data in their heating design due to the preference towards like-for-like boiler replacements to reduce designer liability and the lack of applicability of operational data when a building is undergoing a gut renovation and changing use type.

Table 4: Reliance on existing building BAS trend data in determining peak heating load (n=14)

Category (# designers / total)	Quotes
Would reference operational data (11/14)	*"Probably would reference the data and also do a BTU/sf check to see if they are in a reasonable range."* *"Would reference utility bills if they were available but would not use this for capacity determinations."* *"Look at existing equipment firing rates with outdoor air temperature."*
Most buildings do not have sufficient data (9/14)	*"Rarely [would we reference operational data] because it's rarely available at a high enough quality level, with enough data."* *"Often, it doesn't make sense to [rely on trends], either because the program is changing so radically or because it's difficult enough to get the trends."* *"In the best-case scenario, [building owners] would have trend data to show… [but] the types of clients I work with, they rarely really have that data... More often than not, we're replacing like-for-like [boilers]."* *"[If there is no metering], everyone does like-for-like by default."* *"Operational data isn't as important with boiler replacements because you will likely install like-for-like anyway."*
Would rely on operational data (5/14)	*"There's nothing better than real operational numbers to tell you what the load is."* *"Reality beats a model any day of the week."* *"If you have a BTU meter in place, and it's properly calibrated, you're in great shape."*
Not considered (2/14)	*"Truth be told, as an engineer, the safest approach is, I'm going to put the same capacity boiler in that's already there."* *"If the occupancy is changing, that kind of invalidates anything that's going on right now [in terms of building energy use]."*

In addition to building peak heating load, the application of safety factors is another consideration in determining installed heating equipment capacity. Safety factors are used by designers to add additional capacity to the calculated or metered peak heating load to correct any nonrepresentative assumptions used in the energy modeling process and to cover unexpected increases in building heating demand in the future. Safety factors are predominantly used in new construction projects, which are outside the scope of this research, but are also applied when energy modeling load calculations are completed for existing building retrofits, most commonly for gut renovations or building change of use projects, and when metered building data is recorded from a period of additional monitoring. Table 5 summarizes participant design preferences on the application of safety factors in determining installed equipment capacity.

Table 5: Designer preferences on the application of safety factors (n=14)

Category (# designers / total)	Safety Factor Applied	Quotes
Safety Factor applied to total peak load (7/14)	+10-20%	*"Buildings change so much over time. It's probably not a good plan to install exactly what you are calculating that you need to meet the loads for the design that you think you're doing, without providing some buffer for changes in the future."*
No Safety Factor applied (5/14)	None	*"If I am confident in the use of the building, then I wouldn't apply a safety factor. There is already a safety factor built into how we calculate heating loads."*
Safety Factor applied to facade load only (3/14)	+10-20%	*"I don't typically apply a safety factor, but I do build in some conservatism by padding the U-Value a bit to reduce envelope performance. We've had the issue on some projects where the envelope doesn't perform as well as you would expect them to."*

Half of participants (7 of 14) apply a safety factor of between 10-20% to the total calculated peak heating load. A smaller group of participants (5 of 14) do not apply any safety factor to their calculated design load. They feel that a sufficient margin is already inherent in the system design process, through energy modeling assumptions, heating load calculation procedure, and rounding up the heating load to match the next available boiler size. The final group of participants (3 of 14) elect to apply a safety factor to the calculated facade losses only. This method is intended to compensate for any unexpected reduction in envelope thermal performance in the installed on-site condition as compared to the U-Values communicated among the design team during the design process.

Boiler Selections

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. In addition to new construction projects, this process also applies to gut renovations or building rehabilitations with larger project scopes. 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, as shown in Table 6.

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 6: Designer preference on equipment redundancy (n=15)

Category (# designers / total)	Plant Design	Quotes
Traditional (10/15)	2 boilers @ 50-66%	*"I feel that this is the typical 'standard of care' for commercial buildings."* *"Trying to balance efficiency and redundancy."* *"This is a good place to start but would need to check the efficiency at part load operation."*
Redundant (5/15)	4 boilers @ 30-33% or 3 boilers @ 50%	*"If you lose one boiler, you can still really maintain all demand."* *"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."*
Unequal (4/15)	Primary and Pony Boiler	*"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]."* *"You will see improved efficiency [with unequally sized boilers], as long as everything is working correctly."*
Modular (2/15)	1 boiler, 3 modules @ 33%	*"An advantage to using a modular boiler plant design is to allow for really low turndowns compared to total building load."* *"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."* *"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."*

Some participants favored the Unequal boiler plant design, where the building heating load is met by a small pony boiler sized to meet year-round base building loads and a primary boiler sized to meet the remainder of the design day heating condition. Participants preferred the Unequal plant design because it can improve plant operational efficiencies, since pony boilers are typically used to meet low load conditions, which make up a significant percentage of total annual heating hours (Raftery et al., 2018).

