Cold Climate Air Source Heat Pumps with Energy Storage: Evaluating the Impacts of a Carbon Reduction Strategy for New England

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Abstract

Reaching an energy-efficient, low-carbon future means rethinking how we heat our buildings. Cold climate air-source heat pumps (ASHP), an attractive alternative to direct fossil fuel combustion, are being considered in Massachusetts and elsewhere to support strategic electrification policy. Shifting to ASHP heating could lower primary energy use and carbon emissions but may also impact customers' energy bills in complex ways. To evaluate potential tradeoffs, scenario-based simulations were applied to three commercial building types (Office, Retail, and School). Baseline fossil heating systems were replaced by efficient ASHP to evaluate impacts on energy consumption, peak load, and energy costs. Costs were evaluated under three demand-based electric rate structures. Finally, onsite battery storage was evaluated as an option for mitigating increased electric peaks. Results will inform ongoing policy discussions.

Introduction

Space heating in the U.S. – mostly on-site fossil fuel combustion, Figure 1 – accounts for over 20% of U.S. building-related primary energy consumption. Burning fuels directly to heat buildings, however, wastes high-quality energy. Reaching an efficient, low-carbon future means rethinking how we heat our buildings.

Figure 1. Heating type by region, percent of total heated commercial floor area (2012 CBECS, EIA 2015).

Strategic Electrification

Many local, regional, and global initiatives are exploring policies to support the transition to an efficient, cost-effective, low-carbon energy future. The Commonwealth of Massachusetts (MA), for one, has aggressive

greenhouse gas (GHG) reduction targets, foremost to achieve at least an 80 percent reduction in state-wide GHG emissions by 2050.

To achieve these goals, analysts have found that most space-heating would need to be electrified and ultimately met by renewable power generation (NEEP 2017). Even with ideal conversion efficiency, conventional heating systems that burn fossil fuels cannot be carbon-neutral.

Prior studies have evaluated the ramifications of heating system electrification in California (Tarroja et al. 2018) and residential-sector electrification in different regions (Billomoria et al. 2018). Operating cost impacts for the commercial building sector, however, have received less attention and are less well understood.

This paper considers air source heat pumps (ASHP), an electric space heating technology with a long track record. Although ASHP have gained traction in the MA residential HVAC market, their adoption in commercial buildings has been limited due to concerns about operating costs, particularly in regions with high electric demand charges.

Cold Climate Air Source Heat Pumps

About two-thirds of the total U.S. commercial building space heating energy consumption occurs in cold and very cold climates ($HDD_{18^{\circ}C} > 3000$; $HDD_{65^{\circ}F} > 5400$). Cold climate ASHP, designed to maintain capacity and efficiency at low outdoor temperatures, can yield seasonal coefficients of performance (COP, heat out per unit electricity in) that approach or exceed three.

Briefly, the logic of using ASHP heating can be illustrated with a simple natural gas example. The average thermal efficiency of a modern natural gas-fired electric power plant is about 44%.¹ Using electricity from this source, an efficient cold climate ASHP with a seasonal heating COP of three would yield about $0.44 \times 3 = 1.3$ units of heat per unit of fuel. In contrast, the best available gas furnace could deliver at most about 0.95 units of heat burning the same fuel on site. Put another way, in this example, burning fossil fuels directly for heat would require about 1.4 times more primary energy than first generating electricity and then running an efficient ASHP.²

¹ At peak conditions, combined-cycle gas plants can reach efficiencies above 60%. This illustrative example excludes transmission and distribution losses, typically about 8% from plant to load.

² The average U.S. primary energy conversion efficiency for electricity production – about 33% in 2012 (EIA 2016) – was somewhat lower than the previous example. Even so, a seasonal average heating COP of three would still slightly outperform on-site combustion from an energy standpoint.

ASHP performance can vary significantly and depends on equipment, loading conditions, system design, and critically, outdoor temperature. Real-world performance data, especially for large commercial equipment, are sparse, as cold climate heat pumps have yet to achieve widespread U.S. market share. Consequently, this analysis uses simplified performance models based on the limited available data for larger residential-based systems.

