DUCT SEALING: UNLOCKING ADDITIONAL ELECTRIFICATION EFFICIENCY

MASSACHUSETTES CASE STUDY

APRIL 2026

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2. EXECUTIVE SUMMARY

This paper examines a critical but often under-addressed determinant of electrification performance in existing Massachusetts homes: the interaction between heat pumps and legacy duct systems. While electrification strategies frequently emphasize equipment efficiency and cold-weather capability, real-world outcomes are governed by whether heat pumps are integrated into distribution systems capable of delivering the required airflow.

Legacy duct systems in homes built before 2006 are often highly leaky. Aeroseal data from more than 1,500 existing homes in Massachusetts indicates an average leakage rate of 12 CFM per 100 square feet of conditioned floor area; three times the energy code requirement for new duct systems, which modern equipment is designed to serve. After sealing with Aeroseal, leakage in these legacy duct systems was reduced to an average of 1.5 CFM per 100 square feet of conditioned floor area.

Using a transparent, temperature-bin–based modeling framework grounded in manufacturer performance data and established building science methods, this study evaluates how duct sealing alters electrification outcomes for two representative pathways: (1) whole-home electrification and (2) partial electrification using dual-fuel (heat pump plus gas backup) systems. Results are presented across four metrics relevant to utility and program decision-making: annual site energy consumption, annual operating cost, carbon emissions, and winter peak electric demand.

Whole-home electrification

- ≈**22%/yr** reduction in site energy consumption
- ≈**$541/yr** reduction in heating and cooling operating costs
- ≈**722 kg/yr** of CO_2e emissions reduction
- ≈**3.4 kW** reduction in winter peak electric demand

Partial electrification (dual fuel)

- ≈**59%/yr** reduction in site energy consumption
- ≈**$402/yr** reduction in heating and cooling operating costs
- ≈**722 kg/yr** of CO_2e emissions reduction
- A substantial reduction in gas furnace runtime

From a grid perspective, the findings are particularly consequential. Winter electrification peaks are shown to be sustained over many hours or days, not brief spikes. By reducing both the magnitude and duration of supplemental resistance heat operation, duct sealing functions as a peak shaving and peak shortening measure.

Taken together, the results support a clear conclusion: in Massachusetts, heating electrification succeeds or fails at the air distribution system. For utilities, regulators, and program administrators, duct sealing should be treated as foundational electrification infrastructure.

3. THE HIDDEN CONSTRAINT: DUCT SYSTEMS LIMIT HEAT PUMP PERFORMANCE

Electrification strategies often focus on the superiority of individual components, most notably, high efficiency cold climate heat pumps, under the implicit assumption that improved equipment will translate directly into improved system performance. In existing Massachusetts homes, this assumption frequently fails. The limiting factor is not the heat pump itself, but whether the heat pump is integrated into a distribution system capable of supporting its operation.

Most ducted homes rely on duct systems that were designed decades ago for fossil fuel furnaces and central air conditioners. These systems were optimized for high supply air temperatures in heating and moderate airflow in cooling. When a cold climate heat pump is introduced without addressing the duct system, leakage and airflow constraints often become the dominant determinants of performance, capping delivered heating capacity, degrading efficiency, and increasing reliance on electric resistance backup during cold weather.

3.1 Duct leakage compounds airflow constraints

In leaky systems, a significant fraction of supply air never reaches the conditioned space, and return leaks pull unconditioned air into the system. From the heat pump's perspective, leakage effectively reduces usable airflow while increasing the load the system must serve.

The combined effect is that the heat pump reaches its airflow limit at a lower compressor output than expected. Even if the equipment is nominally sized to meet the design heating load, the system may be unable to deliver that capacity through the ductwork during cold conditions.

3.2 Consequences for capacity, efficiency, and supplemental heat

When a heat pump is constrained by duct airflow, several outcomes follow:

- **Delivered heating capacity is capped below the equipment rating.**
  The heat pump cannot increase output beyond the airflow limit, even if outdoor conditions or indoor load would otherwise require it.
- **Operating efficiency is reduced.**
  Heat pump efficiency depends on maintaining appropriate airflow across the indoor coil. Restricted airflow leads to higher temperature lift, increased electrical input, and degraded coefficient of performance (COP).
- **Supplemental resistance heat is engaged more frequently.**
  When the constrained heat pump output cannot meet the building load, electric resistance heaters are activated to maintain comfort. These heaters operate at a COP of approximately 1, dramatically increasing energy use and winter peak demand. Even

modest reductions in resistance heat operation can dominate winter peak outcomes since resistance heating draws several times more power than heat pump operation per unit of delivered heat.

Importantly, this behavior is not limited to extreme design conditions. In leaky or airflow constrained systems, resistance heat can dominate energy use during a relatively large fraction of winter hours in Massachusetts climates.

3.3 Why upsizing the heat pump does not solve the problem

A common response to concerns about cold weather performance is to install a larger heat pump. However, when duct airflow is the limiting factor, upsizing equipment often fails to deliver the intended benefit.

Larger heat pumps typically require even higher airflow at full output. If the duct system cannot supply that airflow, the additional rated capacity remains inaccessible. In some cases, larger equipment may worsen performance by increasing reliance on resistance heat and introducing part load inefficiencies during shoulder seasons.

In addition to failing to resolve airflow constraints, upsizing a heat pump to meet heating demand can introduce a second, often overlooked issue: a mismatch between heating and cooling capacity. In existing Massachusetts homes, cooling loads are typically much smaller than heating loads. Installing a 5-ton heat pump, whether single stage, two stage, or variable-speed, to compensate for winter delivery losses can result in cooling oversizing, increasing minimum cooling capacity and airflow requirements. Even for variable-speed systems, this can degrade dehumidification performance, increase blower energy use, and introduce comfort and efficiency penalties during cooling operation. These risks arise not from equipment quality, but from system imbalance.

3.4 Implications for electrification planning in Massachusetts

Because Massachusetts has a cold winter climate, high electrification ambitions, and a housing stock dominated by existing ducted systems, these interactions have outsized importance. Analyses that ignore airflow constraints and duct leakage risk overstating heat pump performance, understating winter peak demand, and mischaracterizing cost-effectiveness.

The following sections quantify these effects using a transparent, physically grounded modeling framework that explicitly represents the interaction between heat pump performance, airflow constraints, and duct sealing. The results show that addressing the distribution system is often the determining factor in whether heating electrification delivers its promised benefits at scale.

4. SCENARIO RESULTS: WHOLE-HOME ELECTRIFICATION

This section presents results for Scenario 1: Whole Home Electrification, representing a typical Massachusetts single family home transitioning from a conventional gas furnace and central air conditioner to a ducted electric heat pump system. Results are shown both before and after duct sealing to isolate the incremental impact of improving the distribution system.

Consistent with utility and state program evaluation needs, results are reported using four primary metrics: annual site energy consumption, annual operating cost, annual carbon dioxide equivalent (CO_2e) emissions, and winter peak electric demand.

4.1 Scenario definition and modeled cases

- **Baseline system (existing conditions).**
  The baseline configuration is an 80% AFUE natural gas furnace (80 kBtu/h) paired with a SEER 14, 3-ton central air conditioner. This configuration represents a common installed system in existing Massachusetts homes and serves as the reference point for all savings calculations.

- **Whole home electrification options.**
  The electrification cases evaluate ducted heat pump replacements spanning six units across three product classes, with each unit modeled under pre-sealing and post-sealing duct conditions. This range allows the analysis to capture both premium and more typical equipment options encountered in utility incentive programs.
    - Carrier 27VNA1 series – best in class variable speed cold climate heat pumps
    - Carrier 27VNA3 series – premium cold climate heat pumps (multiple capacities)
    - Carrier 27TPA8 series – representative two stage heat pumps commonly installed

Table 1: Scenario 1 modeled cases and assumptions

Baseline HVAC System	Heating: AFUE80 gas furnace 80 kBtu/hr, Cooling: 14 SEER central AC 3 ton.
Heat Pump Options	1. Carrier 27VNA1 - Infinity Variable-Speed Ultimate Cold Climate Heat Pump, 21.2 SEER2, 12.5 HSPF2, 4.5 tons. 2. Carrier 27VNA3 - Infinity Variable-Speed Heat Pump, 23 SEER2, 10.5 HSPF2, 3 to 5 tons. 3. Carrier 27TPA8 - Performance 18 Two Stage Heat Pump, 18.5 SEER2, 8.5 HSPF2, 3 to 5 tons.
Duct Configuration	Sheet-metal central ductwork located in a basement with insulated ceilings.
House Type	Single family, 2000 sq. ft., two-story, IECC2006 compliant.
Location	MA – Boston.

4.2 Headline outcomes for whole-home electrification

Across all modeled whole home electrification cases, duct sealing consistently functions as enabling infrastructure, improving outcomes across every metric evaluated. A representative, program relevant outcome highlighted in this analysis includes:

- Approximately **22%** reduction in annual site energy consumption, about 6 MMBtu/year.
- Approximately **$541** per year reduction in annual heating and cooling operating costs.
- Approximately **722 kg** of CO_2e emissions reduction per home per year.
- Approximately **3.4 kW** reduction in winter peak electric demand per home.

