Clean heat at what cost?
Economic optimization of residential space heating in Massachusetts

by

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Abstract

Electrifying space heating is a key strategy to reduce greenhouse gas emissions from buildings. The Commonwealth of Massachusetts has adopted a statutory target of net-zero emissions by the year 2050, and the state has predicted that 100,000 homes must be converted each year to electric space heating to reach a state-wide net-zero trajectory. Current progress is inadequate, as fewer than 1,000 homes per year have electrified space heating in Massachusetts in recent years.

This thesis analyzes the prospects and preconditions for the electrification of space heating in the Massachusetts single-family housing stock using an agent-based building optimization model built upon high-resolution building characteristics and a novel heat pump cost estimation methodology.

We argue that widespread heating electrification of existing homes in Massachusetts is unlikely to be economically optimal for households without significant policy change. In particular, the results of our modeling suggest that air-source heat pumps are significantly costlier to operate for primary space heating relative to high-efficiency natural gas furnaces and boilers under current electricity and natural gas rates. Making heating electrification economic for households would require substantially expanding operational subsidies or reforming rate design to reduce the price ratio of electricity to natural gas. Finally, we find that the electrification of space heating could reduce building CO_2e emissions in Massachusetts by 25-35% under current grid carbon intensities.

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1. Motivation

Reducing emissions from buildings is integral to achieving a net-zero emissions future and long-run climate stabilization. Energy consumption in buildings accounted for 30 percent of total US greenhouse gas emissions in 2019 (Cleary and Palmer 2021). These emissions include direct emissions from on-site combustion of fossil fuels and indirect emissions from electricity used by buildings.

Direct emissions are released from the combustion of fossil fuels like natural gas, fuel oil, and propane in buildings for uses like space heating, water heating, and cooking. Direct emissions accounted for 12.5 percent of total US greenhouse gas emissions in 2019 (Cleary and Palmer 2021). Indirect emissions from buildings vary based on the carbon intensity of electricity production and upstream emissions of other fuels. Indirect building emissions accounted for approximately 18 percent of US greenhouse gas emissions in 2019 (Cleary and Palmer 2021).

Space heating is the largest source of direct building emissions. Space heating accounted for 7% of total US emissions in 2019, equivalent to 410 million tons of CO_2 (Vaishnav and Fatimah 2020). For context, in 2019, the emissions released by space heating alone in the US were greater than the entire national emissions of Spain (Gutschow et al 2021). Reducing or eliminating space heating emissions, particularly through electrification, is therefore viewed as a key decarbonization strategy.

1.1 Strategies for reducing building emissions

There are two strategies for reducing building emissions: fuel switching and efficiency.

Fuel switching reduces emissions because different fuels have different emissions intensities. For example, switching from fuel oil (163.45 lbs CO_2 per mmBtu) to natural gas (116.65 lbs CO_2 per mmBtu) for space heating represents a 40% decline in the CO_2 intensity of primary energy (EIA 2021). Electrification can be understood as fuel switching from a fossil fuel (typically gas or oil) to electricity.

Deep decarbonization pathways studies have illustrated that widespread building electrification may be necessary to achieve steep economy-wide emissions reductions at reasonable cost. In particular, electric air-source heat pumps (ASHPs), reversible air conditioners that can provide both heating and cooling, are a promising option for space heating electrification. One recent decarbonization pathways study, Net Zero America

(Larson et al. 2021), projected that 54-80% of US residential buildings would need to electrify space heating with heat pumps in 2050 in a least-cost net-zero emissions scenario.

While electrification eliminates direct emissions from onsite combustion of fossil fuels, the total emissions impact of electrification depends on the emissions intensity of electricity generated on the grid as well as the relative efficiencies of the electric and fossil appliances. Decarbonization pathways studies typically assume a rapid and broad decline in the emissions intensity of electric generation, which then implies that electrification will result in steep emissions reductions. However, the emissions impacts of heating electrification in the US under current grid carbon intensities are highly variable across time and place.

Efficiency is another key strategy to reduce building emissions. Efficiency improvements reduce direct and indirect emissions from buildings by decreasing the energy consumption needed to provide an equivalent level of service. Typical examples of efficiency upgrades include installing improved insulation to reduce thermal losses, or adopting new, technologically-advanced appliances. Research at the National Renewable Energy Laboratory by Wilson et al. (2017) found that 24% of the total primary energy consumed by the single-family detached houses in the US could be saved by adopting economically-feasible building efficiency measures. The study similarly found that a 24% reduction of emissions from single-family homes could be achieved by adopting economically-feasible efficiency packages. The analysis in the present thesis builds on the Wilson et al. (2017) framework and dataset with a detailed focus specifically on space heating electrification in Massachusetts, rather than broad packages of efficiency measures nationwide.

Studies of energy efficiency often overestimate the financial, energy, and emissions savings that are achieved by efficiency measures that are implemented in practice, compared to those that are modeled as economically feasible. This “energy efficiency gap,” as identified by Jaffe and Stavins (1994), consists of the difference between projections and reality of efficiency adoption: technical improvements that are calculated as having a positive net present value, but fail to reach widespread adoption as evidenced by market data. Jaffe and Stavins argue that while the estimated size of the efficiency gap depends on the modeler’s definition of the economic optimum, factors including the discount rate, the costs of externalities, consumer inertia, and uncertainty all contribute to creating the efficiency gap. Due to the uncertainties around efficiency in theory and practice, this thesis examines the economic prospects for heating electrification given constant current building shell efficiencies.

1.2 Emissions impacts of heating electrification

Given that electrification does not completely eliminate emissions from space heating, how can we compare the climate impacts of different heating technologies? The emissions reductions achievable through heating electrification depend on the relative emissions intensities of the fossil fuel and electricity generation mix, and on the relative efficiencies of the fossil and electric appliances.

Emissions intensity per unit of energy for a given fossil fuel is relatively similar across different locations, with the climate impact of utility natural gas in Boston relatively similar to that in Chicago or San Francisco, for example. However, the emissions intensity of grid electricity varies widely across time and place based on the generation mix of the electric utility.

The most common metric of efficiency for fossil furnaces and boilers is the Annual Fuel Utilization Efficiency (AFUE), which is the dimensionless average ratio between heat energy output to heat energy input over the entire heating season. A related metric of heating efficiency for electric air-source heat pumps is the Heating Season Performance Factor (HSPF), which is the average ratio between heat energy output (in Btu) to electrical energy input (in Wh) over the heating season. Then, an electric and fossil heating source have the same emissions impact per unit of energy delivered if:

$$\frac{1}{AFUE} \times EmissionIntensity_{fossil} = \frac{3.412}{HSPF} \times EmissionIntensity_{grid}$$

where the $EmissionIntensity$ is the pollutant mass emitted per unit of energy for each energy source.

We can construct a first estimate of the emissions impact of heating electrification based on nationally representative values for these variables.

Natural gas is the dominant fossil fuel used for space heating in the US. The national average CO_2 factor for stationary combustion of natural gas is 181.04 kg CO_2 per MWh, while the national average CO_2 factor for electricity is 401.06 kg CO_2 per MWh (EPA 2021). In the national average case, an electric appliance must therefore be more than twice as efficient as a gas appliance in converting delivered energy to heat in order to have the same emissions impacts.

The average AFUE for currently-installed natural gas heating appliances in the US is approximately 80% (NREL 2021), which is also the federally-mandated minimum efficiency for new gas furnaces and boilers. Since the national average carbon intensity of electricity is over twice that of gas, an electric heating appliance must be over 160% efficient in order to provide an emissions reduction relative to the average gas appliance. This suggests that all electric resistance heaters, even with a 100% efficiency in converting delivered electrical energy to heat, increase emissions relative to gas in the national average grid carbon intensity case.

Fortunately, electric air-source heat pumps (ASHPs) generally have average efficiencies above 100%, since they use electricity to only transfer heat from outdoors, rather than warming air directly through resistance coils. The national average HSPF for currently installed ASHPs is approximately 7.75, equivalent to a dimensionless efficiency of 227% (NREL 2021). The minimum efficiency standard for new ASHPs in the US is 8.2 HSPF, equivalent to a dimensionless average efficiency of 240%. Under the relationships and assumptions above, a typical ASHP reduces the emissions per unit of delivered heat by 22-26% relative to a typical gas appliance in the national average case.

This simple analysis illustrates the sensitivity of the emissions impacts of heating electrification to appliance efficiencies and emissions intensities. In some cases, heating electrification could increase emissions: for example, when switching from gas to electric resistance heating, when switching from high-efficiency gas equipment to a low-efficiency heat pump, or when the grid carbon intensity is much higher than the national average. However, in the long run, heating electrification will likely result in steeper emissions reductions than this analysis suggests, since heat pump efficiencies have been steadily improving (Clark and Jarzomski 2019), and grid carbon intensity steadily declining, as shown in Figure 1-1.

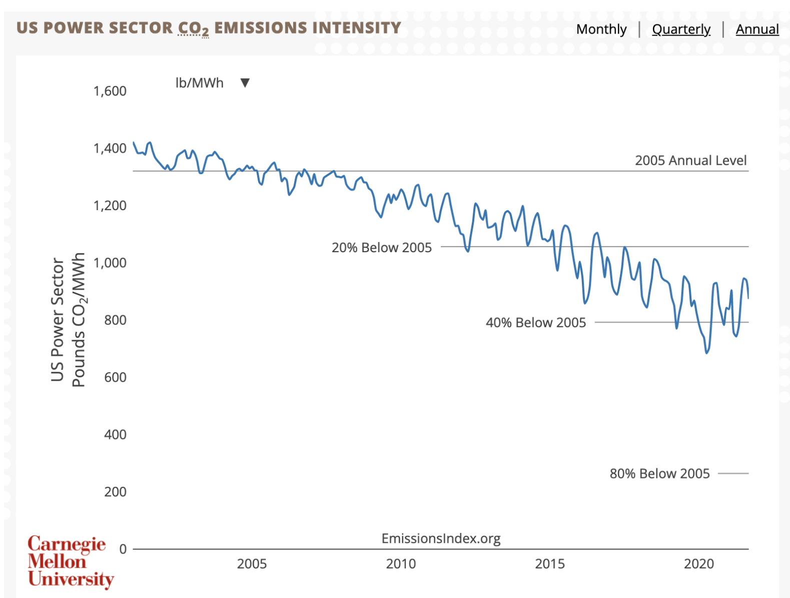

Figure 1-1. Average US CO2 emissions intensity of electricity over time from Scott Institute for Energy Innovation (2022).

The total emissions impacts of electrification are sensitive to additional system parameters that are excluded in the analysis above. For fossil fueled appliances, upstream emissions and leakages strictly increase the emissions intensity of the fossil fuel, possibly by 1.5-8% for natural gas (see Hausfather (2019) and Howarth (2014)).

For electric appliances, line losses are estimated to be 5-7.3% of the electricity transmitted and distributed in the US, which effectively increase the emissions intensity of delivered electricity (EPA 2015). Furthermore, a more accurate estimate of the emissions impacts of electrification may be found by using the marginal, rather than average, carbon intensity of electricity.

The marginal emissions factor represents the additional emissions that are incurred by demanding an additional unit of electricity. The marginal emissions factor is set by the marginal generator (or import source) serving the load, which can change frequently within the course of a typical day. For this reason, the marginal emissions factor is inherently variable, but can be higher than the average emissions factor for a given hour if a fossil-fueled power plant is the marginal generator. For example, Siler-Evans et al. (2012) estimated that for the Northeast NERC region (NPCC) in 2007, the marginal CO2 emissions factor was 25% higher than the average emissions factor. In some other NERC regions, Siler-Evans et al. found that the marginal emissions factor was considerably lower than the average emissions factor. An alternative estimate can be derived from the non-baseload emissions factor, which is a very rough proxy for the marginal emissions factor since the marginal generator is typically non-baseload. EPA eGRID (2020) data implies that the non-baseload emissions factor was 60% higher than the average emissions factor for the entire US in 2019, and fully 70% higher in ISO-NE. This suggests that using the average emissions factor, rather than the marginal emissions factor, may overstate the achievable climate benefits of electrification at the margin.

Electrification is not, by itself, a silver bullet for decarbonizing buildings. The emissions impacts of electrification are sensitive to changes in the relative carbon intensities of grid electricity and the displaced fossil fuel, as well as the relative efficiencies of the fossil and electric appliances. This initial analysis has shown that electrification of space heating with air-source heat pumps reduces the emissions per unit of delivered heat by approximately one-quarter in the national average case.

The bottom-up economic optimization modeling that follows in this thesis expands significantly upon this motivating analysis by using more detailed data, as described in Chapter 3, and more detailed modeling, as described in Chapter 4. We use synthetic building-level data for installed appliances and housing characteristics in Massachusetts. For emissions intensity, we use hourly average emissions factors calculated from the hourly generation mix of ISO-NE in 2019. Since the electric generators serving Massachusetts in

ISO-NE have generally lower emissions intensities than the national average, electrification in Massachusetts should result in steeper emissions reductions than in the nationally representative case considered above.

1.3 Economic impacts of heating electrification

In cold regions like Massachusetts, space heating is a significant cost for households. The relative economic impacts of fossil and electric heating options are central to the prospects for the decarbonization of heat. Unlike many decisions in the energy system which are centralized, regulated, or subject to macroeconomic market pressures, heating electrification is a comparatively decentralized, unregulated, microeconomic consumer-level decision. Building owners are highly responsive to relative capital and operating costs when making decisions to install and operate heating equipment, and may additionally be budget constrained and lack full information.

Meeting the thermal demands for each individual building is a unique problem based on its physical characteristics such as its climate, vintage, size, insulation, and ductwork, which together define the options and costs of possible space heating solutions. Furthermore, non-cost barriers such as consumer education and technical support may play a significant role in further delaying the progress of heating electrification, even if electrification is economically optimal.

Similar to the initial analysis of the emissions impacts of heating electrification above, in this section we construct an initial analysis of the economic impacts of heating electrification. We consider the costs of heating with three energy sources, namely electricity, natural gas, and fuel oil, using national average prices facing residential customers and converting to equivalent units.

In 2020, the national average electricity rate was \$0.106/kWh (EIA 2021), the national average gas rate was \$0.037/kWh (EIA 2022b), and the national average price for distillate home heating oil was \$0.063/kWh (EIA 2022c). Heating demand for residential buildings varies widely based on climate, building size, and building shell efficiency (e.g. insulation). First, assume demand for delivered heat energy in a building is 10,000 kWh in a single year, a conservative estimate based on EIA (2018) and NREL (2021). Next, assume all heating appliances have 20 year lifetimes and the consumer faces a 6% discount rate. We derive installed costs of appliances from EIA (2018), adjusting for inflation to constant 2020 dollars and for differences in reported appliance size. Then, the total costs of heating the same home with various technological options are presented in Table 1-1 below.

Appliance	Average Efficiency	Operating Cost (for 10 MWh delivered heat)	Capital Cost (EIA 2018)	Private Net Present Cost
Gas Furnace, Low Efficiency	80% (AFUE)	$463	$2,164	$7,051
Gas Furnace, High Efficiency	99% (AFUE)	$374	$3,210	$7,075
Oil Furnace, Low Efficiency	83% (AFUE)	$760	$4,355	$12,332
Oil Furnace, High Efficiency	97% (AFUE)	$650	$6,810	$13,458
Electric Resistance Furnace	98% (AFUE)	$1,082	$1,164	$12,806
Electric ASHP, Low Efficiency	240% (8.2 HSPF)	$442	$10,242	$14,445
Electric ASHP, Medium Efficiency	264% (9 HSPF)	$402	$12,882	$16,502

Table 1-1. Representative costs of space heating technologies for a typical US household.

From the net present cost results in Table 1-1, electrification does not appear to be an economic option for the typical household, whether with electric resistance or heat pump equipment. Natural gas furnaces have a combination of low operating costs and low capital costs, which makes natural gas by far the most economic option on a private net present cost basis.

Additionally, Table 1-1 illustrates that oil appliances are very expensive to install and operate. Oil furnaces and boilers are relatively uncommon in most of the US, in just 5% of households, but much more common in the Northeast, in 39% of households in New England (EIA 2018). Typically, fuels like oil and propane are used to heat houses in cold climates without access to natural gas utility distribution systems, frequently in rural areas. However, oil furnaces and boilers also remain in older houses and older installations in regions where natural gas distribution is currently available, as is common in Massachusetts (see section 5.1). This analysis suggests that, under the very low electric resistance capital costs derived from the EIA data, electric resistance may be slightly more economic than fuel oil for space heating.

Air source heat pumps have relatively low operating costs under national average electric and gas rates. In fact, heat pumps may be cheaper to operate than low-efficiency gas furnaces under national average rates. However, the high capital costs of heat pumps outweigh the operational savings, and make heat pumps the least economic option in this analysis on a net present cost basis. Furthermore, the high electricity rates in

Massachusetts pose an additional challenge to the economic viability of heat pumps, as explored in the analysis that follows in this thesis.

As we will see in the review of the literature, the installed capital costs of heat pumps are highly uncertain based on the capacity, efficiency, and design of the appliance. This thesis develops a cost model based on real data from Massachusetts to provide a more detailed and realistic estimate of the installed costs of whole-home heat pumps for cold-climate heating electrification.

The high cost of space heating is already a significant issue in the US with inequitable impacts and considerable policy relevance. Household energy insecurity may manifest as delinquency on utility bills, leaving the home at an unhealthy temperature, reducing or forgoing food or medicine to pay energy bills, or receiving a utility disconnection notice (EIA 2018). Under this definition, nearly one-third (31%) of households in the US experienced energy insecurity in 2015. The share of New England households experiencing energy security was slightly higher at 36%, despite the region's higher-than-average household incomes (EIA 2018). Energy insecurity also varies across space heating fuels, with energy insecurity more common in households that use electricity or fuel oil for heating, than households that use natural gas.

Increases in heating costs harm the poorest households the most, since energy bills make up a higher share of income for poorer households, even after accounting for differences in house size and behavior. A recent study from the Oak Ridge National Laboratory found that low-income households spend an average of 14% of their total annual income on energy costs, compared to just 3% for all other households (Rose and Hawkins 2020).

Policy programs to combat household energy insecurity are in place at both the federal and state levels. The federal Weatherization Assistance Program provides grants to low-income households to make energy efficiency improvements, and serves approximately 35,000 households per year, although this number accounts for less than 1% of all energy-insecure households in the US (DOE 2021). Regulated utilities offer discounted electricity and/or natural gas rates for low-income households in several states, including Massachusetts, California, and New York (Hansen 2018). Finally, some states offer additional subsidies and assistance for heating bills for low-income customers. In Massachusetts, the Low Income Heating Assistance Program (LIHEAP) provides eligible households with fixed subsidies based on household income, with an additional subsidy to households with a "high energy burden." The "high energy burden" qualification thresholds are over 50% higher for households that heat with electricity and oil than with natural gas, reflecting the higher cost of heating with these fuels (Massachusetts 2019). In short, heating costs are a significant equity issue with existing policy mechanisms to reduce the burden on low-income households.

Meeting decarbonization goals may require policy incentives to expand electric space heating, but these goals will need to be carefully analyzed for the potential effect on the energy burden to households. Climate and energy justice policies should evolve together to promote cost-efficient decarbonization goals while ensuring that clean heat is affordable.

This thesis expands upon this motivating analysis by optimizing the investment and operation of heating appliances across a broad range of buildings. Furthermore, it incorporates current policies that change the economic incentives around space heating that face building owners, and it tests and evaluates proposed policies that could change the relative economics of heating technologies, such as alternative heat pump subsidies, mandates, and rate designs.

1.4 Promise and progress on heating electrification in Massachusetts

In this study, we analyze the economics of residential heating electrification in Massachusetts. The Massachusetts state government has adopted ambitious climate goals, including a statutory target of state-wide net-zero emissions by the year 2050 (Wasser 2021). Furthermore, the state has published detailed analysis and goals for building decarbonization and heating electrification as part of its Decarbonization Roadmap.

The Massachusetts Decarbonization Roadmap Buildings Technical Report concludes that 100,000 existing homes must install heat pumps or other clean heat solutions for their primary source of space heating every year until 2050 in order to meet the state's climate goals (MassEEA 2020). The report claims that heat pumps are "available now and ready to be scaled for a large portion of the Massachusetts building stock, especially single family homes," which appears to imply that heat pump electrification is currently economically feasible for typical single-family houses. These ambitious claims by the state government are backed up with significant incentives: the utility-funded efficiency organization MassSave offers a subsidy of up to $10,000 for installing whole-home air source heat pumps (MassSave 2022). If whole-home heat pumps are already economic for many households in Massachusetts, this subsidy should be expected to drive significant progress on electrification.

However, the reality of the progress on heating electrification in Massachusetts is considerably more muted. In 2021, the *Boston Globe* published a headline that described the state of play: "Massachusetts should be converting 100,000 homes a year to electric heat. The actual number: 461" (Shankman 2021). The state also missed its target of installing 15,000 partial-home heat pumps in 2020, installing just 3,300 that year (Shankman 2021). According to data received as part of a Public Records Request to the Massachusetts Clean Energy Center, only 168 all-electric conversions were completed as part of the MassCEC pilot subsidy program between 2019 and 2021 (MassCEC 2021).

Clearly, progress on heating electrification in Massachusetts has not yet met the state's climate promises.

Heating electrification in Massachusetts is particularly difficult because the state has long and cold winters, relatively expensive electricity, and an older building stock. Aggressive policy or rate design interventions may therefore be necessary to achieve widespread electrification and deep decarbonization of buildings.

This thesis provides several contributions. First, it presents a novel cost model for estimating the detailed costs of whole-home heat pump electrification. Second, it presents a bottom-up optimization framework for individual buildings in Massachusetts. Finally, it delivers policy-relevant results that illustrate rate design and subsidy options that could lead to the widespread electrification of space heating.