Research Questions

Energy performance and carbon reductions are only part of the story. Even if the energy and carbon reductions prove viable, customers may face unfavorable billing impacts related to substantially higher facility electric peak demand charges.

In many places, peak demand charges are driven by summertime cooling loads. In a future with widespread electrified heating, winter peak loads – both at building and grid scales – would increase substantially and may exceed summer peaks (NEEP 2017). This would result in higher monthly electric demand charges, and potentially, new rate structures with significant cost implications.

Battery storage systems, deployed in conjunction with ASHP, could play an important role in managing both new and existing electric peaks.

This study, therefore, set out to examine the first-order energy, carbon, and energy-cost tradeoffs that come with switching from conventional natural gas (or oil) heating to ASHP. The analysis considers the energy, cost, and carbon consequences of switching from conventional heating systems to ASHP heating.

This modeling exercise was designed to show how ASHP systems, both with and without and battery storage, compare with conventional on-site fossil-fuel combustion heating systems in terms of:

1. Primary energy consumption
2. Energy costs
3. Carbon intensity

as a function of building type, energy and demand rates, and carbon intensity of the electric grid.

Methods

The effects of switching from fossil fuel heating to electric ASHP were estimated as follows:

1. Select building types and climate
2. Model baseline building
3. Develop ASHP performance model
4. Develop battery storage model
5. Model energy costs
6. Model carbon impacts

Building Models

Three prototypical commercial building models – Office, Retail, and School, Table 1 – were selected in consultation with the project sponsor to represent a range of electric and heating load profiles and demand magnitudes. These building types were selected because they represent a large fraction of the total MA commercial-sector energy use and because they are likely candidates for ASHP retrofits based on initial market traction.

Modeling was performed using EnergyPlus (v8.9) using prototypical building models (2004 new construction vintage) to represent a somewhat average baseline energy performance case for existing buildings. Detailed model characteristics and input files are available online (DOE 2012, prototypical model v.1.4_7.2, Climate Zone 5A).

Table 1. Baseline building summary.

Characteristic	Medium Office	Big-box Retail	Secondary School
Floor Area (000) m ²	5.0	2.3	19.6
Floors	3	1	1
Zones	15	5	46
Heating System	Furnace	Furnace	Boiler
Fuel	Nat. Gas	Nat. Gas	Nat. Gas
Efficiency	80%	80%	78%
Setpoint °C (°F)	21 (70)	21 (70)	21 (70)
Note: ASHP replacements were considered for heating systems only. Baseline cooling systems included packaged, unitary, and chiller, with nominal COP ranging from 2.8 to 3.7.			

The raw models were adjusted in two ways prior to simulation. First, timesteps were changed to 15 min. to generate finer resolution loads for demand analysis. Second, all nighttime thermostat temperature setbacks were disabled. Using night setbacks with heat pumps can yield an intense morning recovery period that would require larger capacity equipment. Night setbacks could also produce more inefficient cold temperature operation and/or higher reliance on auxiliary heat, and potentially increase facility peak demand during recovery. Eliminating setbacks in the baseline avoids these issues while maintaining a consistent basis for comparison. Nighttime ventilation setback schedules, however, were kept as-is, reducing nighttime heating demand in all cases.

Climate Data

New England states including Massachusetts, belong to the cold (3000-5000 HDD_{18°C}; 5400-9000 HDD_{65°F}) and very cold (5000-7000 HDD_{18°C}; 9000-12600 HDD_{65°F}) climate regions. These regions account for about two-thirds of the total U.S. commercial space heating energy consumption. Hourly TMY3 weather data for Boston, MA (447 CDD_{18°C} [804 CDD_{65°F}] and 3270 HDD_{18°C} [5885 HDD_{65°F}]) were used for all simulations. Outdoor temperatures ranged from -20 to 37°C (-4 to 99°F).

