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Responsible Approach To Decarbonization in An Existing Building

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Decarbonization in existing buildings presents many unique challenges and requires a well thought out approach to perform responsibly. The author recently presented a high-level approach to decarbonization in a campus setting in an Engineer's Notebook column.[1] This column will focus on the process of electrifying the hydronic heat generating equipment in several buildings in a higher education setting.

Space heating needs have historically been met by using fossil fuels and combustion-based equipment to generate hydronic hot water. The primary generation equipment is generally inexpensive (boilers are ~$12–$30 per MBH), has high turndown (a number of manufacturers offer 20:1), and use an available, reliable resource for fuel. Building operators are familiar with operating and maintaining this equipment.

As we transition to electrifying the space heating system, heat pumps offer a viable option. Heat pumps have been commonplace in the industry for more traditional airside HVAC applications. More recently, heat pump technology is being used for hydronic heating applications and domestic hot water heating. Heat pumps have their own challenges, such as higher first costs, lower operating efficiency at higher supply temperatures and low ambient operating limitations.

The case study in this column involves a university campus considering transitioning from a cogeneration plant with steam-to-hot water converters at each building to local heating hot water (HHW) plants. The client aspires to achieve carbon neutral status within the next 15 years, and one key mandate is the elimination of natural gas for hydronic and domestic hot water heating. For this project, failing steam infrastructure at a particular section of the distribution was the primary motivation for a centralized heating plant to serve a cluster of three buildings. Two of the buildings were constructed circa 1960, and the third building was constructed within the last five years (*Table 1*).

Recommended practice is to gather available trend data from a facility to benchmark its operation, whereupon, providing the data is granular enough, we can dig into the specific systems. For this project, the university had Btu meters installed on the HHW side of the heat exchangers, which enabled us to analyze the actual operation of the system rather than having to rely on the existing equipment capacity or develop a detailed load calculation to size the new plant. *Table 2* shows that assuming the existing installed equipment

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to be sized correctly results in a grossly oversized system with higher capital costs. Such a system is also likely to encounter limitations due to the existing building infrastructure. From a performance perspective, there would be challenges with operating a heat pump system sized for 250% of the actual peak demand.

The analysis also provided an opportunity to understand other potential issues with the current system operation. As an example, Building A showed a peak heating demand of 27 Btu/h·ft^2 (85 W/m^2) prior to the plant upgrades. This value was not in line with our expectations and data from similar campus buildings. Evaluation of this data allowed the team to be proactive in its approach and to make improvements to correct issues at the load. For example, the design included the replacement of three-way valves with two-way valves, eliminating other bypass means and temperature resets. The post-construction data shows the peak demand to be 10 Btu/h·ft^2 (32 W/m^2).

Beyond looking solely at the peak loads, we needed to dig deeper into the HHW load profile. To develop options for a heat recovery application, the chilled water (CHW) load profile should be overlaid on the HHW load profile to understand the building's simultaneous heating and cooling needs. This campus has a central CHW system available to be used for heat rejection. As such, the project focused only on the HHW profile. *Figure 1* shows a HHW system load profile at Building B in both operating hours and heating output, compared to the original design value of 4,500 MBH (1.3 GW). A majority of the hours of operation can be seen at 20%–30% of the measured peak of 2,041 MBH (598 MW). Similar load profiles were observed in all three buildings in this case study.

Heat pumps used for hydronic systems can be applied as an air-cooled option or water-cooled option and often come as heat-pump-only or heat recovery units (i.e., simultaneous heating and cooling). This project evaluated three options (detailed later in this column). The evaluation considered first costs and carbon emissions as the main key performance indicators (KPIs). This is an oversimplified approach and many other considerations should be taken into account when determining the appropriate system type.

TABLE 1 Existing building characteristics.

BUILDING	USE	YEAR CONSTRUCTED	BUILDING AREA (ft^2)
A	Engineering Classrooms & Labs	1962	93,000
B	Science Classrooms & Labs	2018	110,000
C	Geology and Mathematics Classrooms & Labs	1960	126,000

The university is transitioning from a central steam system; the new baseline system will be a natural gas-fired plant. It will be sized for *N* + 1 capacity and will cover all the buildings' heating needs. The baseline system will use condensing boilers with a peak efficiency of 96%, with an assumed average efficiency of 89%. The existing building distribution and terminal equipment were designed for 180°F (82°C) HHW supply temperature.