2. Literature

Space heating in the US is a globally significant source of emissions. If US space heating were a country, its 410 million tons of CO2e emitted in 2019 would place it in the top-20 emitting nations in the world (Vaishnav and Fatimah 2020). For this reason, the decarbonization and electrification of space heating in the US have attracted significant attention by researchers seeking to understand future energy and climate systems.

This chapter synthesizes the relevant literature on the prospects for heating electrification in the US. It divides analyses of space heating electrification into three categories: decarbonization pathways studies, bottom-up building modeling studies, and energy system modeling studies. It canvasses recent research in each of these categories to draw conclusions that inform and contextualize the analysis that follows.

All three categories of studies have contributions to understanding the economic prospects for heating electrification, yet all have drawbacks and limitations. In particular, we find that the forecasted progress on heating electrification across the literature is highly uncertain and varies by large magnitudes, even within the same study, particularly for retrofits of existing buildings. A related gap in the literature is that the published estimates of the capital and operational costs of heating electrification are highly uncertain, and also vary by large magnitudes even within the same study. Many studies do not seem to use empirical data in heat pump cost estimation, which is a barrier to transparent and replicable analysis. Finally, many studies use coarse assumptions about building characteristics and heating fuels, for example by assuming a single building type or assuming all buildings in the same region use the same heating fuel. We seek to address these gaps and limitations with our analysis.

2.1 Decarbonization pathways and heating electrification

In decarbonization pathways studies, researchers attempt to “chart a course” toward climate stabilization by illustrating the changes in the energy and climate systems that would be necessary to reach climate targets. These studies often use macro-scale models to “backcast” potential scenarios that reach normative climate goals at minimized cost (Loftus et al. 2015). Climate goals can include temperature targets, for example restricting temperature rise to 1.5 or 2 °C relative to pre-industrial levels; or emissions targets, for example reaching an 80 or 100 percent reduction in emissions for a state or country.

Decarbonization pathways studies typically abstract individual dynamics and elements of the energy system in an attempt to model the entire system’s emissions impacts. Additionally, decarbonization pathways studies often lack policy specificity: they illustrate the requisite pace and scale of change to reach a climate goal, agnostic of the actual policies that could be used to actualize that change. Despite these drawbacks, these studies can be powerful tools to explore the magnitude of the climate challenge in individual sectors like buildings, and some of these studies have had considerable salience in energy politics and policy in recent years. In this section, we discuss heating electrification in several recent decarbonization pathways studies.

In 2021, researchers at Princeton University published “Net Zero America,” a detailed decarbonization pathway study that illustrates scenarios in which the US economy could reach net-zero emissions by 2050 (Larson et al. 2021). The study was widely covered in the media, with the *New York Times* describing its core finding that “reaching ‘net zero’ by 2050 appears technically feasible and even affordable” for the US (Plumer 2020). The study includes substantial findings on the contribution of electrification to emissions reductions, including the electrification of space heating. Specifically, the share of US households that use heat pumps as the primary source of space heating increases from 10% in 2020 to 54-80% in 2050 across the study’s cost-minimized scenarios. In Massachusetts specifically, Larson et al. (2021) concludes that 1.5-2.7 million households adopt heat pumps by 2050, with the higher end of this range approaching 100% penetration in the state, as illustrated by Figure 2-1 below.

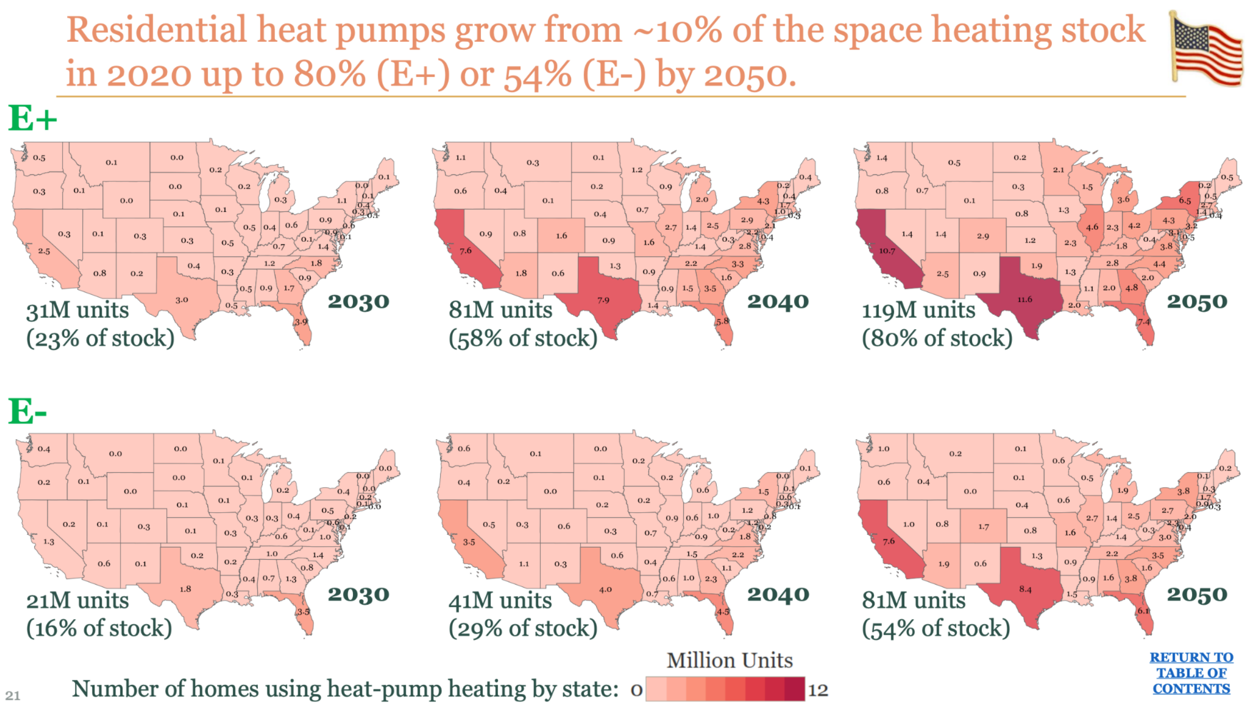

Figure 2-1. Net Zero America residential heat pump projections by state. E+ refers to the "high electrification" scenario, E- refers to "low electrification," in Larson et al. (2021).

To reach net zero emissions at lowest possible cost, Net Zero America concludes that air-source heat pumps need to dominate the space heating market. However, there is still a substantial amount of uncertainty in the deployment of heat pumps within the study. Uncertainty is predetermined by the study's scenario construction: the scenarios are distinguished by "high electrification" and "less high electrification" (Larson et al. 2021). In fact, the fraction of new sales of different building technologies (including heat pumps) is exogenously assumed as an input to the model for different scenarios, rather than a modeling output (Zhang et al. 2021). The study does not attempt to model heat pump adoption as a function of capital and operating costs. The electrification of space heating in this study is essentially "forced" into model, and there is no explicit analysis or representation of the economic decisions on heating technologies made by individual building owners.

Net Zero America is agnostic about policy mechanisms to increase the penetration of heat pumps, and does not attempt to model the sensitivity of electrification rates to other energy system dynamics or parameters. The report concludes that a key short-term goal for policymakers from 2021 to 2030 is to "double (at least) the share of electric heat pumps in home heating and triple heat pumps in commercial buildings," without offering analysis or recommendations on the policy mechanisms or economic impacts on homeowners that this would require (Larson et al. 2021). Net Zero America is an important study for understanding the magnitude of change needed to reach a national net-zero emissions target in 2050: it would require installing millions of heat pumps, in addition to a wide range of other clean energy technologies. However, it does not attempt to model the economic prospects for space heating electrification.

Several other decarbonization pathways studies with a national scope similarly abstract away the core economic dynamics of space heating electrification, particularly by using scenario-based parametric uncertainty to reflect the fundamental uncertainty around future electrification progress.

Williams et al. (2021), using a similar methodology to Larson et al (2021), find that heat pump sales reach >50% of market share by 2030 in all carbon-neutral or carbon-negative pathways for the US by 2050. The study includes more specific policy advice for accelerating the electrification of space heating: for example, the authors argue that subsidy and rebate programs for heat pumps “have the potential to dramatically increase sales, drive innovation, reduce manufacturing costs, and lower purchase prices in a self-sustaining market transformation” (Williams et al. 2021). However, the study lacks analysis or evaluation of these claims or policy measures. It “bakes in” heat pump deployment assumptions via parametric uncertainty and scenario modeling, specifically through “high electrification” and “delayed electrification” scenarios.

Finally, another national decarbonization pathway study, “Vibrant Zero by 2050 USA” by Vibrant Clean Energy (Clack et al. forthcoming), assumes a 100% electrified economy across all scenarios, and then varies the inputs and scenarios to investigate the relative contributions of power system design elements like long-distance electric transmission, distributed energy resource (DER) co-optimization, and novel generation technology.

In sum, several recent publications in the US decarbonization pathways literature have concluded that electric heat pumps must dominate the national space heating market in the next three decades in order to reach net-zero emissions by 2050. However, these studies generally do not assess the economic impact of heating electrification on consumers, nor do they reflect the bottom-up nature of decisionmaking about heating technologies by individual building owners.

Some individual states and localities have been the focus of their own decarbonization pathways studies, which attempt to illustrate how these subnational governments could reach climate targets. In 2020, the Massachusetts state legislature passed a law that calls for net-zero emissions statewide by 2050, and the state government’s Executive Office of Energy and Environmental Affairs developed a decarbonization roadmap study to describe the changes needed to meet that goal (Abel 2021).

Unlike the national studies discussed above, the Massachusetts government conducted a detailed analysis of the economic and technical dynamics of space heating electrification and published these results in a “Decarbonization Roadmap Buildings Sector Report”

(Mass. EEA 2020). In this report, state researchers and consultants attempt to model the contribution of buildings emissions reductions to reaching the state's climate goals. It provides a detailed and useful analysis of the future of building decarbonization in Massachusetts, including projections of the composition of the entire building stock to 2050. The authors model the technological options and costs for buildings emissions reductions across a wide range of building types, from single-family houses and multifamily residences to office buildings, laboratories, and arenas.

As discussed in Chapter 1, the Massachusetts report concludes that 100,000 homes must be converted each year to electric space heating through air-source heat pumps in order for the state to meet its 2050 net-zero goal. However, this adoption rate for electric space heating is not modeled endogenously, but is rather backcasted to meet the 2050 net-zero target. Furthermore, while the study attempts to estimate the costs of electrification, the methodology and results are somewhat unclear.

The study's cost modeling methodology involves applying different "energy conservation measure" (ECM) packages, which comprise different combinations of end-use electrification and energy efficiency improvements, to building archetypes. The ECM packages are numbered from ECM1 to ECM4, where ECM1 represents "electrification only" of space heating, cooling, hot water provision, and appliances, without additional efficiency upgrades. The packages ECM2 through ECM4 represent end-use of electrification in addition to increasing levels of efficiency of both appliances and building shell, along with increased capital costs. The study presents a table that relates building types to the modeled installed costs of ECM upgrades, reproduced below as Figure 2-2.

Total costs of applied ECM packages.

	ECM1	ECM2	ECM3	ECM4
Single Family	$3.01	$15.16	$18.96	$22.26
Small Multifamily	$7.23	$20.58	$29.53	$34.92
Large MF 5-19	$9.40	$23.78	$27.72	$30.41
Large MF 20+ wood	$11.60	$30.56	$34.06	$39.40
Large MF 20+ steel	$11.69	$28.38	$35.99	$42.21
Small Office	$11.99	$31.57	$38.37	$44.29
Medium Office	$11.99	$25.19	$34.30	$39.63
Retail	$11.99	$32.81	$35.09	$39.88
Supermarket	$11.99	$28.41	$30.96	$34.93
Convention/Assembly	$11.81	$21.97	$27.76	$31.35
Office Large	$11.81	$20.97	$28.57	$32.51
School (K-12)	$12.04	$24.09	$30.52	$34.85
Hospital	$19.28	$24.28	$26.99	$28.13
Laboratory	$19.34	$24.34	$26.86	$28.00
Hotel	$13.11	$26.51	$32.37	$36.35
Restaurant	$15.37	$35.34	$40.75	$45.86
Warehouse	$11.99	$34.50	$34.93	$39.10

Figure 2-2. Total cost estimates of electrification and efficiency measures in Mass. EEA (2020).

This table summarizes the report's estimates of the total costs of electrifying typical building types (ECM1). However, the table lacks clear units: the total costs of ECM1 for single-family homes are reported as approximately $3, but the report does not provide any more context for the cost units. Through personal correspondence with the study authors, both from the Massachusetts government and the consultants who worked on the report, we learned that the units are intended to be dollars per square foot of conditioned space.

For a typical Massachusetts single-family house of approximately 1,750 square feet, this implies that the total costs of whole-home electrification are $5,250. This is quite a low estimate relative to observed cost data and other estimates of electrification costs in Massachusetts, as we will see in Chapter 3. In fact, this estimate is lower than other estimates for heating electrification alone in single-family houses within the same study, and it is unclear how the study reached this result. From continued discussions with the study authors, it seems that several consultants and subcontractors were used to develop the cost modeling, which may have resulted in uneven methodology throughout the report. In addition, we were told by multiple stakeholders that these costs were intended to be additional or relative to the gas baseline case, although the report text introducing the table specifically states that these are total, not incremental costs:

> A total costing approach was used to aggregate the costs of individual measures for building envelope, systems and equipment within the ECM package, specific to residential and commercial construction and commercial use type and summed to represent the total 'cost' of the ECM package ([Figure 2-2]). The approach was not an incremental approach which alternately would define the additional cost to implement the ECM package compared to replacement in-kind. (Mass. EEA 2020, p. 36)

Another cost estimate for heating electrification comes later in the report, where the installed cost per ton of heat pumps is estimated at approximately $1,750/ton at present (Mass. EEA 2020, p. 98). This estimate is presented in a figure from the report, reproduced here as Figure 2-3 below. The estimate appears to be constructed from underlying data (hollow dots) with substantial variance, from $750/ton to $3500/ton in the same recent time window, a factor of over four times. This may reflect substantial uncertainty in the installed cost-per-ton of heat pumps at present. Since a ton is 12,000 BTU of output capacity, a moderately sized "3-ton" system of 36,000 BTU would cost $5,200 under the report's central estimate, approximately equivalent to the entire costs of electrification as estimated above in Figure 2-2. Using the range of reported underlying data, the installed cost for that system could evidently range from $2,250 to $10,500.

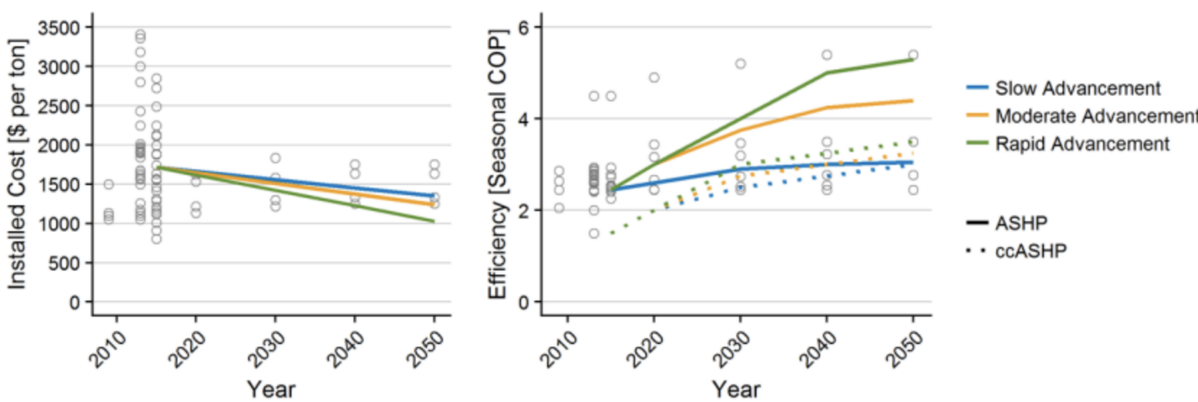

Figure 2-3. Installed unit costs and performance of residential air-source heat pumps in Mass. EEA (2020).

Yet another portion of the study estimates the total installed cost for a whole-home ASHP in a typical pre-1950s single family home is $7,500, and the appliance would not be "paid back" until 2045. The ASHP system does eventually pay off because gas prices are forecasted to increase later in the model's time horizon as "declining [gas] consumption requires higher rates on delivery to recoup the costs of pipeline maintenance" (Mass. EEA 2020, p. 53). The internal economic logic of this dynamic is unclear: if electrification done today would not pay off until 2045, it is unclear why consumers would adopt heat pumps in the short run to begin with. Then, if consumers did not adopt heat pumps, gas consumption would not decline in extremis, and gas rates would not rise to incentivize future electrification in a positive feedback loop. To the contrary, heating electrification could potentially necessitate new upgrades to generation, transmission, and distribution infrastructure, which could raise electric rates and provide a negative feedback loop for electrification. This uncertain economic logic is a significant issue, since the decision to electrify is very sensitive to the relative prices of gas and electricity, as is further explored in our analysis in the present work.

The uncertainty about costs and payback of electric space heating technologies in the Massachusetts report appears to reflect real, deep uncertainty about the economics of electrification, both in the peer-reviewed literature and among policymakers. Despite the apparent inconsistencies in the report's analysis, it still provides a substantial contribution to the literature on the long-term prospects for heating electrification within a decarbonization pathways context. A significant goal of this thesis is to use detailed data and models to support a more transparent analysis of the prospects for space heating electrification in Massachusetts.

In general, decarbonization pathways studies illustrate the ambition and progress needed to decarbonize space heating, but the abstracted lack of economic adoption modeling means that electrification is imposed through fixed inputs rather than economic decisionmaking. Decarbonization pathways studies generally do not assess the potential costs and benefits to consumers of adopting electric space heating. In order to understand the perspectives of building owners in electrifying space heating, we now turn to bottom-up modeling of heating electrification.

2.2 Bottom-up modeling of heating electrification

In this section, we synthesize studies that take the individual building as the fundamental unit of analysis. These studies attempt to model the decision to electrify space heating from the perspective of the building owner.

In 2017, the National Renewable Energy Laboratory (NREL) published "Energy Efficiency Potential in the US Single-Family Housing Stock" (Wilson et al. 2017). This study uses detailed synthetic representations of houses across the US to model the technical and economic potential for energy efficiency measures. Economic potential is defined as upgrades with a positive net present value (NPV) to the building owner, that is, the discounted cash flow projected by the upgrade is positive relative to a baseline. The authors describe this method as analogous to the "participant cost test" used by utilities and regulators, which takes the perspective of the consumer and compares the bill savings of a measure against the costs of installation. This is intended to reflect the economic attractiveness of various efficiency and electrification options to consumers directly, without considering state or local subsidies or policies. The analysis that follows in this thesis uses a similar NPV approach to modeling economic viability, and we additionally incorporate state subsidies and programs.

In developing Wilson et al. (2017), researchers at NREL created ResStock, a high-resolution national database of synthetic residential building characteristics and load profiles that is used intensively in the present work and described in detail in the following chapter. By conducting the analysis with ResStock, the study authors were able to capture the substantial diversity of building types and energy technologies throughout the country, rather than relying upon a single model or coarse assumptions.

The study concludes that efficiency upgrades with a positive net present value could save approximately 22% of the electricity used by the US single-family housing stock, as well as 24% of the primary energy consumption overall and an equivalent 24% of the carbon emissions released by US houses (Wilson et al. 2017). For a more stringent economic criterion that filters for improvements that pay back the initial investment within five years, electricity savings are approximately 13% of the total used by single-family households, and 9% of primary energy. In sum, while the study identifies significant opportunities for saving electricity and energy through economically viable efficiency upgrades, these fall far short of reaching “deep decarbonization” goals, with buildings emissions declines of one-quarter or less relative to the present.

The study tests a wide range of efficiency measures, but the measure with the highest economic potential involves heat pumps. The report concludes that “replacing electric furnaces (and air conditioners) with high-efficiency heat pumps provides the most economic potential electricity savings, with more than twice the potential of the second largest contributing upgrade” (Wilson et al. 2017). This aligns with our analysis in Chapter 1, in which the operational energy costs of electric resistance heating were found to be strictly uneconomic and inefficient compared to heat pumps. However, switching from electric furnaces to heat pumps is not electrification per se, but rather an increase in conversion efficiency of already-electrified buildings. Furthermore, as illustrated in Figure 2-4, the vast majority of the energy and emissions savings from this measure come outside of the Northeast, simply because the Northeast lacks a large amount of electric resistance heating.