Air-Source Heat Pump Model

The ASHP heating coefficient of performance (COP), defined as heat output divided by electricity input, depends mainly on outdoor air temperature, and less so on part-load fraction. Colder temperatures reduce capacity and COP, dropping somewhat linearly from the rated condition and leveling out at colder temperatures. A second steep drop-off may occur at very cold temperatures (below about -23°C [10°F]; Schuetter and Hackel 2015). When this happens, supplemental auxiliary gas or electric resistance heat may be required.

Energy performance data for commercial cold climate ASHP were not readily available. Instead, we consulted a large performance database for residential cold climate ASHP equipment (NEEP 2018). This public database

includes manufacturer-reported COP data measured at up to three temperatures (-15, -8.3, and 8.3°C [5, 17, 47°F]) and capacities (minimum, maximum, and rated) covering over 1200 different equipment models. Performance varied with load fraction, heat pump type (ducted vs. ductless), and outdoor temperature.

Since commercial units tend to be sized much larger than most residential units, we focused on the 78 equipment models with heating capacity ≥ 4 tons (14 kW-th, [48000 Btu/h]), Figure 2. Based on these high-efficiency units, we developed simple correlations for COP as a function of outdoor temperature T (1):

$$COP = A \cdot T^2 + B \cdot T + C \quad (1)$$

where

A	B	C	Units of T
0.00142	0.0784	3.05	°C
0.00044	0.0154	2.11	°F

Note that these relationships are applicable only between about -20 to +15°C (-5 to +60°F). At higher temperatures, performance eventually plateaus. At colder temperatures, performance and capacity could drop off sharply, and auxiliary heat could be required. This situation can be modelled by setting the COP to 1 for the portion of load met by electric-resistance heat. Auxiliary heat was not required for the climate data considered.

Figure 2. ASHP heating COP vs. outdoor temperature and load fraction. Based on NEEP (2018), units ≥ 4 ton (14 kW-th [48 000 Btu/h]). Blue line from Eq. (1).

ASHP performance tends to improve at lower part-loading. We considered modeling this effect using part-load data from (NEEP 2018); however, this approach gave seasonal COP values that were much higher than those found in recent field tests – on the order of 4.5-4.7 vs. less than 3 (Korn et al. 2016). In light of this discrepancy, we ultimately based the COP analysis on maximum capacity performance.

To apply the ASHP models, we estimated the total building heating loads from the baseline simulation's gas heating consumption and heating system efficiency (typ. 80%). Next, we sized the ASHP system to meet the maximum heating load and applied the COP model to

estimate the 15-minute ASHP electric loads for the entire year. Adding the ASHP loads to the building electric loads gives the new building electric load profile.

Secondary advantages of ASHP were not modeled. Variable refrigerant volume/flow systems, for instance, could reduce the need for simultaneous heating and cooling by allowing improved zoning and refrigerant distribution. Fan energy could also be reduced relative to air-based systems, as it takes less energy to circulate refrigerants compared with large volumes of air. Such details are building- and case-specific and were therefore not included in this top-level analysis. Both factors would tend to improve the favorability of ASHP systems.

While more sophisticated and potentially more accurate approaches exist for modeling ASHP performance, these are more appropriate for specific building design simulation. The inherent variability in performance among different equipment models, for instance, would tend to outweigh any potential accuracy improvements.

Battery Energy Storage System Model

Since switching to electric ASHP heating tends to increase facility peaks loads during heating months, an onsite energy storage system (ESS) was evaluated for its potential to mitigate peak loads using the following idealized modeling assumptions:

1. Storage capacity is sized to meet *half the facility annual peak load (15-min.) for four hours.*
2. Roundtrip energy conversion efficiency is 85%.
3. ESS controls minimize monthly on-peak demand (ideal case, perfect knowledge).
4. The battery recharges completely once per day during off-peak hours only.

For each building, the ESS model was applied to the simulated loads for the entire year (8760 hours), yielding a new 15-minute electric load profile with lower monthly peaks and slightly higher total electricity consumption.

Peak demand reduction potentials depend on ESS capacity relative to building peak load. We sized the ESS for 50% of the 15-minute peak demand for all three building types and assumed a four-hour battery capacity (MassCEC and Mass DOER 2016). That is, a facility with a 15-min. peak demand of 400 kW would size the ESS for 200 kW and 800 kWh.

