Eversource Air Source Heat Pump (ASHP) Case Study – Presentation of In Situ Operational Performance

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ABSTRACT

The 2022-2024 Massachusetts energy efficiency programs' Greenhouse Gas (GHG) goal requires a total reduction of 845,000 MT of CO_2 by 2030 and electrification of residential heating loads is critical to achieving this goal (Theoharides, 2021). To support this market transition, Eversource performed weatherization upgrades in 24 units, converted 12 natural gas furnaces to air source heat pumps, and replaced 12 natural gas furnaces with higher efficiency gas furnace models in two side-by-side, similar construction, income-eligible multifamily residential buildings. Upgrading these two buildings provided an opportunity for a side-by-side technology and economic in situ case study.

To quantify the performance, energy impacts, and resulting emissions of heat pumps, field monitoring and data collection was installed for a 12-month period. Analysis of short time step data was combined with utility bill analysis, occupant surveys, and vendor interviews to assess the installation in a wholistic manner. This paper will present findings including system performance across outdoor air temperatures ranging from -10°F to 100°F, the effect of sizing, loading, and cycling on Coefficient of Performance (COP) and comparison to manufacturer rated performance. It also compares operating cost and emissions of two similar buildings, one with new air source heat pumps vs. one with new high efficiency natural gas furnaces, and additionally compares performance of ducted vs. ductless distribution.

The results show performance impacts from sizing and equipment choices. Seasonal efficiencies were below rated performance and equipment sizing is a significant factor. These results will influence future industry standard practices to improve customer outcomes.

Introduction

Eversource performed weatherization and mechanical upgrades at two identical, similarly oriented, 12-unit, income-eligible, multifamily housing buildings located in Springfield, Massachusetts. Building A received ducted air source heat pumps (ASHP) on the first and second floors, non-ducted ASHPs in a 1:2 configuration (one outdoor condensing unit and two indoor heads) on the basement floor. Building B received new downdraft, condensing, high efficiency gas furnaces (GFs) utilizing existing underfloor ductwork. Existing packaged terminal air conditioner (PTAC) units were left in place; however, the focus of this paper is on heating performance. This side-by-side installation provided a unique opportunity to conduct performance monitoring to simultaneously evaluate the performance of both the baseline technology (GFs) and the ex-post technology (ASHPs) in nearly identical side-by-side buildings. This case study established five research questions to be addressed:

- What is the installed heat pump performance?
- What are the energy consumption and economic impacts associated with the installed systems?
- What impacts do ASHPs have on winter and summer peak electric load?
- What are the emissions impacts associated with ASHP operation compared to baseline gas furnace equipment?
- What impacts do ASHPs have on customer comfort and satisfaction?

Building Envelope and Heating System Upgrades

The weatherization, heating electrification, and gas furnace replacement completed at the multifamily complex began in summer 2021 and was completed in May 2022. This work was performed in side-by-side, identical buildings (ASHP building and GF building) each containing twelve 665 sq ft, 1-bedroom apartments arranged in two above grade levels and one partially below grade level. The weatherization performed in each apartment was nearly identical and included pinhole injection foam insulation in the walls, door kit and door sweep installations, and window frame caulking. The only difference in weatherization between the two buildings centered around the through-the-wall packaged terminal air conditioning (PTAC) units. Since the newly installed ASHPs provide cooling in addition to heating, the PTAC units were removed from the ASHP building and the wall penetration sealed and insulated, while the PTAC units were left in place in the GF building.

The GF building received new, single speed, high efficiency gas furnaces with downflow configurations to utilize the existing underfloor ductwork. The ASHP building received two different types of heat pump configurations. Ducted, variable speed, downflow ASHPs were installed in the first and second floor units of the ASHP building to utilize the existing ductwork. To avoid the potential for condensation in the underfloor ductwork during cooling operation, ductless mini-split units were installed in the basement apartments and the underfloor ductwork was not used. The non-ducted units were installed in a 2-to-1 configuration with each apartment receiving an outdoor condensing unit, a floor head in the living room, and a wall head in the bedroom. Details of the installed equipment can be found in Table 1 below.

Table 1: List of equipment tested

Location	Equipment	Model	Heating Output (BTU/h)	Cooling Output (BTU/h)	AFUE* COPh**
GF Building	Gas Furnace	Carrier 59SC5B040E14--10	39,000	-	0.95*
ASHP Building (Basement)	Condenser	Fujitsu AOU18RLXFZH	22,000	18,000	3.7**
	Wall Head	Fujitsu ASU7RLF1	8,100	7,000	
	Floor Head	Fujitsu AGU9RLF	12,000	9,000	
ASHP Building (1st & 2nd Floor)	Condenser	Fujitsu AOU24RGLX	27,000	24,000	3.2**
	Air Handler	Fujitsu AMUG24LMAS	27,000	24,000	

Monitoring and Data Collection Plan

A monitoring plan was developed that documents the metering points, instrumentation, and sensor locations necessary to quantify system performance. Descriptions of the monitoring points are listed in table 2 below. The non-ducted systems required the most complex data collection installation due to the multiple indoor heads. A similar approach was used for the ducted and gas furnace systems; however, fewer monitoring points were required.

Table 2: Field monitoring points summary

		Ducted ASHP		Non-Ducted ASHP		Gas Furnace	
		Simple	Detailed	Simple	Detailed	Simple	Detailed
Compressor - Current	Amps		x		x		
Compressor - Frequency	Hz		x		x		
Condenser Coil – Inlet Air Temp.	°F		x		x		
Condenser Coil – Outlet Air Temp.	°F		x		x		
Indoor Unit - Current	Amps		x		x		
Condenser Fan - Current	Amps		x		x	x	x
Indoor Unit – Inlet Air Rel. Humid.	% RH		x		x		x
Indoor Unit – Inlet Temp.	°F	x	x	x	x	x	x
Indoor Unit – Outlet Temp	°F		x		x	x	x
Outdoor Air – Relative Humidity	% RH	x	x	x	x	x	x
Outdoor Air Temp.	°F	x	x	x	x	x	x
Outdoor Unit - Current	Amps		x		x		
Power/Energy	kW/kWh	x	x	x	x		x

Analytical Approach

The collected 1-minute interval performance data served as the basis for all calculations, analysis, and monthly roll ups. This short time step data is used to illustrate instantaneous and short-term performance of the units, i.e.: comparison to manufacturer ratings, assessing peak capacity and cold snap performance. Daily roll ups are used for high level performance assessments such as COP, apartment or building energy consumption, and heating loads.