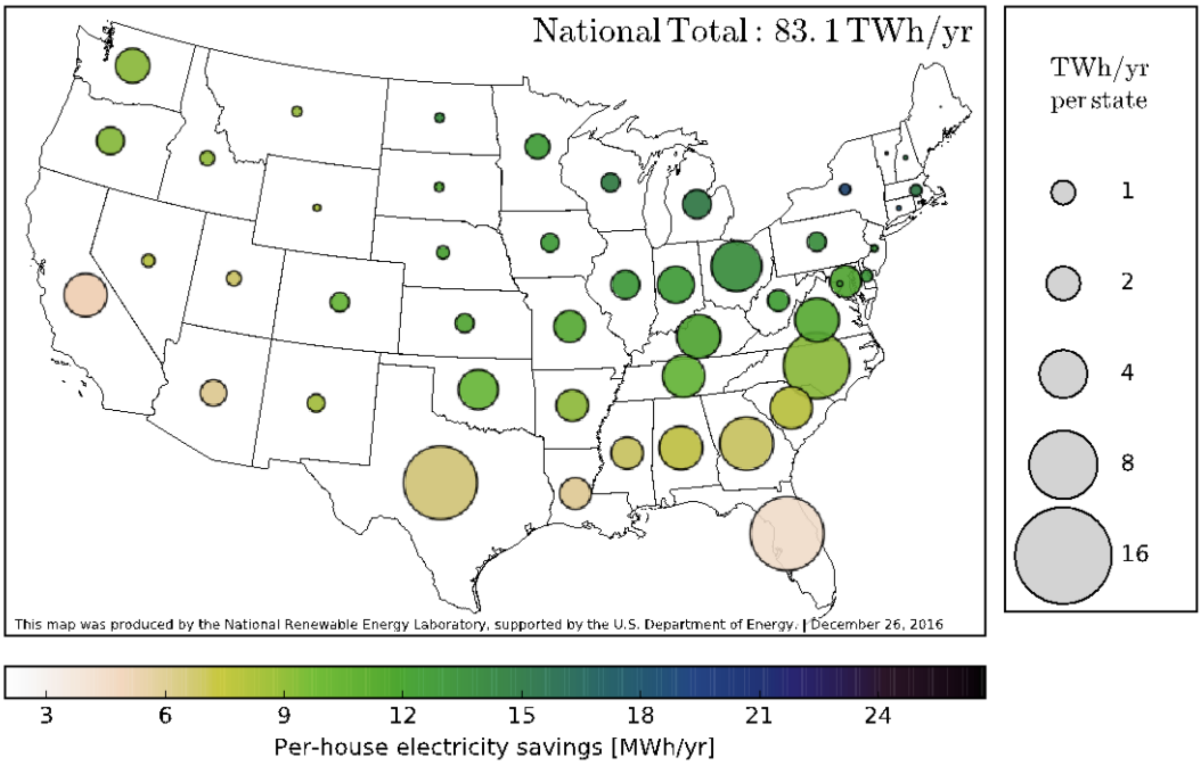

Figure 2-4. Economic potential for electricity savings from replacing electric furnaces with air-source heat pumps at electric furnace wearout in Wilson et al. (2017).

Electrification of space heating is not a major focus of Wilson et al. (2017), since electrification definitionally increases electricity use and can also increase primary energy use and energy costs. An appendix to the report analyzes several different electrification scenarios. It finds that the technical potential (achievable deployment given system constraints) for residential electrification would increase electricity demand by 142 TWh per year, mostly in the Northeast (Wilson et al. 2017, p. 101). This increase is approximately 10% of annual residential electricity demand in the entire US (EIA 2022a). The economic potential of electrification varies significantly across fuels and scenarios, as illustrated in Figure 2-5.

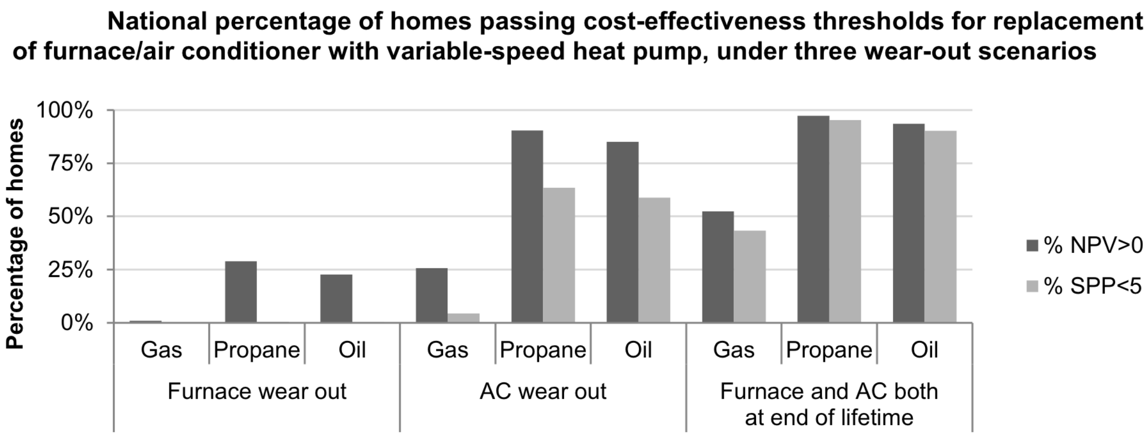

Figure 2-5. Economic potential of electrification by fuel and scenario in Wilson et al. (2017). Economic potential is defined as Net Present Value > 0 or Simple Payback Period < 5 years.

For homes that use high-cost fuels like propane and oil in addition to ACs, electrification of space heating with heat pumps at the end-of-life was found to be economic for the vast majority of consumers. However, for homes with gas furnaces and without ACs (relatively common in Massachusetts) electrification was found to be uneconomic for nearly all homes. This substantial difference illustrates the variability of the economic prospects for heat pump electrification, especially with respect to the existing technologies in place at each individual building.

Wilson et al. (2017) concludes that economically viable electrification packages reduce emissions, given current carbon intensities, by approximately 21 million tons of CO2 equivalent per year. Under a substantially decarbonized grid (10% carbon intensity relative to the present) the emissions reductions of economic electrification packages would approach 50 million tons of CO2 equivalent per year. However, this is less than 15% of the total *building* emissions each year in the US at present, suggesting that “deep decarbonization” of US buildings through electrification is not presently economic.

Several other recent studies have focused more specifically on the prospects for the decarbonization of space heating through air-source heat pumps. Kaufman et al. (2019) make a useful distinction between different types of studies of heating electrification:

> Some studies show near-universal electrification of space heating, suggesting that ASHPs (with some backup from electric resistance heaters) can be almost a silver bullet solution for decarbonizing space heating. These studies start with the assumption that fossil fuel furnaces and boilers will be gradually phased out. Other studies assume that electric heating technologies such as ASHPs will continue to compete

> against fossil fuel burning furnaces and boilers in the decades ahead. These studies conclude that [fossil-fueled] furnaces and boilers will retain a significant share in space heating markets, even with technological progress and strong policy support for ASHPs. (p. 6)

In this quote, the first type of study describes the “decarbonization pathways” approach, while the latter type describes the “bottom-up” approach. Across several studies, Kaufman et al. find that bottom-up approaches estimate that 50% or less of space heating demand will be electrified by 2050, while decarbonization pathways studies reach 60-100% electrification (often by assumption), as shown in Figure 2-6 below from the report.

Authors	Year	Study objective or scenario	Electrification of residential space heating demand by 2050	Technology deployment determined by
Williams et al.[30]	2015	80 percent emissions reductions by 2050	About 100 percent	Expert assumption
White House[31]	2016	80 percent emissions reductions by 2050 (“benchmark” scenario)	About 50 percent	Cost minimization
Electric Power Research Institute[32]	2018	“Transformation” electrification scenario	About 40 percent	Cost minimization
US National Renewable Energy Laboratory[33]	2018	“High” electrification scenario	About 60 percent	Expert assumption
Jacobsen et al.[34]	2018	100 percent energy from wind, water, and solar (“Case C”)	About 100 percent	Expert assumption

Figure 2-6. Electrification rates of space heating by study methodology in Kaufman et al. (2019).

In their own analysis, Kaufman et al. (2019) take the “bottom-up” approach by comparing the costs and benefits of electrification of space heating in three cities: Atlanta, San Diego, and Fargo. They conclude that given a carbon price ($75-150/tCO2) and technological progress of air source heat pumps (15% improvement in performance and costs), heating electrification could be economic or near-economic in all three cities by the middle of the 2030s, as summarized in Figure 2-7 from the report below.

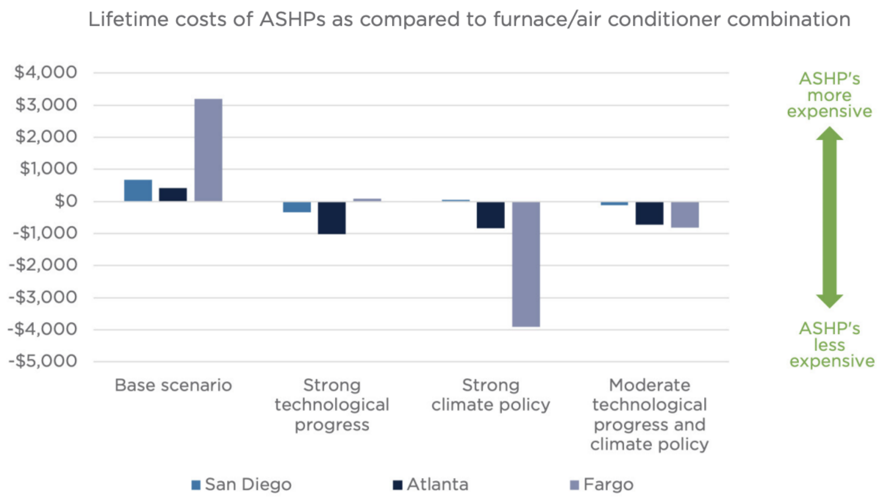

Figure 2-7. NPV analysis of heat pumps for space heating compared with natural gas furnaces in Kaufman et al. (2019).

There are several limitations to this analysis. First, the authors only assume one building in all three locations: a house of typical size (approximately 1,700 square feet) with a natural gas ducted forced-air furnace available. This eliminates the diversity of electrification results that could emerge from the diversity of housing characteristics and fuels.

Second, the installed cost estimates for ASHPs are quite low relative to reported estimates and the data available in the literature. The installed costs of a cold-climate ASHP are estimated at $2,142 in Fargo and approximately $1,500 in San Diego and Atlanta (Kaufman et al. 2019). This estimate is even lower than the low cost estimates in the Massachusetts building decarbonization report discussed above, and the methodology used to develop this cost estimate is unclear. The uncertain costing methodology and simplistic building modeling methodology in this study limit the relevance of its findings to the present work.

Another bottom-up study of heat pump adoption, Billimoria et al. (2018), similarly uses representative buildings in a small number of locations to analyze the economic prospects of heating electrification. This study focuses on the potential for rate design to enable demand flexibility in homes with electric heating. In their cold climate results presented in Figure 2-8, the authors find that the costs of retrofit electrification in Providence or Chicago are slightly higher than the costs of natural gas heating, with or without an AC.

However, the authors conclude that heat pump electrification is economic relative to heating oil and propane. Nonetheless, given a rational consumer seeking to maximize net present costs in a retrofit building, natural gas remains the cheapest option for oil or propane consumers in the cold climates of Providence and Chicago.

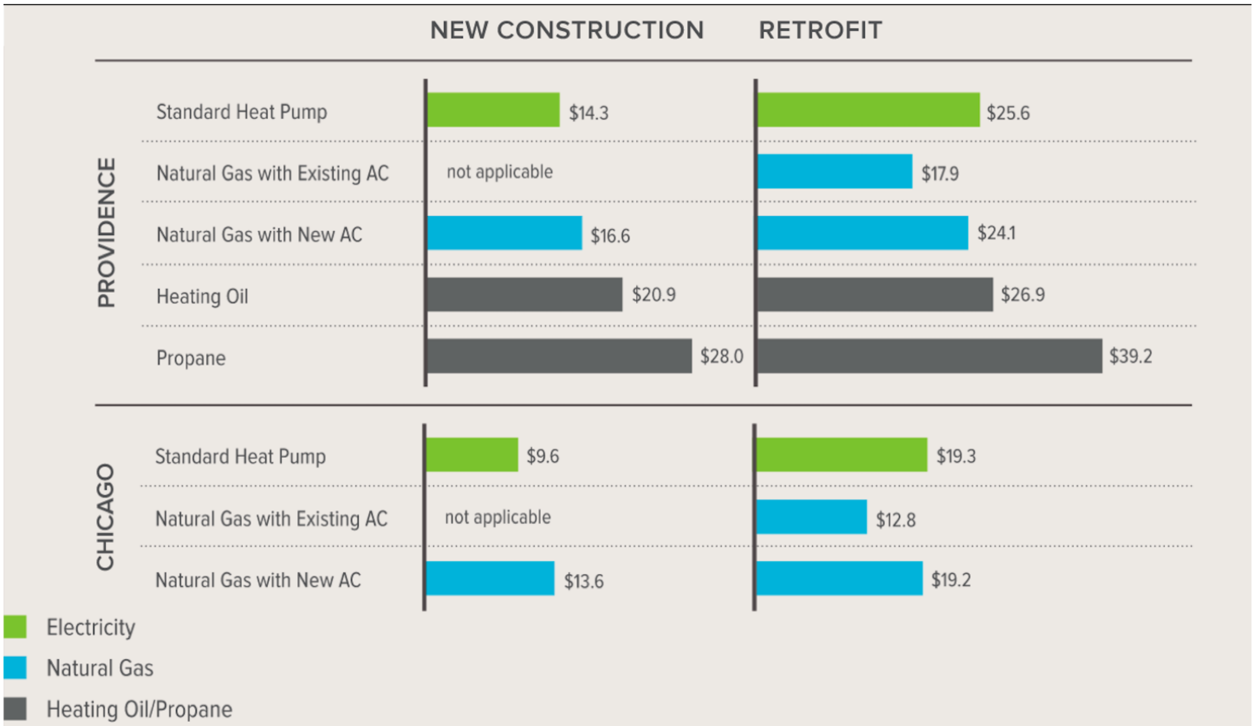

Figure 2-8. Net present costs (in thousands USD) of heating options for representative houses in cold climates in Billimoria et al. (2018).

The motivating analysis in Chapter 1 explored how the grid emissions factor influenced the emissions impacts of space heating electrification. Billimoria et al. (2018) find that since the marginal generator for most of the heating year in Chicago is coal, electrification of space heating in Chicago would increase carbon emissions relative to natural gas. In Providence (a case that is more similar to Massachusetts) the marginal generator is typically natural gas or renewables, and thus electrification results in a 33% reduction in emissions relative to gas, and over 50% relative to heating oil. While these are substantial emissions reductions, these results nonetheless underline that space heating electrification is not a silver bullet for eliminating emissions from buildings, and that the climate impacts of heating electrification are highly sensitive to the decarbonization of the power sector.

How can space heating electrification be made economic for consumers? Billimoria et al. (2018) analyze a variety of possible rate structures, but conclude that typical TOU rate structures are not enough to make electrification economic for households that currently heat with a natural gas furnace. The authors suggest that other policies or rate designs could help accelerate electrification rates, but do not specify what these might look like or what their possible costs or effects would be.

Finally, as with many other studies, the cost estimation methodology for heat pumps in Billimoria et al. (2018) is unclear. The study claims to estimate the installed costs of heat pumps based on wholesale device costs and other sources, with the installed costs of whole-home heat pump electrification in Providence estimated to be $7,522 for the typical retrofit home. It appears that this result comes from an interactive estimation tool on a website called Homewyse, which seems to be a for-profit company with an unpublished cost estimation methodology and relatively little detail on their website portal (Homewyse n.d.). The Homewyse website cites several sources over ten years old for cost data, for example HVAC technical manuals from 2003 and 2009. For these reasons, the heat pump costs used in Billimoria et al. (2018) are likely not reflective of the installed costs of whole-home space heating electrification projects in New England at present.

2.3 Energy system impacts of heating electrification

The third category of studies attempts to model the effects of heating electrification on the energy system. While decarbonization pathways studies typically assume widespread heating electrification to meet climate goals, and bottom-up studies typically focus on the private economic effects of electrification decisions on individual homeowners, energy system studies of heating electrification help illuminate the broader impacts of electrification. These studies typically use detailed models of the electricity grid to provide a higher-resolution representation of the changes in costs, emissions, and electric load that heating electrification would cause.

Vaishnav and Fatimah (2020) assess the effects of households switching from natural gas furnaces to electric heat pumps in 883 locations throughout the US, using typical meteorological year (TMY) data. They conclude that in most of these locations, electrification would both raise heating costs for households and increase damages from CO2 and other air pollutants. As illustrated in Figure 2-9 below, the authors find that heat pumps only provide positive social benefits in regions of the country that predominantly use resistance electric heating, particularly the Southeastern US. These results echo the results of Wilson et al (2017) discussed above, in which switching from resistance to heat pumps for electric heating was found to be economically and environmentally beneficial, while switching from natural gas to electricity was economically and environmentally marginal.

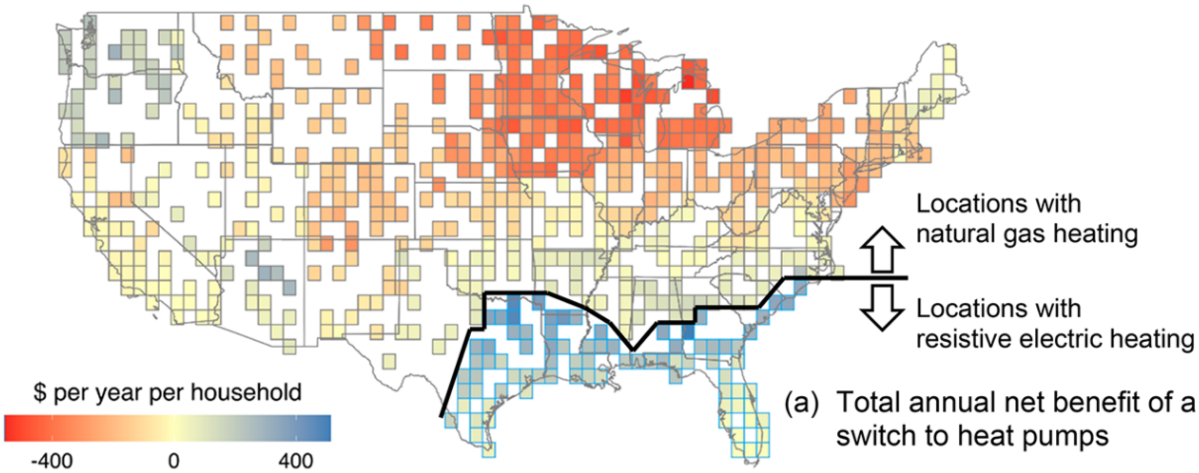

Figure 2-9. Monetized annual net social benefits of air-source heat pumps for primary space heating in Vaishnav and Fatimah (2020).

To estimate the net social benefit of switching to heat pumps, Vaishnav and Fatimah (2020) utilize spatially and temporally resolved power sector emissions data that incorporates emissions of CO2 in addition to criteria pollutants such as PM2.5, NOx, and SO2. Incorporating criteria pollutants in the social cost modeling makes electrification a less attractive option, because on-site combustion of natural gas for space heating emits relatively small amounts of criteria pollutants compared to fossil electric generators.

One significant drawback of the analysis in Vaishnav and Fatimah (2020) is that the study assumes that all households in each location only use natural gas or resistance electric heating. The text of the paper cites this simplification to an NREL dataset, but Wilson et al (2017) is evidence that more detailed data on household heating fuels is now available from NREL. The assumption that all households use natural gas in most of the country results in an underestimate of the potential benefits of heat pumps, which are greater for houses that currently use oil and propane for heating, as clearly described by Billimoria et al (2018). Since Vaishnav and Fatimah (2020) assume that all households in the majority of the US use natural gas, and the economic case for electrifying natural gas-heated homes is the weakest, Vaishnav and Fatimah (2020) could be considered a lower-bound estimate of the economic prospects for electrifying space heating.

Another energy system modeling study, Deetjen et al. (2021), uses the ResStock dataset introduced by Wilson et al. (2017) to model the impacts of heat pump adoption in a diversity of residential buildings throughout the country. Unlike Vaishnav and Fatimah (2020), this study does not assume a single heating fuel for each region. Instead, each house is assigned a heating fuel based on ResStock building characteristics data. Deetjen et al. (2021) conclude that only 32% of US houses would economically benefit from installing a heat pump, although heating electrification in 70% of houses could reduce damages from emissions. The potential heat pump adoption rate varies considerably based on the costs of the heat pump and the efficiencies of heating and cooling, as depicted in Figure 2-10 from the study.

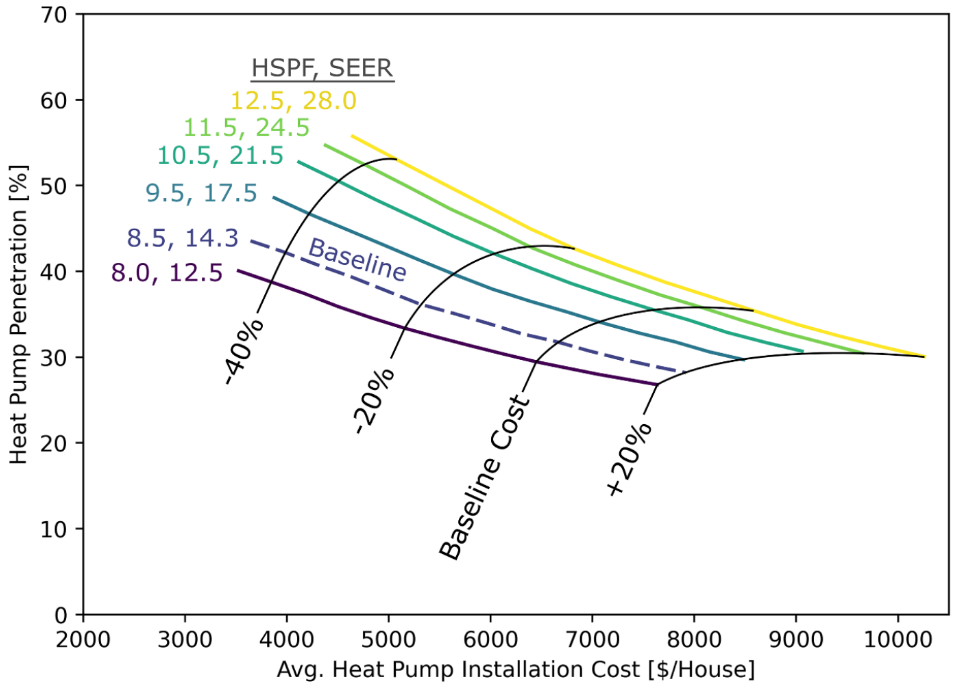

Figure 2-10. Modeled heat pump penetration rates as a function of installation costs and efficiencies in Deetjen et al. (2021).