To control the ESS, we first assessed each day of the year to find the lowest possible on-peak load by discharging the battery fully during the peak-demand period. Next, for each month, we found the limiting day – that with the highest peak after the optimal battery strategy has been applied. Finally, this new limiting peak was used as the new demand threshold to which all days in the month are controlled. This strategy maximizes peak reduction, while minimizing reliance on the battery, therefore avoiding unnecessary costs and penalties associated with charging and discharging losses.

Energy Cost

Three electricity pricing scenarios – designed to represent low, medium, and high monthly demand charges (\$10,

\$20, and \$40/kWp) – were chosen to represent the range of conditions in MA for 2018. While actual on-peak times vary by provider, and in some cases by season, we modeled on-peak hours as 8 A.M. to 9 P.M. on weekdays.

Energy consumption components were modeled using fixed, representative prices – \$100/MWh for electricity and \$1/therm for natural gas (EIA 2018).

Effective electricity prices in \$/MWh resulting from this analysis ranged from 66-91 (Low rate), 131-182 (Med), and 163-265 (High). For comparison, MA, at 159, had the fourth highest average commercial retail electricity price in the U.S. – about 50% higher than the national average of \$107/MWh (for 2017, EIA 2019).

Many regions, including MA, offer competitive energy supply, giving commercial customers access to a range of supply rates, some with variable time-of-year pricing. Other, more complex rate structures could be evaluated readily using the simulated energy and peak data.

Carbon Intensity

To achieve significant GHG reductions through space heat electrification, the CO₂ intensity of the electric grid must be favorably low relative to space heating fuels. Approximate emissions (kg CO₂/MWh) associated with directly burning fuels for heat are 175 for natural gas, 252 for oil, and 318 for coal (EIA 2016). Electric emission intensities vary more strongly among and within countries and change over time, Figure 3.

From 2001 to 2017, the average CO₂ intensity of the U.S. grid fell by 30%, driven due to increased natural gas and wind production, with the largest reductions (58%) occurring in the Northeast (Schivley et al. 2018). If this trend continues, electrified space heating would become even more effective at reducing carbon emissions.

Figure 3. Grid CO₂ intensity of the ten highest electricity-producing countries.

Results

Energy Impact

Simulated load profiles for peak winter and summer weeks, Figure 4, show the main effects of ASHP heating and battery storage. Electric loads increased most significantly during occupied hours, when ventilation contributed most to heating loads.

Winter electric peaks increased greatly with ASHP heating, more than doubling for the retail and school buildings. Annual site electricity consumption also increased by 13, 26, and 28 percent for the Office, Retail, and School, respectively. Summer peaks stayed the same with ASHP, since we did not model cooling system replacement. Adding ESS, however, did significantly reduce the summer peaks.

Battery storage, sized to meet half the peak annual load for four hours, was able to mitigate most of the new peak in the Office, but only part for Retail and School. The storage system also increased annual electricity consumption, but only marginally (about 2%), due to roundtrip conversion losses.

Figure 4. Electric load profiles for peak weeks.

Table 2. Simulated electric and gas consumption.