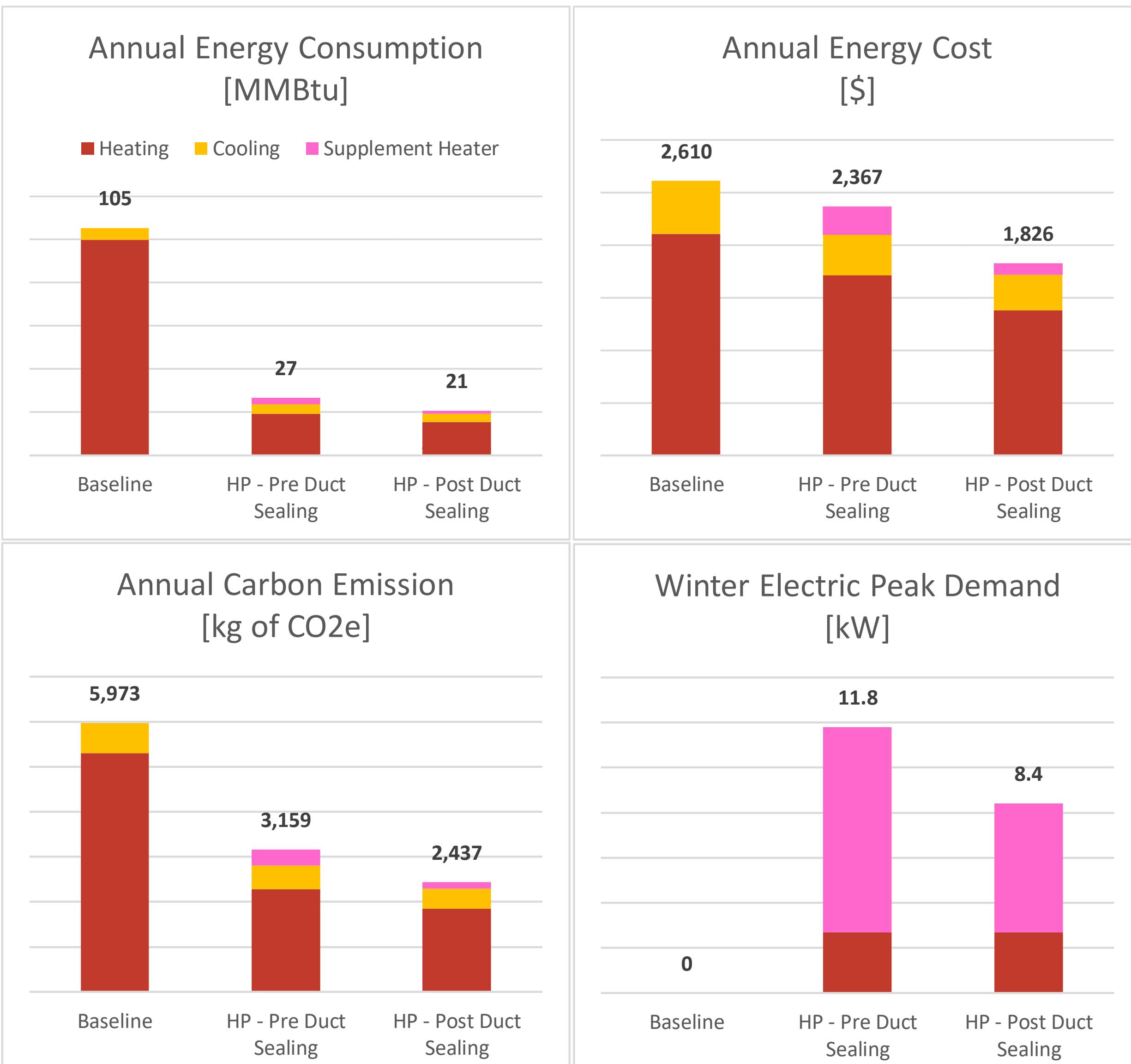

Figure 1: Duct sealing impact in gas to electric heat pump (HP) switch scenario on annual energy consumption, cost, carbon emissions, and winter electric peak demand

5. SCENARIO RESULTS: PARTIAL ELECTRIFICATION (DUAL FUEL)

This section presents results for Scenario 2: Partial Home Electrification, in which a cold climate heat pump is paired with an existing natural gas furnace used as backup heating. This "dual-fuel" configuration is easily deployed in Massachusetts as a transitional electrification pathway, allowing heat pumps to meet a substantial share of heating demand while retaining a fossil backup for the coldest conditions.

The analysis evaluates how duct sealing alters the operating balance between the heat pump and the backup furnace, with particular focus on energy use, operating cost, carbon emissions, and the backup switch temperature, a key determinant of both customer outcomes and system impacts.

5.1 Scenario definition and operating logic

Baseline (existing system).
The baseline is the same as in Section 4: an 80% AFUE gas furnace (80 kBtu/h) with SEER 14, 3-ton central AC, representing a common existing configuration in Massachusetts homes.

Partial electrification configuration.
In the dual fuel scenario, a ducted air source heat pump provides heating whenever it can meet the building load, with the existing gas furnace serving as backup. The backup furnace is assumed to fully meet the heating load when the heat pump is unable to do so due to capacity or delivery constraints.

Control assumption.
In the partial electrification (dual fuel) scenario, the control strategy follows a reliability-based "full-swap" rule: the heat pump operates whenever it can meet the building heating load with a defined safety margin (to maintain indoor comfort), and the gas furnace serves as backup when the heat pump cannot meet the load under that margin. Under this rule, the backup switch temperature is a derived outcome based on the intersection of (1) building load and (2) airflow-constrained heat pump capacity, evaluated with a comfort/reliability tolerance.

Table 2: Scenario 2 modeled cases and assumptions

Baseline HVAC System	Heating: AFUE80 gas furnace 80 kBtu/hr, Cooling: 14 SEER central AC 3 ton.
Heat Pump Options	Carrier 27VNA3 – Infinity Variable-Speed Heat Pump, 23 SEER2, 10.5 HSPF2, 3 tons.
Backup Furnace	AFUE80 gas furnace 80 kBtu/hr

Default Backup Switch Temperature	40 °F [1]
Duct Configuration	Sheet-metal central ductwork located in a basement with insulated ceilings.
House Type	Single family, 2000 sq. ft., two-story, IECC2006 compliant.
Location	MA – Boston.

5.2 Headline outcomes for partial electrification

For the modeled Massachusetts home, duct sealing materially improves the performance of partial electrification across all evaluated metrics. These results demonstrate that duct sealing enhances the effectiveness and economics of hybrid strategies:

- Approximately **59%** reduction in annual site energy consumption.
- Approximately **$402** per year reduction in annual heating and cooling operating costs.
- Approximately **722 kg** of CO_2e emissions reduction per home per year.
- A substantial reduction in gas furnace runtime, driven by a lower backup switch temperature.

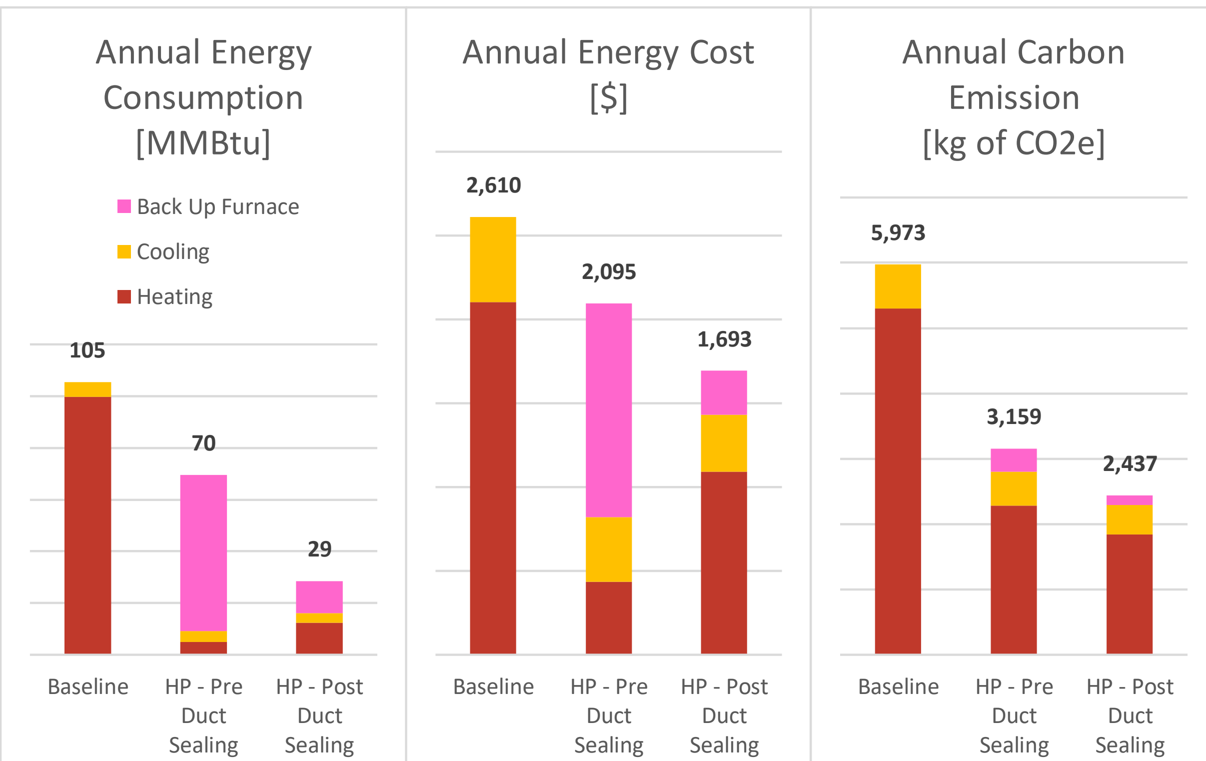

Figure 2: Duct sealing impact on gas to dual-fuel system switch scenario on annual energy consumption, cost, carbon emissions