Findings

To validate the collected field data, the calculated steady state, full load, 1-minute system performance data was compared to manufacturers ratings. This exercise provided confidence in the accuracy of collected data during periods of known operation. The plots in Figure 1 show the results of this ASHP detailed monitoring.

The top upper left plot in Figure 1 compares the peak delivered capacity at 1-minute intervals when the system is operating at or near full load to the rated maximum capacity. The yellow trapezoid represents the maximum and minimum rated heating capacity at four different ambient temperature rating points (-5 °F, 5 °F, 17 °F, and 47 °F). The red squares represent the rated capacity at the common ambient temperature ratings (17 °F and 47 °F). These plots serve as the foundation for all analysis and conveys the accuracy of the field measured ASHP capacity data by showing alignment with the rated full load outputs.

The top upper right plot in Figure 1 compares average delivered capacity with the rated capacity. This plot overlays the average hourly delivered capacity on top of the yellow rated capacity trapezoid with the maximum observed capacity trend (dashed blue line), the average hourly heating load (solid black line) and the minimum rated capacity (dotted red line). This plot conveys the large number of hours of operation below the rated minimum turndown (cycling).

The lower left plot in Figure 1 compares the COP at peak load with rated COP. This plot shows the calculated COP when operating at full heating capacity with a trend line (dashed black line) for the measured data next to rated data (solid red and blue line). This plot conveys that measured COP is in alignment with manufacturer ratings at full load operation.

The lower right plot in Figure 1 compares the COP at peak load with the average daily COP. Fan-only operation reduces the calculated COP. The full load COP trend is also shown to convey the impact that higher outdoor temperatures and resulting part load operation have on daily average COP.

These plots illustrate the measured peak delivered capacity aligns with the maximum rated capacity and full load measured COP aligns with rated performance. However, the system consistently operates below the minimum heat pump turndown when outdoor temperatures are above 35 °F; therefore, measured COP drops significantly below the trendline.

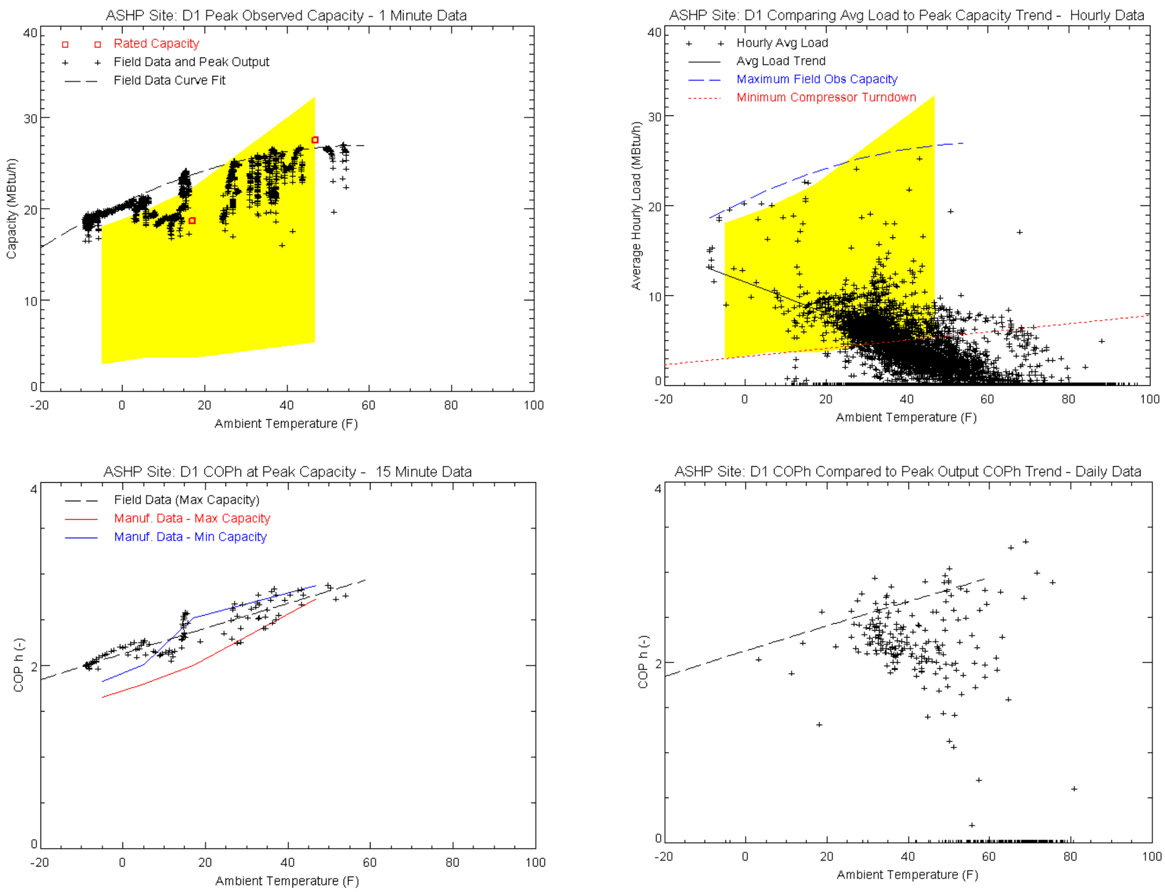


Figure 1. Heating performance validation - ducted unit #1

A similar analysis was performed on non-ducted unit #2 with the plots shown in Figure 2. These plots illustrate that only at lower temperatures, below 20 °F, the measured peak delivered capacity aligns with the maximum rated capacity and full load measured COP is closest with rated performance. However, the system consistently operates below the minimum heat pump turndown when outdoor temperatures are above 20 °F; therefore, measured COP drops significantly below the trendline.