BL = Baseline, HP = Heat Pump, ES = HP + Energy Storage

Office (5 000 m ²)									
	Peak (kW)			Use (MWh-e)			Gas (MWh-th)		
	BL	HP	ES	BL	HP	ES	BL	HP	ES
Jan	129	216	130	48	70	70	76	1	1
Feb	129	178	105	43	58	59	56	1	1
Mar	141	149	86	49	60	61	43	1	1
Apr	162	162	103	45	51	51	25	1	1
May	165	165	108	50	51	52	7	1	1
Jun	197	197	132	55	55	56	2	1	1
Jul	197	197	135	61	61	62	1	1	1
Aug	196	196	129	63	63	64	1	1	1
Sep	177	177	112	53	53	54	1	1	1
Oct	148	148	95	49	51	52	14	1	1
Nov	141	172	108	47	56	56	37	1	1
Dec	129	170	102	47	61	62	56	1	1
Max.	197	216	135	-	-	-	-	-	-
Sum.	-	-	-	609	690	699	320	10	10
Retail (2 300 m ²)									
	Peak (kW)			Use (MWh-e)			Gas (MWh-th)		
	BL	HP	ES	BL	HP	ES	BL	HP	ES
Jan	66	141	92	27	49	49	76	0	0
Feb	65	112	70	24	39	40	58	0	0
Mar	65	90	53	26	37	38	46	0	0
Apr	77	81	44	24	30	31	27	0	0
May	78	78	39	25	26	27	8	0	0
Jun	93	93	49	26	26	27	1	0	0
Jul	94	94	58	30	30	30	0	0	0
Aug	93	93	49	29	29	30	0	0	0
Sep	83	83	38	25	25	26	1	0	0
Oct	65	74	39	26	28	29	14	0	0
Nov	65	105	67	25	34	34	36	0	0
Dec	66	106	64	26	40	41	54	0	0
Max.	94	141	92	-	-	-	-	-	-
Sum.	-	-	-	313	395	403	321	0	0
School (19 600 m ²)									
	Peak (kW)			Use (MWh-e)			Gas (MWh-th)		
	BL	HP	ES	BL	HP	ES	BL	HP	ES
Jan	453	1631	944	186	368	369	624	23	23
Feb	453	1225	701	167	291	295	469	21	21
Mar	615	903	437	194	276	284	360	25	25
Apr	867	867	454	177	215	219	189	21	21
May	805	805	404	195	208	212	82	22	22
Jun	1097	1097	617	231	235	238	38	18	18
Jul	862	862	355	189	189	194	10	10	10
Aug	869	869	355	189	189	195	12	11	11
Sep	911	911	422	205	207	213	26	16	16
Oct	682	682	299	183	206	212	129	20	20
Nov	495	1077	619	180	245	249	283	21	21
Dec	462	1057	553	181	285	291	422	21	21
Max.	1097	1631	944	-	-	-	-	-	-
Sum.	-	-	-	2278	2914	2970	2646	229	229

Monthly and annual values for on-site gas and electricity consumption and demand,³ Table 2 and Figure 5, describe the impacts of the different heating concepts.

Optimal battery storage was able mitigate much of the increased winter demand with a relatively minor energy penalty. In addition, battery storage had considerable year-round benefits, reducing peak loads and associated costs during all months.

Figure 5. Simulated monthly peak electric demand, electricity and gas consumption per floor area.

Carbon Dioxide Emissions

The amount of CO₂ emissions that could be avoided by switching from direct fossil fuel heating to electric heating depends on the carbon intensity of the grid and on the fuels used for on-site heating. Since these values can vary strongly by region and over time, as in Figure 3, we present results first for the specific MA example, Table 3, and then in more general terms.

Natural gas heating in the baseline (for Office, Retail, and School, respectively) represented 34, 51, and 54 percent of total site energy use, and 19, 32, and 35 percent of total building carbon emissions.

Switching to ASHP led to carbon reductions of about 44% of baseline heating-related emissions based on the carbon intensity of today's MA grid. Adding energy storage gives slightly lower carbon reductions – about 37-39% – due to roundtrip efficiency losses.

For current U.S. grid and natural gas heating fuel values, heating-related CO₂ reductions were somewhat lower, at 29-31% (22-24% with storage). Fuel oil heating, which produces about 252 kg CO₂/MWh-th, yields more favorable heating reductions (up to 64% in the MA case).

³ Demand was based on the max. 15-minute power draw on weekdays (9AM-6PM Jun-Sept., 8AM-9PM Oct-May.)

Gas consumption is shown in kWh-thermal to facilitate comparisons (1 therm = 29.3 kWh-th).

To extend these results more generally, we define the electric grid-to-heating-fuel CO₂ intensity ratio, R , as

$$R_{CO2} = I_{electric-grid} / I_{heating-fuel} \quad (2)$$

where $I_{electric-grid}$ is the grid's intensity (kg-CO₂/MWh) and $I_{heating-fuel}$ is that of the baseline heating fuel.