From the review of the literature in this chapter, we can draw several conclusions which contextualize the analysis that follows in this thesis. First, the future prospects for heating electrification in the US are highly uncertain. Estimates of future heating electrification penetration vary by large amounts, even sometimes within the same study. While some decarbonization pathways studies assume near-complete electrification of space heating across the housing stock, many bottom-up studies find that electrification is uneconomic for the most consumers at present. Second, the costs of heating electrification are also highly uncertain, particularly the installed cost of whole-home heat pumps in retrofit applications. Few or no published analyses clearly use real data from completed projects in estimating whole-home heat pump installed costs. Third, many studies use relatively coarse assumptions about building characteristics and heating fuels, which disguises the diversity and complexity of the heating electrification challenge.

These conclusions motivate our contribution to the literature. In our analysis that follows, we quantify the potential electrification of space heating in Massachusetts under various scenarios by using real data to develop transparent estimates of electrification costs from a detailed underlying dataset of building characteristics and heating fuels.

3. Data

This chapter describes the construction and integration of the datasets used for this thesis. The goal of this thesis is to conduct a bottom-up economic optimization of residential space heating electrification in Massachusetts. The optimization model, further discussed in the following chapter on Methodology, seeks to meet thermal demand at lowest cost, defined as the net present value of the capital and operational costs of space heating. Each building is therefore a unique optimization problem based on its characteristics, such as size, location, and insulation; as well as the technological options and costs that it faces to provide space heating.

The analysis therefore requires detailed, building-level data on building characteristics and electrification costs. As found in the literature review in the previous chapter, few studies have used detailed and transparent data for building characteristics and electrification costs. This thesis attempts to fill that gap. The balance of this chapter describes the data sources for the building thermal demand modeling and cost estimation in the optimization analysis that follows. This chapter also provides visualization, description, and discussion of the data.

3.1 Building stock data

In order to construct individual optimization analyses of space heating options in a large number of buildings, it is necessary to have detailed characteristics to represent the building stock. For example, factors such as building size, vintage, insulation, existing appliances, usage, and weather conditions all play a role in defining a building's thermal requirements and energy demand.

ResStock (NREL 2021) provides such data, which this analysis adapts extensively for use in cost modeling and optimization. ResStock is a synthetic residential building database released by the National Renewable Energy Laboratory (NREL) in Fall 2021. It represents the entire US housing stock with approximately 550,000 synthetic residential building profiles. Each of these "ResStock buildings" has an approximately 1:250 weight, and therefore the entire dataset represents the 137 million residential units in the US. The large number of synthetic building profiles enables a very high geographic resolution, with buildings assigned to each Public Use Microdata Area, a US Census division that contains at least 100,000 residents. This means that ResStock can provide representative buildings specific to a single medium-sized city like Cambridge, MA, a rural county, or even a neighborhood in a large city like New York.

The individual building characteristics and profiles in ResStock were created from conditional probability distributions, developed by NREL based on data collected from government, nonprofit, and utility sources. The dependencies of the underlying conditional probability distributions are visualized in Figure 3-1 below.

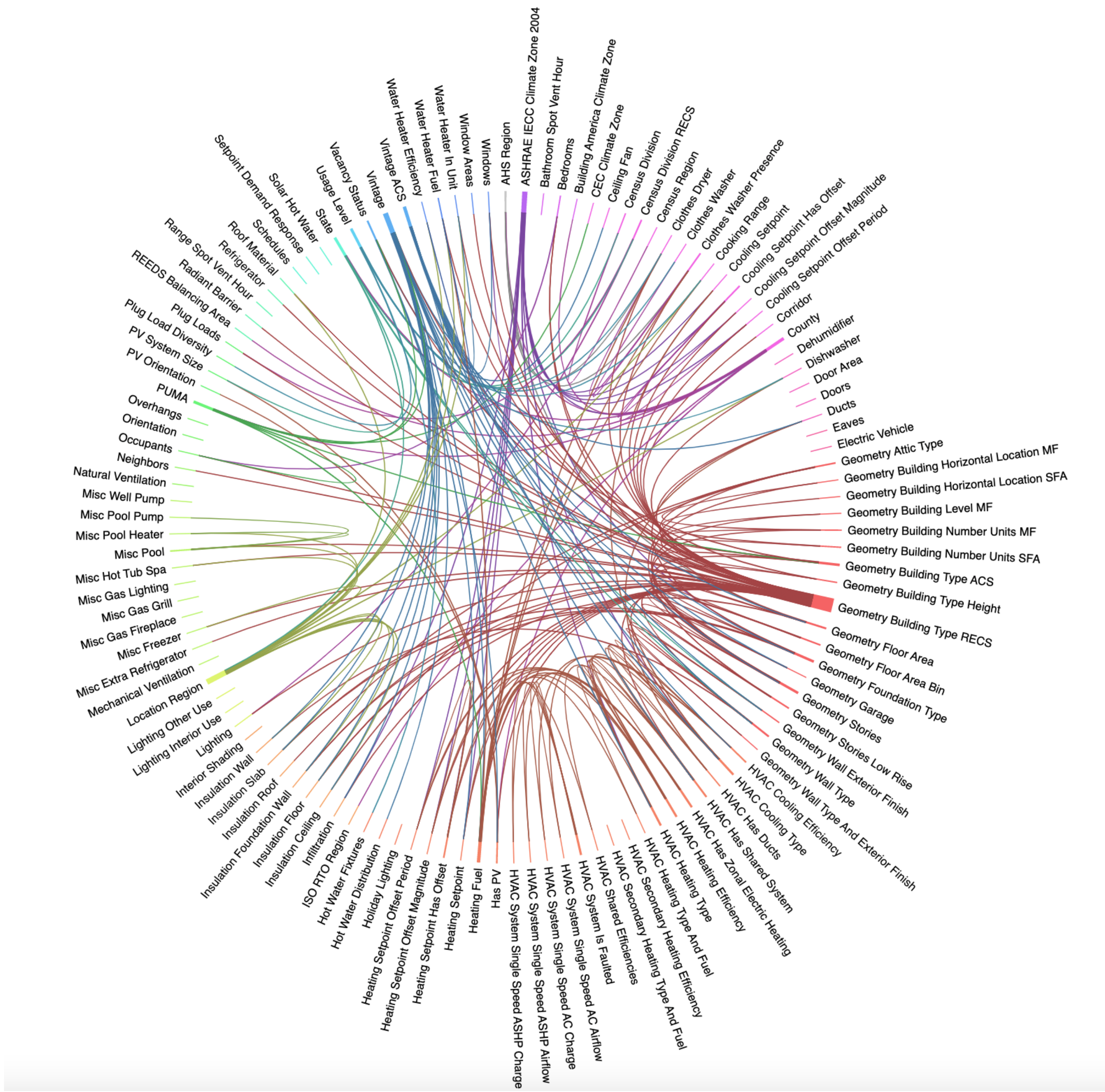

Figure 3-1. ResStock building characteristic conditional probability dependency wheel (NREL n.d.).

While ResStock was released to the public in 2021, it was under development for several years previously, and has already been used in several published analyses, including Wilson et al. (2017), as extensively discussed in the previous chapter. ResStock has been calibrated and validated against both public and proprietary utility data by NREL.

The analysis in this thesis specifically uses the ResStock synthetic buildings for Massachusetts in order to optimize the provision of space heating and cooling; and analyze the prospects for heating electrification. First, we filter the ResStock buildings for single-family houses in Massachusetts. We exclude multifamily units due to the complex design decisions available for heating larger buildings, for example the choice between shared building-wide and individual unit-based heating sources. Additionally, economic decisionmaking in multifamily buildings is more challenging to represent through a model, primarily due to persistent principal-agent problems surrounding capital investment and operational costs of energy in rented units (Murtishaw and Sathaye 2006). After filtering the ResStock database, there are 6,170 synthetic single-family homes in Massachusetts, which represent approximately 1.5 million Massachusetts single-family homes in reality.

Next, we randomly sample 100 of these synthetic buildings for our analysis in order to ensure computational tractability and iterability within our modeling framework. This approach is more appropriate than the data selection approach used by multiple studies cited in the previous chapter, which commonly use a very small number of representative buildings to analyze heating electrification. We performed analysis to check that the distribution of key parameters (such as heating fuels, house sizes, and vintage) of the sample reflected the distribution of these parameters in the filtered population.

Our model, as further discussed in the following chapter, builds a simplified physical representation of each sampled building to estimate heating demand and to optimize investment and operation of heating and cooling appliances. For this analysis, we use many of the building-level variables and data sources provided by ResStock. For construction characteristics, we use the building location, square footage, roof size, and window-to-wall ratio; as well as building envelope specifications such as wall material, wall insulation, window type, roof insulation, and basement insulation. For installed appliances and thermal appliance options, we use the existing heating fuel, existing heating and cooling appliances, efficiencies of these appliances, as well as whether or not the building has ductwork installed.

ResStock provides a wide range of detailed load profiles which are stochastically and synthetically generated from the American Time Use Survey data (US Bureau of Labor Statistics 2022). These sub-hourly load profiles include 47 end uses, varying from natural gas consumption for space heating to electricity consumption for clothes drying, hot tub pumps, and holiday lights. We compile the non-thermal load profiles into hourly “lighting” and “equipment” load profiles for a single year. These load profiles are left unchanged in our analysis as “uncontrolled” energy loads which do not change across our scenarios. This approach has the disadvantage of not capturing the potential response of non-thermal loads to heating and cooling technology options and rate designs. But it has the advantage that it provides an unchanging “control” load that allows the estimation of realistic and comparable energy bills across different heating technology scenarios, and makes it easy to isolate the effects of different heating options within the context of all household energy use.

Besides ResStock, other data sources for building characteristics are also incorporated into the analysis. The model uses weather data for Actual Meteorological Year 2018 from the National Solar Radiation Database published by NREL, which provides data on outdoor air temperature and solar radiation (Sengupta et al. 2018). The solar data includes direct normal and diffuse horizontal radiation, which are used in our building model to estimate solar heat gains in daylight hours, which can significantly offset heating demand depending on building design, and are largely excluded in previous studies. The optimization model can also use solar data to estimate the production of rooftop photovoltaic panels, although rooftop solar is not incorporated in the space heating analysis in this thesis.

The building characteristics and weather data are processed as inputs to the DECARB optimization model, further described in the following chapter on Methodology. The optimization model estimates the thermal demand of the building, and solves for the cost-minimizing investment and operation of thermal appliances, under varied rate designs and policy scenarios. In the future, this data pipeline and optimization methodology could be scaled up or down to analyze individual municipalities or the nation as a whole. The Tactical Thermal Transition project, sponsored by the Massachusetts state legislature, may adopt the method presented in this thesis to advise individual Massachusetts towns and cities on the potential pathways toward the decarbonization of space heating and potential impacts on local gas distribution infrastructure.

3.2 Energy and emissions data

In order to construct an optimization model of space heating electrification, it is necessary to use detailed data on the potential costs (e.g. capital and energy costs) and benefits (e.g. reduced energy use and carbon emissions) of different heating technologies at the building level. This data includes appliance sizing, appliance costs, installation costs (e.g. for labor, parts, and permits), utility rates for electricity and natural gas, fuel oil retail prices, and emissions factors. As observed in multiple prior studies in the previous chapter, published cost estimates of heating electrification have varied widely across the literature, and analyses rarely use real data or transparent estimates of the full costs of heat pump installation.

Estimating the costs of heating electrification is highly uncertain. In Massachusetts specifically, filings with the Department of Public Utilities (DPU), the state energy regulator, have exhibited higher cost estimates than many that have been published in the studies and reports discussed above in the Literature chapter. These cost estimates have been used in regulatory proceedings to determine the potential costs and benefits of utility incentive programs, and inform regulators on potential future trends in space heating in the

Commonwealth. Since these cost estimates are developed by utilities, engineering firms, or consultants, they are typically even less transparent than estimates in publicly published research. Table 3-1 summarizes the wide range of cost estimates of space heating electrification using an air-source heat pump, as compiled from the literature and DPU filings.

Source	Scope	Capital cost (2021 USD)
Massachusetts Decarbonization Roadmap Buildings Technical Report (2020)	MA modeled installed costs, average single-family house	<$5,000
Energy Information Administration (2018)	US assumed installed costs	$5,500-6,500
NREL NREMD (2018)	US assumed installed costs	$3,000-6,500
Mass. D.P.U. 20-80 (2021 E3 modeling)	MA modeled installed costs, typical residence	$15,500
Mass. D.P.U. 18-150 (2020 National Grid modeling)	MA modeled installed costs, typical residence	$13-19,000

Table 3-1. Uncertainty in the costs of heating electrification with a whole-home air-source heat pump for a single representative single-family house.

We received data on the installed costs of heat pumps from the Massachusetts Clean Energy Center (MassCEC) released as part of a public records request in November 2021 (MassCEC 2021). This data includes installed costs of whole-home and partial-home heat pumps.

The whole-home dataset includes 163 projects completed between 2019 and 2021 that received funding and advisory assistance as part of MassCEC's Whole Home Pilot Project program. Figure 3-2 is a histogram of the distribution of installed costs for whole-home heat pumps in the MassCEC dataset.

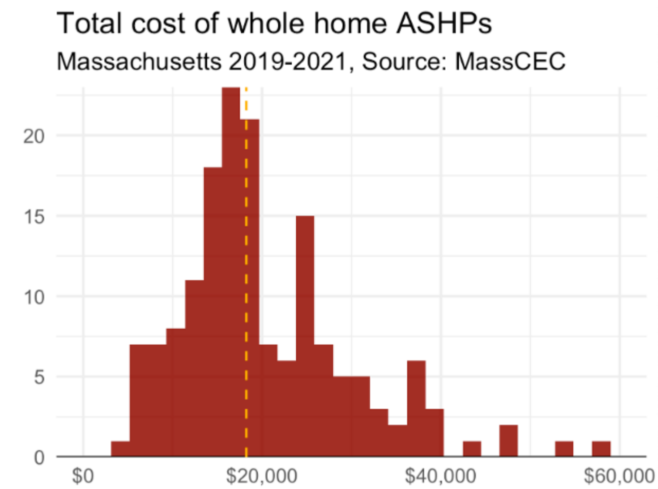

Figure 3-2. Distribution of the total installed cost of whole-home ASHPs in Massachusetts, constant 2021 USD. Own analysis of MassCEC (2021).

The whole-home dataset is highly detailed, as it specifies costs broken out into components which include heat pump equipment, installer and electrician labor, parts, ductwork, removal of the previous system, taxes, and permits. These costs are displayed in a box-and-whisker plot in Figure 3-3.

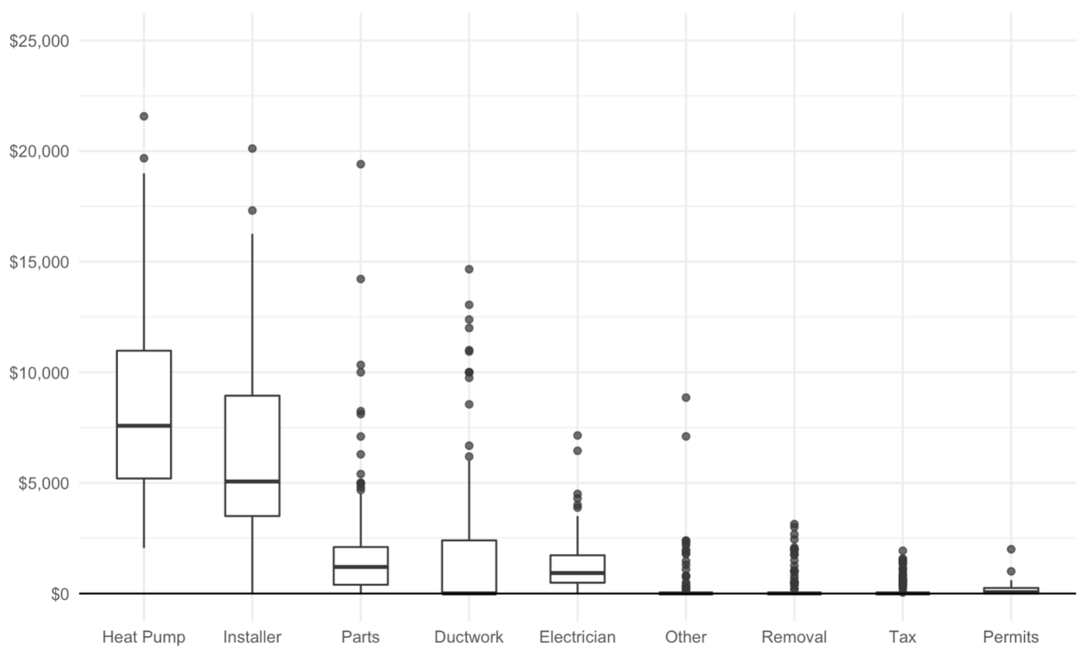

Figure 3-3. Cost components of whole-home heat pump electrification projects in Massachusetts. Own analysis of MassCEC (2021).

One clear conclusion from this data is that heat pump equipment accounts for less than half (median 41%) of the total project costs. Therefore, using heat pump equipment costs (e.g.

from wholesalers) as a proxy or replacement for total installed costs, as done by previous studies, is inappropriate and likely to severely underestimate the total costs of electrification. Furthermore, the cost drivers of electrification are predominantly non-equipment costs. This finding emphasizes the importance of labor costs and installation process efficiencies in reducing the installed costs of heat pumps.

The partial-home heat pump dataset from MassCEC contains a much larger number of projects, at 20,093 from 2014 to 2019. Figure 3-4 presents a histogram of the distribution of total installed costs-per-ton for the partial-home projects. One ton of capacity is defined as 12,000 BTU per hour.

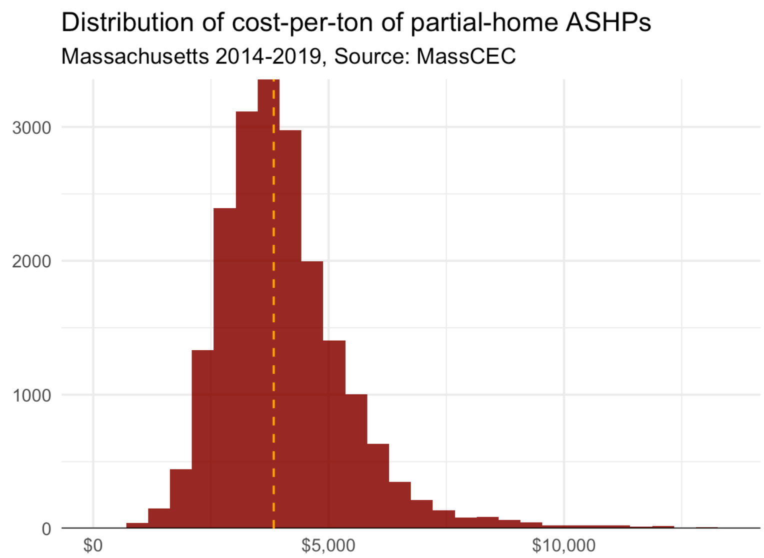

Figure 3-4. Distribution of installed cost-per-ton of partial-home heat pump projects in Massachusetts, constant 2021 USD. Own analysis of MassCEC (2021).

The partial-home projects are typically much smaller than the whole-home projects, with a median capacity of 25,500 BTU per hour, compared to 36,500 BTU per hour for the whole-home data. For this reason, we present the costs-per-ton for the partial-home projects as opposed to the total costs. The median cost-per-ton of the partial-home heat pumps is $3,833, considerably lower than the median cost-per-ton of the whole-home dataset at $5,997. The partial-home cost-per-ton implies a total cost of $11,500 for a typical 3-ton (36,000 BTU/hr) whole-home sized system. In contrast, the median total cost of a 3-ton whole-home system is approximately $18,000. In the partial-home dataset, the heat pumps are not used as the primary source of space heating, and are therefore undersized. These partial-home heat pumps are more likely to be replacements for air conditioning, and perhaps used to provide supplemental heating, while a fossil heating source remains. Additionally, the partial-home cost data is much less detailed than the whole-home cost data, with costs specified only by “Equipment” and “Other” categories. For this reason, we do not use the partial-home heat pump dataset in our cost model.

The MassCEC data includes the model number of the heat pump that is installed in each project, but excludes most other information about the specifications of the heat pump (such as its efficiency in heating or cooling modes). For this purpose, we cross-reference the model number in the MassCEC cost data with a large database of cold-climate heat pumps technical specifications from the Northeast Energy Efficiency Partnership (NEEP). By matching the MassCEC project costs to the NEEP technical specifications, we build a more complete picture of installed project performance and cost drivers.

We use the MassCEC cost data and NEEP efficiency data to build a detailed cost estimation model of the electrification of space heating with whole-home air source heat pumps, as further described in the following chapter on Methodology. Meanwhile, other data sources are incorporated to develop the economic analysis of the costs and benefits of space heating electrification.

Appliance cost data from the EIA is used to estimate non-heat pump appliance costs, for example the installed costs of natural gas and fuel oil furnaces and boilers (EIA 2018). Representative values from the EIA data, adjusted for inflation, are shown in Table 3-2. We scale these costs linearly based on the capacities provided and selected for individual buildings. While this approach is not as detailed as the heat pump cost model presented herein, it is better than using wholesale equipment costs alone, since installed costs are definitionally higher than wholesale costs. One limitation to this analysis is the lack of real installed cost data for fossil heating appliances, especially regarding detailed cost components of completed projects.