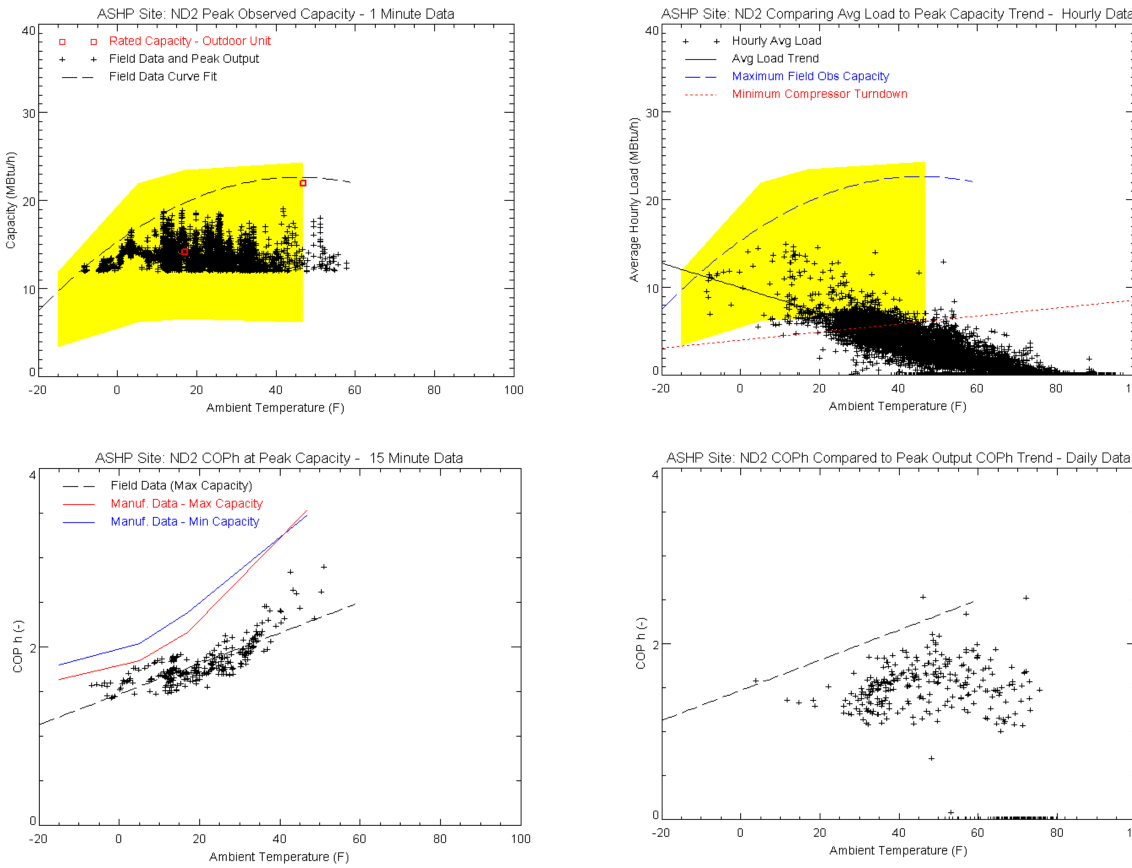


Figure 2. Heating performance validation – non-ducted unit #2

Cold Snap Performance

On February 4th, 2023, the northeast experienced a significant cold snap during which outdoor temperatures dropped below 0 °F and approached -10 °F for a 14-hour period. This provided an ideal opportunity to assess the real-world heat pump performance at extremely cold temperatures. The primary focus of this analysis was to determine the heating output delivered by the installed units and how it compared to the rated output. During this cold snap, return air temperatures remained above 68 °F, indicating occupant comfort was maintained.

Ducted Units

Figure 3 shows the delivered output (black or red plus symbol), the outdoor air temperature (blue line), and the rated output for the unit at 17 °F (green line). Both units show a decrease in the thermal output of 15-20% as the outdoor temperature approaches -10 °F. Unit #1 delivered the full rated capacity and intermittently reduced its output to 75% capacity while unit #2 delivered 50% of the rated heating throughout the cold snap period. The periods of reduced capacity for ducted unit #1 during the cold snap period were identified to be due to reduced fan speeds caused by either reduced temperature setpoint or other internal heat pump controls. The delivered capacity from Unit #2 was incidentally reduced due to the occupant changing the fan speed from auto to low because they did not like the air movement. Since the temperature rise across the interior coil is fixed, the reduced fan speed reduced the capacity the unit could deliver.

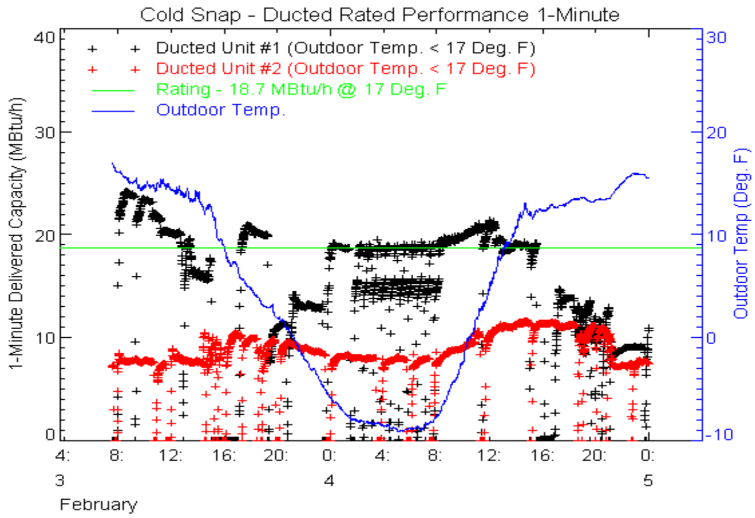


Figure 3. Delivered heat during February 2023 cold snap ducted units #1 and #2

Non-ducted Units

The operation and performance of the non-ducted units during the cold snap period are nearly identical. The thermal output from both units demonstrated capacity in alignment with the 17 °F manufacturer rating point even as outdoor air temperatures approached 5 °F. The thermal output of the non-ducted units decreased 30% as outdoor temperatures dropped below 0 °F and approached -10 °F. This demonstrates that cold temperatures impact the delivered output of the non-ducted units more than the ducted units.

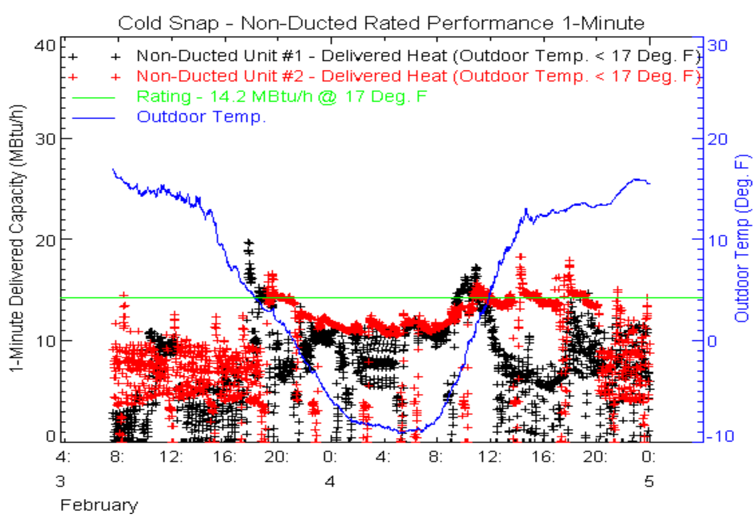


Figure 4. Delivered heat during February 2023 cold snap non-ducted units #1 and #2