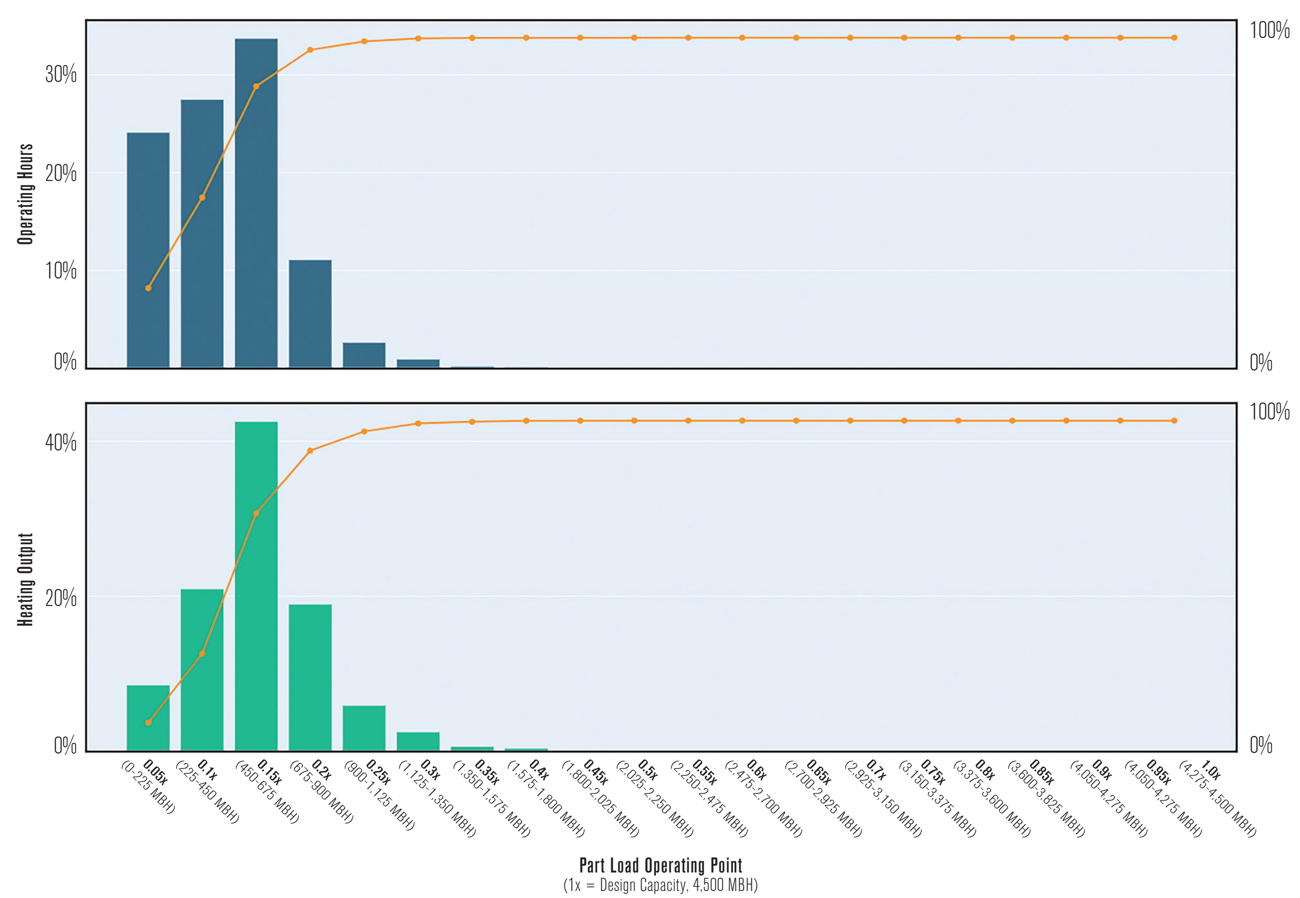
Analysis of the building's reheat coils was performed to implement the lower supply water temperature of 135°F (57°C) used in a condensing boiler system. It was determined 100% of loads could be provided at the one-row heating coils at a reduced HHW supply temperature of 135°F (57°C).[2] The team performed further analysis of the coils at a 110°F (43°C) supply temperature, the design operating temperature selected for heat pumps in the hybrid plant with a gas-fired boiler for peak loads and a heat pump chiller for primary heating needs (see Option 3 below). The HHW supply temperature for the heat pump in this hybrid scenario was selected to maximize efficiency of the heat pump during low-load operation.