[1] Switchover Guide – Ducted Dual-Fuel Air Source Heat Pumps: https://goelectric.comed.com/wp-content/uploads/2024/08/001425_ComEd_SwitchoverGuide_WEB_ADA.pdf

5.3 Backup switch temperature: a critical system outcome

One of the most important results of the partial electrification analysis is the change in backup switch temperature enabled by duct sealing.

In the pre-sealing case, the gas furnace begins operating at 40°F; below which, airflow constraints prevent the heat pump from delivering sufficient capacity. After duct sealing, the backup switch temperature drops to approximately 27°F, while maintaining indoor thermal comfort with a 5 °F safety margin.

This 13°F reduction in switch temperature has outsized implications:

- A much larger fraction of annual heating hours is served by the heat pump
- Gas consumption is substantially reduced
- Peak gas and electric system impacts are both moderated
- Customer experience improves through more consistent heat pump operation

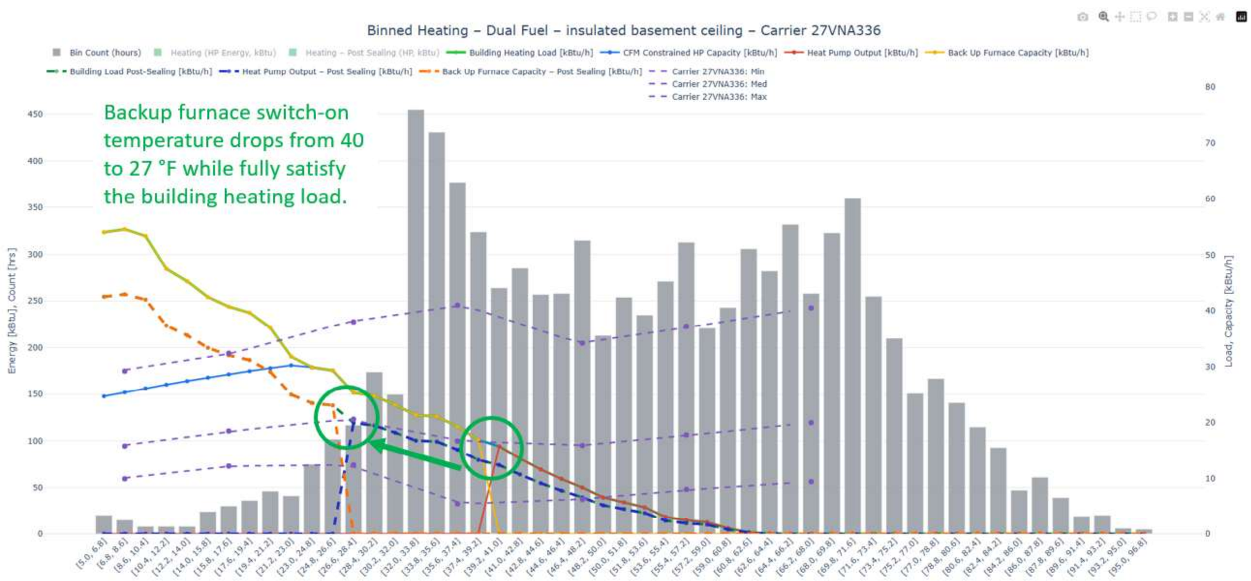

Figure 3: Binned or timeseries plot showing backup switch temperature shift from ~40°F to ~27°F.

6. CONCLUSION: DUCT SEALING AS ELECTRIFICATION INFRASTRUCTURE

The results presented in Sections 4 and 5 demonstrate that duct sealing is not a peripheral efficiency measure, but a foundational enabler of cost effective, scalable heating electrification in existing Massachusetts homes. Across both whole home and partial electrification scenarios, a consistent conclusion emerges – outcomes are governed by system integration, not component efficiency alone.

By integrating duct sealing as enabling infrastructure in heat pump incentive workflows, utilities can capture additional savings, strengthen hybrid electrification as a transition strategy, and lower the likelihood of negative customer experiences that can deter broader adoption.

APPENDIX A: AIR FLOW CONSTRAINED HEAT PUMP PERFORMANCE MODEL

A.1 Purpose and modeling challenge

This appendix documents the airflow-constrained heat pump performance model used in this analysis and explains why a conventional regression-only approach is insufficient for representing heat pump operation in existing ducted homes.

Manufacturer performance data describe how heating capacity, indoor airflow, and electric input vary with outdoor temperature and compressor modulation. However, these data implicitly assume that required airflow can always be delivered. In existing homes, this assumption often fails. Legacy duct systems impose a practical airflow ceiling that limits the amount of heat that can be delivered, regardless of nominal equipment capacity.

The central modeling challenge addressed here is therefore not interpolation of manufacturer data, but enforcement of a physical airflow constraint that binds system performance under cold-weather conditions. The model is explicitly structured to separate these two tasks.

A.2 Why a single-step regression is not sufficient

A natural modeling instinct is to fit a single regression—linear, bi-quadratic, or higher-order, that maps outdoor temperature directly to delivered capacity and power. However, such regressions cannot reliably enforce airflow constraints, for three reasons:

Airflow is an independent limiting variable.

Heating capacity, airflow, and power are jointly determined by compressor operation, but airflow becomes a binding constraint imposed by the duct system, not the heat pump itself. A single regression surface cannot distinguish between equipment limits and delivery limits.

Polynomial regressions smooth through constraint boundaries.

Even higher-order regressions tend to interpolate smoothly across operating regions where, in reality, performance flattens abruptly once airflow limits are reached. This leads to overstated delivered capacity and understated supplemental heat operation.

Constraint violations are silent.

A direct regression of capacity versus temperature provides no explicit signal that required airflow has exceeded what the duct system can support. The model may appear numerically stable while violating physical feasibility.

For these reasons, the analysis deliberately avoids embedding airflow constraints inside a single regression surface. Instead, it adopts a two-step solution approach that mirrors how real systems operate.

A.3 Heat Pump Manufacturer Performance Representation, Building Load, and Operating Logic

Manufacturer heating performance tables are first reshaped into a unified dataset indexed by outdoor temperature and compressor operating state. To simplify interpretation and maintain consistency across products, indoor thermostat dry bulb temperature is fixed at 70 °F for heating and 75 °F for cooling. For each operating point, the performance data include:

- total heating capacity (kBtu/h),
- required indoor airflow (scfm),
- total system electric input (EIR) (kW).

These data describe how capacity, airflow, and power vary jointly as the heat pump modulates in response to load and ambient conditions.

Normalized modulation coordinate M

To represent variable heat pump operation in a continuous and physically realistic way, compressor operation is expressed using a normalized modulation coordinate, M, which spans both off and on states:

- $M = 0$ represents the off condition, with no heat pump operation.
- For active operation, M is bounded below by the minimum compressor modulation capability documented in manufacturer product data. This lower bound corresponds to the minimum achievable heating capacity at a given outdoor temperature and typically reflects inverter limits on the order of 20 – 30% of rated capacity, depending on equipment design and operating conditions.
- $M = 1$ represents operation at the maximum available heating capacity at that outdoor temperature.

For operating points where the heat pump is on, modulation is defined as the fraction of maximum available capacity at that temperature:

This formulation ensures that modulation respects manufacturer documented minimum and maximum capacity limits while allowing continuous interpolation of capacity, airflow, and power within those bounds. By explicitly separating the off state ($M = 0$) from the minimum stable operating point ($M = M_{\min}(T)$), the model avoids unphysical extrapolation below the compressor's achievable operating range and remains consistent with real heat pump control behavior.