Other participants argued strongly against primary/pony boiler systems, citing the increased complexity of HVAC controls leading to commissioning and operational challenges, the lack of duplicate parts between boilers, the lack of lead-lag boiler rotation, and the lack of equipment redundancy if the primary boiler was to fail during the heating season. Participants also mentioned the technological improvement of boiler efficiencies at low load conditions over the last decade, reducing the operational benefits of an Unequal plant design. From one participant's perspective, "having a 1/3 boiler and 2/3 boiler may make sense on paper for projects with dynamic loads, but this is way more complicated to operate and maintain in real buildings. I would rather push for boilers with better turndown to address the low load condition."

Part-load performance is listed as a key boiler selection parameter in ASHRAE Fundamentals Handbook (ASHRAE, 2021) and many participants (10 of 15) mentioned turndown as a consideration in boiler selection, yet all participants think about equipment selection in terms of peak building heating load (e.g., 2 boilers sized at 66% of peak heating load). In comparing the total equipment capacity installed with the calculated peak heating load, we found that a minority of participants (6 of 15) typically install equipment capacity equal to 100% of the calculated peak heating load on a project, while a majority of participants (11 of 15) install equipment capacity greater than 100% of the calculated peak heating load on a project.

The majority of participants were not concerned about installing a boiler that was oversized compared to the heating load of the building. Participants noted that larger capacity boilers were a similar physical size and similar upfront cost compared to boilers one size capacity down. Multiple participants also expressed the notion that right-sizing a boiler would not produce significant energy savings, however research has shown this not to be the case and will be discussed further in Section 4.1 of the Discussion.

3.4 Boiler Controls Preferences

Boiler Staging Controls

Interview participants had strong preferences on whether they controlled boiler staging using the manufacturer's boiler controls or self-programming the boiler staging through the building automation system (BAS).

Some participants felt that using the manufacturer's controls was a simple and reliable solution that reduced individual liability on the mechanical designer, while other participants thought the manufacturer's controls were a "black box" that were not optimized for energy efficiency. Participants in this second group prefer to self-program boiler staging controls through the BAS. Table 7 shows an overview of responses.

Table 7: Designer preferences on boiler staging controls (n=14)

Category (# designers / total)	Benefit	Quotes
Manufacturer's Controls (10/14)	Simple/Trusted Execution	*"[In selecting to self-program boiler staging controls], you'd be sacrificing 'good enough' for 'perfect', and it will likely cause a lot of problems in your construction closeout, and it will cause a lot of headache for the maintenance team."* *"The manufacturer should be able to control their own hardware better than what I could come up with."* *"That controller was built for that unit, and [it's a lot for the designer to take on] the subtle differences between the boiler model, internal safeties, etc."*
	Reduced Liability	*"It's a benefit to not have the liability of self-programming."* *"[Self-programming] can result in finger-pointing with the manufacturer if there are any issues with boiler operation."*
Self-programmed Controls (8/14)	Increased Visibility and Control	*"[I've] had so many issues with packaged boiler controllers. Inflexible controls scheme, proprietary, local rep doesn't know the details of how it works, comes with less desirable measurement devices."* *"[Self-programming] is more about not having a black box do the boiler controls."*
	Operational Efficiency	*"Manufacturers are competing for efficiency rating at AHRI conditions. This number does not reflect staging controls or part load efficiencies. Manufacturers are optimizing for reducing callbacks, and not necessarily the most energy efficient operations."*

Heating Hot Water Temperature Reset

Buildings use HVAC control sequences to reset HHW temperature to reduce building energy use when the building heating loads can be satisfied using lower HHW supply temperatures. HHW temperature reset allows the building to save energy by reducing distribution losses in the system and improving equipment efficiency. There are two main strategies to control HHW temperature reset, outdoor air-based reset and demand-based reset. In a building controlled by outdoor air-based reset, as outdoor air temperatures increase the need for building heating decreases, therefore signaling to the building to reduce the HHW supply temperature. For the demand-based control system, zone level controls connect back to the central system and communicate if they need more heat or if the zone temperature is currently satisfied. If all or most zones are thermally satisfied and meeting heating setpoints, the HHW supply temperature will reset down to a lower HHW temperature setpoint for the building. As soon as the outdoor air temperature starts to drop or building zones start to call for more heating, the HHW temperature setpoint will increase as needed to meet building heating loads.

Most designers use both HHW temperature reset strategies depending on specific project characteristics. Table 8 shows the summary of responses.