TABLE 2 Existing building heating equipment vs. actual heating demand.

BUILDING	USE	INSTALLED HEAT CAPACITY		REQUIRED HEATING CAPACITY	
		HEATING CAPACITY (MBH)	HEATING CAPACITY (Btu/h per ft^2)	PEAK DEMAND (MBH)	PEAK DEMAND (Btu/h per ft^2)
A	Engineering Classrooms & Labs	4,600	49.45	2,543	27*
B	Science Classrooms & Labs	4,500	44.9	2,041	18.5
C	Geology and Mathematics Classrooms & Labs	4,760	37.8	1,618	12.8

* Upon completion of the system upgrades, including replacement of three-way valves and temperature resets, the measured peak demand was 10 Btu/h·ft^2.

FIGURE 1 Building B HHW load profile.



Option 1 is a fully electric option with an air-source heat pump operating in heating-only mode to provide 100% of the building's HHW needs. Although this machine has cooling capabilities, it will be run only in heating mode. This option will consist of two banks of six modules operating in a two-pipe configuration in heating-only mode and will not be tied into the campus chilled water system to reject the cooling water. This system is relatively simple: it is stand-alone. The HHW supply temperature was set to 135°F (57°C) to ensure the existing building coils can meet the loads at the reduced temperature.

In this case, the COP at peak heating operation is approximately 2.12 kW/kW (7.5 kW/ton). The COP will increase if the system can operate at a lower HHW supply temperature; however, the one-row coils within the building require a HHW supply temperature of 135°F (57°C) and further reset is not possible without modifying the coils if the site experiences ambient temperatures below 40°F (4.4°C). In this case, supplemental heating would be required due to limits related to the ambient lift capabilities of this machine.

Option 2 is a fully electric option with a water-cooled heat pump operating in heating-only mode to provide 100% of the building's HHW needs. This option will consist of a bank of six modules operating in a four-pipe configuration in heating-only mode that will tie into the campus chilled water system to reject cooling water. The HHW temperature was set to 135°F (57°C) to ensure existing building coils can meet loads at the lowest possible supply temp. The equipment COP is approximately 5.0. This option requires pumps on the chilled water side to ensure chiller modules maintain the required differential pressure drop across the heat exchanger.

Option 3 is a hybrid option, which will include a water-cooled heat recovery chiller (HRC) operating in heating-only mode to provide 80% of the building's HHW needs (roughly 25% of peak capacity). This option will consist of a bank of modules operating in a four-pipe configuration in heating-only mode that will tie into the campus chilled water system to reject cooling water. For peak loading, supplemental gas-fired boilers will be provided. The HHW supply temperature was set to at 110°F (43°C) when

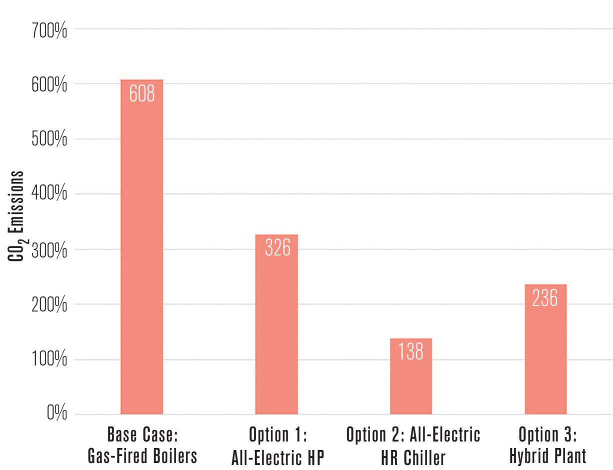
TABLE 3 System options and comparison.