Polynomial regression surfaces are then fit for each performance metric as functions of outdoor temperature and normalized modulation:

where y represents heating capacity, indoor airflow, or electric input. These regressions are interpolations within manufacturer data only and are not used to enforce physical limits. Regression diagnostics and plots included in this appendix document goodness of fit and demonstrate that the fitted surfaces faithfully reproduce published product performance.

Building load representation and temperature binning

Building heating demand is represented using a temperature framework rather than an hourly black-box simulation. Outdoor temperature is discretized into 1 °F-wide bins, and for each bin the model tracks:

- the number of annual hours that outdoor temperature falls within the bin, and
- the mean building heating load over those hours, expressed in kBtu/h.

This approach preserves the strong dependence of heating demand on outdoor temperature while remaining transparent and directly interpretable. It also aligns well with utility planning practice, which commonly relies on temperature indexed demand relationships rather than minute-by-minute control simulation.

The building heating load in each bin, $Q_{\text{load}}(T_{\text{bin}})$, is treated as the average rate of heat required during the hours associated with that temperature range. Annual energy consumption is recovered by multiplying bin-level operating power or delivered heat by the corresponding number of bin hours.

Determination of operating modulation from building load

For each temperature bin, the heat pump operating point is determined by solving the modulation level M required to meet the mean building load in that bin. Specifically, the model seeks an operating point such that the interpolated heat pump heating capacity equals the bin-average load, subject to compressor modulation limits and, subsequently, duct airflow constraints.

This structure ensures that modulation is driven directly by instantaneous load intensity (kBtu/h) rather than by annual or seasonal averages. As a result, the model captures the onset of airflow-constrained operation and supplemental or backup heat engagement at the correct temperature conditions, rather than smearing these effects across the heating season.

Minimum capacity behavior and ON/OFF cycling

At mild outdoor temperatures, the bin-average building load may fall below the minimum achievable heating capacity of the heat pump at that temperature. This minimum capacity is determined by manufacturer documented compressor modulation limits and reflects the lowest stable inverter operating point.

When this condition occurs, the model does not force the heat pump to operate continuously at an unphysical modulation level. Instead, system behavior is represented using a runtime fraction (duty-cycle) approach:

- the heat pump is assumed to cycle ON at its minimum available capacity for a fraction of the bin hours,
- the runtime fraction is calculated as the ratio of the building load to the minimum heat pump capacity, and
- delivered heat and electric input are scaled accordingly.

This treatment applies even for variable speed heat pumps, reflecting the reality that inverter driven systems still have finite minimum capacities and will cycle under low-load conditions. By explicitly accounting for ON/OFF cycling at the bin level, the model avoids overstating efficiency or understating power at light loads while remaining consistent with manufacturer performance data.

Implications for airflow-constrained analysis

Expressing building load as a mean kBtu/h value within narrow (1 °F) temperature bins allows the model to clearly distinguish three physically distinct operating regimes:

1. **Cycling limited operation**, where load is below minimum capacity,

2. **Modulation limited operation**, where load is met within compressor capability, and

3. **Airflow-constrained operation**, where required indoor airflow exceeds duct system limits.

Transitions between these regimes are driven entirely by physical relationships among temperature, load, capacity, airflow, and duct constraints. As a result, resistance or backup heat engagement, winter peak electric demand, and the benefits of duct sealing emerge as mechanistic outcomes of system physics, not artifacts of regression form or control assumptions.

A.4 Electric input and backup heat logic

Electric input for the heat pump is calculated consistently with manufacturer data, using total system power surfaces. Part-load scaling is applied conservatively to reflect non-linear power behavior at reduced modulation.

In whole-home electrification scenarios, any shortfall between building load and airflow-constrained heat pump output is met with electric resistance heat (COP = 1), which dominates winter peak demand when airflow constraints bind.

In partial electrification scenarios, a full-swap dual-fuel control logic is applied. The backup switchover temperature is imposed to 40 °F [2]. Duct sealing shifts this switchover temperature to lower by reducing load and increasing usable delivered capacity.

A.5 Interpretation and role of duct sealing

Within this modeling framework, duct sealing changes outcomes not by altering heat pump technology, but by reducing the frequency and severity of airflow-constrained operation. By improving delivery effectiveness, sealing allows a greater fraction of compressor capacity to be converted into delivered heat before the airflow limit becomes binding.

The result is a qualitative change in system behavior: fewer hours in which resistance or backup heat is required, lower operating cost, and materially reduced winter peak electric demand. These effects arise directly from the enforced airflow constraint and cannot be captured by regression-only models that assume unconstrained delivery.

Regression documentation

Regression plots, residuals, and goodness-of-fit metrics are provided following this appendix to document the diligence applied in representing manufacturer performance data. These materials demonstrate that interpolation error is small relative to the system-level effects introduced by airflow constraints and support the physical conclusions drawn from the analysis.

Table 3: Heat pump performance metrics regression model form, coefficients, and goodness-of-fit (R2)

HEAT PUMP	PERFORMANCE METRICS MODEL	REGRESSION FORM	R2	COEFS	INTER CEPT
Carrier 27VNA1_heating	id_scfm	CFM = a0 + a1*T + a2*M + a3*(T*M) + a4*T^2 + a5*M^2	0.97	[3.0329770449822466, 2631.348097141509, 3.1999132357973297, -0.04138638633062409	-197.78

[2] Switchover Guide – Ducted Dual-Fuel Air Source Heat Pumps: https://goelectric.comed.com/wp-content/uploads/2024/08/001425_ComEd_SwitchoverGuide_WEB_ADA.pdf

				5, -936.7765456135813]	
Carrier 27VNA1_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T + c2*T^2) + M*(m0 + m1*T + m2*T^2)	0.97	[0.00893971414178823, -0.0008318759047875877, 1.15310917048301e-05, 37.92213938220784, 1.790904543652773, -0.024275462174491724]	0.00
Carrier 27VNA1_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.88	[0.3726165989403398, -0.008643137409807591, 0.00017799358338759988, -1.4012171651069194e-06]	0.00
Carrier 27VNA336_heating	id_scfm	CFM = a0 + a1*T + a2*M + a3*(T*M) + a4*T^2 + a5*M^2	0.99	[-1.1402639650091762, -304.32764674786847, 0.0997956275757561, 0.006046120655574504, 1044.7262926376109]	686.14
Carrier 27VNA336_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T + c2*T^2) + M*(m0 + m1*T + m2*T^2)	0.98	[-0.00040478555655053456, 3.5680265446749336e-05, -5.300029322416874e-07, 26.25423622731038, 0.4570250715919022, -0.0040449067328925375]	0.00
Carrier 27VNA336_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.90	[0.40732833294624715, -0.006330439436419268, 6.72210731642726e-05, -	0.00

				4.176910948528593e-07]	
Carrier 27VNA348_heating	id_scfm	CFM = a0 + a1*T + a2*M + a3*(T*M) + a4*T^2 + a5*M^2	0.95	[2.6380905787848925, 550.6350295546481, -2.373150695701384, -0.04727398903797922, 436.4590728390281]	532.04
Carrier 27VNA348_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T + c2*T^2) + M*(m0 + m1*T + m2*T^2)	0.98	[0.0018635700711854503, 9.443978718073933e-05, -2.7720251129423757e-06, 28.169212612922095, 0.6559157910238527, -0.0016617849465992904]	0.00
Carrier 27VNA348_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.91	[0.4221470714000368, -0.006798538910682288, 7.323291184589117e-05, -2.8985806719452403e-07]	0.00
Carrier 27VNA360_heating	id_scfm	CFM = a0 + a1*T + a2*M + a3*(T*M) + a4*T^2 + a5*M^2	0.93	[9.915048729886145, 2147.735859652153, -6.604066338969775, -0.1433375342404113, -772.3259856135564]	399.21
Carrier 27VNA360_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T + c2*T^2) + M*(m0 + m1*T + m2*T^2)	0.99	[6.803711881009211e-05, 2.0443970481883364e-07, -5.452568342417867e-09, 37.70136380645757, 1.3021967247980917, -0.01579435496858785]	0.00
Carrier 27VNA360_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.85	[0.3938562325637709, -0.0074576346933628145, 0.00015717276598630	0.00

				64, -1.3211409120230009e-06]	
Carrier 27TPA836_heating	id_scfm	CFM = a0 + a1*T + a2*M	0.99	[-0.38799353794919933, 732.4785944664069]	483.70
Carrier 27TPA836_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T) + M*(m0 + m1*T)	0.99	[0.0013648749059772746, -4.1704131737877835e-05, 0.0, 13.516377522714556, 0.545777912095005, 0.0]	0.00
Carrier 27TPA836_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.93	[0.5261910772996364, -0.009528883906239372, 0.00010322735549457018, -4.166805290623234e-07]	0.00
Carrier 27TPA848_heating	id_scfm	CFM = a0 + a1*T + a2*M	1.00	[-0.0043572537378595115, 961.8455014978626]	337.47
Carrier 27TPA848_heating	capacity_total_kbtuh_constrained	Q = CFM*(c0 + c1*T) + M*(m0 + m1*T)	1.00	[1.3447761153846198e-05, 4.8794885225275e-06, 0.0, 20.560802931113315, 0.5940795630036565, 0.0]	0.00
Carrier 27TPA848_heating	EIR_constrained	EIR = e0 + e1*T + e2*T^2 + e3*T^3	0.93	[0.49786670818366846, -0.009070981802811979, 0.00010340298423414945, -3.929017390173663e-07]	0.00