The average CO₂ intensity of the U.S. electric grid was 473 kg/MWh-e. Natural gas, meanwhile, had an average intensity of 175 kg/MWh-th (EIA 2018). These values yield an intensity ratio $R_{CO2} = 473/175 = 2.7$. Similarly, for MA, $R_{CO2} = 339/156 = 2.2$. Likewise, a 100% renewable electric grid would yield $R_{CO2} = 0$. This ratio makes it possible to evaluate CO₂ reductions under alternate or hypothetical grid and heating fuel scenarios.⁴

As a function of R_{CO2} , percent reductions in space heating were similar for the three buildings considered, Figure 6, with energy storage resulting in slightly lower GHG reductions. For the cases we considered, the CO₂ breakeven points occurred when R_{CO2} was approximately 3.5 for the ASHP system and 3.8 for the ASHP with battery storage.

In reality, the situation is more nuanced, since the electric grid CO₂ intensity varies as a function of time of year and time of day. On-peak consumption currently tends to be more intensive, and future grid intensities are likely to change over time. Higher renewable adoption, for instance, would tend to reduce intensities. Scenario-based analysis based on expected intensities and renewable production could be applied to annual load profiles to evaluate such tradeoffs.

Figure 6. Percent reduction in space-heating-related CO₂ emissions achieved by switching to ASHP vs. electric-grid-to-heating-fuel CO₂ intensity ratio:

$$R_{CO2} = I_{electric-grid} / I_{heating-fuel}.$$

⁴ In all baseline (fossil-fuel heating) examples, we assumed an 80% fuel-to-heat conversion efficiency. Values could likewise be adjusted based on efficiency ratios.

Table 3. Annual CO₂ emissions and reductions, based on Massachusetts emissions factors.

	Site (MWh)		(mt CO ₂)		Δ (x-BL)	
	Elec.	Gas TOT	Elec.	Gas TOT	Abs.	%
Office						
Baseline	609	320	929	206 50	256	- -
Heat Pump	690	10	700	234 2	235	-21 8%
HP + Storage	699	10	709	237 2	239	-18 7%
Retail						
Baseline	313	321	634	106 50	156	- -
Heat Pump	395	0	395	134 0	134	-22 14%
HP + Storage	403	0	403	137 0	137	-20 12%
School						
Baseline	2278	2646	4924	772 412	1184	- -
Heat Pump	2914	229	3143	988 36	1024	-161 14%
HP + Storage	2970	229	3199	1007 36	1043	-142 12%
MA factors: Elec. Grid 339 kg CO ₂ /MWh-e						
Nat. Gas 156 kg CO ₂ /MWh-th						

Cost Impact

Energy cost tradeoffs are shown for three electric rate scenarios in Table 4 and Figure 7. Baseline heating energy costs of \$2.2-4.8/m² accounted for 7-31 percent of total facility energy consumption, depending on building type (retail and school similar, about twice that of office) and electric rate structure.

Switching to heat pumps increased the total site energy consumption by up to 18 percent for the medium and high rate structures (2-10% at \$20/kWp and 4-18% at \$40/kWp). For the low rate (\$10/kWp), however, savings of 6-12% were observed for all buildings. Cheaper electricity and more expensive heating fuels tend to make space heat electrification more financially attractive.

Figure 7. Energy costs per floor area (\$/m²).

Table 4. Whole building annual energy cost components in \$(000) by scenario.

BL = Baseline, HP = Heat Pump, ES = HP + Energy Storage

Building \ Component	Electric Demand Rate \ Scenario								
	Hi: \$40/kWp			Med: \$20/kWp			Low: \$10/kWp		
	BL	HP	ES	BL	HP	ES	BL	HP	ES
Office									
Elec. Demand	76	85	54	38	43	27	19	21	13
Elec. Supply	61	69	70	61	69	70	30	35	35
Natural Gas	11	0	0	11	0	0	11	0	0
Total	148	154	124	110	112	97	60	56	49
Retail									
Elec. Demand	36	46	26	18	23	13	9	12	7
Elec. Supply	31	39	40	31	39	40	16	20	20
Natural Gas	11	0	0	11	0	0	11	0	0
Total	79	86	66	60	62	53	36	31	27
School									
Elec. Demand	343	480	246	171	240	123	86	120	62
Elec. Supply	228	291	297	228	291	297	114	146	148
Natural Gas	90	8	8	90	8	8	90	8	8
Total	661	779	551	490	539	428	290	273	218

