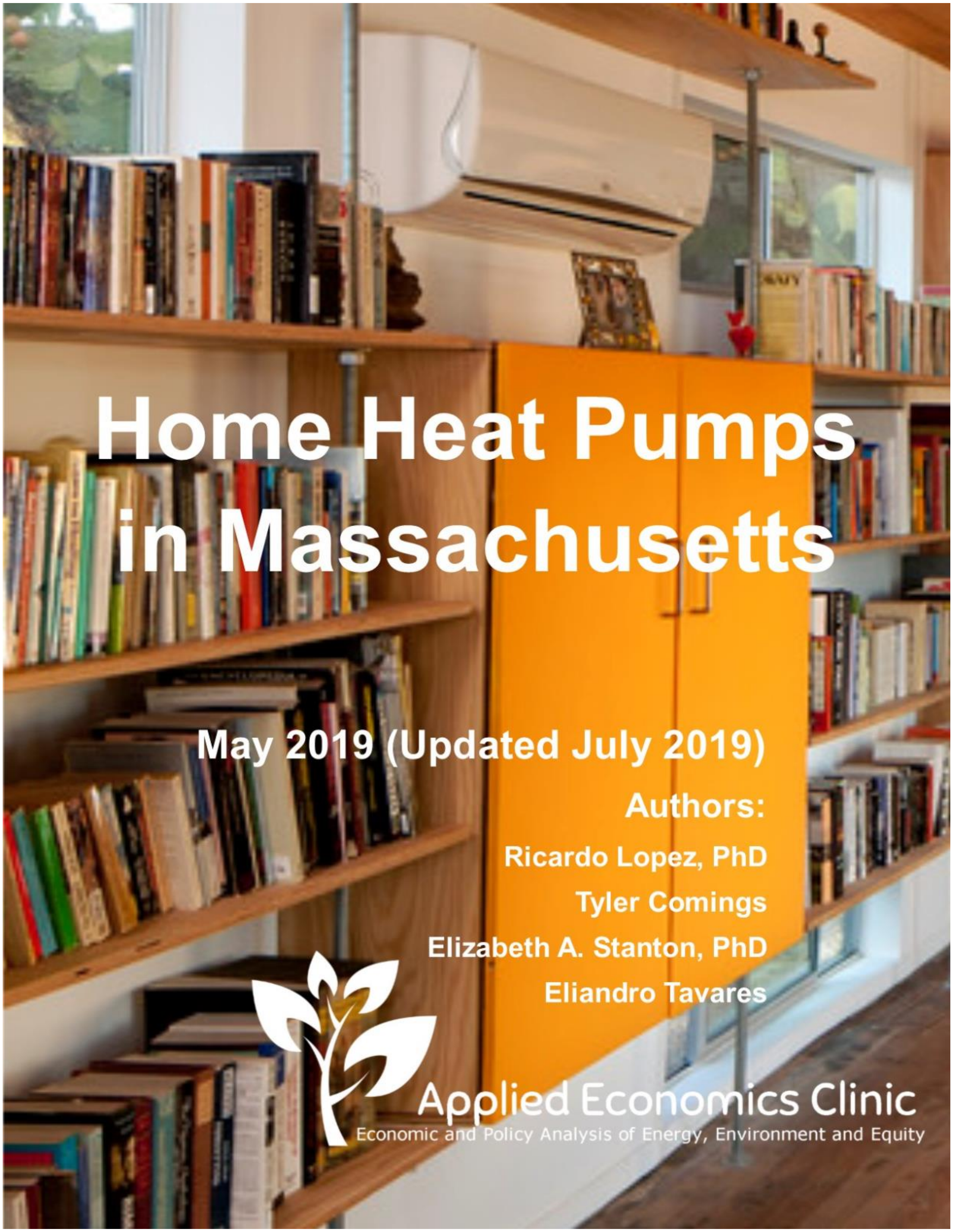

Home Heat Pumps in Massachusetts

May 2019 (Updated July 2019)

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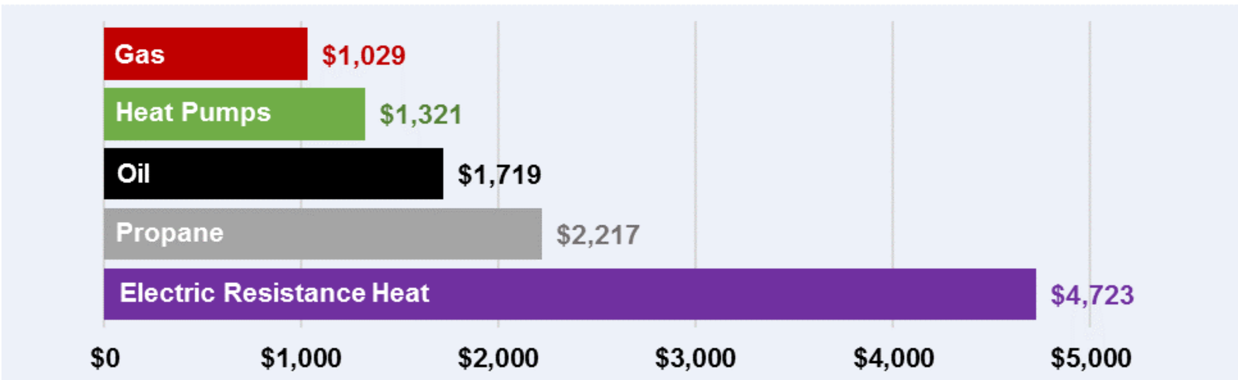
Economic and Policy Analysis of Energy, Environment and Equity

Executive Summary

Converting heating and cooling systems in need of replacement to electric heat pumps (which provide both space heating and cooling) makes economic sense for many Massachusetts homes. Massachusetts Department of Energy Resources (DOER) compared the 2018/19 costs to heat a typical home across a range of technologies and found that "old-fashioned" electric resistance baseboard heating cost four times more to operate than the least expensive options: gas furnaces and modern electric heat pumps (see ES-Figure 1).

ES-Figure 1. Massachusetts DOER's one-year heating fuel/electric costs for typical home (2017$)



The analysis presented in this Applied Economics Clinic study assesses not only the heating operations costs (fuel and electricity) covered by DOER in ES-Figure 1, but also: (1) home cooling costs; and (2) the cost of replacing heating and cooling equipment spread out over the lifetime of the equipment on a cost per year basis. We include cooling costs because electric heat pumps serve a dual purpose—both heating and cooling homes—and more than 80 percent of new New England homes are built with central air conditioning (AC). In 2015, 75 percent of all New England homes—new and old—used some form of AC and 27 percent had central AC, up from 8 percent in the 1990s.

In the absence of all Massachusetts state rebates for replacing old heating systems, purchasing and operating a heat pump costs $650 more than purchasing and operating a gas furnace and electric central air conditioning (AC) over the 18-year lifetime of the equipment—or $36 more each year (see ES-Table 1). With rebates included, the economics of heat pumps in Massachusetts depends on what type of existing heating system will be replaced. (Rebates differ based on whether the system to be replaced runs on gas or oil.)

ES-Table 1. Summary of findings (2017$)

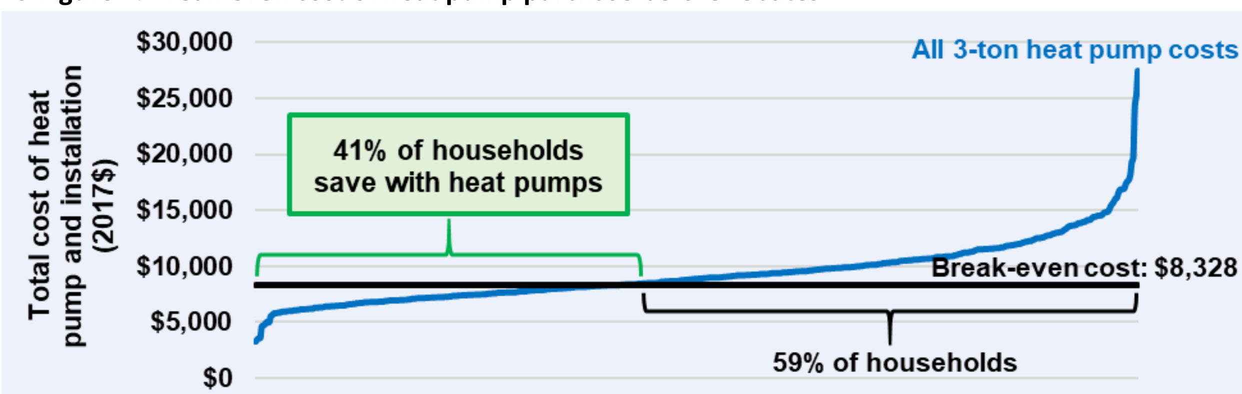
	MassSave Rebate	Annual Cost Savings or Loss	
		No Rebates	With Rebates
New Gas Furnace and Central AC	$1,101	$36	$73 / -$158
Heat Pump (for gas furnace owners)	$431	-$36	-$73
Heat Pump (for oil furnace owners)	$4,594	-$36	$158

With current Massachusetts rebates, owners of aging oil heating systems save $158 per year by choosing to replace with a heat pump instead of a gas furnace and central AC. For owners of gas heating systems, however, rebates for heat pumps are smaller than rebates for new gas furnaces, raising the relative cost of choosing heat pumps from $36 per year with no rebates to $73 per year with rebates.

Heat pumps' cost effectiveness depends on home-specific differences

The median cost for a 3-ton heat pump system (the likely capacity needed for full replacement of a typical Massachusetts home heating and cooling system) was $8,890. This upfront purchase cost estimate, together with operation costs, averages $36 more each year than purchase and operation costs for a new gas furnace and central AC without any rebates. The most recent three years of data on Massachusetts heat pump purchases, however, shows 3-ton system costs ranging from $3,268 to $27,473. Of these systems, 41 percent would result in lifetime heat pump costs that were "break even"—that is, equal to or lower than those of a new gas furnace and central AC (see ES-Figure 2).

ES-Figure 2. Break-even cost of heat pump purchase before rebates



Seventy percent of the reported replacement heat pump costs would result in annual costs within $100 per year of the gas alternative, and 90 percent of these heat pumps were within $248 per year.

Heat pumps' cost effectiveness is robust to changes in prices and financing

Regardless of changes in expected fuel and electric prices and whether or not zero-interest financing (available under the Mass Save HEAT Loan program) is assumed, heat pumps' annual average costs are very similar to those of new gas heating and central AC, with losses from choosing heat pumps ranging from $33 to $51 per year (see ES-Table 2). With no rebates, choosing the gas furnace plus central AC alterative is about 2-3 percent less expensive than choosing heat pumps. With rebates, current owners of gas heating see <u>losses</u> of about 4-5 percent, while owners of oil heating see <u>savings</u> of 9-10 percent.