Table 8: Designer preferences on heating hot water temperature reset (n=14)

Category (# designers / total)	Benefit	Quotes
Outdoor Air-Based (11/14)	Simple/Low Cost	*"Good for smaller buildings, with not a lot of load diversity."* *"Better for projects with limited budgets or for building owners/operators that are less technical."* *"Outdoor air-based reset is usually simpler for the owner."* *"Demand-based can be tricky and you need detailed data for the terminal units."* *"If only minimal control points are available, outdoor air-based reset would be best, since the infrastructure to control by demand-based is probably not in place."*
	Target Perimeter Zones	*"If the boiler is serving predominantly fin tube radiators along the perimeter, then the temperature needs to be reset based on outdoor air temperature."*
Demand-Based (11/14)	Energy Efficiency	*"We use trim and respond, driven by zone demand requests... [All of our projects use ASHRAE Guideline 36]."* *"For a natural gas boiler, outdoor air temperature usually isn't going to be as important. I'd prefer to [control] on demand and try to get the boiler to condense."*
	Target Internal Zones	*"If the building has an AHU that only serves interior zones, it needs to be controlled by demand-based reset."*

A majority of participants (11 of 14) use outdoor air-based HHW temperature resets. Outdoor air-based resets were preferred for simpler building operation with reduced control points and can target heating demand at perimeter zones, particularly if they are served by a dedicated perimeter heating system (e.g., runtal radiators). A majority of participants (11 of 14) also use demand-based HHW temperature resets. Demand-based resets were preferred for projects that have more complex controls capabilities and increased interest in energy efficiency, and this control strategy is important for determining reheat demand at internal zones.

Change in Pumping Strategy

Some boiler retrofit projects also include the installation of new HHW pumps to serve the building. We asked participants to describe their typical design strategy related to the redesign of the HHW pumping system. Participant responses fell into three categories: adding variable frequency drives (VFDs), converting the building to variable/primary pumping, or maintaining the original strategy of primary/secondary pumping. Table 9 shows detailed participant responses.

Most participants (8 of 11) recommend buildings add VFDs during a retrofit project. VFDs control the frequency of power supplied to a pump motor, allowing the pump to modulate flow to match the building heating load. Introducing variable flow capabilities allows a building to save on pump energy and to reduce distribution losses in the system. Buildings commonly convert from a constant volume system to a variable volume system through removing 3-way valves and installing VFDs as an energy efficiency measure.

Some participants (5 of 11) recommend buildings convert from the primary/secondary pumping system, which is common in older buildings, to a variable/primary system. In the primary/secondary system, the HHW pipework system is organized into two interconnected loops. One loop is served by the primary pumps which match the boiler flow rate requirements, and the other loop is served by the secondary pumps which distribute the water throughout the building. In the variable/primary system, one set of primary pumps operate at variable speed to meet boiler flow rate requirements and to distribute hot water throughout the building. Some designers (4 of 11) recommend keeping the primary/secondary pumping strategy to protect the boiler from low water flow conditions which can cause damage to the boiler equipment. However, a primary/secondary pumping strategy puts the system at a high risk of condensing boilers not condensing in operation. If the primary constant speed flow is greater than or equal to the secondary variable speed flow, some hot water supply will feed directly back into the boiler, raising the return water temperature seen by the boiler, and perhaps preventing the boiler from condensing.

A few participants (4 of 11) mentioned capping or removing 3-way valves as part of a building pumping strategy reconfiguration. Most of these participants (3 of 4) referenced the benefit of reducing pumping energy by reducing the volume of water that is moved around the building. A smaller group of participants (2 of 4) referenced the benefit of decreasing return water temperatures. Capping 3-way valve bypasses, and essentially converting them to 2-way valves, will eliminate some of the total system bypass flow, thereby reducing return water temperatures and increasing the operating efficiency of the boiler. One participant (1 of 4) referenced the benefit of reducing system distribution losses. By decreasing the volume of hot water sent around the building, the system will see less heat lost from the HHW loop to the surrounding air.

Table 9: Designer preferences on changes in pumping strategy during a retrofit project (n=11)

Category (# designers / total)	Benefit	Quotes
Add VFDs (8/11)	Energy Efficiency	*"Would consider looking at pumping strategies to reduce [operating] cost. VFDs used to be so expensive…that this has become prevalent only in the last 5-10 years."* *"Most commonly we recommend adding VFDs. Not really intended to create improved performance during winter but should be beneficial during swing seasons… or could reduce energy use if tenants have the ability to control their radiator off [during winter]."*
	Remove 3-way Valves	*"[There's] an opportunity to create some variable flow. A lot of these old systems are constant flow, so you got 3-way valves and all that. It's just not efficient to pump around all this volume, so we definitely look at the system design, [make recommendations, and maybe the building will] put it in the next maintenance cycle."* *"You will find [commercial building] heating systems that use 3-way valves, and so we will convert to 2-way valves, and they might have a constant volume pumping system that we can change to variable speed… Improve some of the other parts of the system that are usually less expensive and sometimes can yield significant or almost equivalent amount of savings."*
Convert to Variable/Primary (5/11)	Energy Efficiency	*"Variable/primary is the best for efficiency if the building is large enough to make that work."* *"Use variable/primary for radiators or underfloor heating"* *"Would consider variable/primary for high mass boiler applications"* *"With variable/primary, you want to rely on pressure controlled valves to open as needed to maintain boiler minimum flows."*
Keep Primary/Secondary (4/11)	Prevent Low Flow Conditions	*"Have done variable/primary boiler plants but found on the heating side there is not that much savings from the pumping side. In a primary/secondary configuration, the primary pumps have such small horsepower motors, and these systems help to protect the boilers from low water flow."* *"With variable/primary, pumps could ramp down too low, and boiler could cut out on low flow condition, and stop heating the building."*

		"Most common to do primary/secondary, with variable speed on the secondary only. Low mass boilers are very sensitive to water flows and can cause issues."