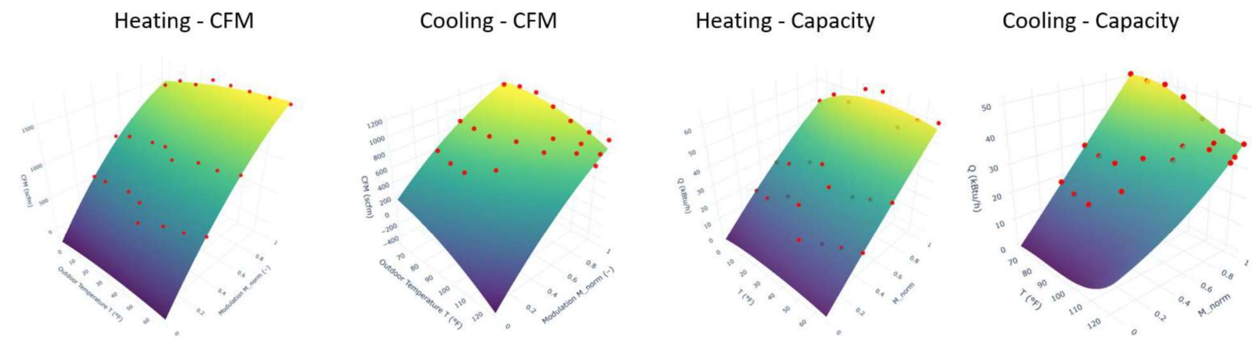

Figure 4: Carrier 27VNA1 performance regression plots

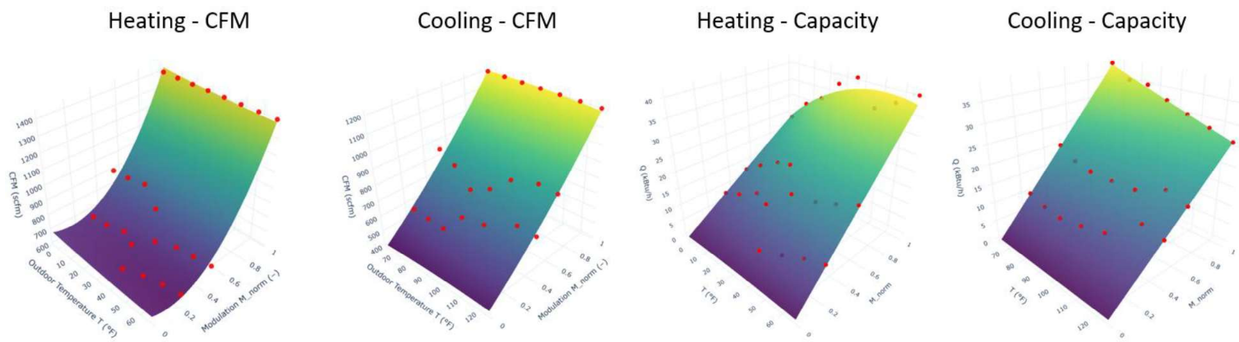

Figure 5: Carrier 27VNA336 performance regression plots

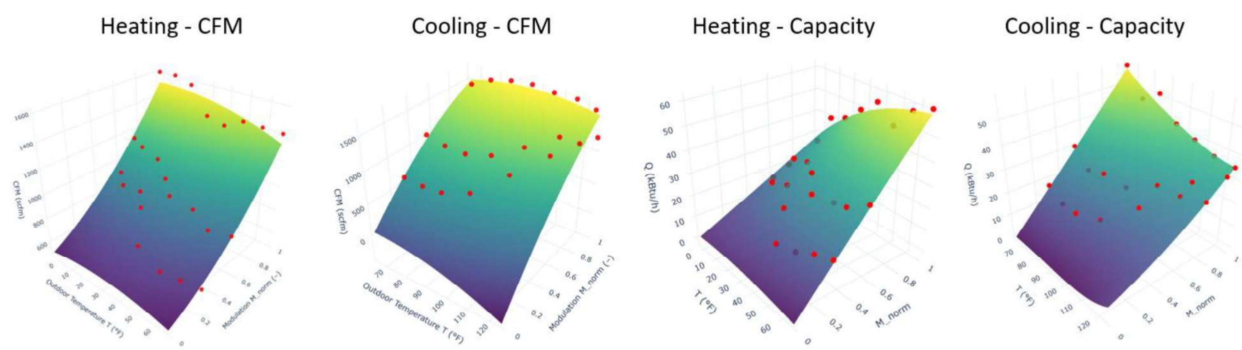

Figure 6: Carrier 27VNA348 performance regression plots

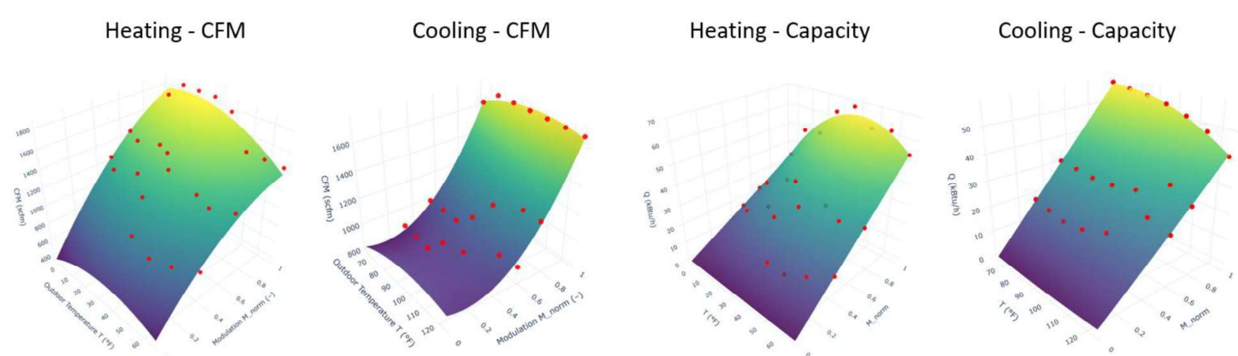

Figure 7: Carrier 27VNA360 performance regression plots

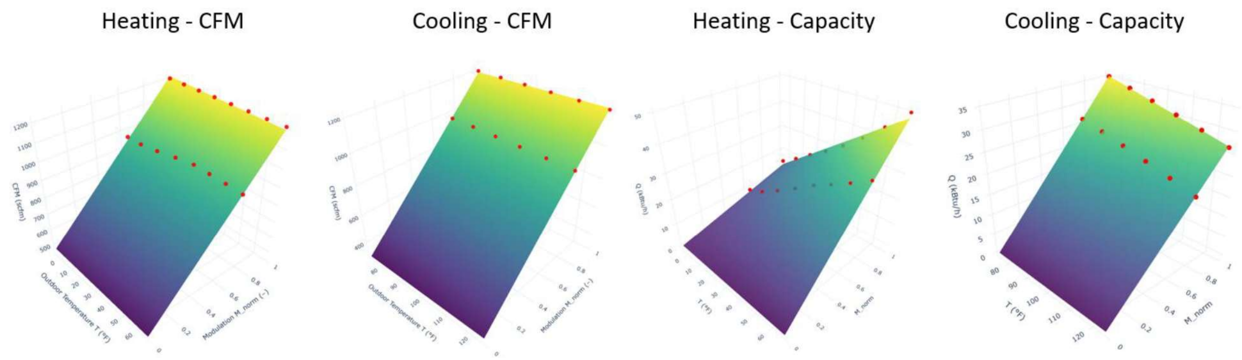

Figure 8: Carrier 27TPA836 performance regression plots

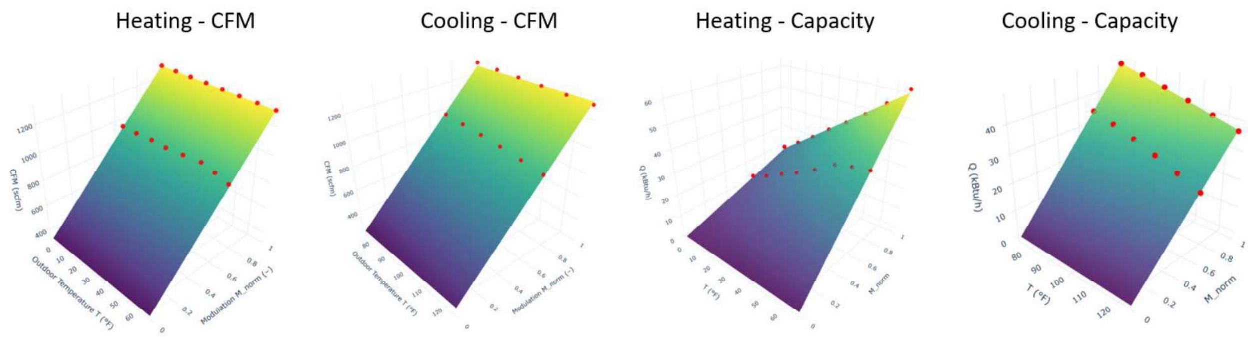

Figure 9: Carrier 27TPA848 performance regression plots

APPENDIX B: ASHRAE 152 INPUTS AND OUTPUTS

This appendix documents how ANSI/ASHRAE Standard 152 is applied in this analysis to represent duct system performance. Specifically, the analysis uses the ASHRAE 152 calculation framework and associated calculators to compute delivery effectiveness (DE) for ducted forced air systems, including the effects of duct leakage, conduction losses, and thermal regain. The study does not implement ASHRAE 152 as a complete standalone distribution efficiency model, nor does it claim formal compliance with the standard. Instead, ASHRAE 152 is used in a targeted manner to quantify delivered thermal performance while preserving transparency in system level modeling.