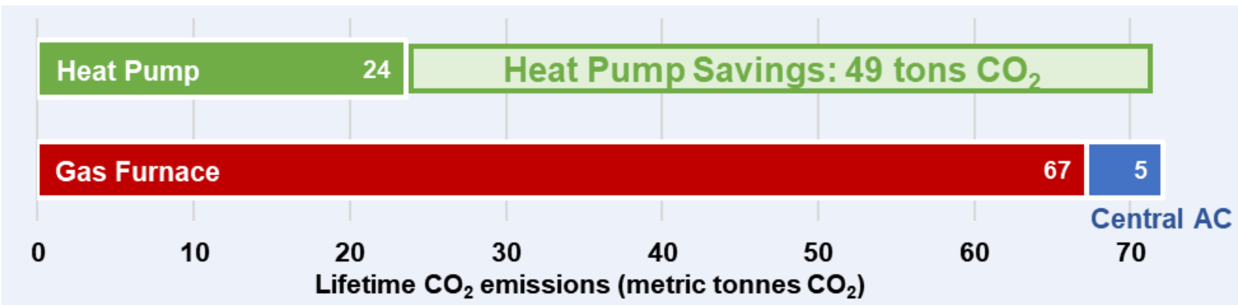
ES-Table 2. Annual losses in future fuel and electric price scenarios (2017$)

	Fuel and Electric Prices (2017$)		
	Low	Base	High
No Financing	**-$33**	**-$36**	**-$47**
With Financing	**-$36**	**-$39**	**-$51**

Heat pumps reduce Massachusetts greenhouse gas emissions compared to gas heating

Choosing heat pumps over gas or oil heating makes an important contribution to the Commonwealth's Global Warming Solution Act (GWSA) mandate to reduce state-wide emissions to 80 percent below their 1990 levels by 2050. Converting a single-home system (with the 3-ton size assumed in this report) from a gas furnace and electric central AC to a heat pump system avoids 49 metric tonnes of CO_2 over an 18-year lifetime (see ES-Figure 3). To put this in context, the 18-year emission savings from a Massachusetts driver switching from gasoline to an all-electric vehicle is estimated at 73 metric tonnes.

ES-Figure 3. Single-home lifetime emissions savings from switching to a heat pump



Converting 20 percent of all gas-heated homes in Massachusetts to heat pumps (per the Massachusetts *2018 Comprehensive Energy Plan*) would reduce 2030 emissions by 0.8 million metric tonnes CO_2. For context, a 100 percent conversion of residential gas and oil-heated homes to heat pumps would result in a 7.2 MMT CO_2 reduction by 2030. While the Commonwealth has not yet set targets for 2030 emission reductions, we estimate that a 5.3 MMT CO_2 reduction would be needed from the buildings sector to keep Massachusetts on track to reach its 2050 emission reduction target.

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1. Introduction

Ductless air-source electric heat pumps, or mini-splits, are one of the most energy-efficient and cost-effective heating and cooling systems currently available. The value that heat pumps provide relative to gas and fuel oil heating (prevalent in the U.S. Northeast) and electric cooling depends on the cost of installation and maintenance of the system and the cost of fuel and electricity. Uncertainty regarding future fuel and electric costs, however, makes the decision of which type of system to choose a challenging one for households.

This report estimates the costs of a typical Massachusetts household's acquisition of a new heating, ventilation and air conditioning (HVAC) system by comparing these two options:

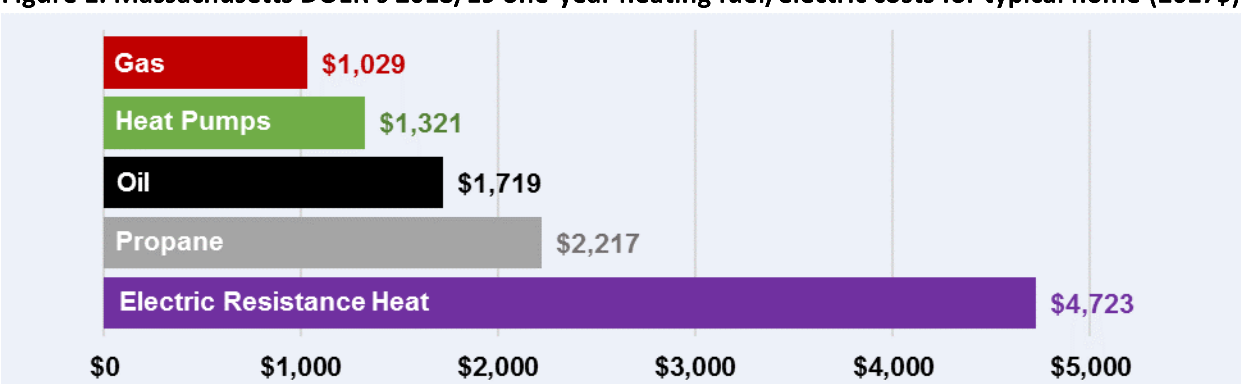
1) install and operate a new electric heat pump system, or,

2) install and operate a new gas furnace and electric central AC unit.

> **Ductless air-source (or "mini-split") heat pumps** use the difference between indoor and outdoor temperatures to create warm air for winter heating and cool air for summer cooling. These systems typically have an outdoor base unit (like a central AC unit) and two or more wall-mounted indoor units.

The Massachusetts Department of Energy Resources (DOER) projects that the cost to heat a typical home in the Commonwealth during the winter of 2018-2019 will be $1,029 for gas heating, $1,719 for oil heating, $2,217 for propane heating, or $4,723 for electric resistance ("old-fashioned" baseboard) heating (see Figure 1).[1] On this basis, our analysis assumes that most households would choose to replace old heating and cooling equipment with the two most economic options—gas furnaces with central AC or electric heat pumps—and would not choose the three least economic options—oil, propane or electric resistance heating.

Figure 1. Massachusetts DOER's 2018/19 one-year heating fuel/electric costs for typical home (2017$)

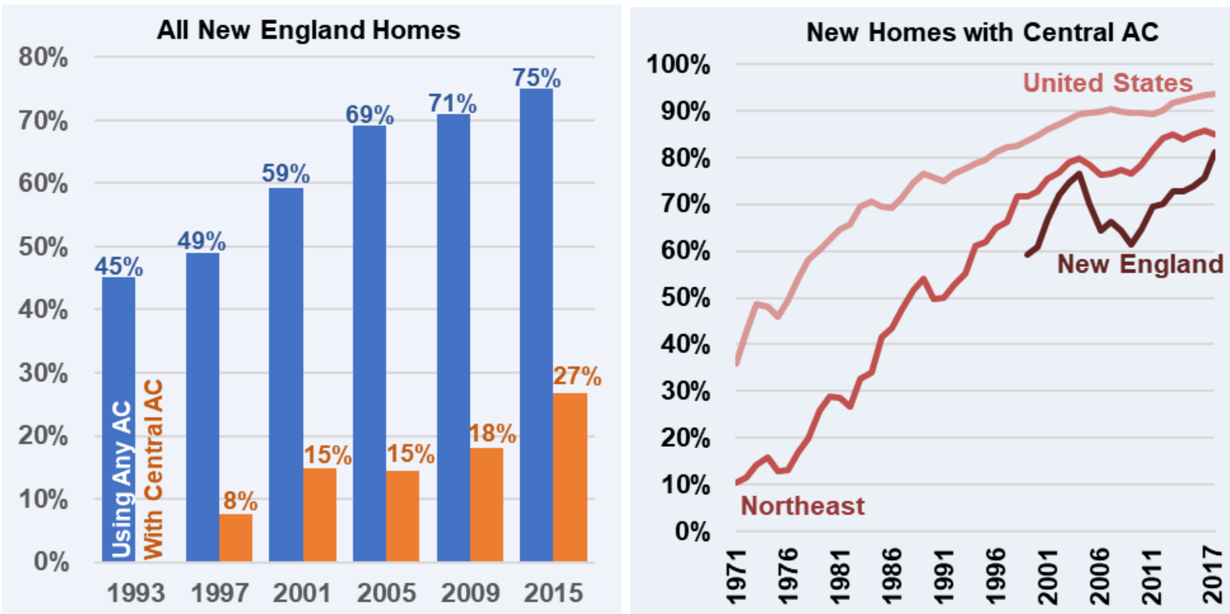


Data source: AEC calculations and Massachusetts DOER. *Household Heating Costs: Forecast of energy prices for heating fuels during 2018/19* Winter *Heating Season*. Available at: https://www.mass.gov/info-details/household-heating-costs.

[1] DOER's assumed heating requirement of 647 therms per year has been raised to 692 therms per year to match the typical home size used throughout this report.

Lifetime heating and cooling cost estimates include installing, maintaining, and operating a gas furnace, central AC system, or a ductless mini-split heat pump system. The heat pump system consists of an approximately 3-ton capacity system that provides the same level of heating and cooling as the gas furnace and central AC combination.[2] In New England, the share of homes with air conditioning of any kind has risen from 45 percent in the 1990s, to 69 percent in the 2000s, up to 75 percent in 2015. (In 2015, 27 percent of New England homes had central AC systems ducted throughout the home—as opposed to window or wall-mounted "room" units—up from 8 percent in 1997.)[3] Most new homes (81 percent) built in New England in 2017 had central AC, compared to 10 percent in the Northeast in 1971 (see Figure 2).[4] This AEC study assumes that Massachusetts home owners replacing their heating systems will consider replacing their room units with central AC or updating an aging central AC system.

Figure 2. Air conditioning adoption trends for New England



Data source: (1) U.S. EIA 2015, 2005, and 1993 Residential Energy Consumption Survey (RECS) data. Available at: https://www.eia.gov/consumption/residential/index.php; (2) U.S. Census Bureau - Survey of Construction (SOC). 1999-2017. Characteristics of New Housing, Microdata. Available at: https://www.census.gov/construction/chars/microdata.html; (3) U.S. Census Bureau. 1971-1999. Historical C25 Publications. Available at: https://www.census.gov/construction/chars/historical_data/

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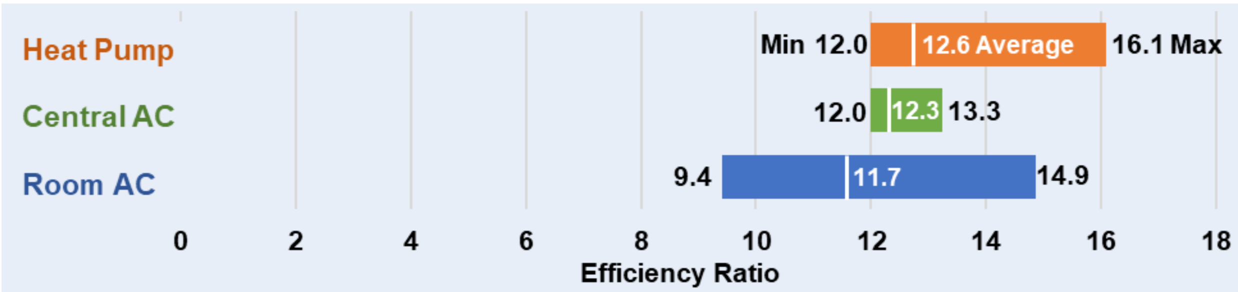
[2] Replacement system for residential, "medium-sized" home of 3-tons: Navigant Consulting. Ductless Mini-Split Heat Pump Costs Study (RES 28). p.7. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/RES28_Assembled_Report_2018-10-05.pdf. Using the Massachusetts Clean Energy Center (MassCEC) database of air-source heat pump residential projects with data from December 2014 to March 2018, we estimated the median residential project cost in Massachusetts for heat pump systems within 10 percent of 3-tons in capacity (i.e. between 32,400 and 39,600 Btus).The dataset is available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ResidentialASHPProjectDatabase.xlsx

[3] U.S. EIA 2015, 2005, and 1993 Residential Energy Consumption Survey (RECS) data. Available at: https://www.eia.gov/consumption/residential/index.php

[4] U.S. Census Survey of Construction 1971-2017. Available at: https://www.census.gov/construction/nrc/index.html

Room AC units are available at lower cooling efficiencies than central AC (see Figure 3), and the less efficient units tend to be far less expensive. What's more, Energy Star standards for AC efficiency have increased over time, with the result that the average efficiency of both room and central AC units purchased today is higher than older units purchased 5 or 10 years ago.[5] Many Massachusetts homes have the potential for efficiency gains and energy savings in replacing aging cooling equipment.