Appliance	Input Capacity (BTU/hr)	Efficiency (AFUE)	Installed Cost	Lifetime (years)
Low-Efficiency Gas Furnace	80,000	80%	$2,138	22
Energy Star Gas Furnace	80,000	95%	$2,858	22
Low-Efficiency Gas Boiler	100,000	82%	$7,484	25
Energy Star Gas Boiler	100,000	90%	$8,214	25
Oil Furnace	105,000	83%	$4,302	27
Oil Boiler	140,000	84%	$9,830	23

Table 3-2. Representative appliance installed costs in EIA (2018).

Electricity and natural gas rates are taken from publicly available sources for Massachusetts including EIA (2020) and the US Utility Rate Database (NREL 2017). We also consider a non-revenue-neutral heating electrification rate funded through state taxes. Finally, we use fuel oil prices for New England in 2019 from EIA (2022b).

To measure changes in building emissions in different scenarios, we use an hourly dataset of average grid CO2-equivalent (CO2e) emissions factors for Independent System Operator-New England (ISO-NE) in 2019. These emissions factors were calculated based on the hourly generation mix of ISO-NE and typical emissions factors for each generation type from IPCC (2014). Imports of electricity to ISO-NE from New York, Quebec and New Brunswick were assumed to have the fixed annual average carbon intensity of generation for these regions in 2019 from eGRID (EPA 2019). Figure 3-8 illustrates the hourly variability in average grid emissions factors across the year 2019 in ISO-NE.

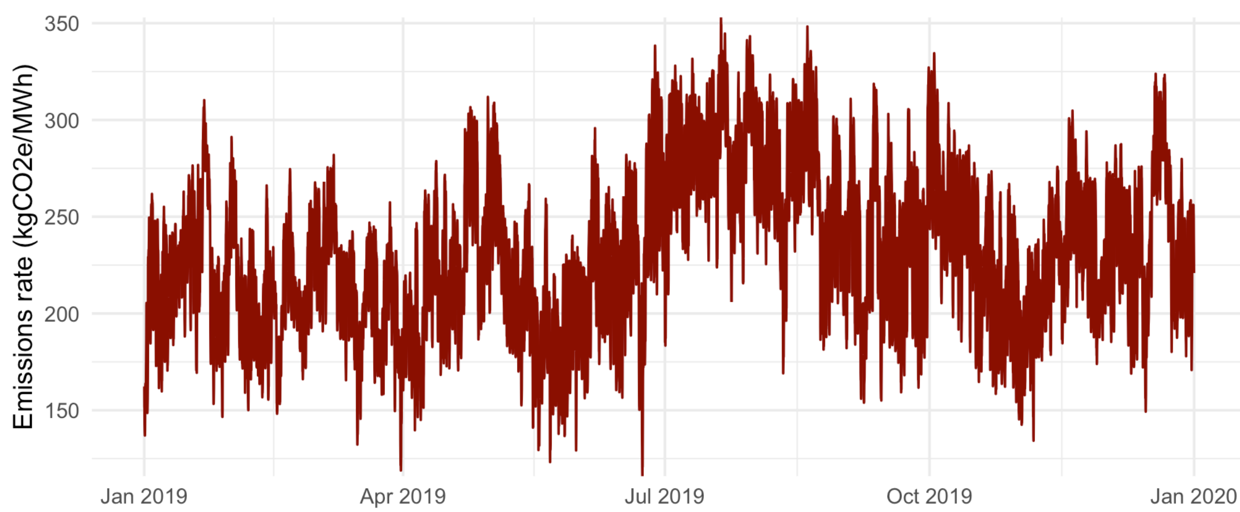

Figure 3-5. Hourly average grid emissions factors (kg CO2e/MWh) for ISO-NE in 2019.

This analysis uses average rather than marginal emissions factors to enable an hourly resolution. Marginal grid emissions factors for ISO-NE are only published at a monthly resolution. As illustrated in Figure 3-5, there is significant variation in the emissions of generation in ISO-NE at the sub-monthly level, which may substantially affect the analysis of space heating, since space heating demand is concentrated in certain hours of the year (e.g. winter mornings and evenings). Furthermore, the marginal and average emissions factors of ISO-NE may not actually be substantially different, as illustrated in Table 3-3. The marginal emissions rate for CO2 in ISO-NE was just 3% higher than the average in 2019, and 2% higher in 2018. This justifies using the hourly average grid emissions factor for an increased temporal resolution at the hourly level.

2019 ISO New England System Average Monthly Generator Emission Rates (lbs/MWh)

Monthly System Emission Rates (lb/MWh)			
Month	NO_X	SO_2	CO_2
1	0.28	0.10	626
2	0.25	0.05	576
3	0.25	0.05	567
4	0.24	0.04	578
5	0.24	0.04	564
6	0.26	0.05	619
7	0.27	0.05	726
8	0.27	0.04	717
9	0.29	0.04	658
10	0.27	0.04	621
11	0.28	0.04	632
12	0.27	0.05	670

2019 Monthly Time-Weighted LMU Marginal Emission Rates—All LMUs (lbs/MWh)

LMU Marginal Emission Rates (lb/MWh)			
Month	NO_X	SO_2	CO_2
1	0.14	0.09	631
2	0.06	0.01	503
3	0.10	0.04	592
4	0.05	0.00	521
5	0.07	0.01	570
6	0.09	0.01	630
7	0.16	0.03	770
8	0.13	0.01	739
9	0.08	0.01	696
10	0.13	0.02	763
11	0.11	0.02	689
12	0.09	0.02	656

Table 3-3. Average vs. marginal emissions rates for ISO-NE in 2019 in ISO-NE (2021).

All of these data sources are integrated in our modeling workflow to estimate the thermal demands of Massachusetts houses, the costs of electrifying space heating with heat pumps in these houses, and the consumer's perspective on the economics of heating electrification. The modeling workflow is described in the following chapter.

4. Methodology

This chapter describes the modeling workflow that comprises the methodology of this thesis. The analysis relies principally upon two models: a model to estimate the costs of electrification of space heating in each Massachusetts home using air-source heat pumps, and a model to optimize the investment in and operation of space heating equipment in each home. The remainder of this chapter describes the two models in turn, provides representations of both models, and offers visualization of the underlying data, representative results, and discussion of the models' development and possible limitations.

4.1 Cost modeling

The goal of the cost model in this thesis is to predict the costs of the electrification of space heating with whole-home air-source heat pumps (ASHP) for any single-family home in Massachusetts based on observed cost data and representative building characteristics from ResStock. For each building, the cost model produces a "menu" of electrification options, with installed cost estimates that vary based on factors including the maximum capacity of the ASHP equipment and the equipment's efficiency in heating mode. Then, the optimization model uses the results of the cost model to choose between these menu options, for example, by trading off the additional capital cost of a higher-efficiency appliance against the long-term savings from reduced operational costs.

As found in the review of the literature, published cost estimates of whole-home electrification of space heating vary widely and do not always clearly use empirical cost data. In contrast, this cost model builds directly on real project cost data gathered by the Massachusetts Clean Energy Center (MassCEC) and released in public records requests, as described in the previous chapter on Data. Using this detailed project-level installed cost data, we build a bottom-up model to predict the element-level costs of heating electrification.

The model structure is based on multiple ordinary least squares (OLS) regression of cost components on building characteristics and equipment specifications. Variable selection and model specification were performed based on visualizing and exploring the relationships in the data and literature between building characteristics, equipment specifications, and cost elements. For example, Figure 4-1 visualizes some of these relationships in the MassCEC whole-home cost database. As illustrated by these scatterplots, some cost components (e.g. the cost of the Heat Pump equipment itself) clearly scale with the ASHP capacity, as could be expected, whereas other cost components (e.g. parts and permits) have a weak relationship with installed capacity.

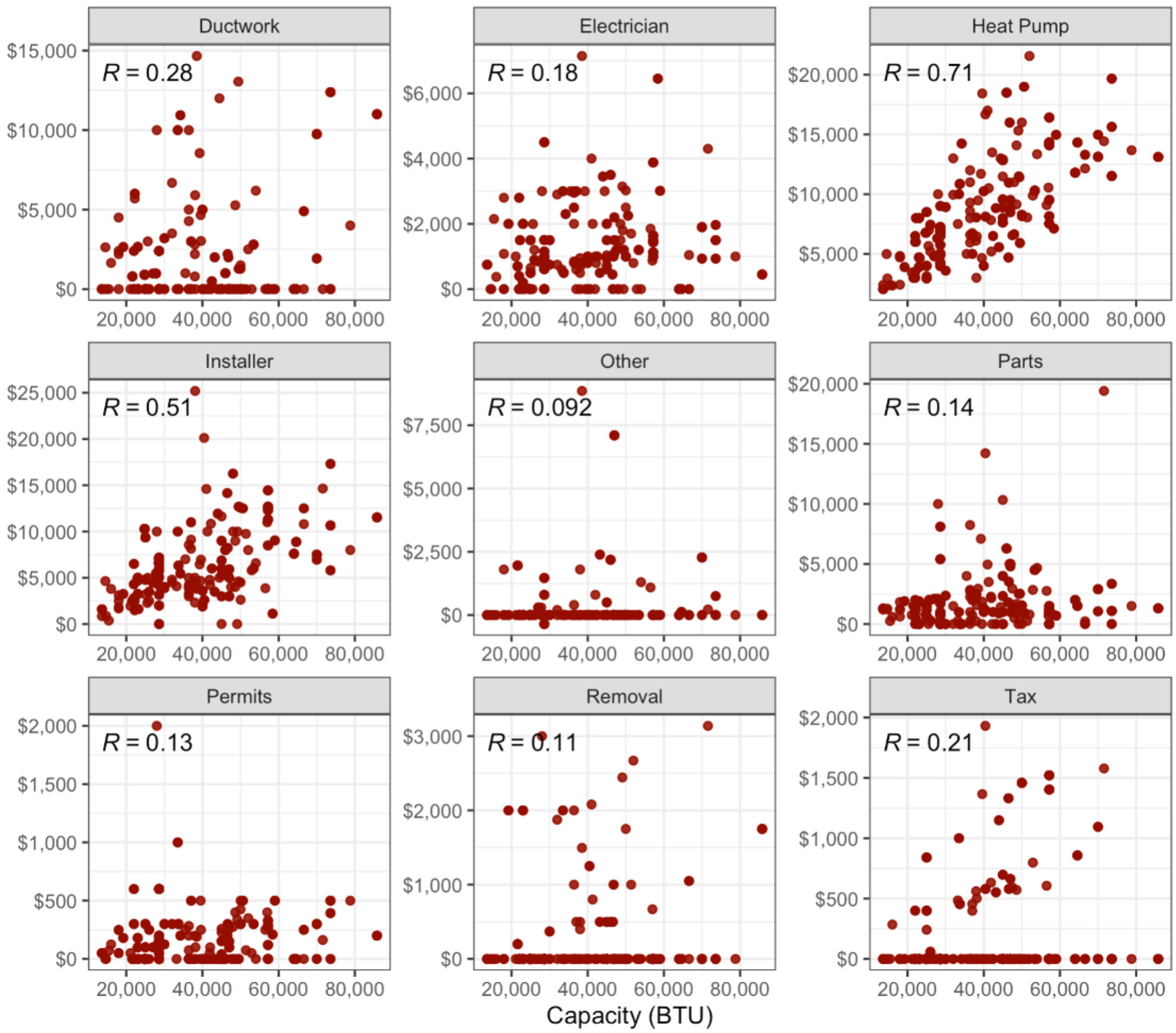

Figure 4-1. Relationships between ASHP capacity and cost components in data from MassCEC (2021).

Heat pump heating efficiency, as summarized by the Heating Seasonal Performance Factor (HSPF) specification, is another potentially significant cost driver. Efficiency specifications were not included in the published MassCEC cost database; however, the model numbers of the ASHP equipment units were included. Using the Northeast Energy Efficiency Partnership (NEEP) cold climate heat pump specification database described in the previous chapter, we matched the units installed in the cost database with the specifications from the NEEP database to get more detail on the performance characteristics of the heat pumps. Figure 4-2 shows the relationship of the cost components to the efficiency rating HSPF for the MassCEC data.

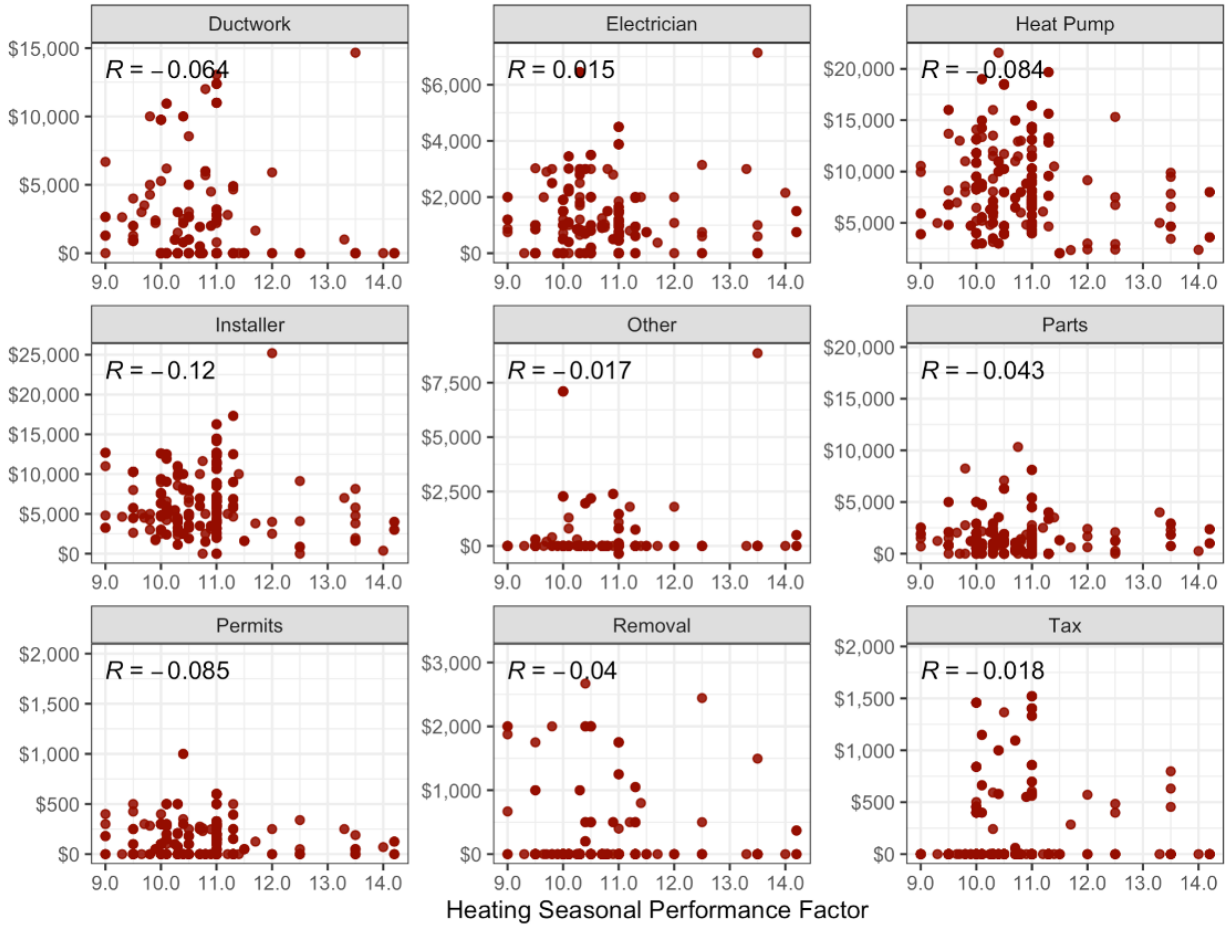

Figure 4-2. Relationships between ASHP heating efficiency and cost components in data from MassCEC (2021).

Surprisingly, there is no obvious relationship between efficiency and cost for most of the cost components in the MassCEC data. There are many potential reasons for this, including that the MassCEC database has a relatively small variance in efficiency: for example, many of the projects install the same Mitsubishi model with the same efficiency rating, as illustrated by the cluster of points at 11.0 HSPF. The above visualization emphasizes that ASHP performance specifications may not be a significant cost driver of the total installed costs of electrification projects.

For the analysis to represent the tradeoff between the capital and operational costs of ASHP efficiencies, higher-efficiency ASHPs should cost more. Therefore when modeling efficiency, we use additional data gathered from retailing of heat pump equipment, specifically Ecomfort (2022). We compiled the retail prices of mini-split ASHPs listed for sale in early 2022, filtered for ASHPs from Mitsubishi with the same capacity to limit confounding variables, and estimated a cost premium of 9% per 1 HSPF above or below a central HSPF of 10. The filtered retail cost dataset is intended to represent the most common configuration of the ASHPs in the MassCEC dataset. By including an “efficiency premium” of 9% per 1 HSPF, the cost model can reflect the supposed tradeoff between higher capital costs and lower operational costs from higher-efficiency units.

The overall model structure and heuristics used to combine various cost drivers and cost components in the OLS regressions are described in Table 4-1. We gather the individual cost components reported in the MassCEC dataset into the modeled cost categories. Then, we model each of the cost categories as a function of the cost drivers, using OLS multiple regression. Finally, we add the cost categories together to produce a bottom-up cost estimate for each ASHP option for a given house.

Modeled cost	**Components**	**Heuristic**
Appliance	Heat pump	Scale with capacity and squarefootage (and efficiency from wholesale dataset)
Labor	Installer, electrician	Scale with capacity and squarefootage
Ductwork	Ductwork	If no ducts, add mean (“expected value” of design decision)
Scaled misc.	Parts, removal	Scale with squarefootage
Flat misc.	Permits, tax, other costs	Flat cost adder (contingencies)

Table 4-1. Electrification cost model structure.

The model specifications of the individual cost components are developed from regressions of the cost components on the building and appliance characteristics in the MassCEC dataset. The model equations as estimated using the whole-home MassCEC data are reproduced below.

$$ApplianceCost_{est} = 933.88 + 0.1480 * Capacity_{BTU} + 1.1126 * ConditionedArea_{sqft} + EffAdjustment(Capacity_{BTU}, ApplianceEff_{HSPF})$$

$$LaborCost_{est} = 2286 + 0.1179 * Capacity_{BTU} + 0.6556 * ConditionedArea_{sqft}$$

$$Ductwork_{est} = \{Ductwork = 1: 0 \mid Ductwork = 0: 0.883 * ConditionedArea_{sqft}\}$$

$$ScaledMiscCost_{est} = 74.797 + 1.1028 * ConditionedArea_{sqft}$$

$$FlatMiscCost_{est} = 180$$

$$TotalCost_{est} = ApplianceCost_{est} + LaborCost_{est} + DuctworkCost_{est} + ScaledMiscCost_{est} + FlatMiscCost_{est}$$

The cost model estimates the costs of a menu of options for the whole-home electrification of space heating for each house. For example, given a typical Massachusetts house of 1,700 square feet and without ductwork, a representative menu of heat pump electrification options is displayed in Table 4-2. The capacity of the heat pump equipment varies on the vertical axis, whereas the average efficiency of the heat pump equipment varies on the horizontal axis.

	10 HSPF	11 HSPF	12 HSPF
37,000 BTU	$19,019.85	$19,850.01	$20,680.18
46,500 BTU	$21,405.38	$22,376.16	$23,346.93
57,200 BTU	$24,092.25	$25,221.40	$26,350.54
70,000 BTU	$27,306.45	$28,625.04	$29,943.64

Table 4-2. Modeled installed costs of whole-home air-source heat pump options for a 1,700 square foot Massachusetts home without ductwork.

The costs of electrifying space heating for this typical home are estimated to range from approximately $19,000 to $30,000 based on the capacity and efficiency selected as design decisions. The wide range of costs reflects the variance of installed costs by these factors in our model; notably, a relatively small unit still has substantial installed costs.

From the output of the cost model, the optimization model can choose between the “menu” of heat pump options by estimating the building’s thermal demand (based on its size and envelope characteristics) as well as the capital and operational energy costs (based on utility rates and installed cost estimates) to make an economically optimal heating equipment decision, as further described in the following section.

4.2 Optimization modeling

The goal of the optimization model in this thesis is to meet each building’s energy and thermal demands at the lowest net present cost possible. For this purpose, we use the Distributed Energy Consumption in Actively Responsive Buildings (DECARB) model, which is under development at the MIT Energy Initiative to do bottom-up techno-economic analysis. This model builds on a previous building energy optimization model called DR-DRE, which has been used in studies including Pérez-Arriaga et al. (2016), Tapia-Ahumada and Dueñas (2016), Lee (2019) and others. As of the time of this writing in early 2022, the DECARB model is in preparation for an open-source release.

The inputs to the DECARB model include non-thermal hourly load profiles, energy prices, weather data, and technology parameters, such as heat pump and gas furnace costs and performance specifications. The optimization algorithm, implemented with the Gurobi solver and the JuMP package suite in the Julia language, solves for the investment and hourly operation of the building's energy resources to meet the building's thermal and energy demands while minimizing net present costs (Dowson 2022, JuMP.jl 2022). The schematic in Figure 4-5 illustrates the model's internal workflow.