ASHRAE 152 was developed to address a fundamental limitation of conventional HVAC analysis: equipment efficiency ratings assume that thermal energy produced at the heat exchanger is delivered intact to the conditioned space. In existing homes, this assumption often fails due to duct leakage, heat transfer to buffer zones, and pressure driven infiltration. ASHRAE 152 provides a physically grounded method for accounting for these effects by separating equipment performance from distribution system performance, enabling realistic estimates of delivered energy and capacity.

In this analysis, the ASHRAE 152 calculators are used to calculate delivery effectiveness (DE) under representative heating and cooling conditions. These calculations explicitly incorporate:

- Supply and return duct leakage fractions
- Duct location and insulation condition
- Ambient temperatures of surrounding buffer zones
- Thermal regain to the conditioned space [3]

The resulting DE values represent the fraction of equipment thermal output that is effectively delivered to the conditioned space after accounting for distribution system losses and regain, consistent with the definitions and procedures in ASHRAE 152.

The calculated DE values are then used as inputs to the broader modeling framework, rather than as final performance metrics. Specifically, DE is applied to:

- Adjust effective delivered heating and cooling capacity
- Quantify the impact of duct sealing on usable heat pump output
- Inform the interaction between duct performance, airflow constraints, and building loads

[3] **Modera, M.P.** (2005). *ASHRAE Standard 152 and Duct Leaks in Houses*. **ASHRAE Journal**, March 2005.

ASHRAE 152 distribution system efficiency (DSE) is not used directly. Instead, the analysis resolves downstream impacts: annual energy use, operating cost, carbon emissions, and winter peak electric demand, through an explicit, temperature-bin-based system model. This approach preserves the physical intent of ASHRAE 152 while avoiding aggregation that could obscure key mechanisms central to this study, particularly airflow-constrained heat pump operation and sustained winter peak behavior.

This selective use of ASHRAE 152 reflects the different objectives of the present analysis. While ASHRAE 152 is designed primarily for seasonal energy accounting and diagnostic evaluation of distribution systems, this study focuses on cold climate heat pump performance, delivered capacity, and grid-relevant peak demand impacts. Using ASHRAE 152 to calculate DE provides a rigorous, industry-recognized basis for representing duct losses and regain, while explicit system modeling extends the analysis beyond the original scope of the standard.

In summary, ASHRAE 152 provides the methodological foundation for delivery effectiveness calculations used in this study. By explicitly documenting how the standard's calculators, inputs, and definitions are applied, this appendix ensures that the treatment of duct systems is technically grounded, transparent, and interpretable within an established industry framework, strengthening confidence that the modeled impacts of duct sealing reflect real physical behavior rather than modeling artifacts.

Table 4: ***Duct location fractions and thermal regain factors used in ASHRAE 152 delivery effectiveness calculations.***
Fractional distribution of supply and return duct surface area across attic and basement configurations, along with corresponding thermal regain factors. These parameters define the portion of duct losses assumed to be recovered within the building thermal boundary and are used as inputs to the ASHRAE 152 delivery effectiveness (DE) calculations.

Duct Location Fraction & Thermal Regain Factor	frac_supply_attic	frac_supply_basement_uninsulated	frac_supply_basement_insulated_walls	frac_supply_basement_insulated_ceiling	frac_return_attic	frac_return_basement_uninsulated	frac_return_basement_insulated_walls	frac_return_basement_insulated_ceiling	regain_supply	regain_return
uninsulated basement	0.2	0.8	0	0	0.2	0.8	0	0	0.5	0.5
insulated basement walls	0.2	0	0.8	0	0.2	0	0.8	0	0.75	0.75
insulated basement ceiling	0.2	0	0	0.8	0.2	0	0	0.8	0.3	0.3

Table 5: ***Pre- and post-duct-sealing duct leakage assumptions for ASHRAE 152 analysis.***
Supply and return duct leakage rates (CFM) assumed for heating and cooling operation prior to duct sealing, and reduced leakage rates applied post-sealing. These leakage inputs are used by the ASHRAE 152 calculators to quantify changes in delivery effectiveness resulting from improved duct tightness.

Pre & Post Duct Sealing CFM	leakage_supply_heating	leakage_return_heating	leakage_supply_cooling	leakage_return_cooling	leakage_post_sealing
uninsulated basement	240	240	240	240	25

insulated basement walls	240	240	240	240	25
insulated basement ceiling	240	240	240	240	25

*Table 6: **ASHRAE 152 delivery effectiveness (DE) and distribution system efficiency (DSE) before and after duct sealing.***

Seasonal heating and cooling delivery effectiveness and distribution system efficiency calculated using ASHRAE 152, shown for pre- and post-sealing conditions. Reduction factors summarize the relative improvement attributable to duct sealing across basement configurations

Duct Sealing Delivery Effectiveness (DE) & Distribution System Efficiency (DSE)	Delivery Effectiveness heating_seasonal	Delivery Effectiveness cooling_seasonal	Distribution System Efficiency heating_seasonal	Distribution System Efficiency cooling_seasonal	Delivery Effectiveness heating_seasonal_post_sealing	Delivery Effectiveness cooling_seasonal_post_sealing	Distribution System Efficiency heating_seasonal_post_sealing	Distribution System Efficiency cooling_seasonal_post_sealing	DE_heating_reduction	DE_cooling_reduction	DSE_heating_reduction	DSE_cooling_reduction
uninsulated basement	0.78	0.88	0.74	0.83	0.93	0.97	0.88	0.92	0.84	0.91	0.84	0.90
insulated basement walls	0.87	0.98	0.83	0.93	0.97	0.99	0.92	0.94	0.90	0.99	0.90	0.99
insulated basement ceiling	0.7	0.85	0.66	0.81	0.89	0.97	0.85	0.92	0.79	0.88	0.78	0.88

APPENDIX C: DETAILED ENERGY, COST, AND EMISSIONS RESULTS BY DUCT CONFIGURATION

C.1 Purpose and Scope

This appendix provides detailed modeling results for additional duct configurations representative of the Massachusetts housing stock that are not shown in the main body of the paper. Specifically, results are presented for (1) uninsulated basement duct systems and (2) basement duct systems with insulated walls.

For each configuration, results are reported across all HVAC system scenarios evaluated in the study and include annual site energy consumption, annual operating cost, annual carbon dioxide equivalent (CO_2e) emissions. These tables are provided for completeness and transparency. Key findings and comparative insights are synthesized in Sections 5–7 of the main report.

Unless otherwise noted, all assumptions related to equipment performance, weather data, energy prices, emissions factors, and duct sealing effectiveness are identical to those used in the primary analysis.

C.2 Results for Uninsulated Basement Duct Configuration

The following tables present results for homes with ductwork located in an uninsulated basement, a common condition in older Massachusetts housing stock. This configuration is characterized by relatively high duct losses but moderate thermal regain, consistent with ASHRAE 152 assumptions.

Table 7: Annual site energy consumption by end use for uninsulated basement duct configuration (MMBtu).

HVAC SYSTEM SCENARIO	HEATING	COOLING	SUPPLEMENTAL HEATER	TOTAL
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	100	6	—	105
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	84	5	—	89
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	18	4	1	24
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	15	4	0	20
PREMIUM HP – CARRIER 27VNA360 (5 TON)	20	5	6	31
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	17	4	3	25
PREMIUM HP – CARRIER 27VNA348 (4 TON)	21	4	2	27

PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	18	4	1	22
PREMIUM HP – CARRIER 27VNA336 (3 TON)	19	4	3	27
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	17	4	2	22
STANDARD HP – CARRIER 27TPA848 (4 TON)	23	5	3	31
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	19	5	2	26
STANDARD HP – CARRIER 27TPA836 (3 TON)	23	6	5	33
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	20	5	3	27

Table 8: Annual operating cost by end use for uninsulated basement duct configuration (USD).