24/7 Boiler Plant Operations and Leak Risk

Some buildings operate their HHW system 24/7 due to fears of water leaks from system couplings as the water temperature decays overnight. We asked participants about their experience with this condition to gain a better understanding of how prevalent this is in practice. Table 10 shows a summary of the results.

Table 10: Designer experiences with 24/7 boiler plant operations and HHW system leaks (n=11)

Category (# designers / total)	**Quotes**
Has seen 24/7 plant operation (7/11)	*"I suspect controls were never set up properly. Maybe a time clock controller was never put in at the boiler."* *"[One project's] heating system ran 24/7 due to pipe leaking concerns."* *"Yes, very often. Projects would run the boiler plant in the South throughout the summer to keep the fittings from leaking."* *"Yes, boiler running 24/7 because the HHW pipework had bad seals."* *"Scheduling [plant operations] is the best energy efficiency measure in existence, and it's disturbing how often you find these opportunities."*
Has seen HHW system leaks (8/11)	*"[Leaky pipework] is a relatively common occurrence."* *"This comes up with some frequency on projects."* *"130°F, 120°F (55°C, 50°C) degree water probably okay. The loop was at 65°F, 70°F (18°C, 21°C) which caused the leaking problems."* *"Yes, pressure came off the loop and the water settled."* *"Recommend using soldered or brazed fittings, never pressed fittings, to avoid leaks. Large temperature delta (40°F-180°F, 4°C-82°C) in HHW piping is too risky to use any other connection method."* *"Operators from one building said they only felt comfortable above 160°F (70°C), or they thought there was a risk of leaks."*

Most participants (7 of 11) were familiar with buildings which operate their heating plant 24/7, and a similar group of participants (8 of 11) were also familiar with buildings that have experienced water leaks when the HHW system temperature dropped to ambient temperatures due to system maintenance, equipment failure, or a power outage. The potential for leaks from the HHW system at lower water temperatures is of concern as we look to transition towards heat pumps and electrified heating equipment which produce lower supply water temperatures. Reducing heating hot water temperatures in existing buildings will be discussed further in Section 4.3 of the Discussion.

3.5 Existing Building Decarbonization

At the time of this writing, there are very few commercial decarbonization and electrification retrofit projects happening in industry, and the few projects that we did hear about are predominantly in the design phase and are not yet under construction. Most projects are gut retrofits, where all existing plant room mechanical equipment, distribution ductwork and pipework, and zone level equipment is removed and an entirely new system is installed.

Although there were few examples of active existing building decarbonization and electrification projects, almost all participants have investigated an electrification retrofit option for a past project or were in early stages of design development on an electrification retrofit. We asked participants to describe some of the main challenges with electrification retrofits and to discuss important decarbonization design considerations. We have summarized participant responses in the following sections.

Challenges

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.

Of all responses, the challenges mentioned with the highest frequency were additional equipment space requirements, change of HHW operating temperatures, and heat pump equipment cost increase. The challenges mentioned with the second highest levels of frequency include potential structural impacts, need for increased electrical service to the building, and substantial electrical rework within a building. Table 11 summarizes the results.

Table 11: 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
	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).

Design Considerations

We asked participants to describe their experiences with the decarbonization of existing buildings. A number of key themes and design considerations presented themselves through these discussions, including evaluate every electric heating option, reduce peak heating loads, consider partial electrification, consider decentralized systems, design for overall carbon reduction, consider district systems, change the heating load calculation process, include additional equipment redundancy, transfer heat within buildings, and propose staged electrification strategies for large buildings. Table 12 provides additional information on each of the key themes.

Table 12: Decarbonization design consideration (n=16)

Category (# designers / total)	Quotes
Consider all electric heating equipment options (10/16)	*"VRF systems are pretty mature technologically speaking and are doing similar things to heat pumps… but they operate much more reliably. Millions made compared to some new heat recovery chillers hitting the market and selling hundreds."* *"We would probably need an electric boiler in series with the ASHP to boost heating temperatures for peak days. The current building is designed for 180°F (82°C) and the building has a large heat load, single pane glass."* *"Is electric resistance reheat really that bad? Yes, you don't have a high COP, but you get to take the copper pipework out of the project and avoid distribution losses. The grid is getting cleaner and cleaner - Do we care about the COP in the future?"*
Reduce peak heating load (9/16)	*"Storage tanks would save a lot of cost overall in comparison to ASHP equipment costs and have much lower service requirements."* *"Thermal storage could be used to dampen out the peak load."* *"Mitigate electrical capacity issues with thermal storage."* *"The campus was okay with starting morning warmup earlier in the day to help the heat pumps operate better during colder outdoor air conditions."* *"Reduce peak by improving the envelope, triple pane when building windows need replacing anyway."* *"How can the building change operationally to buy less heat pump? Add thermal energy storage? Maybe not doing as dramatic a nighttime setback or running for extended hours to reduce peak loads."* *"We have to reduce building demand in order for the electrification mission to make sense."* *"Buildings need to look into options to reduce their heating demand by tightening their envelopes - air sealing, swapping out windows and window frames, double pane, Passive House solutions, external panelized rigid insulation."*
Partial Electrification (8/16)	*"Electrification strategies may be a little bit blunt force. Strategies where you could have a base load air-source or heat recovery chiller-based solution, then peak load covered with condensing boilers."*