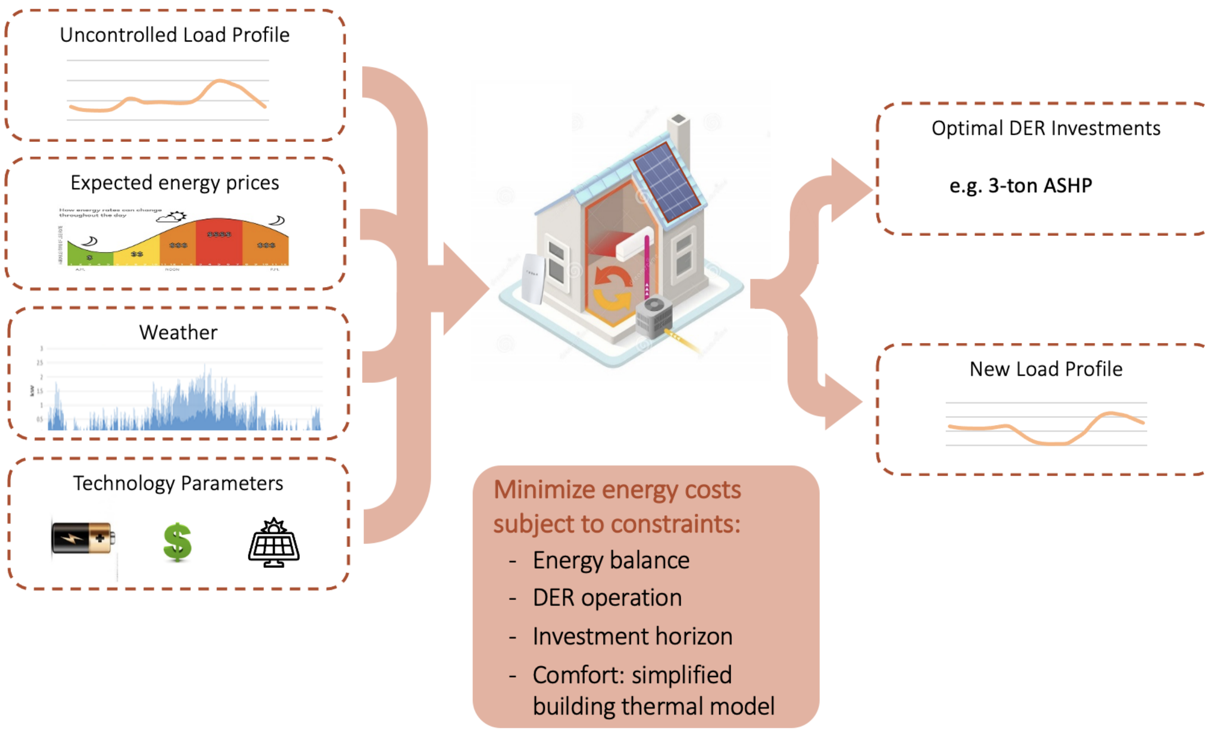

Figure 4-5. Schematic overview of DECARB model.

The goal of the thermal demand component of the model is to operate the heating and cooling equipment in order keep the inside of the building at a temperature between a given range of setpoints, which reflects occupant thermal comfort as well as other potential factors including occupant behaviors in setting the thermostat, or "smart thermostats" that can respond automatically to time-variable rates or weather conditions. In this way, DECARB enables a high-resolution hourly optimization of the operation of heating equipment.

The objective of the model is to minimize net present costs (equivalent to maximizing net present value) over the lifetime of the installed equipment, which is taken to be 15 years for ASHPs and 20 years for fossil equipment. We assume a 6% discount rate, reflecting the opportunity cost of typical returns available to a homeowner through capital investment. The annualization of investment costs in the total cost function is performed over the appliance lifetime with the selected discount rate. The objective function of the model is described by the equation:

$$Min\ Cost = \sum_{t}^{P} (vNSEcost_t + vNSTcost_t + vNSHWcost_t + vQcost_t - vQearn_t + vGOcost_t) + (vHVACinv + vWHinv + vCHPinv + vPVinv + vBESSinv) + vQmxcost$$

In this equation, the variable and parameter names correspond to:

$vQcost_t$	Cost of purchasing electricity [$]
$vQearn_t$	Income from selling electricity [$]
$vGOcost_t$	Cost of purchased fuel: natural gas or diesel [$]
$vNSEcost_t$	Cost of non-served electricity [$]
$vNSTcost_t$	Cost of non-served temperature [$]
$vNSHWcost_t$	Cost of non-served hot water [$]
$vHVACinv$	Annualized investment cost of HVAC [$]
$vWHinv$	Annualized investment cost of water heater [$]
$vCHPinv$	Annualized investment cost of CHP [$]
$vPVinv$	Annualized investment cost of PV [$]
$vBESSinv$	Annualized investment cost of electricity storage [$]
$vQmxcost$	Cost of peak capacity [$]

The thermal model within DECARB is a simplified representation of the key thermal characteristics of a building, derived from previously published studies including Martín-Martínez et al. (2016). The thermal model predicts the temperature of the building in the next hour as a function of the temperature of the building in the previous hour, the outdoor air temperature, the thermal resistance and capacity of the building, the solar heat gains to the building, and the generation of heat by equipment and occupancy within the building. The following equation describes the thermal balance of the model:

$$\left(\frac{1}{R1}\right)\left(vT_{in,t} - vT_{in,t-1}\right) + \frac{\Delta t}{R1R2_tC}\ vT_{in,t-1} = (vQ\_HTAC_t + pQ\_IHG_t) - \left(1 - \frac{\Delta t}{R1 \cdot C}\right)(vQ\_HTAC_{t-1} + pQ\_IHG_{t-1}) + \frac{1}{R2_t}\left(\frac{\Delta t}{R1 \cdot C} pT_{out,t-1}\right) + \frac{\Delta t}{R1 \cdot C} pQ\_R_{t-1}$$

In this equation, the variable and parameter names correspond to:

Decision variables:

$vT_{in,t}$	Indoor temperature at time t [°C]
vQ_HTAC_t	Thermal energy produced by heating/cooling equipment at time t (thermal gain) [kWh]

Parameters:

pQ_IHG_t	Convective heat [kWh]
pQ_R_t	Radiative heat [kWh]
$R1$	Thermal resistance R1 [C°/kW]
$R2_t$	Thermal resistance R2 [C°/kW]. Temporal variation dependence on conductivity due to ventilation (outside temperature, occupation)
C	Heat capacitance [kWh/C°]
$pT_{out,t}$	Outdoor temperature at time t [°C]
$\Delta \boldsymbol{t}$	Time step

The internal structure of the thermal model within DECARB is a 2RC model because it includes two specifications of thermal resistance and one specification of thermal capacitance for each building. The resistance $R1$ is invariant with time, while the resistance $R2_t$ changes with each hour to reflect the changes in ventilation from outdoor air temperature and occupancy. Thermal capacitance C is calculated from the thermal characteristics of the constituent building elements that contain thermal mass, such as the walls and the foundation or slab. Thermal resistances $R1$ and $R2$ are calculated from the thermal resistance of the walls, foundation/slab, and ventilation.

Figure 4-6 describes the full input and output data streams of the model in more detail. These outputs are specified based on data described in the previous chapter, including building characteristics, load profiles, utility rates, and weather data; as well as the cost estimations from the electrification cost model discussed above and the fossil heating equipment estimates derived from EIA (2018).

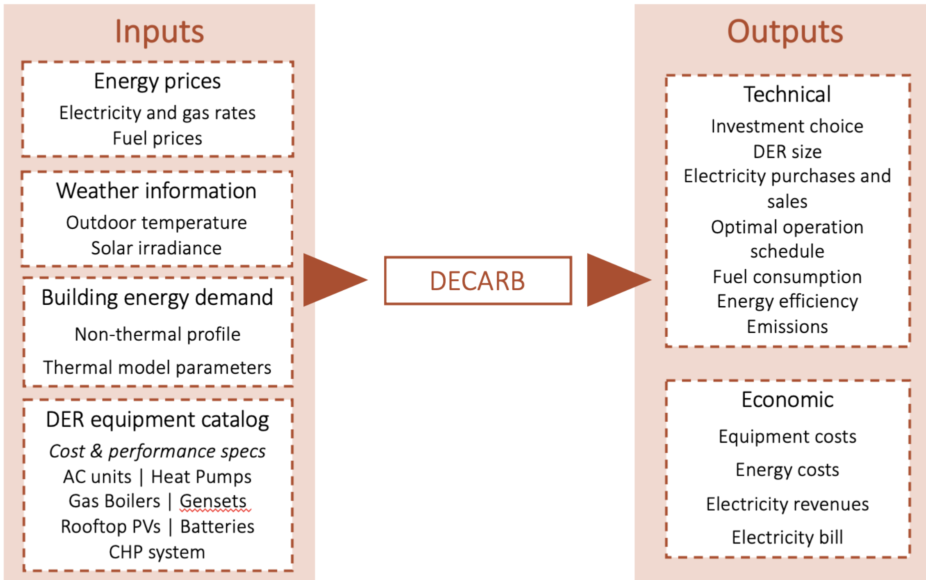

Figure 4-6: Input and output data of DECARB model.

Using an optimization model that seeks to minimize the net present costs of thermal comfort has advantages and disadvantages. It effectively assumes that consumers are rational and have unlimited access to financing at the discount rate. As discussed above, estimates of the economic potential of building-level efficiency measures frequently overestimate the actual adoption of these measures achieved in reality, in the phenomenon known as the "energy efficiency gap." For this reason, defining economic potential using relative net present costs could overestimate future electrification rates.

However, economic potential may also *under*estimate adoption in some cases, for example for consumers who are motivated to electrify their building's space heating for non-cost reasons such as emissions reduction, comfort benefits, or state or local mandates. As will be seen in the results that follow, many of the whole-home ASHP projects in the MassCEC database that were electric conversions from natural gas likely had higher net present costs relative to installing a new high-efficiency gas furnace or boiler.

In essence, economic potential isolates the microeconomics of the heating technology decision, and avoids some of the social and psychological factors that influence adoption in practice. Integrating economic and adoption/diffusion models to project future heat pump deployment is a promising area for future research.

We iterate the cost estimation and optimization models over the buildings in our sample across a variety of cases to experiment and illustrate the prospects for the bottom-up electrification of space heating in Massachusetts. The cases and results are described in the following chapter.

5. Results and Discussion

This chapter presents the results of the economic optimization analysis of space heating in Massachusetts. First, the scenarios of the analysis are defined and discussed. Then, the results for each scenario are presented in turn. The economic and emissions impacts of the heating technology choices in each of the scenarios are summarized and visualized, with a particular focus on the impact of space heating decisions on costs to consumers and CO2e emissions from buildings.

For each of the scenarios, we present three comparable visualizations of results.

First, we visualize the composition of the primary energy sources of heating demand: the quantity of electricity, natural gas, and fuel oil that is used for space heating across the buildings. This illustrates the bottom-line progress on heating electrification achieved in the optimized results for each scenario.

Second, we visualize the distribution of annual energy bills, investment costs, and carbon emissions across the buildings in each scenario. This illustrates the economic and environmental impacts of the optimized space heating decisions on key consumer-level metrics for policymakers.

Third, we visualize the daily electricity load profiles that result from the buildings across the year. This illustrates the potential impacts on electricity demand from heating electrification, which has implications for the future of electricity generation, transmission, and distribution systems.

The discussion that follows for each scenario interprets the scenario results and discusses implications for policymakers and advocates for understanding the future of heating electrification in Massachusetts.

Scenario definitions

There are five scenarios in this analysis:

1. *Baseline*
2. *Current Policy*
3. *Free Heat Pump*
4. *Mandated Electrification*
5. *Electrification Rate*

The *Baseline* scenario provides a control case for comparison by using only the currently installed equipment as specified by ResStock data, without allowing for any new investment. In this scenario, many homes have low-efficiency gas and fuel oil heating equipment. The operation of the heating equipment is optimized by the model to minimize operational expenditure, with no capital expenditure on heating equipment allowed. This scenario is intended to reflect the present state of affairs for space heating in Massachusetts.

The *Current Policy* scenario re-optimizes space heating across all buildings under current heat pump subsidies and energy rates in Massachusetts. Optimal investment in electric, natural gas, and fuel oil heating equipment is enabled. Each building can also choose between installing a heat pump or a traditional air conditioner (plus a fossil furnace or boiler) to meet cooling demand in the summer. Whole-home heat pumps enjoy a $10,000 rebate on the capital costs, which reflects the subsidy from MassSave as of 2021 (MassSave 2021). Operation of the installed equipment is optimized to meet thermal demands at the lowest net present cost.

The *Free Heat Pump* scenario makes whole-home heat pumps available at no investment cost to households, and optimizes investment and operation to meet thermal demands subject to the free availability of heating electrification. This represents the logical extreme of policy incentives that subsidize the capital costs of heat pumps. We use this case to explore the implications and possible limitations of using installation cost rebates to achieve ambitious electrification goals, given current rate designs and relative costs.

The *Mandated Electrification* scenario forces all homes to adopt electric space heating while providing whole-home heat pumps at no investment cost to households. Optimization of investment is enabled, but no new or existing fossil appliances are allowed. This scenario builds on the *Free Heat Pump* scenario by not only giving away heat pumps at no installation cost, but also preventing households from using natural gas or fuel oil heating sources. This allows the exploration of the possible effects of “forcing electrification” upon households through policy, and the impacts on household energy bills and emissions, under current rate levels and grid carbon intensities.

The *Electrification Rate* scenario provides a substantial rate reduction for households that switch to electric heating, in addition to an expanded capital cost subsidy available to households. This scenario explores the effect of the cost differential between electricity and fossil heating sources, and the importance of operational subsidies or rate reform in achieving substantial heating electrification in Massachusetts.

5.1 Scenario 1: Baseline

In the *Baseline* scenario, investment is disabled and the DECARB optimization model only optimizes operation of existing installed heating and cooling equipment specified by ResStock. Heating and cooling equipment is sized sufficiently to meet each building's thermal demands. Figure 5-1 provides a visualization of the energy sources for space heating per building across sample.

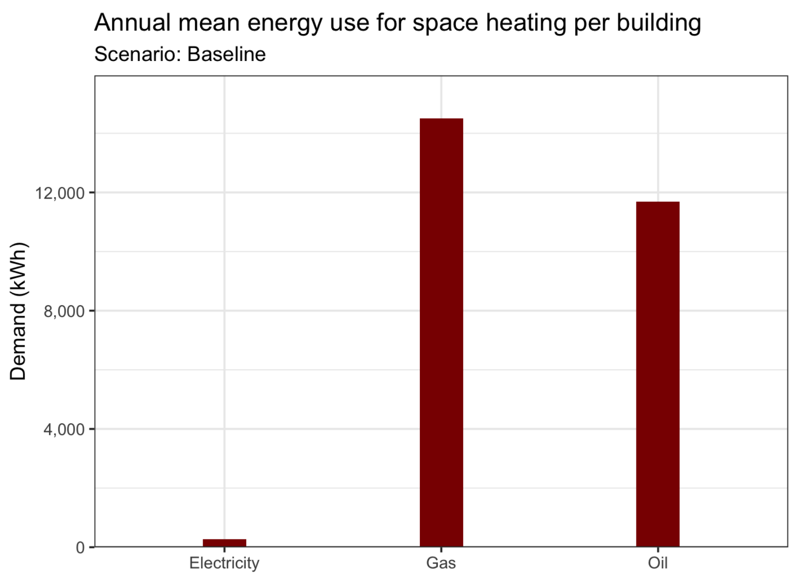

Figure 5-1. Energy sources of space heating in the *Baseline* scenario.

In the *Baseline* scenario, very little electricity is used for space heating. Since investment is disabled, all houses have the heating equipment that is specified by ResStock, and ResStock does not specify any existing installations of heat pumps for Massachusetts houses. The small amount of electricity demand that exists is from inefficient electric resistance appliances, such as electric baseboard heaters and electric furnaces. As discussed previously in this thesis, electric resistance appliances are rarely an optimal choice for new investment in houses today given current electricity and gas rates and carbon intensities.

The results in Figure 5-1 reflect the dominance of natural gas for space heating in Massachusetts. Meanwhile, a significant share of households use fuel oil for heating. The average amount of fuel oil used is relatively higher than the share of households using fuel oil, representing the typical relative inefficiency of fuel oil heating equipment relative to natural gas.

Next, we visualize the distribution of costs and emissions across the results of the buildings in the *Baseline* scenario. Figure 5-2 illustrates the distribution of operational costs, investment costs, and carbon emissions across the sampled buildings given currently installed appliances.

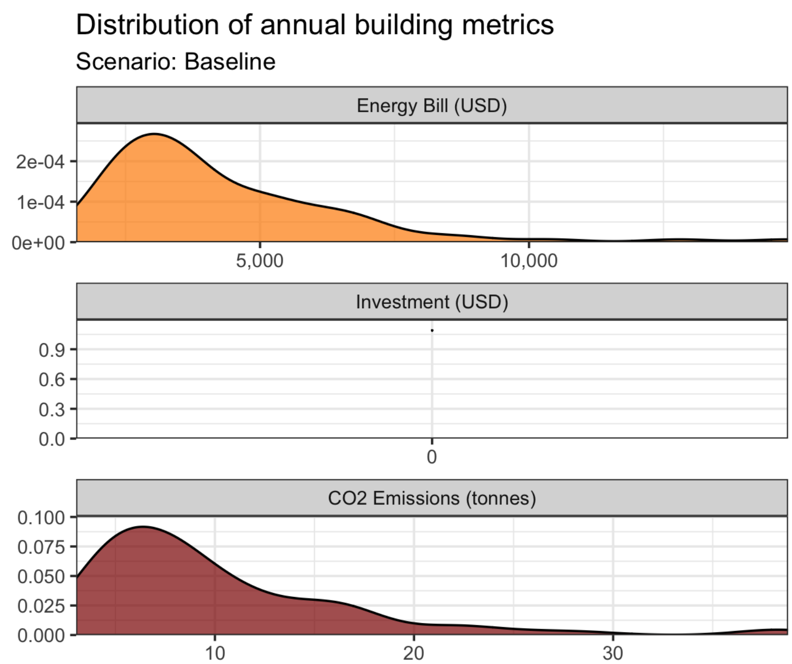

Figure 5-2. Probability distribution of costs and emissions in the *Baseline* scenario.

In the *Baseline* scenario, the median household pays energy bills of $3,555 annually, or approximately $300 per month. This incorporates the cost of electricity, natural gas, and fuel oil for heating, as well as non-thermal end uses like lighting and cooking. Investment cost in heating equipment is zero for all buildings in this scenario because investment is disabled. In terms of emissions in the base case, the median household accounts for approximately 8 metric tonnes of CO2e. This includes both the direct emissions released by the onsite combustion of oil and natural gas in the building, as well as the indirect emissions attributed to the building by its electricity use throughout the year.

These results align well with public data about households' utility costs in Massachusetts. Massachusetts has the second highest average utility bills in the country, with typical monthly bills of $302 per month reported in 2020 (Morrison 2020). The *Baseline* emissions results also align well with national estimated emissions data. According to the EPA, 19.8 percent of US greenhouse gas emissions was attributable to residential buildings in 2020 (EPA 2022). Then, with 142 million housing units and 6.558 billion metric tonnes of total CO2e emissions in the US in 2019, the average residential building nationally accounts for 9 tonnes of CO2e emissions per year (EPA 2022). From this comparison, we see that Massachusetts single-family homes in the *Baseline* scenario have slightly lower emissions than the national average house, likely due to the cleaner than average electricity grid in New England.

Next, we explore the electricity load profiles for the buildings in the *Baseline* energy case. Figure 5-3 shows the daily average electricity demand across all of the buildings in the sample, with the bold black line representing the daily average electricity demand across all houses.

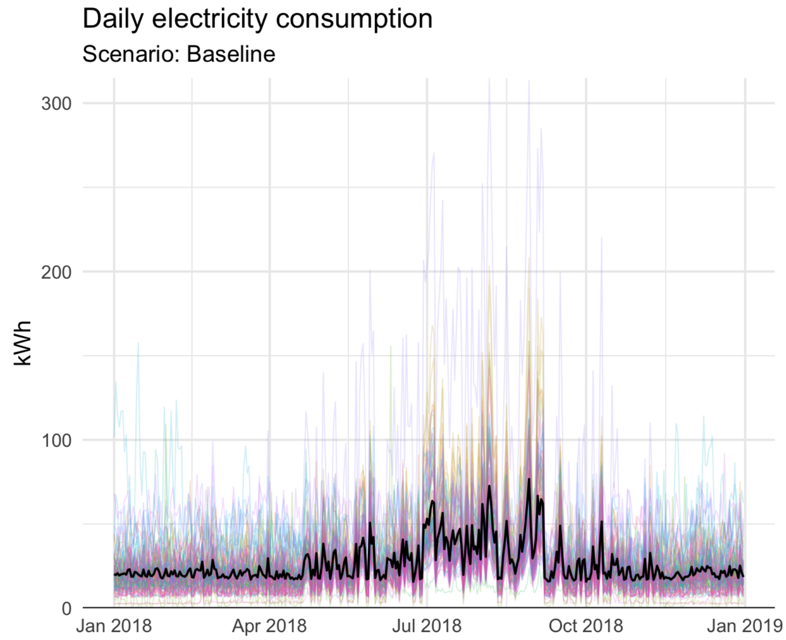

Figure 5-3. Daily electricity demand in the *Baseline* scenario.

In the *Baseline* load profiles, there is a significantly higher electricity demand in the summer than in the winter months, reflecting the increased electricity use from air conditioners used for cooling. Furthermore, the individual house load profiles (in transparent colors) exhibit sharp individual daily peaks across both summer and winter. In the summer, these reflect large houses with high air conditioning demands; in the winter, these reflect houses with electric resistance heat.

Overall, the *Baseline* results reflect the typical assumptions about the current state of space heating and energy use in Massachusetts. Natural gas dominates the energy used by households for space heating, with less fuel oil and significantly less electricity used on average. Energy bills are relatively high, in part due to the high electricity rates in Massachusetts relative to the rest of the country. Carbon emissions per house are slightly lower than the national average, with ISO-NE's relatively clean electricity grid generation mix offset by the higher use of fossil fuels for space heating due to the colder weather than most of the country.