Figure 3. Range and midpoint of EER efficiency rates of current cooling equipment



Data source*: ENERGY STAR. ENERGY STAR Certified Product Data Sets and APIs - Room Air Conditioners, Central AC - CACs and Coils, and Heat Pumps - Mini-Split and Multi-Split Systems*. Available online: https://www.energystar.gov/productfinder/advanced

Note: Midpoint shown in white. ENERGY STAR Room Air-Conditioners data set includes the Combined Energy Efficiency Ratio (CEER). For comparison, the CEER was converted to EER using a CEER to EER ratio weighted by the prevalence of each Room AC product type in the ENERGY STAR Room AC data set. The ratio was derived from a 2014 Room AC CEERtoEER crosswalk from ENERGY STAR. The resulting weighted ratio was 1.01 EER to CEER. (ENERGY STAR Draft 1 Version 4.0 Room Air Conditioners Data Package - "2. RAC Crosswalk". 2014. Available online: https://www.energystar.gov/products/spec/room_air_conditioner_specification_version_4_0_pd).

Heat pumps work well in Massachusetts' climate but may not be the best choice for every home or building. Differences in building types, sizes, and layouts can make the installation of heat pump systems more or less economical.

We present the savings of choosing to replace an old heating system with an electric heat pump (as opposed to a new gas furnace and central AC) for a household with typical heating and cooling needs; sensitivities of those savings to fuel costs, installation costs and rebates; financing costs; and estimated emissions reductions from switching to heat pumps. In order to calculate lifetime costs, we collected data on the retail cost of equipment, installation, annual maintenance of each type of system, life expectancy, operating costs (including projected fuel costs), and existing financial incentives (including Massachusetts state rebates and zero-interest financing through the Mass Save HEAT loan program). (See Appendix A: Methodology and Key Assumptions and Appendix E: Data sources for details on cost assumptions and data sources.)

[5] Navigant Consulting, Inc. 2015. *Residential End Uses: Area 1: Historical Efficiency Data.* Prepared for U.S. Energy Information Administration. Available at: https://www.eia.gov/analysis/studies/residential/pdf/appendix-a.pdf

Do heat pumps work in cold climates?

Although many consumers may think otherwise, today's heat pumps work well in Massachusetts' climate. A survey by the Northeast Energy Efficiency Partnerships (NEEP) showed that one important barrier to the adoption of heat pumps is the perception that they will not work in below freezing temperatures.[a]

Advances in technology, however, have made it possible to produce heat pumps suitable to cold climate regions such as New England. According to the MassCEC database on heat pump purchases in Massachusetts, the most popular heat pump systems purchased between 2014 and 2018 can operate in temperatures as low as –15° F. In Boston, the temperature has never dropped below -10° F in the last 10 years. The last time Boston's temperature fell below –15° F was February 1934.[b]

Limitations of older models may also cause consumer concern regarding the performance or efficiency of heat pumps in cold temperatures. In Massachusetts, however, consumers who purchase heat pumps eligible for Mass Save rebates are required to choose the equipment from a list of "Cold Climate Air Source Heat Pumps" compiled by NEEP.[c] To be included in the list, the heat pump must have a Coefficient of Performance (COP) greater than 1.75 at 5 F° (meaning 1 kWh of electricity will generate 1.75 kWh of heating).

Notes

[a] NEEP. *Northeast/Mid-Atlantic Air-Source Heat Pump Market Strategies Report 2016 Update*. January 2017. Available at: https://neep.org/sites/default/files/NEEP_ASHP_2016MTStrategy_Report_FINAL.pdf

[b] Source: "Boston – Lowest Temperature for Each Year." *Current Results: Weather and Science Facts*. n.d. Available at: https://www.currentresults.com/Yearly-Weather/USA/MA/Boston/extreme-annual-boston-low-temperature.php

[c] NEEP. *Cold Climate Air Source Heat Pump (ccASHP) Product List*. Available at: https://ashp.neep.org/#!/

We find that, across HVAC systems of the same size, the lifetime cost (including equipment, fuel and electricity) of a gas furnace and central AC system is very similar to the lifetime cost of a heat pump system. Over an 18-year period (the assumed life of a gas furnace), heat pumps' total costs are approximately $650 more than new combined gas heating and electric central AC: a 2 percent addition to heating and cooling costs over the 18-year lifetime of the equipment before Massachusetts state heating replacement rebates are taken into consideration:

- **Replacement of gas heating system:** For owners of gas heating in need of replacement, these rebates increase the new gas system's cost advantage. Replacement with a gas furnace plus central AC costs 4 percent less than a heat pump in total heating and cooling costs over the 18-year equipment lifetime. Choosing heat pumps costs **$73 more** per year than a gas furnace and central AC.
- **Replacement of oil heating system:** For owners of oil heating, the rebates turn the tables to give heat pumps a cost advantage. Replacement with a gas furnace plus central AC costs 9 percent more than a heat pump in total heating and cooling costs over the 18-year equipment lifetime. Choosing heat pumps costs **$158 less** per year than a gas furnace and central AC.

These results hold across a range of forecasted gas and electric prices, and financing options.

Massachusetts' *2018 Comprehensive Energy Plan* most aggressive residential heat pump targets (converting one-fifth of gas heating systems and one-third of oil heating systems) achieve 27 percent of the 2030 emissions reduction necessary from the buildings sector to keep the Commonwealth on track to meet its Global Warming Solution Act mandate for 2050.[6] The same level of gas conversions combined with converting three-quarters of oil heating systems (per another Commonwealth-sponsored report) to heat pumps conversions achieves 42 percent of the 2030 emission reductions needed in the buildings sector.

2. Comparing the Cost of HVAC Systems

For Massachusetts households, investing in a heat pump system instead of a combination of a new gas furnace and central AC system either costs an additional $73 per year or saves them $158 per year, depending on weather the household currently owns a gas or an oil heating system. Past rebates provided strong incentives for switching from gas or oil heat to heat pumps. Currently, Massachusetts' efficient heating rebates still provide a strong incentive for switching from oil heating to a heat pump system. For owners of aging gas heating, however, incentives to upgrade to a new gas furnace are more than double those for adopting heat pumps (see Table 1).[7] Current rebates for oil heating system owners provide an incentive to switch to heat pumps that is higher than their costs, whereas rebates for owners of existing gas systems provide an incentive to choose a new gas furnace and electric AC over switching to heat pumps.

Table 1. Massachusetts efficient heating and cooling rebates (2017$)

	Massachusetts Rebate	
	Before April 2019	After April 2019
New Efficient Gas Furnace	$957	$957
Central AC	$144	$144
Heat Pump (for gas furnace owners)	$1,982	$431
Heat Pump (for oil furnace owners)	$6,145	$4,594

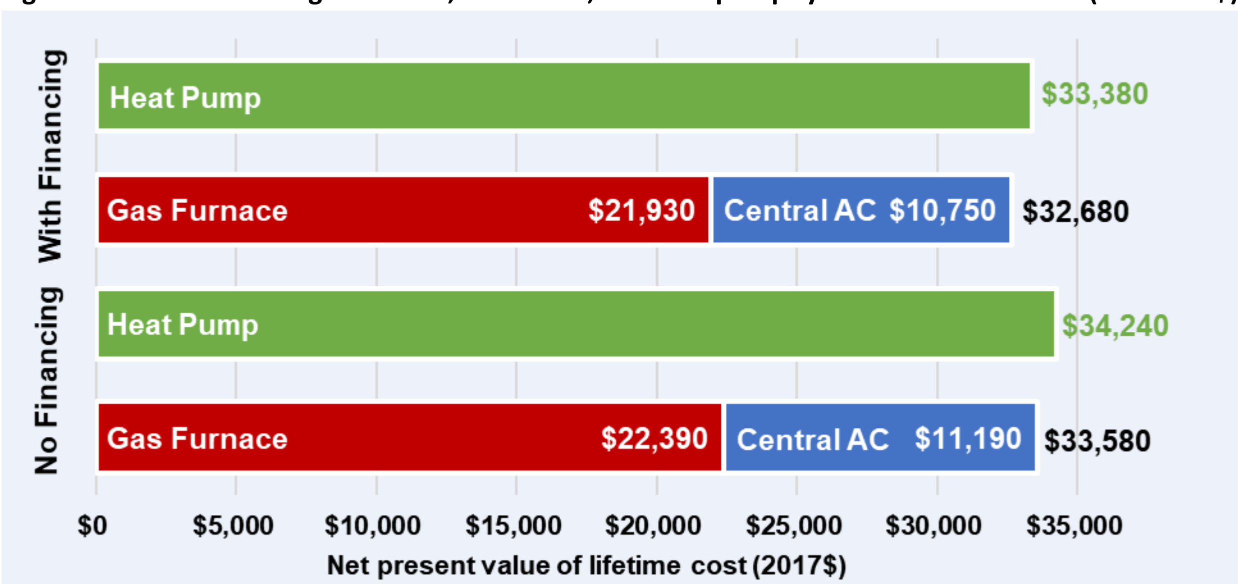
Note: Heat pump rebates for January 2019 include the median MassCEC rebate for 3-ton heat pumps ($1,551).

[6] Woods, B., Stanton, E. A. & Lopez, R. 2019. *Gas Utilities and the Fight to End Climate Change*. Applied Economics Clinic Policy Brief.
[7] Mass Save. High-Efficiency Natural Gas Heating Equipment Rebates. Available at: https://www.masssave.com/-/media/Files/PDFs/Save/Residential/2019MSHC13593712019-GasNetworks-Rebate-FormsFILL.pdf?la=en&hash=71142B6EFD962ED4A38BE59F444D9AB78ED1B45C. Central Air Conditioning and Heat Pump Rebate Amounts. Available at: https://www.masssave.com/-/media/Files/PDFs/Save/Residential/2019/2019-CentralAirCHP-RebateForm.pdf?la=en&hash=AE83319EAD2C12E468DED58DD415545C9ECC2AE6.