	"The heat pump is sized for the base load. It's projected to cover 60% of yearly heating load, and only 20% of peak heating load. The boiler will top-up water temperature when needed." *"[Due to packaged rooftop unit equipment constraints (not all tonnages are available with heat pumps)], we ended up putting natural gas in the multizone packaged units and electric resistance reheat at the zone level."* *"We've done geothermal wells plus a peaking boiler. Geothermal handles about 50% of heating load, then using the boiler to peak up the water temperature when needed."* *"Design includes natural gas at the DOAS units with electric reheat everywhere else. We were worried about getting a large enough transformer connection… with all-electric."*
Decentralized Systems (7/16)	*"You could use fan convectors instead of radiators [to increase capacity with lower water temperatures]."* *"Evaluate which zones do not meet heating load at 120°F (50°C) water. Add additional systems to outlier zones so they can meet heating load, like an additional coil in the box if pressure drop is okay, separate electric reheat wall mounted unit, electric runtal, etc."* *"I anticipate that new construction will move away from central systems because of the piping losses and piping costs."* *"Multifamily buildings have circuits available for window units, which have a lot of draw to them. Similar electrical draw that would be required to achieve electrical heating. But centralized VRF plants would need 600-800 amps of service to one specific location."*
Design for overall carbon reduction (6/16)	**"***[You] need a heat pump COP of 2.8 to break even from a carbon perspective [on the UK grid]."* *"Hard to justify [geothermal] on a greenhouse gas emissions basis since the grid in Canada is dominated by coal. So electrifying plus distribution losses leaves you with more emissions than just using a natural gas boiler."* *"Carbon benefits of electrification are very grid dependent. It's worth it to look into the marginal grid emissions projections [for a project location]."* *"Need to add time of use incentives to the code to really address carbon use from heating systems."*
District Systems (5/16)	*"If utilities took the lead on this transition, communities could share thermal storage reservoirs and ambient loops running around downtowns, instead of each building needing to invest and establish their own infrastructure."* *"[On one project we are] proposing one central plant to serve three buildings. Will save on the maintenance, but we will need to run pipework between the buildings."*

	"Neighborhood development implemented campus ambient loop - houses need net heating, commercial office spaces need net cooling." *"High-rise commercial buildings will need to rely on a centralized heating loop provided publicly or developed through a public-private partnership."*
Change heating load calculation process (4/16)	*"We need to adopt a more detailed approach to heating calculations, similar to cooling calculations, now that there is a large cost impact for additional equipment capacity."* *"You cannot match BTU output from boiler to heat pumps. That will never pencil out. We need to gain a more nuanced understanding of building loads."* *"We should carry out thermal and electrical load studies of current building conditions. Design mechanical systems to operate within the electrical capacity of the building."* *"Really important to find non-intrusive ways to get data, like ultrasonic BTU meters."* *"One project is currently running a winter test with reduced heating water temperatures to see how the building performs. We're gathering trend data to prove that the lower temperature will work."*
Additional Redundancy (3/16)	*"Heat pumps are more expensive and less reliable than gas boilers. HHW heat pumps are not where they need to be in terms of maturity and reliability."* *"Across the board, I will never do a project with a single heat pump central plant. We always break it up into ideally 3 or more smaller heat pumps… Because heat pumps do require more frequent maintenance than a boiler, and when they go down, they go down. When you have a compressor failure, the unit is inoperable… I want to be able to cover 60% of the load [with the remaining equipment] if one unit goes down."*
Transfer heat within building (3/16)	*"Trying to use data room cooling for domestic hot water heating for the showers."* *"Heat transfer from space to space - Using heat pump to transfer heat from data room to perimeter of building."*
Staged Electrification Strategy (2/16)	*"[For a high-rise tower], we are proposing a gut rehabilitation project which will allow for a staged electrification approach with tenant turnover."* *"Proposing a 15-year transition plan, including demoing chiller, cooling tower and boilers when they are at end of life. Looking to implement modular heat pumps over time. Installing about 300 tons now to make up for the cooling capacity delta [caused by the chiller being undersized]."*

The most common decarbonization design consideration (10 of 16) is the understanding that multiple all-electric heating technologies may need to be included in an electrification retrofit.