OPTIONS	GAS FIRED BOILERS			HEAT PUMP TECHNOLOGY						EQUIPMENT WEIGHT	ELECTRICAL - MOP @480V/3PH	CENTRAL EQUIPMENT COST ($)
	HEATING CAPACITY (MBH)	MINIMUM HEATING CAPACITY (MBH)	PEAK HEATING EFFICIENCY (COP)	HEATING CAPACITY (MBH)	MINIMUM HEATING LOAD (MBH)	FULL LOAD HEATING EFFICIENCY (COP)	CHW CAPACITY (TONS)	COOLING EFFICIENCY (COP)	SYSTEM EFFICIENCY (COP)			
Base Case	6,200	310	0.9	N/A	N/A	N/A	N/A	N/A	N/A	6,000	*	$200,000
Option 1: HP Chiller	N/A	N/A	N/A	8,300	690	2.2	730	9.728	N/A	50,000	1,600	$1,600,000
Option 2: HR Chiller	N/A	N/A	N/A	6,400	530	N/A	365	N/A	5.3	18,500	800	$600,000
Option 3: Hybrid Plant	4,000	200	0.9	2,200	220	N/A	145	N/A	8.5	9,500	250	$400,000

the HRC is operating at low-load conditions (and higher ambient temperatures) and 135°F (57°C) when the gas-fired boilers are operating at peak heating needs. In this case, the HRC equipment COP is approximately 7.0. The HRC requires pumps on the chilled water side to ensure the chiller modules maintain the required differential pressure drop across the heat exchanger. Gas-fired boilers are designed as part of the system for condensing temperatures and will operate during peak loads, when the HRC can no longer maintain system loads.

Table 3 provides an overview of assumptions for each option compared to the baseline natural gas-boilers. This methodology is used to simplify the calculations and evaluate the options at a high level. *Figure 2* compares the annual carbon impacts. For simplicity, a more detailed life-cycle cost analysis (LCCA) has not been included here but should be considered for any project. *Table 3* provides a quick overview and comparison of system options. Option 1 is a fully independent heating system but presents significant challenges related to weight, physical size, electrical requirements and first costs. The existing facility that would house the new heat pump equipment (Building B) has an 800A electrical service, which would require Option 1 to upsize the electrical service to the building. Option 2 presents a similar challenge. These electrical upgrade costs have not been factored into *Table 3* and would further impact the return on investment (ROI) on such a project. Option 3 is the only viable option of those presented here, without requiring an upgrade to the electrical infrastructure. To confirm Option 3 was viable, a meter read of the facility was performed, which determined the actual load (plus a 25% safety factor) was 343A of the total available 800A.

FIGURE 2 Operational carbon analysis.



Emission Factors:
Electrical grid CO_2 Emissions: 453.2 lb/MWh,[3]
Natural gas CO_2 Emissions: 53.11 kg/MBtu.[4]

One of the project's main KPIs was to understand the carbon impacts of the proposed system. Option 1 is an improvement from the base case; however, the COP of 2.12 for an air-source heat pump does not give the desired impact compared to a gas-fired boiler with a peak efficiency of 96% at a fraction of the cost for the equipment. Option 2 is the most desirable from an operational carbon perspective, but is still limited based on first costs and impacts to the existing building's electrical infrastructure. Option 3, the hybrid plant, provides a viable option to electrify the existing HHW system with minimal impacts to the existing building infrastructure. Options 1 and 2 could be achievable but would require HHW thermal storage to downsize the heat pumps to avoid an upgrade to the electrical infrastructure or would require an upgrade to the electrical service.

Many factors came into consideration to finally determine a hybrid plant was the most viable solution to move toward electrification. This campus has over 110 facilities, and the stakeholders were looking to introduce heat pump technology as a pilot project to determine the feasibility of introducing the technology throughout the campus. The hybrid plant offered them the opportunity to introduce the newer technology to the campus while also providing a back-up gas-fired system the university was much more accustomed to maintaining and operating. It also gave some resiliency to the system, making it not reliant solely on the electrical grid. The hybrid approach gave the university a satisfactory solution to significantly reduce their carbon emissions by operating the HRC for a majority of hours of operation, while significantly improving their ROI compared to an all-electric plant. Moving forward, we will need to evaluate the impact of having decentralized electrified HHW plants in a campus setting with a central CHW, with a likely outcome being a move to a more centralized electrified plant with HHW and CHW storage.

As designers, we need to consider the impact of pursuing electrification for heating systems and be equipped to guide owners to make an informed decision on implementing these systems on a large scale at their campuses and buildings.

References

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