Multi-head Operation – Impacts on COP

The non-ducted multi head heat pump systems experienced significant performance impacts related to single head operation and minimum compressor turndown constraints. A 1-hour period on October 31st, 2022, was selected to illustrate this concept. The outdoor unit had a rated capacity of 22 MBtu/h and a minimum capacity of 6.2 MBtu/h (28% of rated capacity at 47 °F). During this period, the floor head operated continuously between 4 and 6 MBtu/h (18% - 27% system capacity) while the wall head cycled on and operated for three five-minute intervals at 5 MBtu/h (23 % system capacity). When only the floor unit was in operation the delivered capacity fell below the rated minimum capacity. When the wall unit kicked on the delivered capacity increased to exceed the minimum capacity.

During this period of operation significant variation in system COP can be observed in Figure 5. When both heads operated, and delivered capacity exceeded the minimum rating, system COP approached 2.5. When a single indoor head operated, and delivered capacity was below the minimum rating, system COP approached 1. This shows that COP is driven not only by outdoor air temperature but also system loading. This finding, along with the low observed apartment loads, led to performance modeling and equipment sizing analysis discussed later.

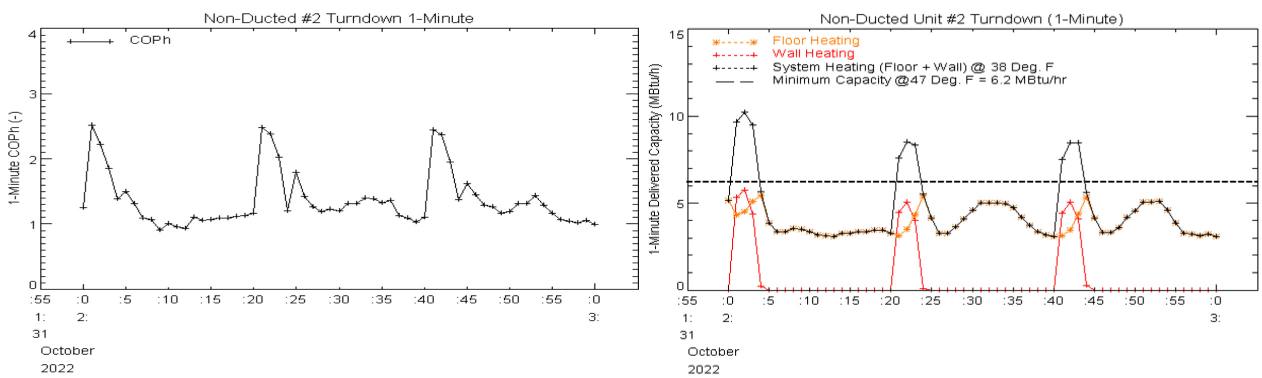


Figure 5. Impacts of operation below minimum turndown on COP

Resident Comfort

Resident comfort and satisfaction were anecdotally evaluated through discussions with the facilities manager. During the first winter ('22 – '23) zero service calls or resident comfort complaints were received related to the ASHP systems. This includes during the February 5th cold snap when outdoor temperatures dropped to -10 °F and indoor return temperatures maintained above 68 °F. The one common complaint received across all occupants (ASHP and GF) was related to challenges with the thermostats and controls. Many residents voiced challenges with operating the installed heat pumps due to the increased thermostat complexity. This applied to both the wall mounted smart thermostats for the ducted systems as well as the single portable remote that operates both indoor heads of the non-ducted system.

- The new wall mount thermostats installed in both the GF building and ducted ASHP units include a touch screen face and more control settings including scheduling and fan speed.
- The single portable remote and thermostat that controls both indoor heads for the non-ducted ASHPs provides complexity that appears to not be understood or necessary.

Operational Challenges

Several operational challenges were identified during the field monitoring period. These did not impact system performance or occupant comfort; however, are important to note to assist with the broader deployment of these systems. These include:

- Wall mounted thermostat for the ducted system allows for changing the ASHP fan speed. One occupant reduced fan speed due to comfort preferences and limited heating capacity.
- The screen on one of the remotes broke and the occupant was unable to see the operating mode (heating versus cooling) of the units or control the ASHP as intended.
- Both the new thermostats (wall mounted and portable) provide more customization and control than typical thermostats, adding complexity seen as a hinderance to operation.

Annual Performance

The short time step data was used to calculate the annual energy use and delivered heat for each apartment shown in Table 3 and Table 4. Significant variation in heating loads was seen across all twelve (12) apartments with two (2) ASHP systems showing zero heating operation across the 12-month period. The balance point, shown in tables 3 and 4, represents the temperature at which the system switches between heating and cooling operation.

Apartment design day load was determined by plotting daily delivered capacity versus outdoor air temperature and fitting a linear trend for each apartment. The trend was then evaluated at 0 °F to determine the daily average load on the design day. The ducted systems achieved better annual heating performance than the non-ducted systems, achieving an annual ducted system COP of 2.21 versus the non-ducted system COP of 1.44.

Table 3. Annual performance - GF building

Floor	Heating Load (Mbtu)	Gas Use (therm)	Balance Point (x-intercept)[1]	Avg. Design Day (0 Deg. F) Load (Mbtu/h)	EFLH[2]	Eff. (%)
B	21,388	23,169	55	14.0	548.4	92%
B	50,924	58,043	60	28.6	1,305.7	88%
B	1,959	2,266	45	3.3	50.2	86%
B	41,157	46,837	60	24.0	1,055.3	88%
1st	8,793	9,486	55	5.2	225.5	93%
1st	15,415	17,918	50	13.1	395.3	86%
1st	46,018	52,768	62	22.8	1,180.0	87%
1st	21,620	25,050	60	11.3	554.4	86%
2nd	14,662	16,315	55	11.6	376.0	90%
2nd	20,884	23,383	65	10.6	535.5	89%
2nd	4,767	5,413	55	3.1	122.2	88%
2nd	13,581	15,574	45	13.1	348.2	87%
Total:	261,168	296,223	-	-	-	-
Avg:	21,764	24,685	55.6	13.4	558.1	88%