In addition to air-source heat pumps (ASHP), designers included variable refrigerant flow (VRF), radiant systems, geothermal, electric resistance reheat, electric boilers, and water-to-water heat pump boosters in their all-electric solutions. By far the most common of these approaches is VRF. Compared to air source heat pumps, VRF has increased market maturity and operational reliability. However, VRF systems come with environmental challenges such as increased refrigerant volume and construction challenges such as disruptive construction at the zone level due to the installation of branch selectors and terminal unit rework or replacement.

The second most common decarbonization design consideration (9 of 16) is the importance of reducing building peak heating load. Reducing peak heating load allows designers to install fewer heat pumps, reduce electrical rework, and reduce project cost. Designers can reduce building peak heating load by incorporating envelope upgrades into the project, such as air sealing, new windows, or additional insulation. Designers can also shave the peak heating load or spread the heating load out over a longer period of time, thereby reducing the incident peak heating load which determines the installed plant equipment capacity. Typically, commercial buildings experience their peak heating load for a few hours during building morning warm up after the heating system ramped down at night for a nighttime setback. Programming the system to warm up the building (including operating without ventilation air for several hours prior to pre-occupancy ventilation purge) over a longer period of time will result in shaving the peak heating load. Designers can also investigate the option of not including a nighttime setback or adopting a smaller nighttime setback on particularly cold days, though this may cause an increase in building energy use on these days.

Another option to reduce installed heat pump capacity is to use thermal storage. As described in Gill (2021), MacCracken (2020) and Nadel and Perry (2020), thermal storage has a critical part to play in large building electrification. Thermal storage allows a smaller heat pump to accumulate hot water in a large tank to meet the peak building load when it occurs. Thermal storage would also allow the heat pumps to operate during the daytime hours when the grid is often supplied by more renewable energy resources reducing the associated carbon emissions, and includes the benefit of operating the heat pump during warmer outdoor air temperatures.

The third most common decarbonization design consideration (8 of 16) is the idea of partial electrification. For a typical commercial office building, the heating system is operating far below the peak capacity for the vast majority of the year. A partially electrified system would include a heat pump or other electrified heating equipment designed to cover the typical heating base load throughout the year, and a natural gas boiler to cover the remaining building heating load on particularly cold days. In some cases, it may be possible to retain the existing boiler equipment for this purpose and generate substantial carbon savings where a full electrification project is infeasible due to current project constraints.

Other decarbonization design considerations include the benefit of decentralized systems in reducing electrical rework and in making up any heating capacity deficiencies caused by lower centralized HHW temperatures, design for overall carbon reduction by considering local grid emissions (however per Rumsey et al. (2021) almost all cities in the U.S. would see a carbon benefit from electrification), benefit of using district systems to help large buildings electrify and decarbonize, changing the heating load calculation process to be more precise (McGowan (2021) suggests basing equipment sizing on diversified load calculations) and to rely on real existing building operational data, recommendation for additional heat pump redundancy (N+1, N+2), transferring heat within a building for free heating, and developing staged electrification strategies for building owners over 10-15 year time horizons (Nadel and Perry (2020) describe the multiphase retrofit of Vancouver City Hall to all-electric systems).

4. Discussion

In this section, we will highlight the main 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.

4.1 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, peak heating load is calculated using the location-specific winter design day outdoor air temperature held constant for the entire day. This method includes conductive heat transfer through the building envelope, and heat loads required for ventilation and caused by infiltration. 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 et al., 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 et al., 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 thermal 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 important of installing a right-sized boiler on all projects to improve system efficiency at low load conditions.

Oversized boilers should not be installed on projects, but there are heat loss pathways that occur in every building that are often not considered by designers in their heating load calculations. One heat loss pathway to consider is boiler standby losses, typically 1-4% of nominal capacity. Though small, this loss occurs continuously when the heating system runs, and over an entire year can comprise a significant component of overall heating energy consumption. Using smaller, appropriately-staged boilers will directly reduce this loss.

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 this capacity 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 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 that project.

4.2 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 would not feel comfortable using the monitored operational performance to determine peak heating load and installed equipment capacity. Only about 30% of participants felt 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 felt 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.

4.3 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 Heating Hot Water (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 likely existing equipment could 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.

4.4 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), 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 across U.S. climate zones.

4.5 Reduce building emissions even if all-electric is infeasible

Many participants expressed the challenges of designing all-electric with ASHPs 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. For example, designing a geothermal system in such a region could yield higher overall emissions, since you are using coal-generated electricity and also introducing electrical distribution losses into the system. In this situation, a natural gas boiler may ultimately reduce building emissions. 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 et al., 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.

5. 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 Esram, 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, and 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.

References

ASHRAE. (2021). 2021 ASHRAE Handbook Fundamentals.

Bennett, G., Elwell, C., & Oreszczyn, T. (2018). Space heating operation of combination boilers in the UK: The case for addressing real-world boiler performance: *Building Services Engineering Research and Technology*. https://doi.org/10.1177/0143624418794552.

Burton, S., Lelyveld, T., & Orr, G. (2009). In-situ monitoring of efficiencies of condensing boilers and use of secondary heating. *The Energy Saving Trust*. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/180950/In-situ_monitoring_of_condensing_boilers_final_report.pdf.