Adding a large battery energy storage system led to significant energy cost savings in all three scenarios, with the highest benefits in the high demand scenario. Lifecycle cost-effectiveness depends strongly on installed costs, which for battery storage system can vary widely. Installed costs for long-duration ESS like those considered here currently range from about \$1500-4000 per MW or \$300-800 per kWh (DOE 2018). The market is evolving quickly and prices are expected to decline.

A forward-looking optimistic battery storage scenario, Table 5, shows simple payback periods (SPP) of as low as 3.6 years under the high rate case and as high as 17 years under the low rate case. This assumes \$250/kWh installed cost with no ongoing operational costs or degradation.⁵ Practical constraints related to capital budgets or desired SPP are likely to influence actual system designs, tending to prefer those with lower first costs and short payback.

Table 5. Battery storage system cost, savings, and simple payback period, relative to ASHP heating case.

	Battery Storage		Inst. \$(000)	Savings \$(000)/yr			SPP (years)		
	Cap. kW	Cap. kWh		H	M	L	H	M	L
Office	108	430	108	30	15	7	3.6	7.3	15
Retail	76	310	78	19	9	4	4.1	8.7	17
School	834	3340	835	228	111	56	3.7	7.5	15

Note: Elec. Demand: H (\$40 per kWp), M (\$20), L (\$10).
Assumes storage installed cost of \$250/kWh.

While not a focus of this study, future work should consider the lifecycle cost tradeoffs of commercial ASHP. Since the market adoption of ASHP in commercial

buildings in New England has been modest to date, more data are required to accurately characterize real-world average cost and lifecycle and performance. Results from this study could complement such lifecycle assessments.

Conclusion

Space heat electrification has the potential to be an important component of GHG reduction policy. Air-source heat pumps, in particular, offer a compelling path for strategic electrification for commercial buildings, with modest impacts on overall customer utility bills.

In Massachusetts, switching in 2019 from natural gas heat to an efficient ASHP could:

- Reduce space heating-related carbon emissions by up to 44%
- Increase winter peak loads by a factor of 2 or more (on par with summer peaks)
- Increase total site energy costs by 4-18% (high demand rate) or decrease them by 5-7% (low)
- Increase heating-related energy costs by 55-130% (high demand rate), 17-55% (med), or decrease them by 12-40% (low).

Supplemental battery storage systems that are operated to minimize peak loads and sized to meet 50% of peak load for four hours could:

- Offset most or all of the winter peak increase while reducing peak load year-round
- Reduce total site energy costs relative to the heat-pump case by 20 to 29% (high demand rate) and 13 to 20% (low)
- Increase annual site kWh usage by about 2%
- Simple payback in 4-17+ years depending on installed costs and electric demand rates

Carbon reductions vary linearly with the ratio of carbon intensities of the grid to that of the baseline heating fuel.

Impacts on customer utility bills are highly sensitive to rates. Lower electric rates and higher heating fuel costs make ASHP more favorable on their own. Rates with high demand charges make battery storage systems more favorable.

Recommended topics for further study include:

1. Field measurement of real-world energy and capacity performance of commercial building ASHP vs. outdoor temperature and loading
2. GHG impact analysis based on scenarios with time-variable grid carbon intensity
3. Incremental and lifecycle cost analysis of using ASHP for new construction, major renovation, and retrofit replacement cases
4. Consider other energy storage system sizing options, control strategies, and cost models
5. Evaluate future energy rate structures to reflect scenarios with high adoption of renewables

⁵ In practice, battery capacity decreases over time due to cycling and temperature-related aging. Components would likely

require a major overhaul or replacement approximately every ten years.

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