[1]Observed temperature the system transitions between cooling and heating

[2]Equivalent Full Load Hours (EFLH) = heating load/unit rated capacity

Table 4. Annual performance - ASHP building

Floor	HP Type[1]	Heating Load (Mbtu)	Energy Use (kWh)	Balance Point (x-intercept)	Avg. Design Day (0 Deg. F) Load (Mbtu/h)	EFLH	COP
B	ND	12,634	2,419	60	6.7	574	1.53
B	ND1	4,808	1,216	55	5.5	219	1.16
B	ND	20,690	3,918	65	8.9	940	1.55
B	ND2	23,106	4,446	65	10.4	1,050	1.52
1st	D	7,225	948	50	6.7	268	2.23
1st	D	32,062	4,079	62	15.1	1,187	2.30
1st	D	-	-	-	-		
1st	D1	17,843	2,284	58	10.2	661	2.29
2nd	D	15,578	1,995	60	8.7	577	2.29
2nd	D	1,964	266	40	4.2	73	2.17
2nd	D2	11,523	1,707	55	7.4	427	1.98
2nd	D	-	-	-	-		
Total:		147,434	23,277	-	-	-	-
Avg - ND:						696	1.44
Avg - D:						532	2.21
Avg:		14,743	2,328	57.0	8.4	597.6	1.90

[1]D = ducted, ND = non-ducted

Demand

The peak 15-minute demand impact from the electrified 12-unit apartment building was 21.75 kW as shown in Figure 6. On this day the installed heat pumps consumed 385 kWh, resulting in an average demand increase of 16 kW. Since two of the heat pump units did not operate in any consistent or significant manner during heating season, and four of the units did not operate in cooling the building demand is representative of ten apartments for heating and eight apartments for cooling.

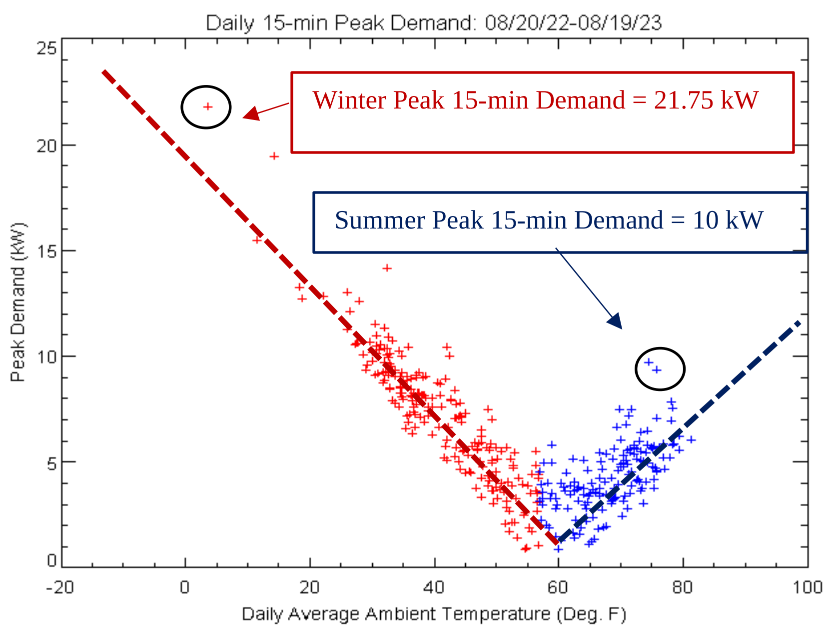


Figure 6. Daily 15 minute peak demand – aggregated ASHP building

Economics

Measured heating loads in the GF building are 48% higher than the heat pump building, after assuming average ASHP operation for the two systems that did not operate. This is due to improved insulation and weatherization in the heat pump building from removal of the PTAC units and resident preferences. The impacts of occupant temperature setpoints were not assessed as the study was focused on real world behavior and resulting energy consumption.

It cost 170% more ($5,460.95) to serve the ASHP building heating loads with the heat pumps than it did to serve GF building heating loads with gas furnaces ($3,209.37). If the GF building served the lower ASHP building heating loads the cost difference would increase as gas furnace operating costs would drop to $2,092.59. Table 5 below shows operating cost by month.

Table 5. Operating costs – ASHP and gas furnace building

	Gas Furnace Building					ASHP Building			
Month	Heating Load (MBtu)	Gas Use (MBtu)	Efficiency (%HHV)	Operating Cost[1]	Gas Furnace Operating Cost - ASHP Bldg. Heating Loads[1]	Heating Load (MBtu)	Electric Use (kWh)	COP	Operating Cost[2]
Sep	3,232	3,826	87.2%	$40	$5	387	60	1.89	$12
Oct	13,401	15,647	88.4%	$164	$83	7,029	1,116	1.85	$225
Nov	28,876	33,758	88.3%	$354	$245	20,610	3,168	1.91	$640
Dec	49,670	57,772	88.7%	$607	$379	32,008	5,190	1.81	$1,048
Jan	46,482	54,218	88.5%	$569	$368	30,971	4,765	1.91	$962
Feb	51,985	60,707	88.4%	$637	$386	32,472	5,119	1.86	$1,034
Mar	40,602	47,960	87.4%	$504	$345	28,723	4,305	1.96	$870
Apr	17,332	20,454	87.4%	$215	$161	13,384	1,864	2.10	$377
May	7,278	8,647	86.9%	$91	$96	7,963	1,087	2.15	$220
Jun	2,269	2,267	87.8%	$28	$31	2,613	361	2.12	$73
Total	261,127	305,256	-	$3,209	$2,099	176,160	27,035	1.91	$5,461

[1]Natural Gas Rate = 1.05/therm

[2]Electric Rate = $0.20/kWh

The primary driver for these increased heating costs for the electrified building is due to the fundamental difference in cost per unit energy (MBtu) between natural and electricity. The site utility costs reveal that electricity is five times more expensive than natural gas. While heat pumps offer significant efficiency improvements compared to natural gas furnaces, these efficiency improvements are not large enough to make up for this current price discrepancy.

Emissions

The calculated emissions values in Table 6 show that the gas furnaces building resulted in the most CO_2 emissions since it had larger energy loads. The ASHP systems evaluated using the 2030 Emissions Rates resulted in the lowest CO_2 emissions. The emissions produced by gas furnace systems serving identical loads as the ASHP system, when evaluated using present day non-baseload emissions rates[1], produces marginally lower (-4.3 %) emissions. As the grid decarbonizes and reaches the MA 2030 emissions target of 213 lb CO_2 / MWh the ASHP system will produce significantly lower emissions (-76 %) than the gas furnace system.