Figure 4 presents the total lifetime costs of two options (both of which do not include the Massachusetts rebates presented above in Table 1) and both over a period of 18 years (2019 through 2036): a heat pump system, and a gas furnace and central AC system.[8]

Both HVAC options are assumed to provide the same levels of heating and cooling, based on the typical Massachusetts household's gas furnace and central AC usage.[9] (See Appendix A: Methodology and Key Assumptions for a detailed explanation of our methodology and assumptions.) We present these results for households that pay upfront (i.e. no financing) and those that finance their purchase through the Mass Save HEAT Loan, which offers homeowners a zero-percent interest rate loan to purchase qualified heating or cooling equipment systems of up to $25,000, payable over a maximum of seven years.[10] The estimated difference in costs or savings of between the two system types are small but robust under varying assumptions including the likely range of future fuel and electric prices, heat pump equipment costs, and of the existence or absence of zero-interest financing.

Figure 4. Lifetime cost of gas furnace, central AC, and heat pump system without rebates (NPV 2017$)



[8] Eighteen years corresponds to the useful life of a gas heating system, according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers. *Equipment Life Expectancy Chart*. Available at: https://www.naturalhandyman.com/iip/infhvac/ASHRAE_Chart_HVAC_Life_Expectancy.pdf

[9] A typical Massachusetts household uses 69.2 MMBtus of natural gas per year and 328 kWh of electricity per year for gas heating, and 1,530 kWh for cooling. See Appendix A: Methodology and Key Assumptions.

[10] Mass Save HEAT Loan Program. Available at: https://www.masssave.com/en/saving/residential-rebates/heat-loan-program/. When households finance their purchase with a zero-interest loan, the lifetime cost of both HVAC systems is lower than the cost in the case of no financing. Defrayed costs have less value today (that is, we apply a discount rate of 3 percent to future costs).[10]

3. Sensitivity Analysis

The results presented above are based on Massachusetts-specific forecasts of gas and electricity prices as well the cost of purchasing and installing an HVAC system. The finding that the lifetime cost of a heat pump system is very similar to the lifetime cost of a gas heating and electric cooling system is robust under different assumptions regarding fuel and electric prices, but is sensitive to the variations in heat pump equipment costs associated with specific home installations.

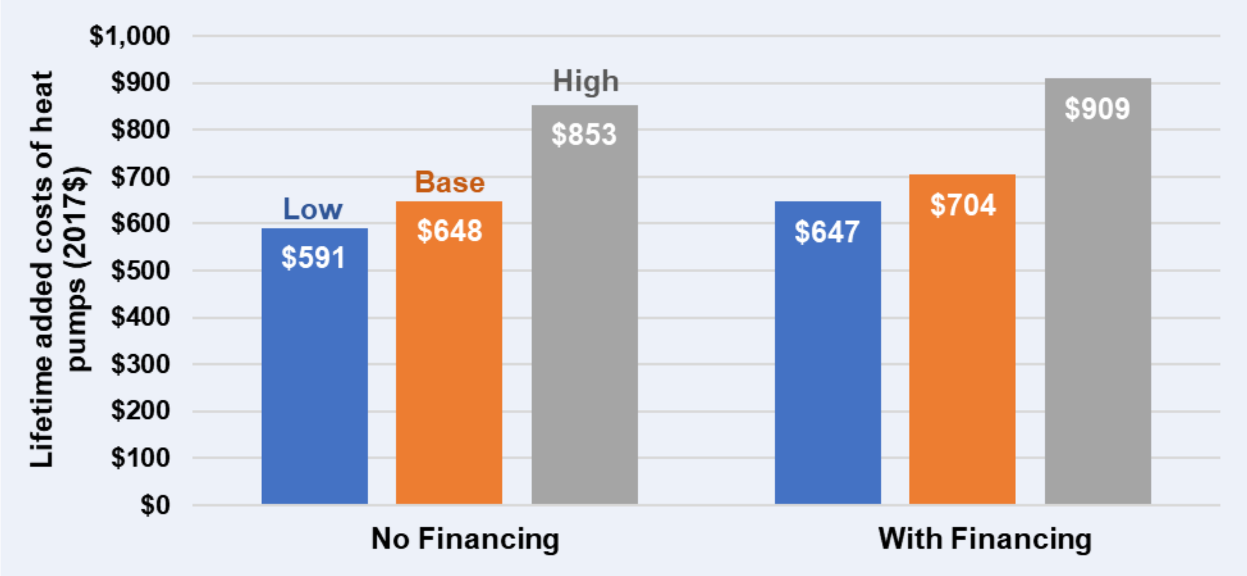
Sensitivity to gas and electricity prices

Lifetime HVAC system costs change very little in response to varying assumptions regarding future prices of gas and electricity. We tested the sensitivity of HVAC costs to different future levels of gas and electric prices. Starting with the actual Massachusetts gas heating and electric costs for 2018, we project gas and electricity prices using forecasted rates of price growth for the New England region from the Energy Information Administration's (EIA) 2019 Annual Energy Outlook (AEO 2019). We considered two sensitivities: 1) a low price case where gas and electric prices grow at a slower rate, 2) a high price case where prices grow at a faster rate.[11]

Lifetime additional costs from a heat pump system compared to a gas furnace and central AC combination, both without rebates, range from $591 to $909, depending on fuel prices and financing (shown in Figure 5). As discussed further in Appendix A: Methodology and Key Assumptions, the prices of gas and electricity are both expected to increase over the 18-year modeling period. Electric and gas prices are closely correlated because power plants that burn gas typically set the price of electricity in New England.[12] Thus, operating costs of household's HVAC options will increase under both HVAC types (gas or electric heat pump).

[11] The assumptions used in these two cases are explained in EIA. Annual Energy Outlook 2019. Case Descriptions. January 2019. Available at: https://www.eia.gov/outlooks/aeo/pdf/case_descriptions.pdf
[12] See: DRAFT 2017 ISO New England Electric Generator Air Emissions Report, Figure 4-7. Available at: https://www.iso-ne.com/static-assets/documents/2019/04/2017_emissions_report.pdf

Figure 5. Heat pumps lifetime added costs (no rebate) by fuel and electric price (Delta NPV 2017$)



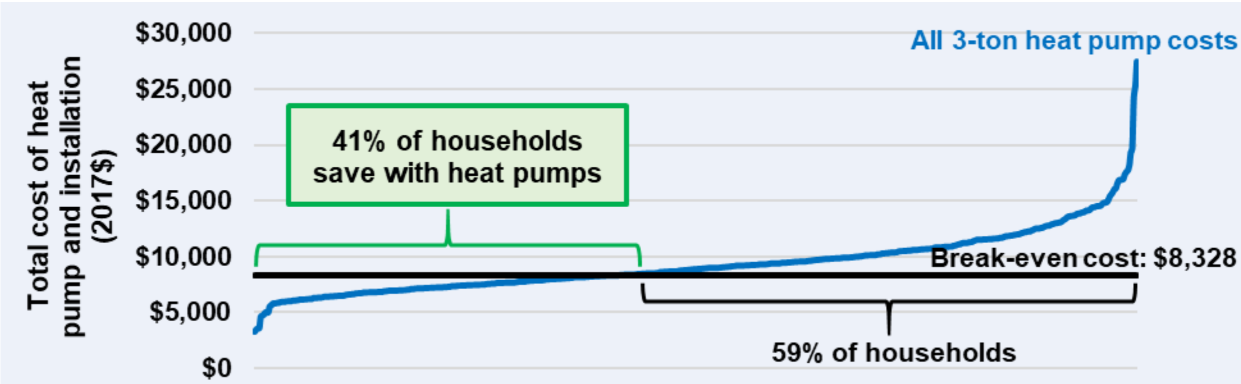
Sensitivity to the cost of heat pump installation

Lifetime cost differences between HVAC options are sensitive to the upfront cost of equipment installation. Since the market for heat pumps is not as mature as the market for traditional heating and cooling equipment, and because housing structures vary, we examine the sensitivity of our results to different costs of heat pump equipment using recent historical data for Massachusetts. Based on data from the Massachusetts Clean Energy Center (MassCEC) database of heat pump installations of systems approximately 3 tons in size (36,000 British thermal unit (Btu)),[13] the total installed cost of a heat pump system that would "break-even" with (or be exactly equal to) the lifetime cost of the gas furnace and central AC system is $8,328 under the no financing, no rebates scenario. MassCEC data show Massachusetts actual heat pump installation costs of a 3-ton system ranging from $3,268 to $27,473 in 2014-2018 (Figure 6, shown in blue). Our main estimate of heat pump system costs, above, uses the median cost for this size of system, $8,890.

Based on these actual Massachusetts costs, 41 percent of households that installed heat pumps in 2014-2018 spent less than the break-even cost while 59 percent spent more. Seventy percent of the reported 3-ton heat pump costs would result in annual costs within $100 per year of the gas alternative, and 90 percent of these heat pumps were within $248 per year.

[13] The dataset is available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ResidentialASHPProjectDatabase.xlsx. Our analysis is limited to data for households with one outdoor unit and two indoor units, the most common heat pump system size in the dataset.

Figure 6. Distribution of heat pump cost and break-even cost (no financing, no rebates) (2017$)



Sensitivity to rebates

The household HVAC system decision is sensitive to the existence of Massachusetts financial incentives for the adoption of highly efficient HVAC systems. In the absence of all Massachusetts state rebates for replacing old heating systems, purchasing and operating a heat pump costs $650 more than purchasing and operating a gas furnace and electric central AC over the 18-year lifetime of the equipment—or $36 more each year (see Table 2). With current Massachusetts rebates, owners of aging oil heating systems save $158 per year by choosing to replace with a heat pump instead of a gas furnace and central AC. For owners of gas heating systems, however, rebates for heat pumps are smaller than rebates for new gas furnaces, raising the relative cost of choosing heat pumps from $36 per year with no rebates to $73 per year with the rebates.

Table 2. Annual cost savings and losses by heating system type (2017$)

	MassSave Rebate	Annual Cost Savings or Loss	
		No Rebates	With Rebates
New Gas Furnace and Central AC	**$1,101**	**$36**	**$73 / -$158**
Heat Pump (for gas furnace owners)	**$431**	**-$36**	**-$73**
Heat Pump (for oil furnace owners)	**$4,594**	**-$36**	**$158**

Our study includes rebates that are available to Massachusetts households switching to heat pumps regardless of the type of installation. On May 8, 2019, MassCEC announced that it has allocated $500,000 on a pilot program (not included in this analysis) that would provide rebates both for whole-house heat pumps systems that replace the entire gas system of a house (including gas cooking and hot water), and for new construction.[14] These pilot program rebates start at $2,500 per residence and go up to $5,000 for lower-income households. At present, the program is short-term and has budget sufficient to serve only 100-200 Massachusetts households.

[14] MassCEC. May 8, 2019. "Whole-Home Air-Source Heat Pump Pilot Manual. Available at: https://files-cdn.masscec.com/get-clean-energy/residential/air-source-heat-pumps/WholeHomePilotManual.pdf

Increased energy usage

It is possible that households purchasing a heat pump system would use it more than they would have used another type of HVAC system. For example, households may perceive that they are saving money and therefore find it less important to conserve.