Cohn, C., & Esram, N. W. (2022). Building Electrification: Programs and Best Practices. *American Council for an Energy-Efficient Economy (ACEEE)*. https://www.aceee.org/research-report/b2201.

Gill, B. (2021). Solving the Large Building All-Electric Heating Problem. *ASHRAE Journal*, *63*(10). https://www.taylorengineers.com/news-1/new-article-in-the-ashrae-journal.

IEA (International Energy Agency). (2020). Energy Technology Perspectives 2020. *International Energy Agency, Energy Technology Perspectives*. https://iea.blob.core.windows.net/assets/7f8aed40-89af-4348-be19-c8a67df0b9ea/Energy_Technology_Perspectives_2020_PDF.pdf.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis, Summary for Policymakers*. International Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf.

Leung, J. (2018). *Decarbonizing U.S. Buildings*. Center for Climate and Energy Solutions (C2ES). https://www.c2es.org/wp-content/uploads/2018/06/innovation-buildings-background-brief-07-18.pdf.

MacCracken, M. (2020). Electrification, Heat Pumps and Thermal Energy Storage. *ASHRAE Journal*, *62*(7). http://www.calmac.com/stuff/contentmgr/files/0/7a1a97ca8602d53f7f054875ce3ecd6c/pdf/electrification_heatpumps_and_thermal_energy_storage_ashrae_journal.pdf.

McGowan, M. K. (2021). How Can Designers Increase Boiler Energy Efficiency? *ASHRAE Journal*, *63*(1). https://technologyportal.ashrae.org/journal/articledetail/2265.

Nadel, S., & Perry, C. (2020). Electrifying Space Heating in Existing Commercial Buildings: Opportunities and Challenges. *American Council for an Energy-Efficient Economy (ACEEE) Publication*. https://www.aceee.org/research-report/b2004.

Raftery, P., Geronazzo, A., Cheng, H., & Paliaga, G. (2018). Quantifying energy losses in hot water reheat systems. *Energy and Buildings*, *179*, 183–199. https://doi.org/10.1016/j.enbuild.2018.09.020.

Rumsey, P., Le Garrec, J., & Levasseur, A. (2021). How Building Decarbonization Can Transform HVAC. *ASHRAE Journal*, *63*(9). https://www.ashrae.org/technical-resources/ashrae-journal/featured-articles/how-building-decarbonization-can-transform-hvac.

Sacramento Municipal Utility District (SMUD). (2022). *Business Rebates*. https://www.smud.org/en/Business-Solutions-and-Rebates/Business-Rebates. Accessed 02/16/2022.

TRC, & P2S Engineers. (2022). *2021 Reach Code Cost-Effectiveness Analysis: Non-Residential Alterations*. California Energy Codes & Standards. https://localenergycodes.com/download/960/file_path/fieldList/Nonresidential%20Alterations%20Cost-effectiveness%20Report.pdf.

United States Department of Energy (US DOE). (2022). Building Energy Efficiency Targeting Tool for Energy Retrofits (BETTER). https://better.lbl.gov/. Accessed 02/16/2022.

United Nations Environment Program (UNEP). (2021). *2021 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector*. https://globalabc.org/sites/default/files/2021-10/GABC_Buildings-GSR-2021_BOOK.pdf.

United States Energy Information Agency (US EIA). (2021, September). *Commercial Buildings Energy Consumption Survey (CBECS)*. https://www.eia.gov/consumption/commercial/data/2018/bc/html/b2.php. Accessed 01/19/2022.

Zhang, Y. (2013). Multifamily Central Domestic Hot Water Distribution Systems. *California Energy Commission*, *Publication Number: CEC-500-2013-011*. https://www.redwoodenergy.tech/wp-content/uploads/2017/07/Zhang-mutlifamily-PIER-study-CEC-500-2013-011.pdf.

Appendix A: Interview Questions

Complete list of interview questions:

1) **General background**
   i) 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?
      (a) *Company and role*
      (b) *Engineer of record*
      (c) *Years of experience*
   ii) Have you worked on boiler retrofit projects for large commercial VAV Reheat buildings?
      (a) Where have these projects been located?
      (b) About how many office retrofit projects have you worked on?
   iii) In your experience with large commercial VAV buildings, typically what prompted the replacement of the boiler?
      (a) *End of life*
      (b) *Redundancy requirement*
      (c) *Regulations*
      (d) *Energy efficiency project*
   iv) On these projects, what were other typical updates being made at this site as part of the project?