Table 6. CO2 emissions – ASHP and gas furnace building

	Gas Furnace Building					ASHP Building				
Month	Heating Load (MBtu)	Gas Use (MBtu)	Eff. (%HHV)	CO_2 (lb)[1]	GF CO_2 ASHP Bldg. Loads (lb)[1]	Heating Load (MBtu)	Electric Use (kWh)	COP	MA CO_2 2021 (lb)[2]	MA CO_2 2030 (lb)[3]
Sep	3,232	3,826	87.2%	446	53	387	60	1.89	56	13
Oct	13,401	15,647	88.4%	1,825	957	7,029	1,116	1.85	1,036	238
Nov	28,876	33,758	88.3%	3,938	2,811	20,610	3,168	1.91	2,942	675
Dec	49,670	57,772	88.7%	6,739	4,343	32,008	5,190	1.81	4,820	1,105
Jan	46,482	54,218	88.5%	6,325	4,214	30,971	4,765	1.91	4,425	1,015
Feb	51,985	60,707	88.4%	7,081	4,423	32,472	5,119	1.86	4,754	1,090
Mar	40,602	47,960	87.4%	5,594	3,958	28,723	4,305	1.96	3,999	917
Apr	17,332	20,453	87.4%	2,386	1,842	13,384	1,864	2.10	1,731	397
May	7,278	8,647	86.9%	1,009	1,104	7,963	1,087	2.15	1,010	232
Jun	2,269	2,667	87.8%	311	358	2,613	361	2.12	336	77
Total:	261,126	305,655	-	35,655	24,064	176,161	27,034	-	25,109	5,758

[1]EIA Natural Gas Emissions Rate = 116.65 lb CO_2 / MMBtu

[2]eGrid MA 2021 Non-Baseload Emissions Rate = 928.77 lb CO_2/MWh (0.464385 Ton/MWh)

[3]MA EEA Est. 2030 Emissions Factor = 213 lb CO_2/MWh (0.10650 Ton/MWh)

ASHP Sizing Analysis

One of the most dramatic findings from this applied technology demonstration was the number of part load operating hours. This led to an investigation into the impact of equipment sizing driving both the number of part load hours and the resulting performance. In this ASHP application there were several constraints that impacted the selected equipment including downflow configuration and small apartments and heating loads.

A sensitivity analysis was performed, first matching the heat pump size perfectly to the observed load, and then continued to decrease the heat pump size, supplementing with conventional heating systems to meet the remaining load. The overall impact on heat pump COP, energy and demand, emissions and economics was quantified.

The idea is that systems should be sized to maximize performance in temperature ranges where the bulk of runtime occurs. By including a backup heating system, sizing can be designed for the temperatures with the most runtime instead of worst-case heating load. Figure 7 shows the outdoor temperature distribution during the 5,817 hours of measured heating operation. In the 12-month period over 85% of the heating runtime occurred when outdoor temperatures were greater than 30 °F.

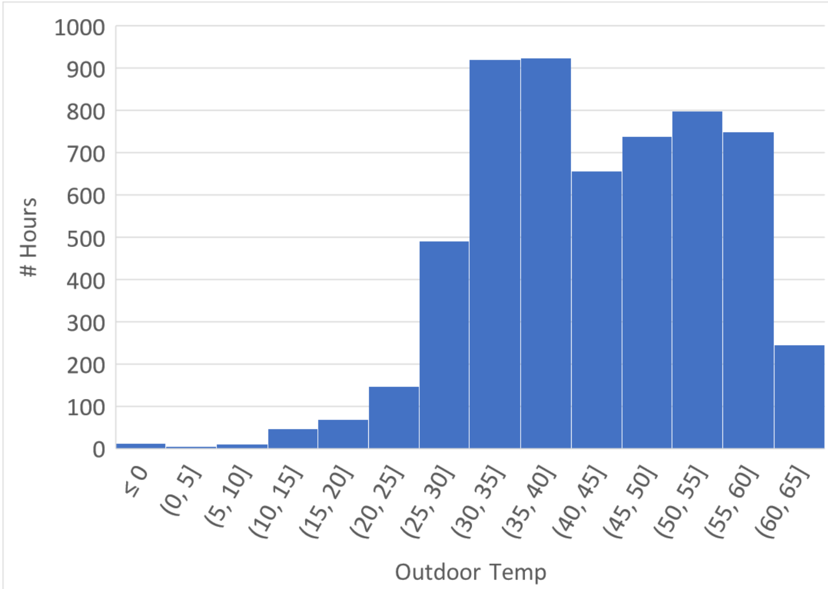


Figure 7. Outdoor temperature – heating operation

Table 7 below shows the frequency, by temperature bin, of the ducted and non-ducted systems operating under the rated minimum capacity by temperature range. A high percentage of runtime below the minimum capacity indicates an opportunity to reduce installed capacity and improve system performance.

Table 7. Heating runtime under rated minimum capacity

	Ducted				Non-Ducted			
Temp. Range (°F)	Min Output (Mbtu/hr)	Heating Runtime (hrs)	Runtime < Min. Cap. (hrs)	% Runtime < Min Cap	Min Output (Mbtu/hr)	Heating Runtime (hrs)	Heating Runtime < Min Cap. (hrs)	% Runtime < Min Cap
<10	3.7	52	1	2%	6.2	52	2	4%
10 to 20	3.7	110	9	8%	6.2	110	15	14%
20 to 30	3.6	617	16	3%	5.9	617	123	20%
30 to 40	3.9	1857	201	11%	5.7	1857	950	51%
40 to 50	5.2	1390	755	54%	6.0	1390	801	58%
>50	7.9	1791	693	39%	7.1	1791	673	38%
Total:		5817	1,675	1,675		5817	2,564	2,564

To determine the impacts of alternative equipment sizing on performance (COP, kWh, kW, operating cost, CO_2 emissions), the daily apartment load line, ambient temperature data, and unit performance from the monitoring study were used. A normalized model for system COP as a function of load factor (delivered capacity / minimum rated capacity) and outdoor air temperature was developed. Table 8 shows the outdoor air temperature bins used in the model.