Information on potential increases in energy usage with heat pump usage is limited. In the absence of a robust literature on this topic, we estimated the break-even additional energy usage that would make the lifetime cost of a heat pump exactly equal to the lifetime cost a gas furnace and central AC system for households that switch from oil heating and receive the current Mass Save rebates. For the purposes of this report, we quantify this increased usage as a percentage increase in energy consumption relative to the typical household usage. For example, if a heat pump would use 100 Btus to generate the same level of heating and cooling as a gas furnace and a central AC combination, but the household ends up using 102 Btus, then the increased energy usage would be 2 percent.

With base gas and electric prices and current Massachusetts financial incentives, for a household switching from oil heating the increased energy usage that would make the lifetime costs of the gas furnace and heat pump alternatives equal is 12.4 percent without financing and 12.1 percent with financing (see Appendix D: Calculation of break-even for details).

4. Global Warming Solutions Act

With lifetime costs now on par with gas heating with electric central AC systems, conversion of HVAC systems in need of replacement to heat pumps makes economic sense for Massachusetts families. Choosing heat pumps over gas and other fossil fuel heating also makes an important contribution to the Commonwealth's Global Warming Solution Act (GWSA) mandate to reduce state-wide emissions to 80 percent of their 1990 levels by 2050.[15]

Massachusetts DOER's 2018 *Comprehensive Energy Plan*[16] presents three future scenarios of heat pump adoption:

- A business-as-usual **Sustained Policies** scenario (with no change to current day policies): 2 percent of Massachusetts single-family homes heat and cool with heat pumps by 2030
- A **High Electrification** scenario: 25 percent of all oil-heated buildings and 10 percent of all gas-heated in 2030 (together, 12 percent of Massachusetts homes)
- An **Aggressive** scenario: 33 percent of all oil-heated buildings and 20 percent of all gas-heated in 2030 (together, 19 percent of Massachusetts homes)

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[15]The General court of the Commonwealth of Massachusetts. 2008. Acts 308-80. An Act Establishing the Global Warming Solutions Act. Chapter 298. https://malegislature.gov/Laws/SessionLaws/Acts/2008/Chapter298
[16] Massachusetts Department of Energy Resources. 2018. *Massachusetts Comprehensive Energy Plan.* Available at: https://www.mass.gov/files/documents/2019/01/10/CEP%20Report-%20Final%2001102019.pdf.

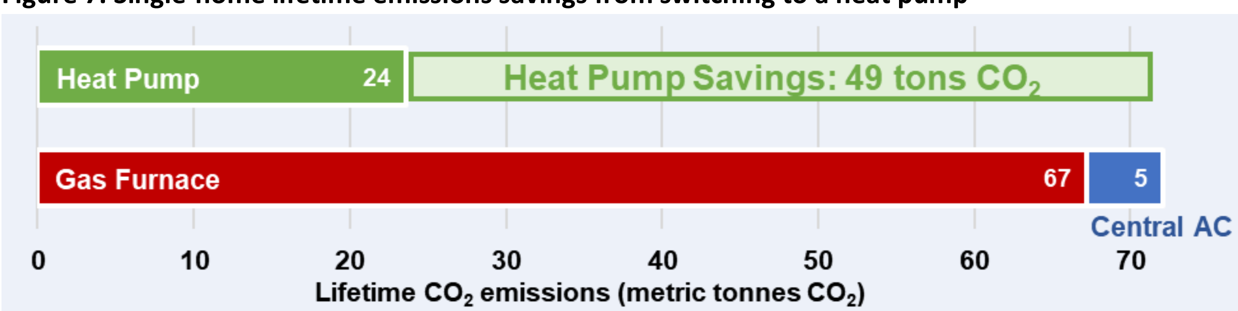
HVAC emissions in the *Comprehensive Energy Plan*'s Aggressive scenario are 1.8 million metric tonnes (MMT) CO_2 lower than in the Sustained Policies Scenario in 2030.

The Executive Office of Energy and Environmental Affairs *2015 Update to the Massachusetts Clean Energy and Climate Plan for 2020*[17] expected its renewable thermal policies (which include heat pumps, solar thermal and solar hot water) to result in a 1.0 MMT carbon dioxide equivalent (CO_2-e) reduction to Massachusetts' greenhouse gas inventory by 2020.

Both the business-as-usual scenario in the 2018 *Comprehensive Energy Plan* and the reduction forecast in the *2015 Update to the Clean Energy and Climate Plan* are roughly consistent with the projected rate of heat pump installations forecast in a 2014 study commissioned by Massachusetts DOER, the *Commonwealth Accelerated Renewable Thermal Strategy*[18] (CART) report. The CART report presented two future scenarios of heat pump market penetration: by 2030, the business-as-usual scenario reaches 220,000 residential heat pumps in Massachusetts and the High State Support scenario reaches 521,000 heat pumps. In contrast to the 2018 *Comprehensive Energy Plan*, both CART report scenarios focus exclusively on conversion of aging oil heating systems to heat pumps (i.e. gas system conversions are not considered): at this rate of conversion, 74 percent of residential oil-heating systems would be converted to heat pumps by 2030 under the CART High State Support scenario, resulting in approximately 1.5 MMT CO_2-e emission reduction.[19]

Converting a single-home HVAC system, of the average size assumed in this report, from gas furnace and electric central AC to a heat pump system avoids 49 metric tonnes of CO_2 over an 18-year lifetime (see Figure 7). To put this in context, the U.S. Department of Energy estimates 18-year emission savings from a Massachusetts driver switching from gasoline to an all-electric vehicle to be 73 metric tonnes.[20]

Figure 7. Single-home lifetime emissions savings from switching to a heat pump



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[17] Massachusetts Executive Office of Energy and Environmental Affairs. 2015. *Massachusetts Clean Energy and Climate Plan for 2020.* Available at: https://www.mass.gov/files/documents/2017/01/uo/cecp-for-2020.pdf.
[18] Massachusetts Department of Energy Resources. 2014. *Commonwealth Accelerated Renewable Thermal Strategy.* Navigant and Meister Consultants Group. Available at: https://www.mass.gov/files/documents/2016/08/tx/carts-report.pdf.
[19] CARTS residential emission reduction estimated as 1/8th total 2030 emission reductions; CARTS Figure 3-9 presents residential BAU emissions that are 1/8th total emissions.
[20] U.S. Department of Energy. n.d. Alternative Fuels Data Center website. "Emissions from Hybrid and Plug-In Electric Vehicles." Available at: https://afdc.energy.gov/vehicles/electric_emissions.html

Massachusetts *2018 Comprehensive Energy Plan* residential conversions: 1.4 MMT CO_2 in 2030

Converting 20 percent of all gas-heated homes in Massachusetts to heat pumps (per the *2018 Comprehensive Energy Plan*) would reduce 2030 emissions by 0.8 MMT CO_2.[21]

Converting 33 percent of all oil-heated homes in Massachusetts to heat pumps (per the *2018 Comprehensive Energy Plan*) would reduce 2030 emissions by 0.7 MMT CO_2. (Emission savings are the difference between gas plus electric central AC and a heat pump: all homeowners replacing oil heating are assumed to choose between replacing it with gas heating or a heat pump.)[22]

Massachusetts 2014 CART study residential conversions: 1.5 MMT CO_2 in 2030

Converting 74 percent of all oil-heated homes (and no gas-heated homes) in Massachusetts to heat pumps (per DOER's 2014 CART study) would reduce 2030 emissions by 1.5 MMT CO_2 (in comparison to converting these oil heating systems to gas).[23]

Combining the potential emission reductions from gas to heat pump and oil to heat pump conversions results in a range of 2030 emission reductions from 1.4 to 2.2 MMT CO_2, or 1 to 2 percent of the Commonwealth's 1990 emission level.

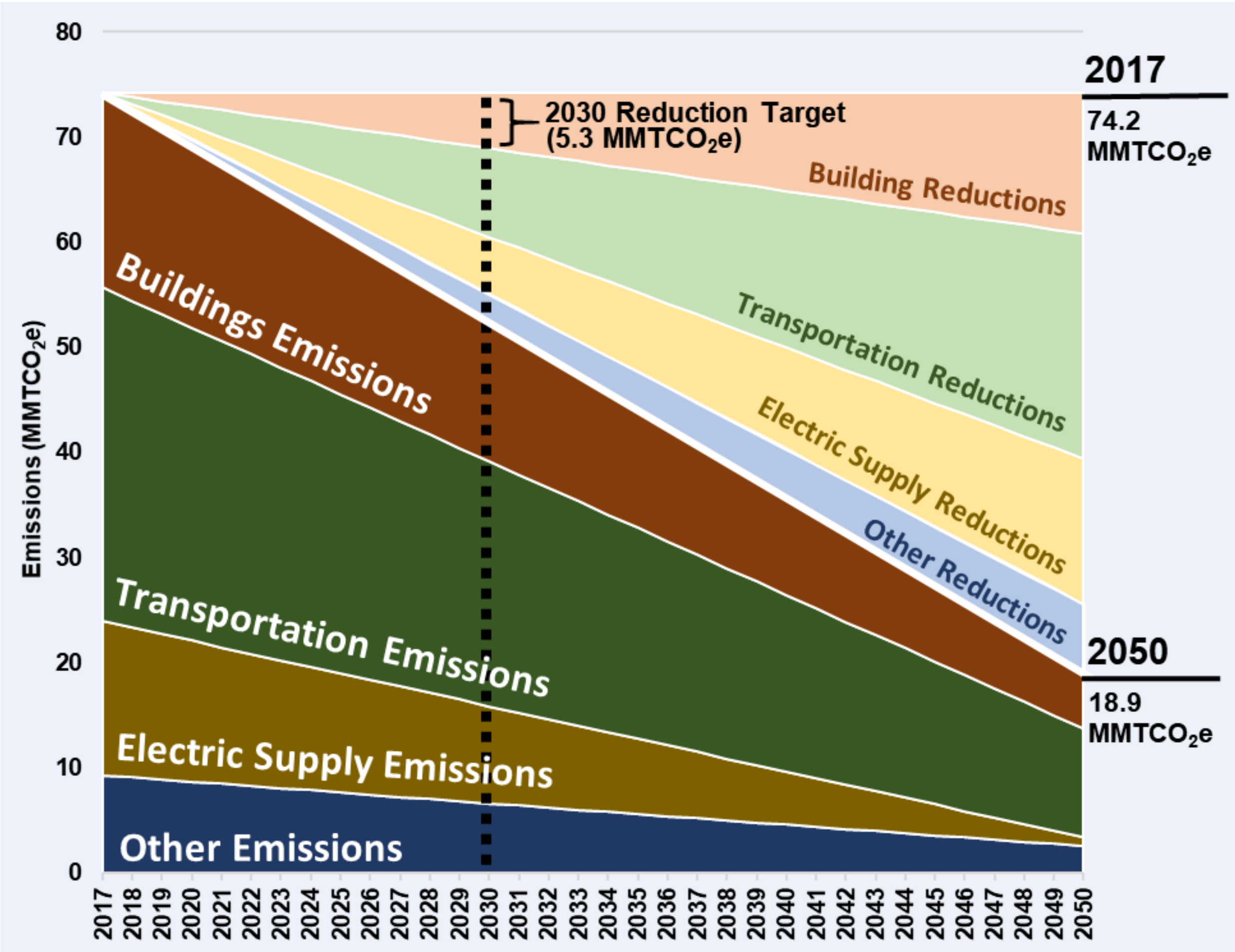
100 percent residential conversion by 2030: 7.2 MMT CO_2 in 2030

To give these numbers some additional context, using these same assumptions, conversion of all residential gas and oil heating systems (with electric central AC) to heat pumps would result in a 7.2 MMT CO_2 reduction in 2030, or 8 percent of 1990 emissions levels. (This reduction would be incremental to the emission savings of converting all oil heating to gas, which would result in an additional 1.4 MMT CO_2 reduction.)[24]

While the Commonwealth has not yet set targets for 2030 emission reductions, 1 percent of 1990 emission levels (0.9 MMT CO_2) is equivalent to 18 percent of the 2030 building sector emissions reductions (5.3 MMT CO_2) needed to keep Massachusetts on track to reach its 2050 emission target (Figure 8). The *2018 Comprehensive Energy Plan's* aggressive residential heat pump targets achieve 27 percent of the necessary 2030 buildings sector emission reduction; increasing oil to heat pump conversions to the CART level (while keeping the same level of gas conversions) achieves 42 percent. A 100-percent conversion of all residential Massachusetts gas and oil HVAC systems to heat pumps would slightly exceed the 2030 goal.