2) **Selecting a replacement boiler, loads and design considerations:**
   i) Can you walk us through your typical design process on a heating hot water boiler retrofit project in a large commercial VAV building?
      (a) *Estimating loads*
      (b) *Redundancy requirements*
      (c) *Sizing*
      (d) *Specifying boiler*
   ii) What steps are typically taken to understand the heating load of the building?
      (a) Do you conduct any tests of the systems to understand performance / load / operating temps / capacities?
         (i) What if meters or past building trends are not available?
      (b) Do you include any safety factors in your design loads?
         (i) If so, what factor do you apply?
   iii) What HHW temperatures do you commonly see on projects?
      (a) Are you able to determine operating temps vs. design temps?
      (b) What is a typical design Delta T on a project?
      (c) What would you expect the operational Delta T to be on a typical day?
   iv) What is a typical BTU/sf heating load for your project location?
      (a) Has this rule of thumb changed over time? How?
   v) What design considerations typically influence the model and size selection of the new boiler?

(a) *Warmup peak?*
(b) *Average load?*
(c) *Minimum load?*
(d) *Turndown?*
(e) *Next size up, next size down?*
(f) *Minimum flow of HHW pumps?*
(g) *System volume?*
(h) *Piping losses?*

vi) What type of new boiler do you generally spec?
(a) *Condensing*

vii) Typically, do heating hot water boiler retrofits in large commercial VAV buildings include equipment redundancy?
(a) If so, who typically suggests plant redundancy – client or designer?

viii) If a client does (or were to) request redundancy, how do you size each boiler?
(a) *Percentage of total design heating load*
(b) *Percentage of total hours of the year*

ix) Have you ever designed a boiler plant in a large commercial office building with unequally sized boilers?
(a) If so, what was the reason for doing so and what issues did you encounter, if any?
(i) *Improve turndown efficiency*

x) Have you ever designed a boiler plant in a large commercial office building with only one boiler?
(a) What drove this design decision?

3) **<u>Controls implemented before and after boiler replacement:</u>**

i) 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?
(a) Boiler staging controls or do you rely on the BAS to control the boiler?
(b) Manufacturing controls of self-programmed? Staging
(c) What's your preference if you could choose?

ii) What control strategies do you use (if any) to try to reduce the load on the boiler?
(a) *Zone min adjustments*
(b) *OA damper adjustments*
(c) *Warmup strategies*
(d) *Plant operating hours*

iii) What design strategies and control strategies do you use (if any) to prevent boiler short cycling in commercial retrofits?
(a) *Design: Buffer tank, recirculation loop, smaller boiler*
(b) *Controls: Bandwidth of water temperature*

iv) What heating hot water supply temperature reset strategies do you typically use?
(a) *Demand based reset*
(b) *OA based reset*

v) Have you worked on a commercial office building retrofit project that has a boiler which operates 24/7? (AKA when the building is not occupied)
   (a) What was the reason for this?
      (i) If due to the (perceived or real) risks of leaks occurring at low water temps – Where did leaks occur (if any)?

vi) Have you ever considered changing supply water temperatures during a commercial retrofit project? Why or why not?

vii) Have you ever considered changing the HHW pumping strategy during a commercial office retrofit? Why or why not?
   (a) *Primary/Secondary --> Variable/Primary*

4) **Electrification experience, or electrification potential**

i) Have you had experience working on the full or partial electrification of HHW systems in existing commercial office buildings?
   (a) Can you walk us through your typical design process for an electrification project?
   (b) What was the main driver to electrifying the system?
   (c) What challenges did you come up against, and how were they resolved?
   (d) Are you able to share specific project names?
   (e) Are you able to share design drawings with us?

ii) Have you ever proposed the full or partial electrification of a system, but were not able to get key stakeholder buy-in?
   (a) Who was opposed and what were the main points of concern?

iii) If you have not electrified these systems on a project, think back to your last boiler retrofit. How would you have fully or partially electrified that system?
   (a) What are some challenges you foresee in trying to accomplish this, and how would you address them?

iv) In your opinion, what resources would be useful to designers to assist in electrifying existing buildings?
   (a) *Datasets*
   (b) *Tools*
   (c) *Examples*
   (d) *Case studies*

5) **Wrap Up**

i) Based on this interview, what questions are you curious about that you think we should be asking (if any)?

ii) We are forming a Hot Water Technical Advisory Committee to continue work on topics related to heating hot water system performance and operation. Would you be interested in joining?

iii) We are going to continue to conduct these interviews over the next few weeks. Do you have any suggestions of other mechanical designers that you think we should reach out to?

Appendix B: Design Tools

Designers recommended the following tools to assist in the design process:

Design Software Overview	
	HOMER Software Developed by: UL, previously developed by NREL Description: The HOMER (Hybrid Optimization of Multiple Energy Resources) Software provides cost optimization modeling for hybrid power systems, including microgrids, distributed generation, and energy storage. https://www.homerenergy.com/
	Cambium Developed by: NREL Description: Cambium provides data sets which contain hourly emission, cost, and operational data for modeled futures of the U.S. electric sector with metrics designed to be useful for long-term decision-making, looking ahead through 2050. https://www.nrel.gov/analysis/cambium.html
	Space Allowances Software Developed by: LowCarbonComfort Description: Space Allowances provides equipment selections, layouts for plant rooms and risers in buildings, tests for clashes, and outputs layouts in a variety of formats, including Word, CAD, SketchUp, and Revit. http://www.lowcarboncomfort.com/