Table 8. Outdoor Air Temperature (OAT) and Load Factor (LF) ranges used for COP modeling

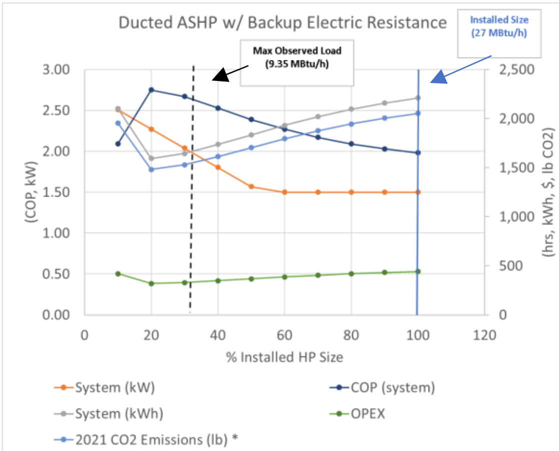
Ducted					Non-Ducted				
Load Factor Range	OAT Range	# Hrs	%	COP	Load Factor Range	OAT Range	# Hrs	%	COP
0 <LF≤0.1	-10<°F≤65	917	15.8	1.5	0<LF≤0.1	-10<°F≤65	655	11.3	1.3
0.1< LF≤3	-10<°F≤15	65	1.1	1.8	0.1<LF≤1.25	-10<°F≤35	1,641	28.2	1.3
0.1<LF≤3	15<°F≤45	3,210	55.2	2.0	0.1<LF≤1.25	35<°F≤45	1,581	27.2	1.6
0.1<LF≤3	45<°F≤ 55	1,537	26.4	2.0	0.1<LF≤1.25	45<°F≤60	1,878	32.3	1.6
0.1<LF≤3	55<°F≤ 65	79	1.4	1.9	0.1<LF≤1.25	60<°F≤65	0	0.0	1.5
3<LF≤100	-10<°F≤ 65	9	0.2	1.9	LF > 1.25	-10<°F≤65	62	1.1	1.5
Total:		5817	100				5817	100	

The developed model was used to determine annual performance for smaller heat pump sizes decreasing in 10% increments. This analysis assumed that a backup heat source was installed and operates in parallel with the heat pump to supplement capacity when heating loads exceed the unit's rated capacity at the given operating temperature. This analysis was performed for both the ducted and non-ducted models and for both electric resistance heat (efficiency = 100%) and gas furnace (efficiency = 80%) backup.

The results from this modeling exercise can be found in graphical and tabular form below for the ducted ASHP in Figure 8 and Table 9 and for the non-ducted ASHP in Figure 9 and Table 10. This analysis revealed that installed ducted and non-ducted systems capacity could have been reduced by 40% and 50% respectively without requiring backup heat (blue highlighted region in Table 9 and Table 10). This would result in a 12% reduction in annual kWh consumption, operating costs, and emissions for the ducted systems. Improvements to the non-ducted system performance would be even higher with an estimated 17% reduction in annual kWh consumption, operating costs, and emissions due to the higher minimum capacity.

System COP (ASHP + supplemental heat), emissions, energy consumption, and economics are optimized as installed equipment size is reduced to 20% (green highlighted region in Table 9 and Table 10. Any smaller sizing and the impact of the runtime as well as the efficiency of the supplemental heat source negatively impacts system performance. There are some operational challenges associated with implementing this reduced sizing approach such as minimum ASHP capacity including available equipment size (5.4 MBtu/h) and the grid demand impacts driven by the supplemental backup heat demand when using electric resistance backup.

If these systems were installed with backup heat, the installed equipment could have been reduced by 80% of the nameplate rating (green highlighted region in Table 9 and Table 10). This would have resulted in minimal runtime of the backup heat sources (271 hours for ducted system, 73 hours for non-ducted) while reducing annual kWh consumption, operating costs, and emissions by 25% compared to the installed equipment.



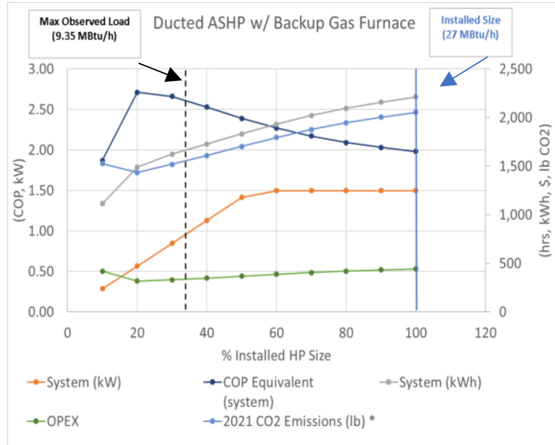


Figure 8. Annual heating performance graphs – alternative sized ducted ASHP systems

Table 9. Annual heating performance tables – alternative sized ducted ASHP systems

Ducted – Backup electric resistance heat													
% Size	Rated Cap. @ 47°F MBtuh	Backup Runtime Hrs	Sys. (kWh)	Sys. (kW)	ASHP (kWh)	ASHP (kW)	Backup Heat (kWh)	Backup Heat (kW)	COP ASHP	COP Sys.	Annu. Opex	2021 CO_2 (lb)[1]
100	27	0	2,211	1.50	2,211	1.50	0	0.00	1.98	1.98	$ 442	2,053
90	24.3	0	2,157	1.50	2,157	1.50	0	0.00	2.03	2.03	$ 431	2,004
80	21.6	0	2,095	1.50	2,095	1.50	0	0.00	2.09	2.09	$ 419	1,946
70	18.9	0	2,020	1.50	2,020	1.50	0	0.00	2.17	2.17	$ 404	1,876
60	16.2	0	1,931	1.50	1,931	1.50	0	0.00	2.27	2.27	$ 386	1,794
50	13.5	9	1,833	1.57	1,832	1.41	1	0.16	2.39	2.39	$ 367	1,703
40	10.8	16	1,736	1.80	1,728	1.13	7	0.67	2.53	2.53	$ 347	1,612
30	8.1	58	1,645	2.04	1,624	0.48	22	1.19	2.69	2.67	$ 329	1,528
20	5.4	271	1,594	2.27	1,489	0.57	105	1.71	2.88	2.75	$ 318	1,481
10	2.7	2,557	2,104	2.51	1,113	0.29	1,113	2.22	3.05	2.09	$ 421	1,954
Ducted – Backup gas heat												
% Size	Rated Cap. @ 47°F MBtuh	Backup Runtime Hrs			ASHP (kWh)	ASHP (kW)	Backup Heat (cf)		COP ASHP	COP Sys.	Annu. Opex	2021 CO_2 (lb)[1]
100	27	0			2,211	1.50	0		1.98	1.98	$ 442	2,053
90	24.3	0			2,157	1.50	0		2.03	2.03	$ 431	2,004
80	21.6	0			2,095	1.50	0		2.09	2.09	$ 419	1,946
70	18.9	0			2,020	1.50	0		2.17	2.17	$ 404	1,876
60	16.2	0			1,931	1.50	0		2.27	2.27	$ 386	1,794
50	13.5	9			1,832	1.41	4		2.39	2.39	$ 367	1,702
40	10.8	16			1,728	1.13	30		2.53	2.53	$ 346	1,609
30	8.1	58			1,624	0.85	91		2.69	2.66	$ 326	1,519
20	5.4	271			1,489	0.57	436		2.88	2.71	$ 303	1,435
10	2.7	2,557			1,113	0.29	4,096		3.05	1.87	$ 273	1,527