HVAC System Scenario	Heating	Cooling	Supplemental Heater	Total
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	$2,105	$506	—	$2,610
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	$1,772	$432	—	$2,204
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	$1,617	$395	$94	$2,106
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	$1,372	$358	$29	$1,759
PREMIUM HP – CARRIER 27VNA360 (5 TON)	$1,753	$408	$552	$2,713
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	$1,517	$371	$305	$2,193
PREMIUM HP – CARRIER 27VNA348 (4 TON)	$1,822	$354	$200	$2,376
PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	$1,553	$322	$93	$1,968
PREMIUM HP – CARRIER 27VNA336 (3 TON)	$1,711	$388	$269	$2,367
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	$1,461	$352	$142	$1,956
STANDARD HP – CARRIER 27TPA848 (4 TON)	$1,996	$446	$292	$2,735
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	$1,704	$405	$167	$2,276
STANDARD HP – CARRIER 27TPA836 (3 TON)	$2,020	$500	$418	$2,938
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	$1,735	$454	$243	$2,432

Table 9: Annual CO_2e emissions by end use for uninsulated basement duct configuration (kg CO_2e).

HVAC SYSTEM SCENARIO	HEATING	COOLING	SUPPLEMENTAL HEATER	TOTAL
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	5,298	675	—	5,973
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	4,461	577	—	5,038
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	2,159	527	126	2,811
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	1,831	478	38	2,347
PREMIUM HP – CARRIER 27VNA360 (5 TON)	2,339	545	737	3,621
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	2,024	495	407	2,927
PREMIUM HP – CARRIER 27VNA348 (4 TON)	2,432	472	267	3,171
PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	2,073	429	124	2,627
PREMIUM HP – CARRIER 27VNA336 (3 TON)	2,283	517	359	3,159
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	1,951	470	190	2,611
STANDARD HP – CARRIER 27TPA848 (4 TON)	2,664	596	390	3,650
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	2,274	541	222	3,038
STANDARD HP – CARRIER 27TPA836 (3 TON)	2,696	667	558	3,921
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	2,316	606	325	3,246

C.3 Results for Basement Duct Configuration with Insulated Walls

The following tables present results for homes with ductwork located in a basement with insulated foundation walls, representing a higher performance distribution environment with increased thermal regain and reduced conduction losses relative to uninsulated basements.

Table C-1B. Annual site energy consumption by end use for basement duct configuration with insulated walls (MMBtu).

Annual heating, cooling, supplemental heating, and total site energy consumption for each HVAC system scenario evaluated, assuming ducts located in a basement with insulated walls.

Table 10: Annual site energy consumption by end use for basement with insulated walls duct configuration (MMBtu).

HVAC SYSTEM SCENARIO	HEATING	COOLING	SUPPLEMENTAL HEATER	TOTAL
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	100	6	—	105
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	84	5	—	89
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	18	4	1	24
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	15	4	0	19
PREMIUM HP – CARRIER 27VNA360 (5 TON)	20	5	6	31
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	16	4	3	23
PREMIUM HP – CARRIER 27VNA348 (4 TON)	21	4	2	27
PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	17	4	1	21
PREMIUM HP – CARRIER 27VNA336 (3 TON)	19	4	3	27
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	16	4	1	21
STANDARD HP – CARRIER 27TPA848 (4 TON)	23	5	3	31
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	18	4	1	24
STANDARD HP – CARRIER 27TPA836 (3 TON)	23	6	5	33
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	18	5	2	26

Table 11: Annual operating cost by end use for basement with insulated walls duct configuration (USD).

HVAC System Scenario	Heating	Cooling	Supplemental Heater	Total
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	$2,105	$506	—	$2,610
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	$1,772	$432	—	$2,204
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	$1,617	$395	$94	$2,106
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	$1,289	$346	$17	$1,652
PREMIUM HP – CARRIER 27VNA360 (5 TON)	$1,753	$408	$552	$2,713
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	$1,437	$358	$237	$2,032
PREMIUM HP – CARRIER 27VNA348 (4 TON)	$1,822	$354	$200	$2,376

PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	$1,463	$311	$69	$1,843
PREMIUM HP – CARRIER 27VNA336 (3 TON)	$1,711	$388	$269	$2,367
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	$1,379	$340	$106	$1,826
STANDARD HP – CARRIER 27TPA848 (4 TON)	$1,996	$446	$292	$2,735
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	$1,608	$392	$129	$2,129
STANDARD HP – CARRIER 27TPA836 (3 TON)	$2,020	$500	$418	$2,938
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	$1,638	$438	$201	$2,277

Table 12: Annual CO_2e emissions by end use for basement with insulated walls duct configuration (kg CO_2e).

HVAC SYSTEM SCENARIO	HEATING	COOLING	SUPPLEMENTAL HEATER	TOTAL
80% GAS FURNACE (80 KBTU/HR) + SEER14 AC (3 TON)	5,298	675	—	5,973
95% GAS FURNACE (80 KBTU/HR) + SEER18 AC (3 TON)	4,461	577	—	5,038
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON)	2,159	527	126	2,811
PREMIUM CCHP – CARRIER 27VNA1 (4.5 TON) – POST SEALING	1,721	462	22	2,205
PREMIUM HP – CARRIER 27VNA360 (5 TON)	2,339	545	737	3,621
PREMIUM HP – CARRIER 27VNA360 (5 TON) – POST SEALING	1,918	478	316	2,713
PREMIUM HP – CARRIER 27VNA348 (4 TON)	2,432	472	267	3,171
PREMIUM HP – CARRIER 27VNA348 (4 TON) – POST SEALING	1,953	415	93	2,460
PREMIUM HP – CARRIER 27VNA336 (3 TON)	2,283	517	359	3,159
PREMIUM HP – CARRIER 27VNA336 (3 TON) – POST SEALING	1,841	454	142	2,437
STANDARD HP – CARRIER 27TPA848 (4 TON)	2,664	596	390	3,650
STANDARD HP – CARRIER 27TPA848 (4 TON) – POST SEALING	2,146	523	172	2,841
STANDARD HP – CARRIER 27TPA836 (3 TON)	2,696	667	558	3,921
STANDARD HP – CARRIER 27TPA836 (3 TON) – POST SEALING	2,186	585	268	3,040

C.4 Conclusion: Duct Sealing Benefits Are Consistent Across Common Massachusetts Duct Configurations

To test whether the benefits of duct sealing and rightsized electrification depend on duct location or thermal environment, the analysis evaluated two more basement duct configurations representative of the Massachusetts housing stock: uninsulated basement ducts and basement ducts with insulated walls.

Table summarizes the baseline to best case outcomes for both configurations. The baseline system is an 80% AFUE gas furnace with a SEER 14 air conditioner, and the best case system is a right-sized 3-ton premium cold-climate heat pump (Carrier 27VNA336) with post-sealing ducts.

Table 13: Baseline to best case savings across representative Massachusetts duct configurations. Savings compare an 80% AFUE gas furnace with SEER 14 air conditioning to a right sized premium cold climate heat pump (Carrier 27VNA336, 3 ton) with post sealing ducts.

METRIC	UNINSULATED BASEMENT	BASEMENT WITH INSULATED WALLS
ANNUAL SITE ENERGY SAVINGS (MMBTU)	83	82
PERCENT ENERGY REDUCTION	79%	77%
ANNUAL OPERATING COST SAVINGS (USD)	$654	$492
PERCENT COST REDUCTION	25%	19%
ANNUAL CO_2E EMISSIONS REDUCTION (KG CO_2E)	3,362	3,146
PERCENT EMISSIONS REDUCTION	56%	53%

Across both duct configurations, the magnitude and direction of benefits are remarkably consistent:

- Energy savings exceed 75% in both cases, despite differences in duct thermal environment.
- Operating cost reductions range from 19% to 25%, reflecting the combined effect of electrification, reduced resistance heating, and avoided oversizing.
- Carbon emissions reductions exceed 50% in both configurations, reinforcing the climate value of duct sealing as part of electrification.

While absolute savings vary modestly with duct location and insulation, the qualitative outcome does not change: duct sealing enables rightsized heat pump systems to deliver large, durable reductions in energy use, cost, and emissions across duct configurations common to Massachusetts homes.

This consistency supports the treatment of duct sealing as foundational electrification infrastructure, rather than an efficiency add-on.

APPENDIX D: MODELING FRAMEWORK AND ASSUMPTIONS

The analysis presented in this paper is intentionally designed to support utility planning, incentive program design, and large-scale deployment decisions. Rather than optimizing for maximum model fidelity, the modeling framework prioritizes three guiding principles: robustness, transparency, and scalability. These principles reflect the practical requirements of stakeholders who must understand, trust, reproduce, and apply results across diverse building and program contexts.