[21] Assumes heat pumps of the size described in this report.
[22] Assumes heat pumps of the size described in this report.
[23] Assumes heat pumps of the size described in this report.
[24] Assumes emission reductions proportional to those from the heat pumps described in this report.

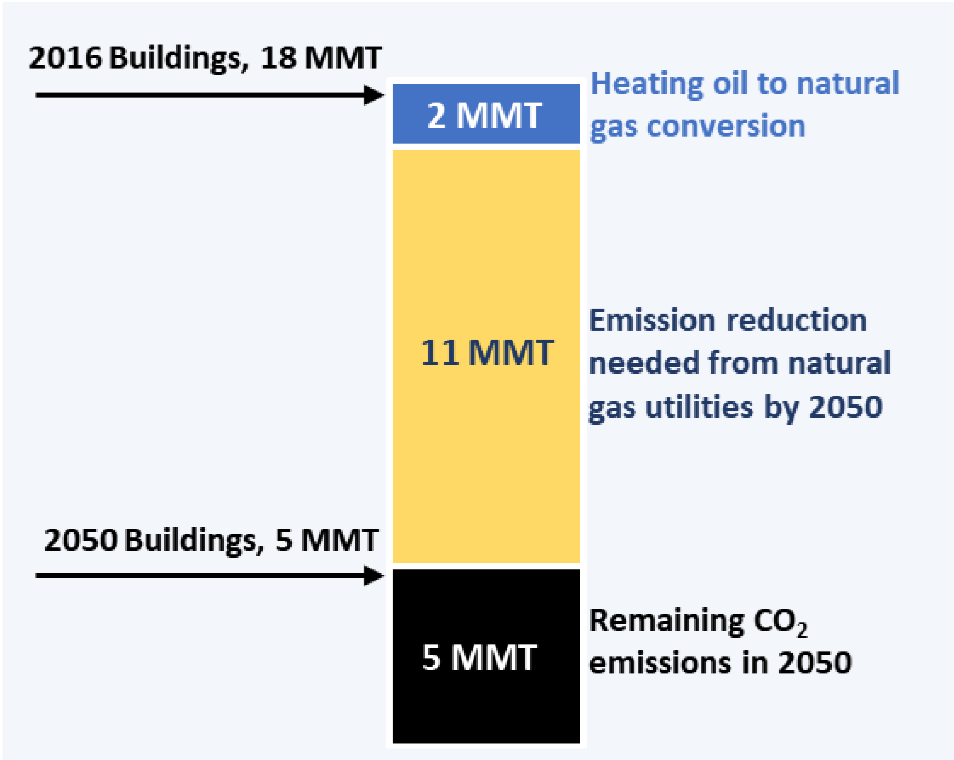
Figure 8. Massachusetts state-wide emissions reductions for GWSA compliance



Source: For the purposes of this figure, 2017 emissions are assumed to be equal to 2016 emissions in MA DEP, *Appendix C: Massachusetts Annual Greenhouse Gas Emission Inventory: 1990-2016, with Partial 2017 Data* (https://www.mass.gov/lists/massdep-emissions-inventories); 2017 emission reporting was not available as of the publication of this white paper; 2050 emissions per MA Executive Office of Energy and Environmental Affairs. 2015. *Massachusetts Clean Energy and Climate Plan for 2020.* (https://www.mass.gov/files/documents/2017/01/uo/cecp-for-2020.pdf).

Note that the emissions savings from heat pumps discussed in this report include only the difference in emissions between the gas furnace and central AC and the heat pump alternatives. There is, however, an additional source of emission savings that would occur simultaneously from the replacement of existing oil heating systems. Converting all Massachusetts oil heating to natural gas would save approximately 2 MMT CO_2 (see Figure 9). This amount is prior to (and in addition to) the emissions savings of choosing heat pumps instead of new natural gas systems.

Figure 9. Massachusetts total building sector emissions and potential reductions



Source: Reproduced from Woods, Stanton, and Lopez. April 2019. *Gas Utilities and the Race to End Climate Change*. Applied Economics Clinic Policy Brief. https://aeclinic.org/publicationpages/2019/4/12/performance-based-incentives-for-gas-utilities

Technical Appendices

Appendix A: Methodology and Key Assumptions

Table 3 presents values used to calculate the lifetime cost of a combined gas furnace and electric central AC and the lifetime cost of a 3-ton heat pump system, including installation costs, useful life, efficiency levels, rebates, and annual consumption of gas and electricity for gas furnace and central AC in Massachusetts.[25] All the data sources used in this report are also listed in Appendix E: Data sources.

Table 3. HVAC cost assumptions

	Gas Furnace	Central AC	Heat Pump Mini-Split
Equipment and Installation Cost (2017$)	$5,557	$4,650	$8,880
Annual Maintenance Cost (2017$)	$40	$73	$73
Life Expectancy -Median (Years)	18	15	15
AFUE (%)	95		
SEER (BTU/watt-hr)		16.5	19
HSPF (BTU/watt-hr)			11
Annual Natural Gas Consumption (MMBTU)	69.2		
Annual Electricity Consumption (kWh)	328	1,530	
MassSave Rebate (2017$)	$957	$144	$431

We assume that the residential heating and cooling systems have efficiency levels high enough to receive a rebate from the Mass Save program in 2019. For the gas furnace, this would mean an Annual Fuel Utilization Efficiency (AFUE) of 95 percent.[26] (This AFUE means that for every 100 Btus of gas used, the furnace produces 95 Btus of heating energy.) For AC, we assume a central system with a Seasonal Energy Efficiency Ratio (SEER) of 16.5 Btu/watt-hour.[27] The SEER measures the cooling output of a system in Btus per watt-hour of electricity used. The higher the SEER, the more efficient the unit. Mass Save rebates are given either by unit in the case of a gas furnace or by “refrigeration ton” in the case of central AC and heat pump systems.[28] We assume that both the central AC system and the heat pump system have a capacity of approximately 3 refrigeration tons.[29]

[25] The electricity consumed by the gas furnace is used to operate furnace components, such as the fan and the ignitor.
[26] Mass Save Available Rebates, Natural Gas Equipment. Available at: https://www.masssave.com/en/saving/residential-rebates/gas-heating-equipment/
[27] Forecast for central AC systems until 2050. Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
[28] As of 2019, the Mass Save rebate for a gas furnace with an AFUE of at least 95% is $1,000. For a central AC system with a SEER greater or equal to 16, the rebate is $50 per ton, while for a ductless heat pump with a SEER of at least 15 and an HSPF of at least 10 is $150 per refrigeration ton. A refrigeration ton is approximately 12,000 Btu per hour.
[29] Replacement system for residential, “medium-sized” home of 3-tons: Navigant Consulting. Ductless Mini-Split Heat Pump Costs Study (RES 28). p.7. Available at: http://ma-eeac.org/wordpress/wp-

For the heat pump system, we assume that it has a SEER of 19 Btu/watt-hour and a Heating Seasonal Performance factor (HSPF) of 11 Btu/watt-hour.[30] The HSPF measures the heating output of a heat pump in Btus per watt-hour of electricity used.

For any of the installations (gas furnace, central AC, or heat pumps), households have the option of applying to the Mass Save HEAT Loan, which allows homeowners to obtain a zero-percent interest rate on a loan of up to $25,000 and payable in seven years to finance the purchase of high efficiency heating and cooling equipment.[31] We present our results in which the typical household pays for the equipment in full at the year of installation (no financing), and also for the case in which the household qualifies for the HEAT Loan (with financing).

Annual consumption of gas is assumed to be the Massachusetts average of the last five winters available (2013/2014 through 2017/2018) reported by DOER. Massachusetts annual consumption of electricity for central AC comes from a 2018 Navigant Consulting report.[32] We also calculate the amount of electricity used by a heat pump system that generates the same level of heating and cooling as the gas furnace and central AC combination (see Appendix C: Calculation of heat pumps heating and cooling costs for a detailed explanation).

To calculate the lifetime cost of energy consumption for the gas furnace and AC system we use projections of the price of gas and electricity for the next 18 years. For gas, we use the average price of gas heating in Massachusetts for the winters of 2017/2018 and 2018/2019, reported by the Massachusetts DOER,[33] as the price for 2018 and project it through 2036 using the forecasted rate of growth for New England by the EIA in its Annual Economic Outlook 2019 Reference Case.[34] For electricity, we use the average price of electricity for residential customers in Massachusetts for 2018 reported by EIA,[35] and project it through 2036 using the projected rate of growth in electric prices from

content/uploads/RES28_Assembled_Report_2018-10-05.pdf. Using the Massachusetts Clean Energy Center (MassCEC) database of air-source heat pump residential projects with data from December 2014 to March 2018, we pulled the median residential project cost in Massachusetts for heat pump systems within 10 percent of 3-tons in capacity (i.e. between 32,400 and 39,600 Btus). The dataset is available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ResidentialASHPProjectDatabase.xlsx

[30] Using the MassCEC database of air-source heat pump residential projects, we found that the average SEER and the average HSPF of heat pumps systems of one outdoor unit and two indoor units purchased by residential customers between April 2017 and March 2018 (the last 12 months of data available) is 19.2 and 10.6, respectively. Thus, we round the SEER to 19 and the HSPF to 11. The dataset is available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ResidentialASHPProjectDatabase.xlsx

[31] Information on the Mass Save HEAT Loan can be found at: https://www.masssave.com/en/saving/residential-rebates/heat-loan-program/

[32] Navigant Consulting. RES 1 Baseline Load Shape Study. Report Prepared for the Electric and Gas Program Administrators of Massachusetts, Part of the Residential Evaluation Program Area. July 2018. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/RES-1-FINAL-Comprehensive-Report-2018-07-27.pdf

[33] Massachusetts Department of Energy Resources. *Household Heating Costs: Forecast of energy prices for heating fuels during 2018/19 Winter Heating Season*. Available at: https://www.mass.gov/info-details/household-heating-costs