[1]eGrid MA 2021 Non-Baseload Emissions Rate = 928.77 lb CO_2/MWh (0.464385 Ton/MWh)

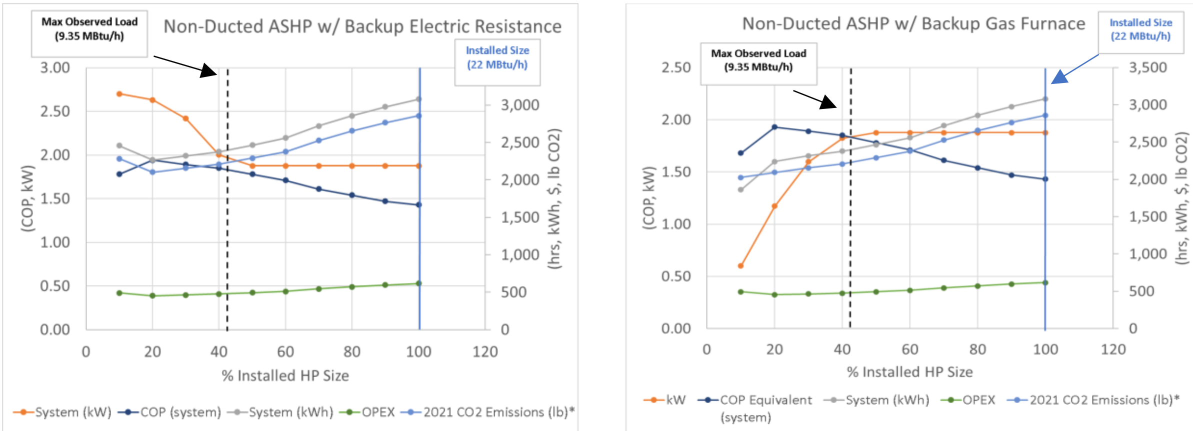


Figure 9. Annual heating performance graphs – alternative sized non-ducted ASHP systems

Table 10. Annual heating performance tables – alternative sized non-ducted ASHP systems

Non-Ducted – Backup electric resistance heat												
% Size	Rated Cap. @ 47°F MBtuh	Backup Runtime Hrs	Sys. (kWh)	Sys. (kW)	ASHP (kWh)	ASHP (kW)	Backup Heat (kWh)	Backup Heat (kW)	COP ASHP	COP Sys.	Annu. Opex	2021 CO_2 (lb)[1]
100	22	0	3,079	1.88	3,078	1.88	0	0.00	1.43	1.43	$ 616	2,859
90	19.8	0	2,976	1.88	2,976	1.88	0	0.00	1.47	1.47	$ 595	2,764
80	17.6	0	2,858	1.88	2,858	1.88	0	0.00	1.54	1.54	$ 572	2,655
70	15.4	0	2,721	1.88	2,721	1.88	0	0.00	1.61	1.61	$ 544	2,527
60	13.2	0	2,559	1.88	2,559	1.88	0	0.00	1.71	1.71	$ 512	2,377
50	11	0	2,466	1.88	2,466	1.88	0	0.00	1.78	1.78	$ 493	2,290
40	8.8	7	2,378	2.00	2,377	1.82	1	0.18	1.85	1.85	$ 476	2,208
30	6.6	13	2,323	2.42	2,316	1.60	7	0.82	1.89	1.89	$ 465	2,158
20	4.4	73	2,266	2.63	2,239	1.17	27	1.46	1.95	1.94	$ 453	2,105
10	2.2	2,141	2,460	2.7	1,862	0.60	598	2.10	2.04	1.78	$ 492	2,284
Non-Ducted – Backup gas heat												
% Size	Rated Cap. @ 47°F MBtuh	Backup Runtime Hrs			ASHP (kWh)	ASHP (kW)	Backup Heat (cf)		COP ASHP	COP Sys.	Annu. Opex	2021 CO_2 (lb)[1]
100	22	0			3,079	1.88	0		1.43	1.43	$ 616	2,859
90	19.8	0			2,976	1.88	0		1.47	1.47	$ 595	2,764
80	17.6	0			2,858	1.88	0		1.54	1.54	$ 572	2,655
70	15.4	0			2,721	1.88	0		1.61	1.61	$ 544	2,527
60	13.2	0			2,559	1.88	0		1.71	1.71	$ 512	2,377
50	11	0			2,466	1.88	0		1.78	1.78	$ 493	2,290
40	8.8	7			2,377	1.82	3		1.85	1.85	$ 475	2,208
30	6.6	13			2,316	1.60	31		1.89	1.89	$ 464	2,154
20	4.4	73			2,239	1.17	113		1.95	1.93	$ 449	2,093
10	2.2	2,141			1,862	0.6	2,471		2.04	1.68	$ 403	2,027

[1]eGrid MA 2021 Non-Baseload Emissions Rate = 928.77 lb CO_2/MWh (0.464385 Ton/MWh)

Conclusions

While this study is focused on a specific multifamily residence, these findings are applicable to the general heat pump market. Ducted ASHP systems should be prioritized for energy efficiency program offerings as they demonstrated better operational performance than

Mulitsplit systems. Multisplit ASHPs should be investigated further for ways to overcome degradation in efficiency during periods of non-simultaneous loads on the indoor units. ASHP systems demonstrated maintaining occupant comfort during sub-zero temperatures; however, operating costs are considerably higher when compared to high efficiency GFs. Modeling showed a significantly smaller ASHP, down to 20% of the installed capacity, with a supplemental heating source to support the coldest hours would maximize system efficiency while demonstrating other benefits around peak demand, operational cost, and grid emissions. Distinct differences between GF and ASHP systems and how sizing impacts system performance were demonstrated in this case study. A successful utility heat pump program must focus on new sizing methodologies including auxiliary heating sources to optimize heating system performance and improve customer results.

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