D.1 Design principles of the modeling approach

The modeling framework is grounded in well-established building science methods and publicly recognized technical references that are widely used by utilities, regulators, and researchers. Each major input – building loads, weather, duct systems, and equipment performance – was selected to maximize realism, reproducibility, and relevance to the existing Massachusetts housing stock.

- **Building loads and representative housing characteristics**

  Residential heating and cooling loads are derived from the U.S. Department of Energy (DOE) residential prototype building models[4]. These models are widely used in code development, policy analysis, and building energy research and represent one of the most rigorously vetted sources of residential load data available. Among available archetypes, the single-family prototype provides a close approximation to a "typical" detached home and serves as a practical baseline for program-scale analysis.

  The building envelope characteristics are based on IECC 2006, which is representative of a substantial majority of existing single-family homes in Massachusetts. According to the U.S. Energy Information Administration's Residential Energy Consumption Survey (RECS), homes built prior to the widespread adoption of more recent energy codes account for more than 80 percent of the existing housing stock[5]. Using this baseline avoids overstating electrification performance by assuming envelope conditions that are not yet common in the field.

  This choice intentionally reflects existing conditions, not aspirational new construction, aligning the analysis with the realities faced by electrification incentive programs.

- **Weather data and climate representation**

[4] DOE Building Energy Codes Program – Residential Protype Building Models https://www.energycodes.gov/prototype-building-models#Residential

[5] EIA Residential Energy Consumption Survey (RECS) https://www.eia.gov/consumption/residential/data/2024/

Weather inputs are based on Typical Meteorological Year (TMY3) data for Massachusetts locations, representing long-term average climate conditions over the 2009–2023 period[6]. TMY3 data are widely used in both building simulation and utility planning and provide a consistent basis for temperature-bin analysis of heating and cooling performance.

Using temperature bins derived from TMY data allows the model to clearly associate system behavior, including heat pump output, resistance heater operation, and peak demand, with specific outdoor temperature conditions, which is especially important for winter peak analysis.

- **Duct system configuration and distribution efficiency**

Duct system configuration, leakage levels, and distribution effectiveness are represented using methodologies established in ASHRAE Standard 152, which remains the most widely recognized framework for quantifying duct distribution system efficiency. Rather than applying generic or fixed efficiency penalties, the model explicitly represents:

  - Supply and return duct leakage
  - Location-dependent thermal losses
  - Delivery effectiveness and distribution system efficiency

This approach ensures that duct impacts are treated as physical constraints on system operation, not abstract adjustment factors. As a result, the modeled interaction between duct performance, airflow, and heat pump capacity reflects conditions commonly observed in existing homes.

- **Heat pump performance data and equipment selection**

Heat pump performance is based on manufacturer-reported engineering data from Carrier, which offers some of the most complete and granular cold-climate heat pump performance datasets available. Using manufacturer data avoids reliance on idealized performance curves and allows capacity, airflow requirements, and electrical input to be modeled consistently across operating conditions.

To reflect the diversity of equipment commonly encountered in utility programs, the analysis includes six heat pump units spanning three product classes:

- VNA1 series: best-in-class variable-speed cold-climate heat pumps
- VNA3 series: premium cold-climate heat pumps
- TPA series: representative two-stage heat pumps commonly installed today

[6] Climate.OneBuilding.Org TMYx weather data https://climate.onebuilding.org/#gsc.tab=0

Including multiple capacities and product tiers allows the analysis to assess how duct sealing interacts with both premium and more typical equipment choices, strengthening the relevance of results for incentive program design.

- **Conservative, bounded modeling philosophy**

Across all inputs, the modeling framework avoids extrapolation beyond documented equipment operating envelopes or assumptions unsupported by existing literature. The objective is not to estimate best-case performance under ideal conditions, but to represent plausible, repeatable outcomes consistent with how ducted heat pump systems actually operate in existing Massachusetts homes.

This conservative, reference-driven approach underpins the robustness of the results and supports their use in program planning, cost-effectiveness screening, and grid impact assessment.

Transparent: bin-based operation instead of black-box simulation

A central design choice in this analysis is the use of a temperature bin–based modeling approach, rather than relying entirely on a black-box or grey-box whole-building simulation engine. While detailed simulation tools such as EnergyPlus are powerful, their internal control logic and equipment interactions can be opaque to non-modelers, making it difficult for program administrators and evaluators to trace cause-and-effect relationships.

In contrast, the bin-based framework used here explicitly resolves system operation at discrete outdoor temperature intervals. For each bin, the model calculates:

- Building heating load
- Available heat pump capacity under airflow constraints
- Heat pump electrical input
- Supplemental resistance heater operation when required
- Gas furnace backup switch point

This structure makes system behavior immediately interpretable. The conditions under which resistance heat is engaged, the extent to which heat pump capacity is constrained, and the contribution of each component to energy use and peak demand are all directly observable in the results.

For utility and regulatory audiences, this transparency is critical. It allows reviewers to understand why outcomes change with duct sealing, equipment sizing, or climate conditions, rather than simply accepting aggregate annual results without insight into system operation.

Scalable: reproducible, extensible, and scenario-driven

The full modeling workflow is implemented in Python using a modular, data-driven architecture comprising more than 6,000 lines of documented code. This implementation enables rapid replication of results and straightforward extension to additional scenarios, including:

- Different building archetypes or envelope conditions
- Alternative duct configurations and leakage levels
- Multiple heat pump models and sizes
- Whole-home and partial-electrification strategies
- Sensitivity analyses across climate conditions or energy prices

Because inputs, assumptions, and intermediate calculations are explicitly defined, the framework is well suited for iterative program design and evaluation. Results can be reproduced, audited, and adapted without re-engineering the underlying methodology.

This scalability distinguishes the approach from one-off case studies or highly customized simulations. The intent is to provide a program-ready analytical framework that can inform decisions at scale, not just individual project outcomes.

D.2 Key modeling components

Building loads and climate representation

Heating and cooling loads are represented using temperature-dependent profiles consistent with Massachusetts climate conditions. Outdoor temperature bins are derived from typical meteorological year data, enabling seasonal energy use and peak demand to be calculated directly from bin-level system operation.

This approach aligns well with utility planning practices, which frequently rely on temperature-indexed demand analysis rather than hour-by-hour black-box simulation.

Heat pump performance representation

Cold-climate heat pump performance is represented using regression models derived from manufacturer performance data. Heating capacity, required indoor airflow, and electrical input are expressed as functions of outdoor temperature and operating point. This allows the model to capture both capacity degradation at low temperatures and the increasing airflow requirements associated with heat pump operation.

Crucially, heat pump capacity is solved subject to airflow constraints, reflecting the interaction between equipment capability and duct system limitations. Details of the regression formulation and airflow-constrained capacity logic are provided in Appendix A.

Duct leakage and airflow constraints

Duct systems are modeled as active constraints on system operation rather than passive efficiency penalties. Leakage reduces effective delivered airflow and increases building load, while airflow limits cap the maximum usable heat pump output. These effects are applied consistently across all temperature bins, allowing the model to capture their cumulative impact on energy use, resistance heat operation, and winter peak demand.

D.3 Why this framework is appropriate for program and planning decisions

For utilities and state energy agencies, the value of a modeling framework lies not only in numerical precision, but in its ability to support clear, defensible decisions. The approach used here is intentionally designed to:

- Reveal the physical drivers of electrification performance
- Avoid hidden assumptions embedded in opaque simulation engines
- Scale efficiently across large numbers of homes and scenarios
- Support transparent review by evaluators and regulators

By explicitly resolving airflow constraints and bin-level system operation in both heating and cooling modes, the framework captures not only heating shortfalls and resistance heat operation, but also the cooling-season implications of heating-driven oversizing, including increased minimum capacity and reduced latent performance, effects that are often obscured in black-box simulation approaches.

D.4 Energy Prices and Emission Factors

Energy cost and carbon emissions calculations are based on publicly available, state-specific reference data to ensure transparency and reproducibility. Retail energy prices reflect Massachusetts state average residential rates in 2024, consistent with recent Energy Information Administration (EIA) data. Electricity prices[7] are expressed on a per-kWh basis and converted to equivalent $/MMBtu for comparison with fossil fuels. Natural gas[8], heating oil, and propane prices are based on standard EIA state-level residential price statistics.

Carbon emissions are calculated using fuel-specific emissions factors[9] expressed in kilograms of CO_2e per unit of delivered energy. Electricity emissions reflect the Massachusetts grid average, while fossil fuel emissions are based on established combustion emissions factors for natural gas, heating oil, and propane. These values are applied consistently across all modeled scenarios. Using standardized state-level prices and emissions factors avoids bias toward any particular technology or outcome and ensures that results reflect conditions relevant to Massachusetts utility and policy analysis.

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[7] EIA Electric Power Monthly https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

[8] EIA Natural Gas Prices https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm

[9] Energy Star Portfolio Manager Technical Reference: Emissions https://www.energystar.gov/buildings/benchmark/understand-metrics/how