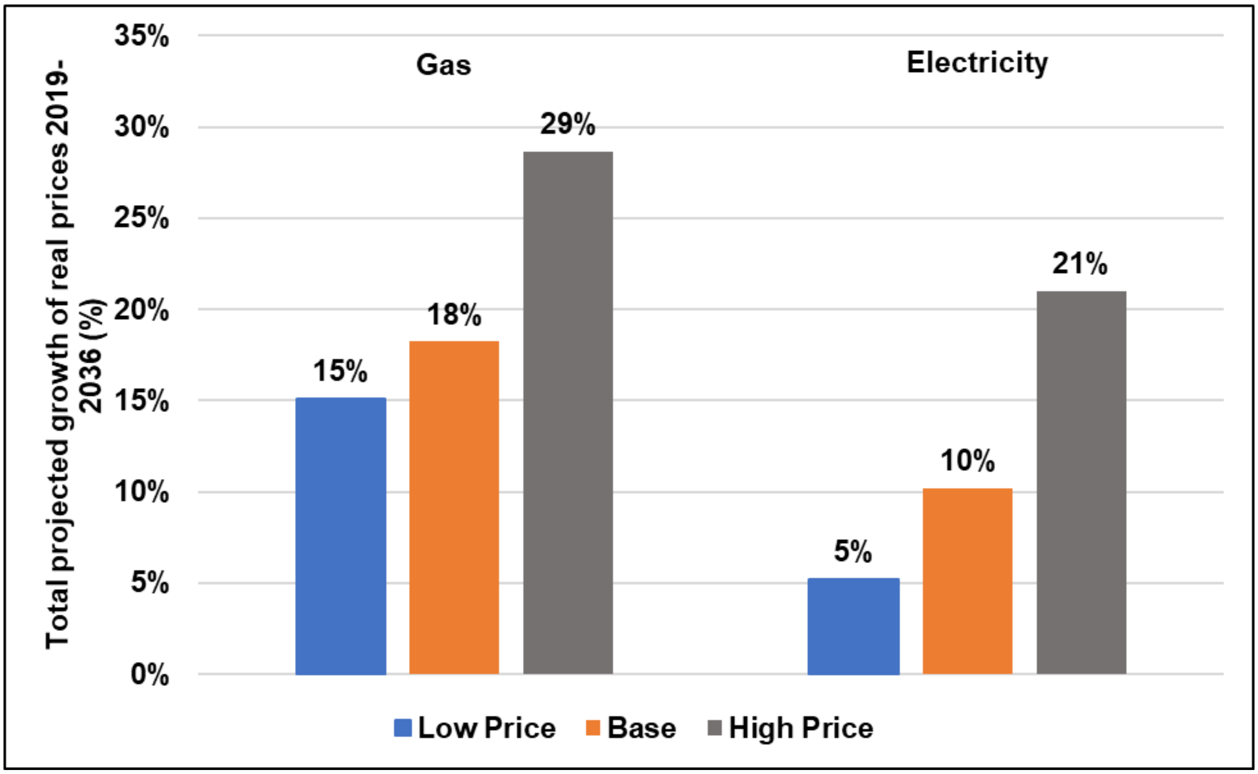
[34] EIA. *Annual Energy Outlook 2019*. Reference Case. Available at: https://www.eia.gov/outlooks/aeo/

[35] EIA. *Electric Power Monthly. Table 5.6.B*. February 2019. Available at: https://www.eia.gov/electricity/monthly/

the same AEO 2019 Reference Case. We use the EIA's "High Oil and Gas Resource and Technology" scenario for the low gas/electricity price sensitivity and the "Low Oil and Gas Resource and Technology" scenario for the high gas/electricity price sensitivity.

Figure 10 shows EIA's projected growth of gas and electric prices in New England for the low, base, and high price cases for 2019-2036. As shown in the graph, the real (i.e. inflation-adjusted) price of gas is expected to grow between 15 percent and 29 percent. The price of electricity grows 5 percent in the low-price case and 21 percent in the high-price case. For this reason, savings from heat pumps are expected to be lower in the high price case compared to the low price and base cases.

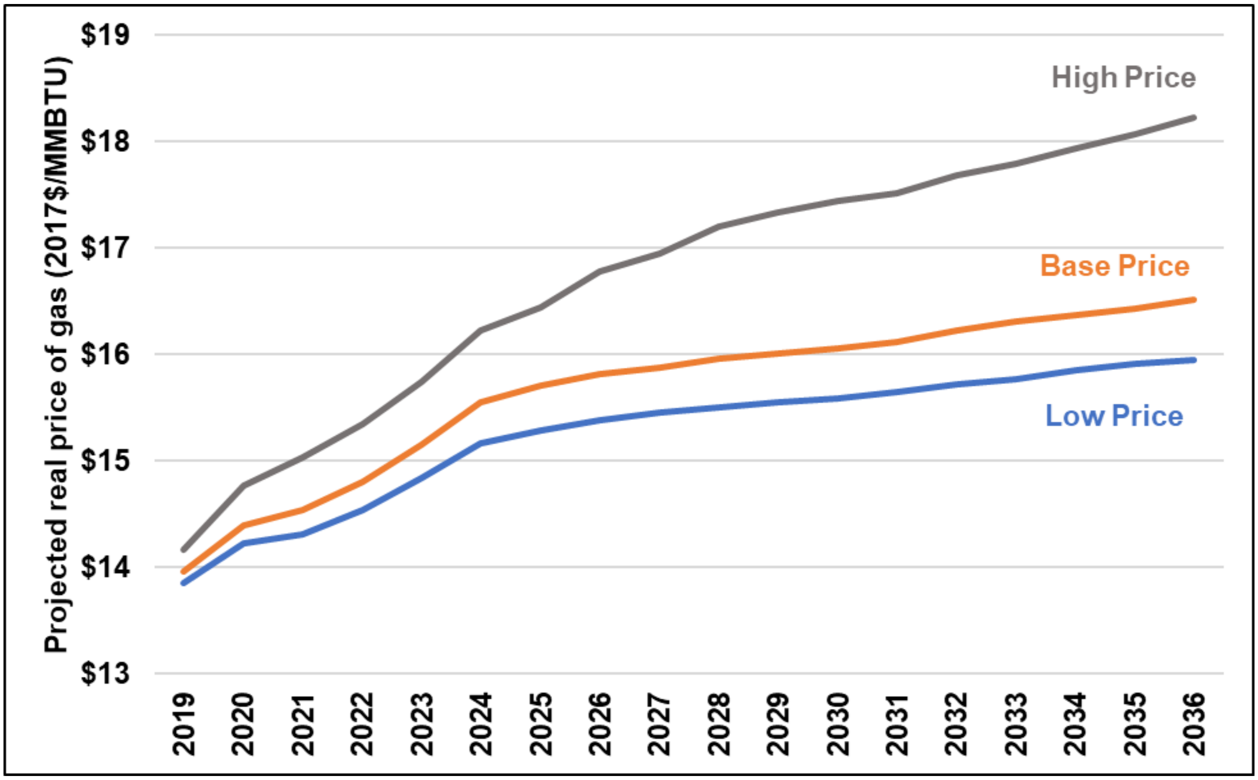
Figure 10. Total projected growth of gas and electricity real prices (2019-2036)



Source: EIA. *Annual Energy Outlook 2019*. Available at: https://www.eia.gov/outlooks/aeo/

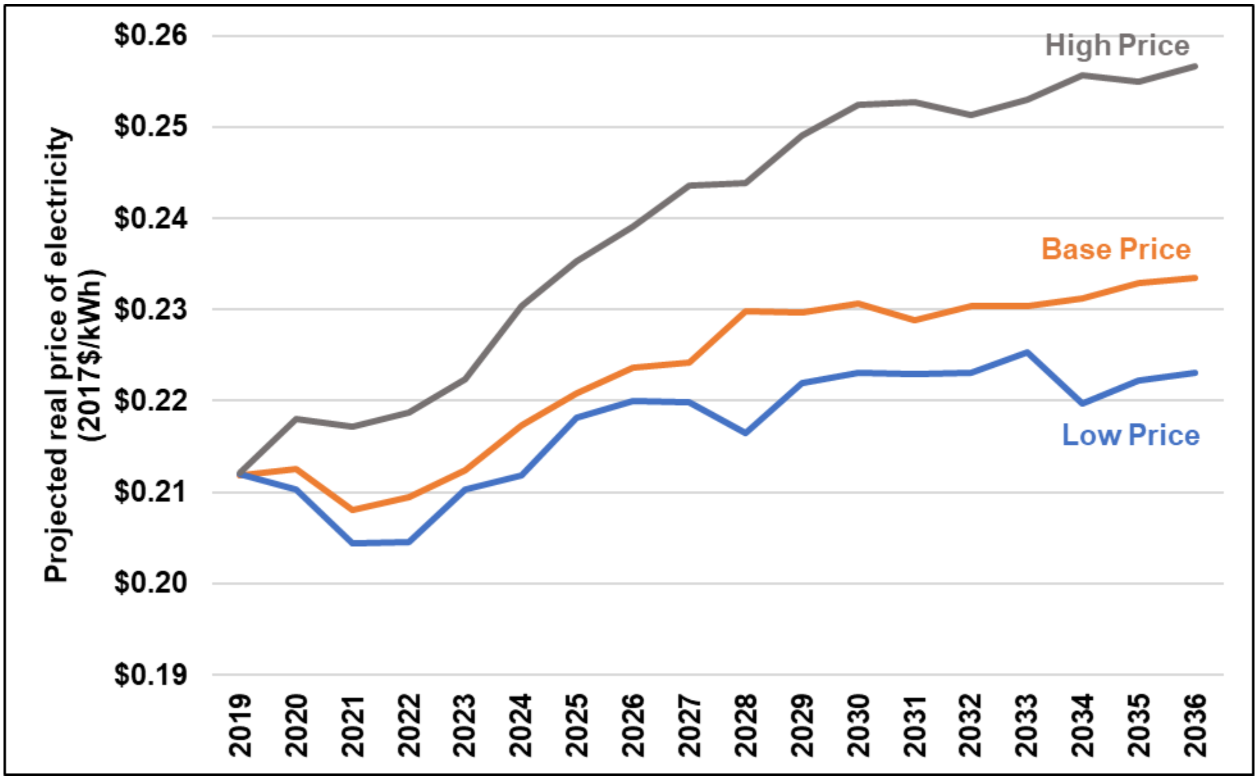
Figure 11 and Figure 12 below show the projected path of gas and electric real prices under the three price scenarios: low, base, and high price.