For policymakers, these baseline "business as usual" results are troubling: energy costs are already high for Massachusetts households, and emissions are significant. Reducing emissions from residential buildings should not come at the expense of further increasing energy costs, as this could exacerbate existing concerns around energy insecurity that face Massachusetts households at present. We will now see how these results change across other scenarios.

5.2 Scenario 2: Current Policy

In the *Current Policy* scenario, investment in space heating equipment is enabled and optimized, along with hourly operation, to meet each building's thermal demand at the lowest cost. The households can receive a $10,000 subsidy for the capital costs of a whole home heat pump, and can also choose between gas, oil, and electric resistance equipment options. Finally, households can choose between installing an ASHP or a conventional AC (along with a fossil heater) to meet summer cooling demands. Figure 5-4 illustrates the topline results for the energy sources of space heating in the *Current Policy* scenario.

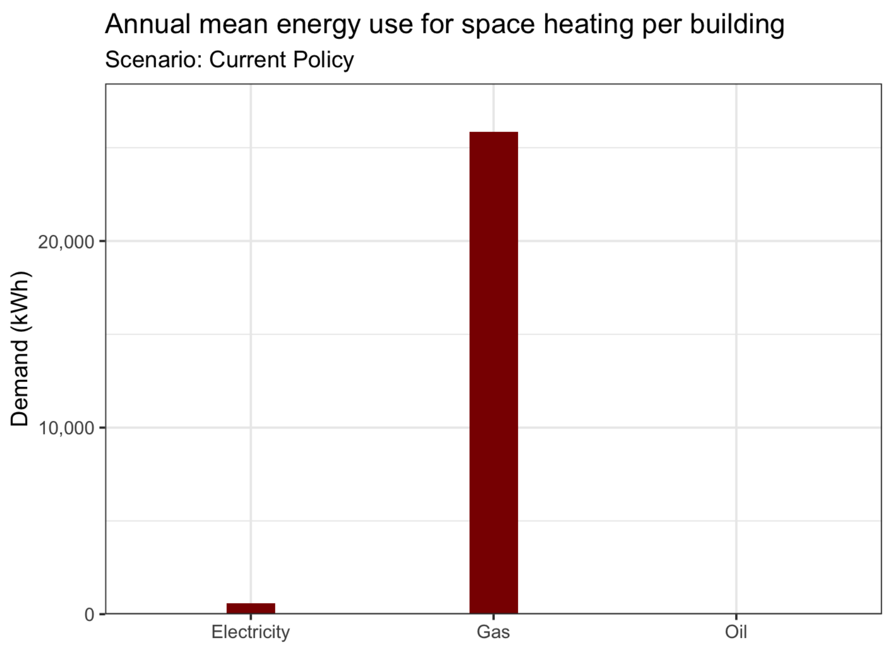

Figure 5-4. Energy sources of space heating in the *Current Policy* scenario.

Despite the large subsidy to ASHP costs, the vast majority of households in the *Current Policy* scenario choose to install high-efficiency (>90% AFUE) natural gas furnaces and boilers along with traditional air conditioners. While the capital costs of heat pumps and gas appliances are comparable in this scenario for many houses (for example, a small house that benefits from the flat $10,000 subsidy relatively more than a large house) the operational costs of heat pumps are too high relative to natural gas to make electrification of space heating optimal. As indicated by Figure 5-4, the small amount of space heating demand that is met by electricity in the *Current Policy* scenario reflects a small share of heat pump installations.

Specifically, the cost ratio of electricity (~$0.22/kWh) to natural gas (~$0.05/kWh), under 2021 rates facing customers in Massachusetts, means that electricity is over four times more expensive than natural gas per unit of energy. While ASHPs are much more efficient than natural gas heating equipment, with effective efficiencies well above 100%, they are not so much more efficient as to make them cheaper than natural gas to operate, especially given the performance degradation of ASHPs in cold outdoor air temperatures. High-efficiency natural gas heating equipment remains more cost-effective than ASHPs per unit of delivered heat. For this reason, the optimal choice of heating technologies for nearly all of the single-family homes is to install high-efficiency natural gas equipment.

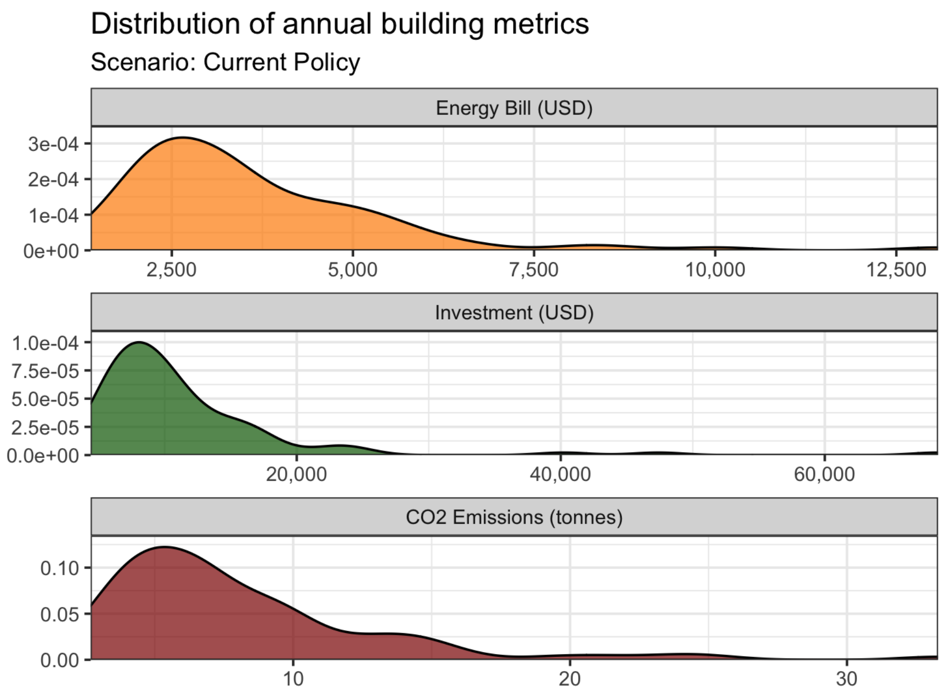

Figure 5-2. Probability distribution of costs and emissions in the *Current Policy* scenario.

The *Current Policy* scenario represents an improvement upon the *Baseline* scenario in key building-level metrics, as depicted above in Figure 5-5. The median energy bill faced by households is $3,216, compared to $3,555 in the *Baseline* scenario, 9.5% lower than the *Baseline* scenario. The median CO2e emissions is 6.8 tonnes, 19% lower than the *Baseline* scenario.

These improvements in energy bills and CO2e emissions reflect the increased economic and environmental performance of high-efficiency natural gas heating appliances installed in the *Current Policy* scenario, relative to the lower-efficiency gas, electric resistance, and oil appliances installed in the *Baseline* scenario.

Finally, investment costs are relatively high, with a median of $8,389 per house. This reflects the “greenfield” costs of installing new thermal equipment to meet both the heating and cooling needs of buildings, and therefore includes both furnace/boiler and AC costs. The installation costs of the furnace/boiler + AC package, which varies based on the installed capacity and are approximately $8,500 for a typical house, are potentially competitive with the subsidized installed costs of ASHPs. For example, for a household that can meet heating and cooling demands with a whole-home heat pump estimated by the cost model at $15-20,000 installed cost, the $10,000 subsidy could be enough to make the ASHP an attractive option on the basis of installed costs for some homes. However, the higher operational costs of ASHPs for heating nonetheless make them uneconomic for the vast majority of houses.

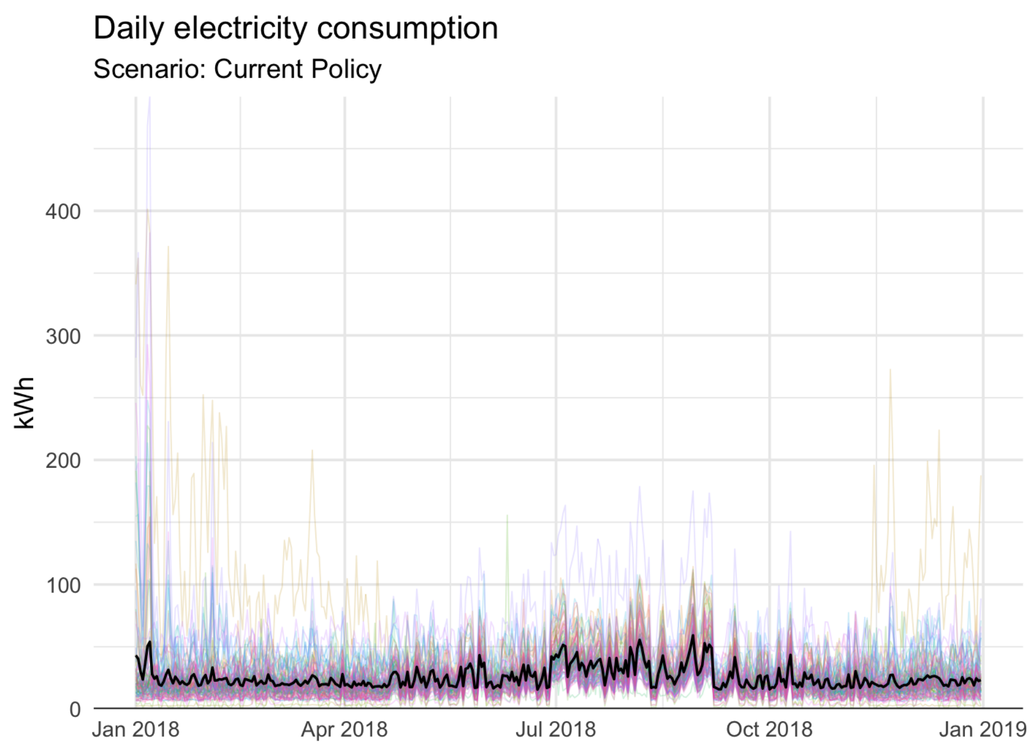

Figure 5-6. Daily electricity demand in the *Current Policy* scenario.

As shown in Figure 5-6, the daily patterns of electricity consumption in the summer and winter are not significantly changed in the *Current Policy* scenario compared to the *Baseline* scenario. The few houses that install ASHPs for space heating in the *Current Policy* scenario are clearly visible in the Winter demand profiles, with daily electricity consumption exceeding 200 kWh in some hours in the first week of January, for example. This illustrates the magnitude of the increase in electric demand caused by electrifying space heating in individual houses, and suggests the large impact that small amounts of heating electrification can potentially have on aggregate peak loads, and subsequently on distribution systems. These effects are further explored in the companion TPP thesis Lee (2022).

5.3 Scenario 3: Free Heat Pump

In the *Free Heat Pump* scenario, households optimize their investment and operation in heating equipment, with a sufficiently sized whole-home ASHP available at zero capital cost. This represents the logical conclusion of subsidizing the installed capital costs of heat pumps in an attempt to incentivize electrification. However, surprisingly, the vast majority of houses still choose to install natural gas heating appliances, as summarized in Figure 5-7.

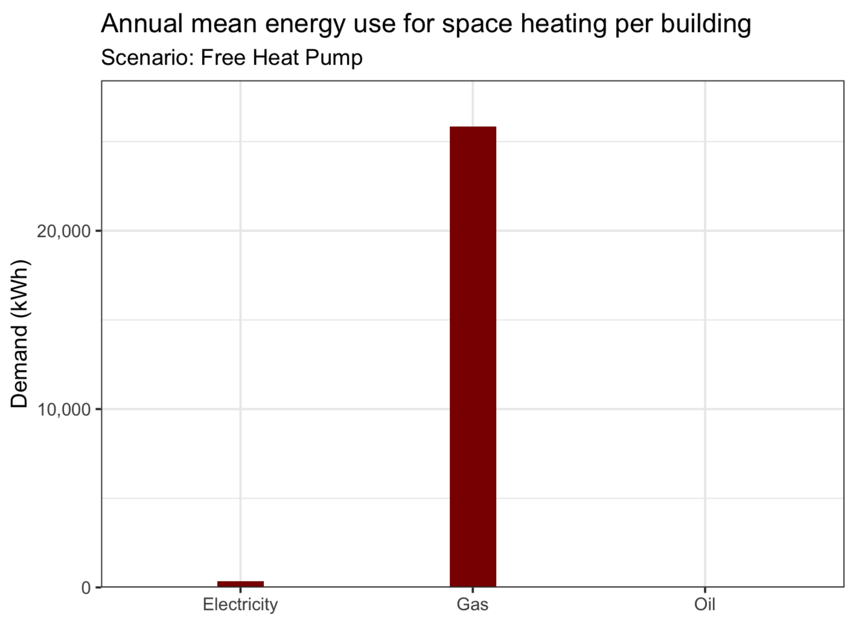

Figure 5-7. Energy sources of space heating in *Free Heat Pump* scenario.

Even when heat pumps are literally given away, they are more costly to operate for heating on a net present value basis than new (costly) high-efficiency natural gas furnaces and boilers. This suggests that the primary barrier to the widespread electrification of space heating in Massachusetts is the cost premium for electricity over natural gas, which overwhelms the cost savings from the high efficiency of heat pumps, and makes even “free” heat pumps uneconomic compared to gas for heating.

Even though heat pumps are not used for heating in the *Free Heat Pump* scenario, heat pumps are nonetheless installed. Since a source of space cooling is now available to residents for free, all households install ASHPs to provide high-efficiency cooling in the summer, in lieu of installing traditional air conditioners. This suggests that under current rates and price differentials, heat pumps may continue to gain market share as capital costs come down, but as space cooling sources (and supplemental heat sources) rather than primary space heating sources. As illustrated in the following figure, the deployment of ASHPs in place of traditional ACs for cooling has benefits in reducing energy bills and household carbon emissions — but is far from the “deep decarbonization” of buildings sought by advocates of space heating electrification.

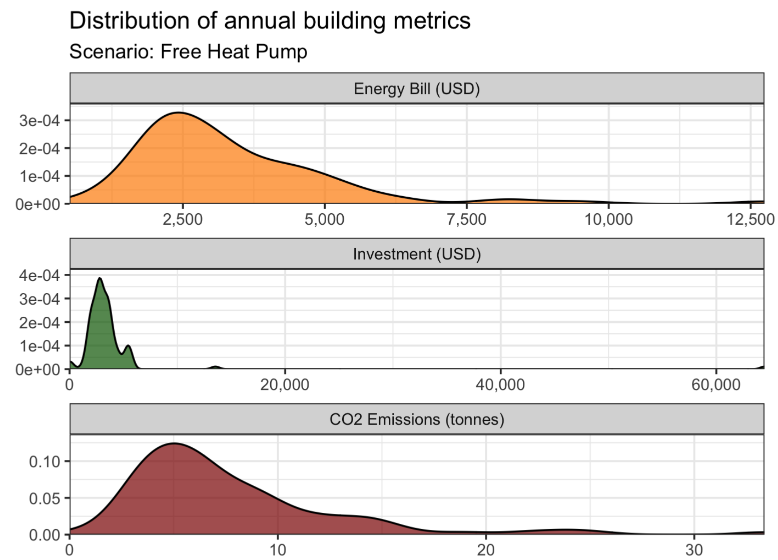

Figure 5-8. Probability distribution of costs and emissions in the *Free Heat Pump* scenario.

The distributions of key building-level metrics in the *Free Heat Pump* scenario are illustrated in Figure 5-8. A very small number of sampled buildings use the free ASHP to meet their heating needs, as illustrated by the small probability density at 0 on the Investment panel. However, since households use the free ASHPs to provide cooling, and the ASHPs are considerably more efficient than traditional air conditioners available on the market, energy bills and emissions both decrease in this scenario. The median energy bill of $2,956 in the *Free Heat Pump* scenario is 8% lower than the *Current Policy* scenario, while the median CO2e emissions of 6.4 tonnes is approximately 6% lower than the *Current Policy* scenario. Deploying ASHPs instead of conventional air conditioners can therefore result in a decrease in both energy bills and emissions from space cooling, even if the ASHPs are not used for primary space heating.

In general, the results of the *Free Heat Pump* scenario indicate that increased subsidies for the capital costs of heat pumps may be insufficient to drive heating electrification in Massachusetts. Increasing the capital cost subsidy to heat pumps (in an attempt to drive electrification) could also be an inefficient use of government expenditure relative to other potential policies, for example, reducing the price premium of electricity to natural gas through rate design or rate subsidy.

The costs of capital subsidies could be significant relative to state and utility budgets. For example, if all 3 million housing units in Massachusetts installed whole-home heat pumps with the currently available $10,000 per home subsidy, the total cost of the subsidy could approach $30 billion, or nearly two-thirds of the state's entire budget for 2022. Meanwhile, as illustrated by the *Free Heat Pump* results, the energy and emissions savings from expanding capital subsidies may be marginal if the heat pumps are not used to displace fossil space heating.

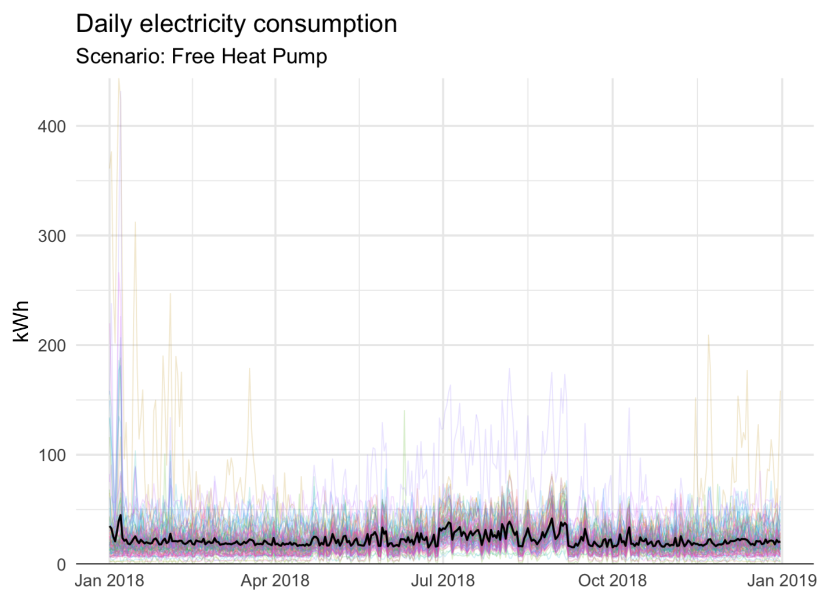

Figure 5-9. Daily electricity demand in *Free Heat Pump* scenario.

Although most houses do not use the free heat pumps as their primary space heating source, the daily electricity demand patterns are significantly changed relative to the baseline. The few houses that do use their ASHP for space heating are clearly visible in Figure 5-9, as their daily electricity demand exceeds 200 kWh in the coldest parts of the year. Furthermore, electricity demand in the summer is decreased relative to the *Baseline* and *Current Policy* scenarios, as ASHPs provide equivalent cooling for less electricity. The highest average electricity demand day in this sample is now in January rather than in July, which illustrates the small amount of heating electrification that could result in transitioning the Massachusetts grid from a summer-peaking to a winter-peaking system. This has implications for energy system planning at the regional level, as the New England energy system is designed for a summer peak at present.

5.4 Scenario 4: Mandated Electrification

In the *Mandated Electrification* scenario, all households are given a free heat pump and required to use it as their primary source of space heating and cooling. This policy would cost more than $30 billion to implement in the entire state, assuming installed costs of heat pumps over $10,000 for each of 3 million residential units in Massachusetts. The mandated electrification scenario helps to illustrate the potential "end state" of space heating electrification, and enables the estimation of the effects of electrification on energy bills and carbon emissions relative to present. Similar to the *Baseline* case, the *Mandated Electrification* case effectively disables the economic optimization of investment; instead, investment is only enabled for electric heat sources.

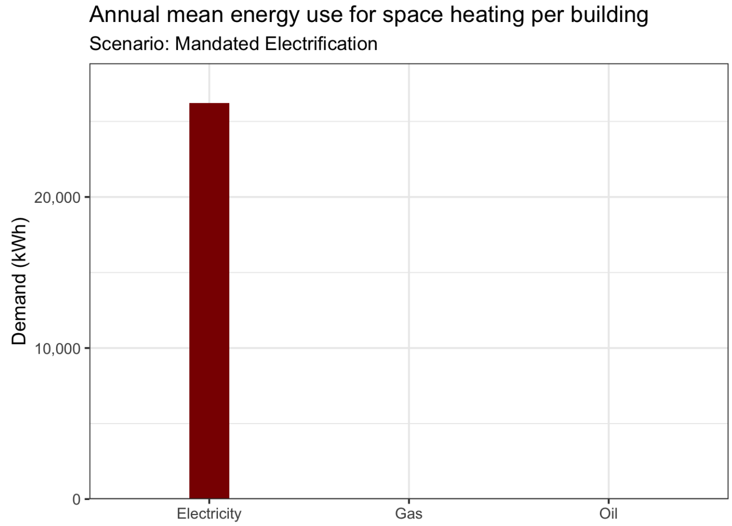

Figure 5-10. Energy sources of space heating in *Mandated Electrification* scenario.

As shown in Figure 5-10, all space heating demand is definitionally met by electricity in the *Mandated Electrification* scenario. While mandating electrification is not currently under discussion in Massachusetts statewide policy, it could be viewed as the natural extension of currently discussed plans to create a cap or “budget” on emissions from heating fuels (Mass. EEA 2022).