Figure 11. Projected real price of gas (2017$/MMBtu)



Source: Massachusetts Department of Energy Resources. *Household Heating Costs: Forecast of energy prices for heating fuels during 2018/19 Winter Heating Season*. Available at: https://www.mass.gov/info-details/household-heating-costs. EIA. *Annual Energy Outlook 2019*. Available at: https://www.eia.gov/outlooks/aeo/

Figure 12. Projected real price of electricity (2017$/kWh)



Source: EIA. *Electric Power Monthly. Table 5.6.B*. February 2019. Available at: https://www.eia.gov/electricity/monthly/. EIA. *Annual Energy Outlook 2019*. Available at: https://www.eia.gov/outlooks/aeo/

Appendix B: Net present value calculation

To compare the cost of the different HVAC alternatives, we calculate the net present value (NPV) of the cost of installing and operating a gas furnace and a central AC system with the NPV of the cost of installing and operating a heat pump for both heating and cooling. We assume that the life expectancy of a gas furnace is 18 years, while for central AC systems and mini-split heat pumps the life expectancy is 15 years.[36] We express all dollar values in 2017 dollars using the Consumer Price Index and calculate NPV using a real discount rate of 3 percent.[37]

For a gas furnace that operates for 18 years, the NPV is calculated as follows:

$$NPV_{Gas} = C - R + \sum_{t=1}^{18} \frac{F_t + E_t}{(1+r)^{t-1}}.$$

[36] These numbers are taken from the ASHRAE Equipment Life Expectancy Chart, available at: https://www.naturalhandyman.com/iip/infhvac/ASHRAE_Chart_HVAC_Life_Expectancy.pdf
[37] Bureau of Labor Statistics. Consumer Price Index (CPI) Databases. Available at: https://www.bls.gov/cpi/data.htm

C is equal to the installed cost of the gas furnace, R is the rebate from Mass Save, F is the annual spending on equipment maintenance, E_t are energy costs (gas and electricity), r is the real rate of discount (assumed to be 3 percent).

Since central AC systems and heat pumps are assumed to last only 15 years, we calculate the NPV for those two as:

$$NPV_{AC\ or\ HP} = \sum_{t=1}^{18} \frac{LC_t}{(1+r)^{t-1}},$$

where LC_t is the levelized cost of the central AC system or the heat pump system, calculated as:

$$LC_t = c_t l_t^{i,om} + c_t p_t,$$

where c_t is the consumption of electricity (in kWh per year), p_t is the price of electricity per kWh ($/kWh), and $l_t^{i,om}$ is the levelized installation and maintenance cost per kWh, calculated as:

$$l_t^{i,om} = \frac{C - R - \sum_{i=1}^{15} \frac{F_i}{(1+r)^{i-1}}}{\sum_{i=1}^{15} \frac{c_t}{(1+r)^{i-1}}}\ for\ 0 < t < 16,$$

and:

$$l_t^{i,om} = \frac{C - \sum_{i=1}^{15} \frac{F_t}{(1+r)^{i-1}}}{\sum_{i=1}^{15} \frac{c_t}{(1+r)^{i-1}}}\ for\ 16 \geq t \geq 18.$$

In other words, we assume that the rebate is given only for the first purchase of a central AC or heat pump and that the cost of buying and installing a central AC system and a heat pump in year 16 is equal to the cost in 2019 in real terms.

Appendix C: Calculation of heat pumps heating and cooling costs

We calculate the amount of electricity that the heat pump would consume to generate the same level of heating than the gas furnace and the same level of cooling than the central AC system. For heating, we calculate this as:

$$Heating\ HP\ (kWh) = \frac{NGC\ \times AFUE \times 10^3}{HSPF},$$

where NGC is the consumption of gas used for heating (in MMBtu), and HSPF is the Heating Seasonal Performance Factor of the Heat Pump.

We calculate the electricity consumption needed to generate the same level of cooling that a central AC system using the formula:

$$Cooling\ HP\ (kWh) = \frac{ACC\ \times SEER^{AC}}{SEER^{HP}},$$

where ACC is the central AC system electricity consumption (in kWh), while $SEER^{AC}$ and $SEER^{HP}$ correspond to the Seasonal Energy Efficiency Ratio for a high-efficiency central AC system and for a heat pump, respectively.

Appendix D: Calculation of break-even increased energy usage for households that switch from oil heating

To calculate the break-even increased energy usage (ieu) that would make the NPV of a heat pump system equal to the NPV of installing a gas furnace and a central AC system for a household switching from oil heating we assume:

$$NPV_{HP}(ieu) = NPV_{Gas} + NPV_{AC},$$

$$\sum_{t=1}^{18} \frac{LC_t(ieu)}{(1+r)^{t-1}} = NPV_{Gas} + NPV_{AC},$$

$$\sum_{t=1}^{18} \frac{c_t l_t^{i,om} + (1+ieu)c_t p_t}{(1+r)^{t-1}} = NPV_{Gas} + NPV_{AC},$$

$$(1+ieu)\sum_{t=1}^{18} \frac{c_t p_t}{(1+r)^{t-1}} = NPV_{Gas} + NPV_{AC} - \sum_{t=1}^{18} \frac{c_t l_t^{i,om}}{(1+r)^{t-1}}.$$

Therefore, the break-even increased energy usage is calculated as:

$$ieu = \frac{NPV_{Gas} + NPV_{AC} - \sum_{t=1}^{18} \frac{c_t l_t^{i,om}}{(1+r)^{t-1}}}{\sum_{t=1}^{18} \frac{c_t p_t}{(1+r)^{t-1}}} - 1.$$

Appendix E: Data sources

Table 4. Data sources

Variable	Source
Equipment and Installation Cost: Gas Furnace	Navigant Consulting, Inc. Water Heating, Boiler, and Furnace Cost Study (RES 19), prepared for: The Electric Program Administrators of Massachusetts Part of the Residential Evaluation Program Area. April 2018. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/RES19_Task5_FinalReport_v3.0_clean.pdf
Equipment and Installation Cost: Central AC	Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
Equipment and Installation Cost: Heat Pump System	MassCEC database of air-source heat pump residential projects with data from December 2014 to March 2018. Available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-pumps/ResidentialASHPProjectDatabase.xlsx
Annual Maintenance Cost: Gas Furnace	Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
Annual Maintenance Cost: Central AC	Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
Annual Maintenance Cost: Heat Pump System	Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
Life Expectancy of Equipment	ASHRAE Equipment Life Expectancy Chart. Available at: http://www.culluminc.com/images/ASHRAE_Chart_HVAC_Life_Expectancy%201.pdf

Table 2. Data sources (continued)

Variable	Source
Heat Pump System Capacity	Navigant Consulting, Inc. Ductless Mini-Split Heat Pump Cost Study (RES 28), prepared for: The Electric Program Administrators of Massachusetts Part of the Residential Evaluation Program Area. October 2018. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/RES28_Assembled_Report_2018-10-05.pdf
Annual Gas Consumption: Gas Furnace	Massachusetts Department of Energy Resources, Household Heating Costs: Forecast of energy prices for heating fuels during 2018/19 Winter Heating Season. Available at: https://www.mass.gov/info-details/household-heating-
Annual Electricity Consumption: Gas Furnace	Navigant Consulting, Inc. EIA - Technology Forecast Updates – Residential and Commercial Building Technologies – Reference Case, prepared for the U.S. Energy Information Administration. April 2018. Available at: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf
Annual Electricity Consumption: Central AC	Navigant Consulting, Inc. RES 1 Baseline Load Shape Study, prepared for the Electric Program Administrators of Massachusetts Part of the Residential Evaluation Program Area. July 2018. Available at: http://ma-eeac.org/wordpress/wp-content/uploads/RES-1-FINAL-Comprehensive-Report-
Mass Save Rebate	Mass Save - Residential Rebates and Incentives. Available at: https://www.masssave.com/en/saving/residential-rebates/
MassCEC Rebate	MassCEC database of air-source heat pump residential projects with data from December 2014 to March 2018. Available at: http://files.masscec.com/get-clean-energy/residential/air-source-heat-
Price of Gas in Massachusetts	Massachusetts Department of Energy Resources, Household Heating Costs: Forecast of energy prices for heating fuels during 2018/19 Winter Heating Season. Available at: https://www.mass.gov/info-details/household-heating-
Price of Electricity in Massachusetts	EIA, Electric Power Monthly, Table 5.6.B., February 2019. Available at: https://www.eia.gov/electricity/monthly/

Appendix F: Avoided emissions

Avoided emissions from gas per heat pump conversion: 69 MMBtus annually at EIA's 117 pounds of CO_2 per MMBtu of gas.[38]

Avoided emissions from fuel oil per heat pump conversion: 69 MMBtus annually at EIA's emission rate for gas. All homeowners replacing oil heating systems are assumed to choose between replacing it with gas or with a heat pump.

Avoided emissions from electric central AC and electric fans used in fossil fuel heating systems, and emissions from heat pump electric use: 0.59 pounds of CO_2 per kilowatt-hour at ISO-NE's 2017 marginal emissions rate[39] for all unit forecast to future years assumption a 5 percent rate de-escalation rate.[40]

Number of heat pump conversion estimated using:

- 2012-2017 average of number of Massachusetts household by heating type,[41] total number of Massachusetts households held constant throughout the modeled period
- Number of existing heat pumps in 2019: 49,000, based on the CARTs study[42] and assuming—in the absence of any data—that all existing heat pumps in 2017 were conversions from oil-heating systems
- Heat pump market penetrations estimates from the 2018 *Comprehensive Energy Plan*[43] and 2014 CARTS study[44]

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[38] EIA. Carbon Dioxide Emissions Coefficients. Available at: https://www.eia.gov/environment/emissions/co2_vol_mass.php

[39] ISO-NE. 2017. *Draft ISO New England Electric Generator Air Emissions Report.* *https://www.iso-ne.com/static-assets/documents/2019/01/DRAFT_2017_emissions_report_20190122.docx.*

[40] AEC assumption: forward going change in marginal emissions rate from ISO-NE 2017 marginal emissions rate; de-escalation rate based on review of ISO-NE. 2017. *Draft ISO New England Electric Generator Air Emissions Report.* https://www.iso-ne.com/static-assets/documents/2019/04/2017_emissions_report.pdf*; and* Stanton EA et.al. 2018. *An Analysis of the Massachusetts 2018 'Act to Promote a Clean Energy Future'*. Applied Economics Clinic. Available at: https://aeclinic.org/publicationpages/2018/6/18/an-analysis-of-the-massachusetts-2018-act-to-promote-a-clean-energy-future

[41] American Community Survey. 2017. Massachusetts tenure by house heating fuel 5-year estimates. U.S. Census Bureau. Available at: https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=ACS_17_5YR_B25117&prodType=table.

[42] Massachusetts Department of Energy Resources. 2014. *Commonwealth Accelerated Renewable Thermal Strategy.* Navigant and Meister Consultants Group. Available at: https://www.mass.gov/files/documents/2016/08/tx/carts-report.pdf.

[43] Massachusetts Department of Energy Resources. 2018. *Massachusetts Comprehensive Energy Plan.* Available at: https://www.mass.gov/files/documents/2019/01/10/CEP%20Report-%20Final%2001102019.pdf.

[44] Massachusetts Department of Energy Resources. 2014. *Commonwealth Accelerated Renewable Thermal Strategy.* Navigant and Meister Consultants Group. Available at: https://www.mass.gov/files/documents/2016/08/tx/carts-report.pdf.

- Massachusetts 1990 statewide emissions level: 94.4 MMT CO_2 [45]

[45] Massachusetts Department of Environmental Protection. 2017. *Appendix C: Massachusetts Annual Greenhouse Gas Emissions Inventory 2990-2016, with Partial 2017 Data.* https://www.mass.gov/lists/massdep-emissions-inventories.