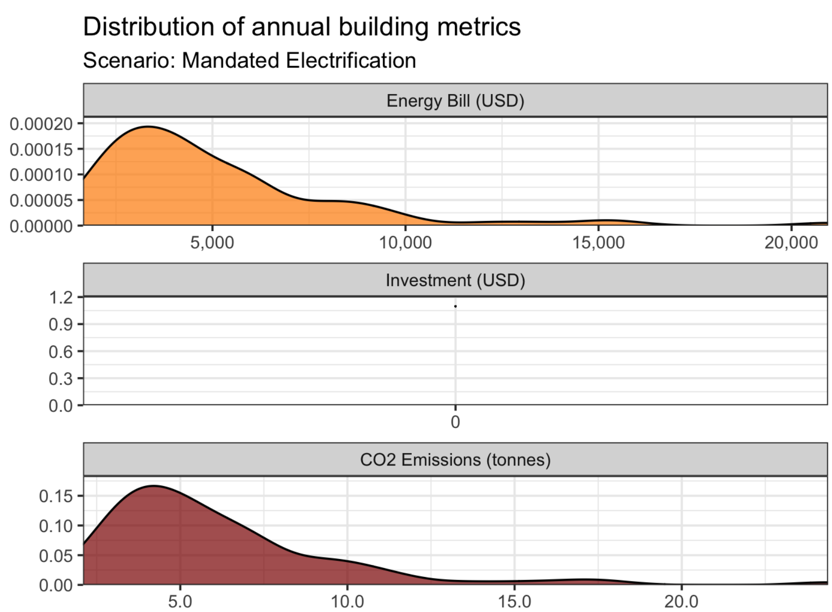

Figure 5-11. Probability distribution of costs and emissions in the *Mandated Electrification* scenario.

In the *Mandated Electrification* scenario, investment is zero by design, since heat pumps are available at no cost to all residents. Energy bills are generally higher than the *Baseline*, *Current Policy*, and *Free Heat Pump* scenarios. The median energy bill of $4,200 is 18% higher than the *Baseline* scenario, in which households generally have low-efficiency gas and oil heating equipment. At current rates, therefore, all-electric space heating would increase the typical energy bills in Massachusetts by nearly one-fifth. Mandating electrification under current rates would be costly to Massachusetts households, even without taking into account capital costs.

Emissions in the *Mandated Electrification* scenario are lower than in the other scenarios, but only marginally. The median house in the *Mandated Electrification* scenario accounts for 5.23 tonnes of CO2e, a 35% decrease in emissions relative to the *Baseline* scenario. The policies that would be required to create this scenario in practice would be especially expensive: significant costs would arise from the total subsidization of heat pump capital costs, and consumers would face higher electricity bills. Given current rates and grid carbon intensities, the emissions-reduction value of mandating space heating electrification is relatively low.

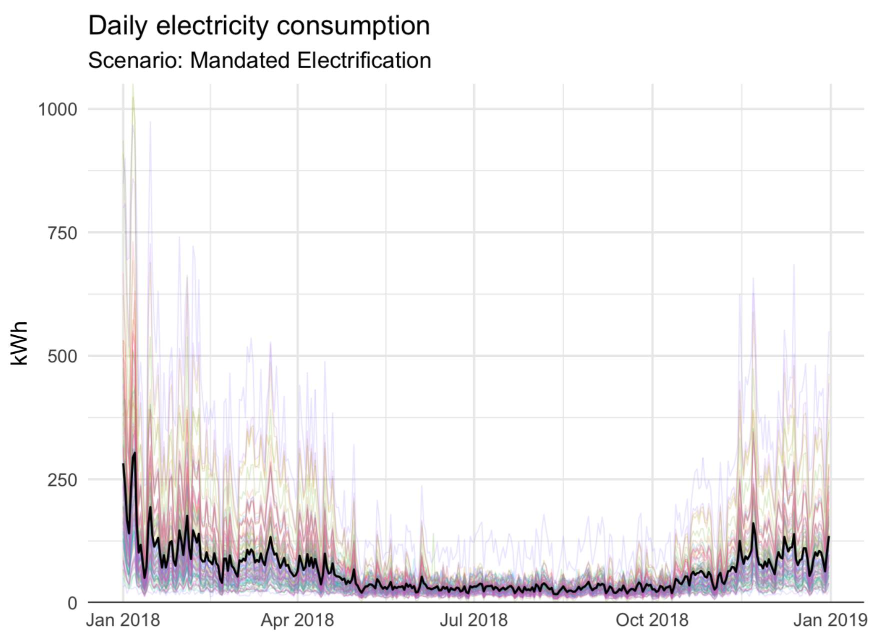

Figure 5-12. Daily electricity consumption in *Mandated Electrification* scenario.

Mandating electrification sharply increases winter electricity demand. The average house exceeds 200 kWh of electricity use per day in the coldest parts of the year. Electricity demand in especially cold hours is exacerbated by the declining efficiency of ASHP equipment in low outdoor air temperatures. In this dramatically winter-peaking scenario, substantial transformations to generation, transmission, and distribution systems would likely be necessary across the region to meet the electricity demand from space heating. The widespread deployment of “smart” controls and time-variant electricity pricing could help reduce the extremity of the winter space heating peaks; however, this result would certainly entail a significant transformation in the New England energy system.

5.5 Scenario 5: Electrification Rate

In the *Electrification Rate* scenario, consumers receive a discount on their electric rates for electrifying space heating. There is a precedent for this in Massachusetts, as utilities presently offer a discount on electric rates for customers that have primary electric heating sources. In the Greater Boston area, Eversource currently offers a Residential Space Heating rate that decreases the network charge portion of the bill from $0.137 per kWh for standard offer residential service, to $0.121 per kWh for customers that primarily heat their homes with electric equipment (Eversource 2022). In the context of the full electric rate facing customers that combines network and supply costs, this amounts to approximately a 5% decrease in electricity unit cost.

To make the impact of operational subsidies and rate design reform clearer, this scenario uses a much more substantial rate reduction of $0.10 per kWh, or 45%, which reduces the electric rate faced by customers to $0.12 per kWh. Furthermore, this reduces the price differential of electricity to natural gas from four times to two times as expensive.

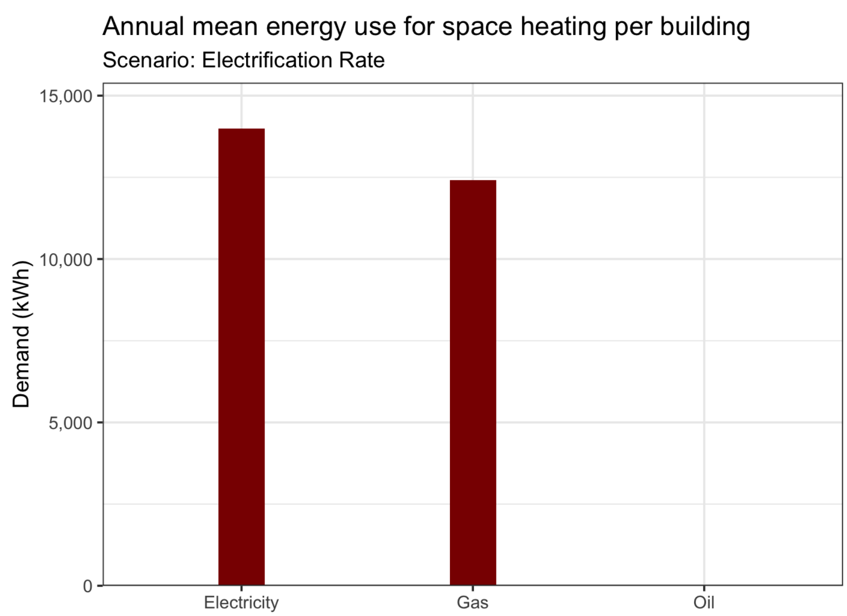

Figure 5-13. Energy sources of space heating in the *Electrification Rate* scenario.

In the *Electrification Rate* scenario, a significant portion of households chooses to electrify, as depicted in Figure 5-13. Notably, many households still choose to adopt high-efficiency gas furnaces and boilers, which is an indication of the heterogeneity of electrification that could be expected with expanded operational subsidies.

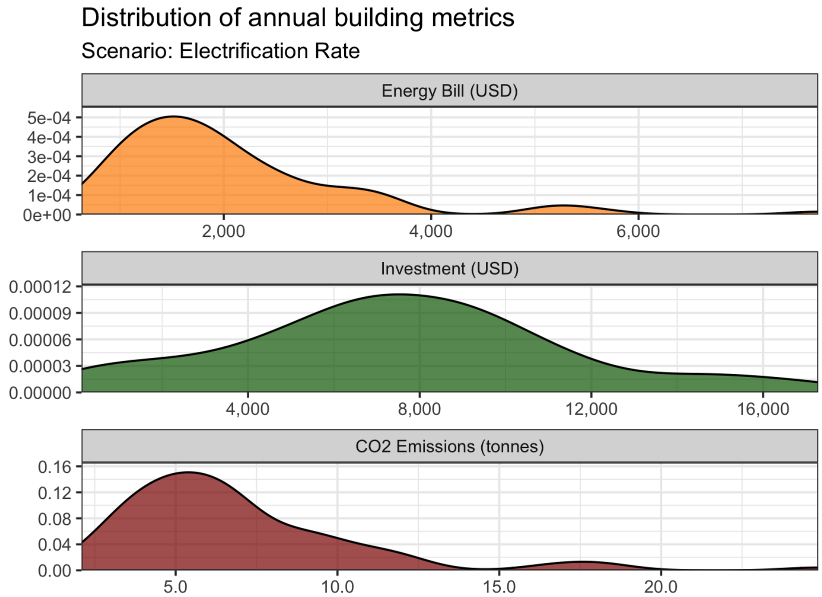

Figure 5-14. Probability distribution of costs and emissions in the *Electrification Rate* scenario.

Next, we see in Figure 5-14 that the *Electrification Rate* scenario results in energy bill, investment, and CO2 emissions reductions relative to *Baseline* and *Current Policy* results. Median energy bills, at $1,786 per year, are lower than in any other scenario under consideration. However, this Electrification Rate scenario would likely have to raise taxes (or rates on other customers) in order to pay for the rate subsidy, and those effects are not considered in this analysis. Investment costs reflect the costs of a subsidized ASHP (with the current $10,000 whole home subsidy) or the costs of a new gas heating appliance plus an air conditioner.

Emissions are low in this case, with a median of 6 tonnes CO2e per year. This is 25% lower than the *Baseline* results and 12% lower than the *Current Policy* results. The emissions savings of space heating electrification achieved in the *Electrification Rate* scenario are somewhat marginal, and may not be justified by the cost of the policies that would lead to these results. As the grid carbon intensity declines in the future, emissions savings from electrification will become more substantial.

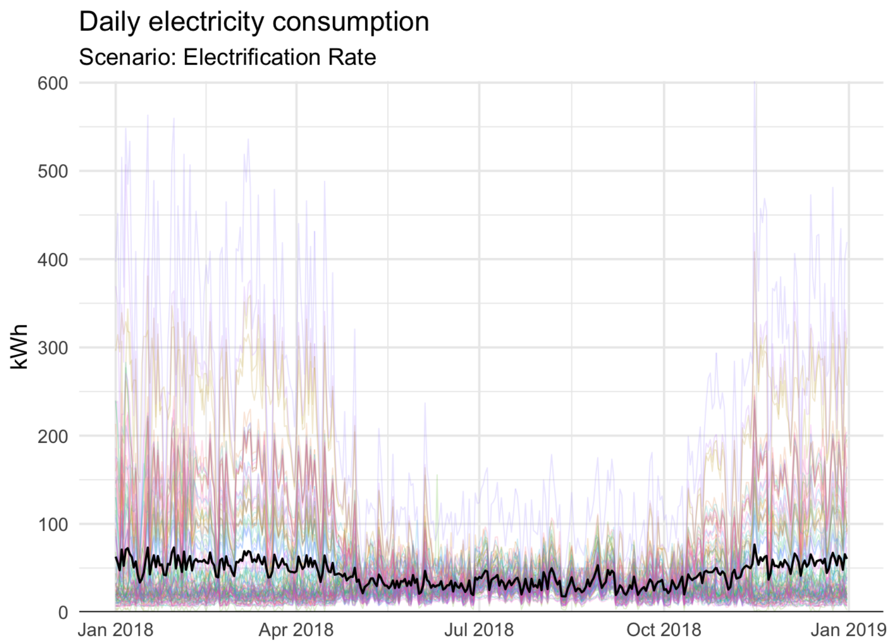

Figure 5-15. Daily electricity consumption in the *Electrification Rate* scenario.

Similar to the results of the *Mandated Electrification* scenario, the daily electricity consumption in the *Electrification Rate* scenario suggests a winter-peaking system with substantially increased loads from electrified houses, combined with a relative decrease in electricity demand from cooling in the summer. Compared to *Mandated Electrification*, the households that choose to electrify in the *Electrification Rate* scenario are minimizing net present cost. Incentivizing consumers to make economic decisions to electrify space heating, rather than forcing some or all households to electrify through mandates, may result in lower total costs and more cost-effective emissions reductions.

5.6 Conclusion

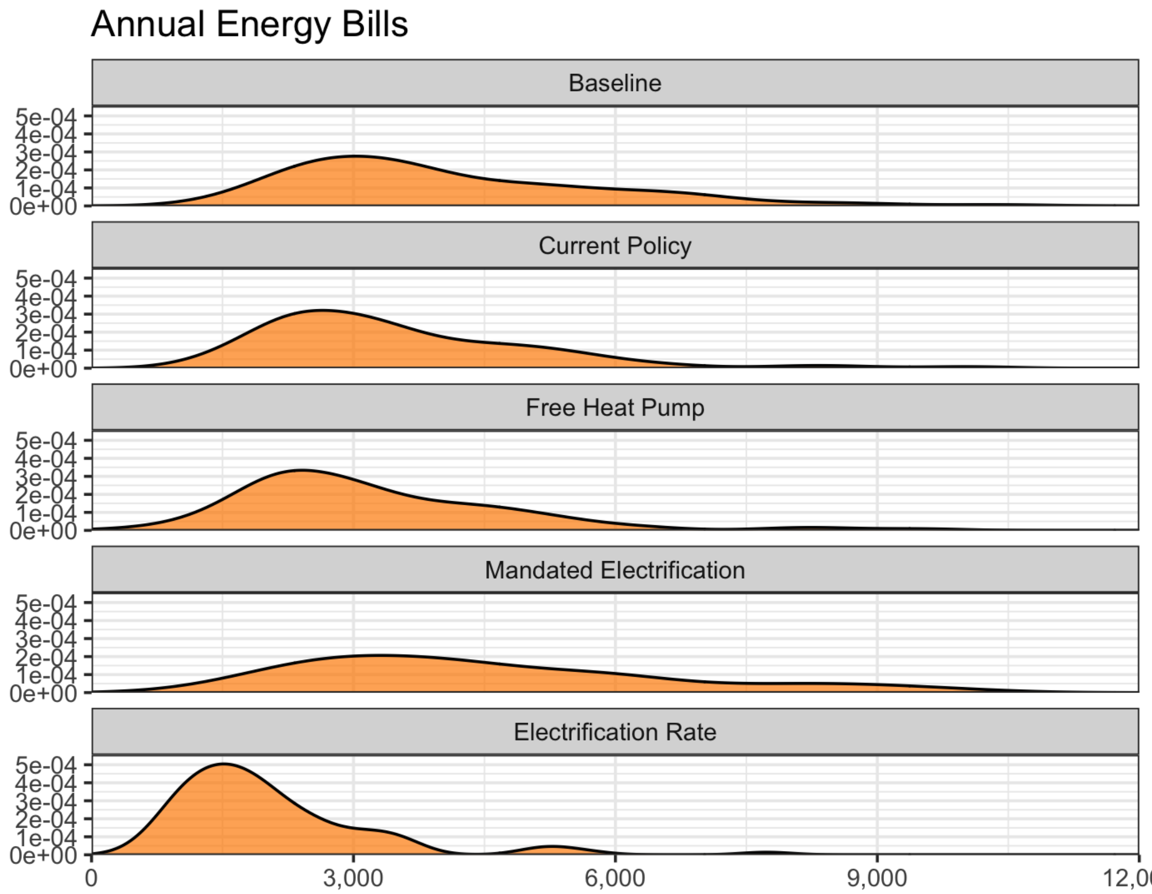

Figure 5-16. Summary of distribution of annual energy bills across all scenarios.

These five scenarios explore the preconditions for widespread electrification of space heating in the current single-family housing stock in Massachusetts.

In order to reach the state's ambitious climate goals and decarbonize the vast majority of buildings by 2050, changes to electricity and natural gas rates (or aggressive mandates) will likely be needed. At present, even if heat pumps were available for free, they would be costlier to run relative to high-efficiency natural gas furnaces and boilers. As illustrated in Figure 5-16, energy bills in the *Mandated Electrification* scenario are higher than in the *Baseline* scenario, while the availability of cheaper electricity for space heating in the *Electrification Rate* scenario has a clear effect in bringing down energy bills and, presumably, energy burdens. Rate reform or operational subsidy is therefore necessary for widespread economic electrification of space heating.

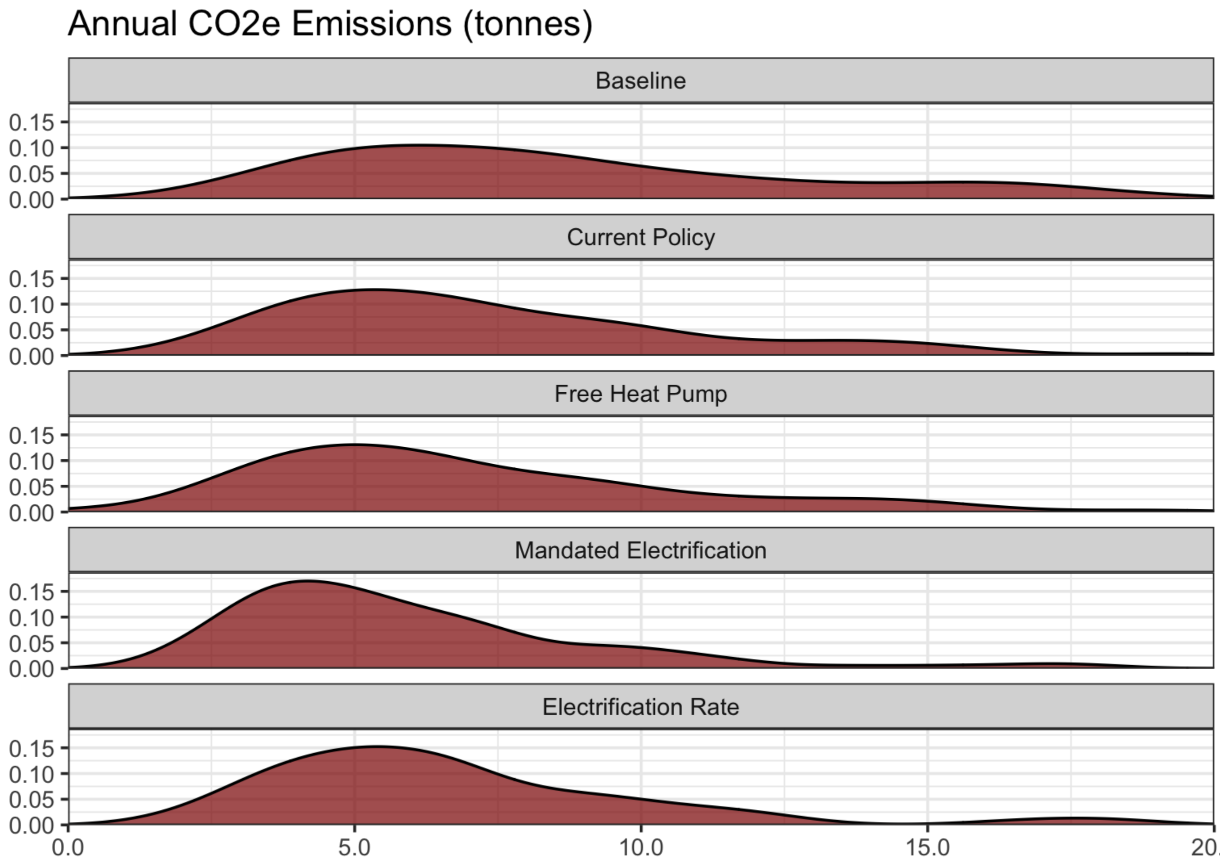

Figure 5-17. Summary of annual CO2 emissions across all scenarios.

The emissions reductions from heating electrification are positive but relatively small (25-35%) given the current carbon intensity of the electricity supply in New England, as illustrated in Figure 5-17. In the *Current Policy* and *Free Heat Pump* scenarios, little space heating demand is electrified, and therefore heat pump deployment results in minimal emissions reductions. The *Mandated Electrification* scenario reduces CO2e emissions by 35% relative to the *Baseline*, while the *Electrification Rate* scenario reduces CO2e emissions by 25%. While aggressive policy in support of electrification clearly reduces emissions relative to business-as-usual, the relatively small effect emphasizes that space heating electrification does not eliminate building emissions given the current grid carbon intensity in ISO-NE.

In order to reduce building emissions and incentivize electrification, policymakers need to focus on keeping electric rates low and minimizing the cost premium of electricity over natural gas. This is a counterintuitive result that has not been clearly illustrated by previous studies of heating electrification, and has significant implications for the future of ratemaking and climate policy. Currently, many emissions-reductions programs are financed through explicit or implicit additions to electricity rates; for example, efficiency programs, distributed generation support programs, and Renewable Portfolio Standards. By increasing electricity rates, these programs disincentivize electrification, which undermines the effects of climate policies on reducing emissions.

Furthermore, as electrification and DER deployment progresses, distribution and transmission systems may require upgrades to handle the new loads and bidirectional flows. If these investments are financed through electric rates, as in the traditional model, electrification will become even less attractive to homeowners. In short, heat pumps are far from a “silver bullet” for heating electrification in Massachusetts at present, and ambitious policy change is needed to make electrification economic and reduce emissions from buildings.

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