A Case for Electrifying Heat in End-Use Residential Sector Towards Carbon-Free Buildings

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Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

June 2019

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ABSTRACT

Space and water heating account for nearly two-thirds of energy consumption in U.S. homes, and a large contributor to energy costs of end-use residential dwellings. Most home heating systems in the United States are fueled by fossil fuels – natural gas and fuel oil (heating oil) – representing more than 50 percent of all U.S. homes' heating. These heating systems result in higher greenhouse gas emissions than electric heating systems now, and the emissions difference will increase as the grid trends toward lower carbon intensity in the decades ahead. Electrification of residential heating systems, by eliminating site fossil fuel use for heating, provides an important element of ultimately achieving carbon-free buildings.

The objective of this research is to analyze the heating load of end-use residential dwellings. The research for this thesis achieves this by first conducting a survey of energy usage profile of some residents in Boston, Massachusetts and Houston, Texas. It then applies a thermal model to simulate building heat load, which was used in developing an electrification cost model to verify and validate the case for electrification of residential dwellings. Thermal models were developed for two cities, Boston and Houston, having contrasting winter weather and electricity rates. The model simulated heat load demand and energy outputs from heat pumps in both cities and analyzed resulting data and potential tradeoffs compared with electric resistance and gas furnace heating systems.

Results show that heat in residential dwellings using electric air-source heat pumps (ASHPs) is more cost-effective and energy efficient compared with other heating systems. Model analyses indicate that heat demand in residential dwellings, which increase as outside temperature decreases due to heat loss, is disproportionately higher at low temperatures because the performance of ASHPs drops with outside temperature. However, ASHP performance is higher in Houston compared to Boston due to milder winter temperatures in the former. And the "*balance point*" between heat load and energy output decreases as capacity of ASHP increases.

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ACKNOWLEDGEMENTS

I would like to thank my advisor, Harvey Michaels, for his consistent support and intellectual advice throughout the course of this thesis. His leading and push on electrification of building sector and knowledge on democratizing energy in the retail sector has helped shape my thesis' focus and led me to further explore this end-use sector as a critical component to achieve carbon-neutrality and reduce greenhouse emissions.

I also want to thank my thesis reader, Michael Golay, who was my graduate instructor in Sustainable Energy course in Fall 2018 and gave me the inspiration and desire to continue work in this area. His insights and ideas in course of writing this thesis have been invaluable.

Throughout my program at Massachusetts Institute of Technology (MIT), I have learned a lot from the top Professors in one of the greatest institutions in the world. It has been a challenging and rewarding journey for me these past two years (Fall 2017 to Spring 2019). I have worked with smart students and cohorts on various projects, learned new topics, developed new ideas, and employed hands-on applications of what was learned. This I can take with me and apply in my future endeavors.

Finally, I want to acknowledge my family who supported me during the thesis journey and my 2-years Master's program at MIT; most importantly, my wife who stood with me and held the fort while I was away to fulfill the program's one-semester on-campus requirement. Her constant support, encouragement helped me to overcome various challenges, excel in my courses and reach this stage of completing my thesis. And also, my kids for giving me the motivation to keep going.

Tolu O. Sodeinde

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1. Introduction

Several climate data and models have led to conclusion that the earth is getting warmer and the cause of the warming effect is man-made. The Intergovernmental Panel on Climate Change (IPCC) agreement in Paris in 2011 set a target of not more than 2°C earth's temperature rise above pre-industrial temperatures, but with an aspirational target of 1.5°C. But depending on our definition of when "pre-industrial" is, our available carbon budget may be smaller than expected. [1] However, we are not on track to meet even the most conservative target of 2°C. To stay below the 1.5°C, we need to embark on another green industrial revolution to transition from fossil fuels. The developed world needs to reduce energy-related carbon in electric production, transportation, and building end use for heating and hot water by 85% to achieve a carbon balance that stops further warming, along with some changes in agriculture and beef consumption. The Paris treaty if adhered to and extended would achieve this balance in 2068 at 3.5°C. To limit to 1.5°C we need to achieve this by 2040 and reach 50% by 2030. Unfortunately, transitioning from fossil fuels to non-carbon-based fuels and renewables alone does not stop global warming. We will also need to embark on carbon-sink solutions to remove excess carbon trapped in earth's atmosphere. Such solutions include planting of trees and cover crops, direct air and seawater capture of carbon and stored underground or in long-lived products, and "*enhanced weathering*", which is the natural reaction of carbon-dioxide with some minerals thereby turning carbon from a gas into a solid. [2]

Though the United States is no longer party to the Paris agreement, some states in the country are moving to adhere to the premise of the agreement by commissioning programs and setting their own carbon emission targets, as have hundreds of cities worldwide. [3] Cities like Boston and New York City have developed strategies that enable them to achieve carbon neutrality goals. Carbon-neutrality implies that cities like Boston and New York run on 85% clean energy. [4] Massachusetts already has law requiring 80% clean electric power grid by 2050. The city of Boston has issued its 2019 "Carbon-free Boston" report outlining its carbon-neutrality goal. [5] California also has a law that requires 100% of the state's electricity to come from carbon-free sources by 2045. [6]

Colorado is rolling out legislation that would cut total greenhouse gas emissions drastically 90% as compared to 2005 levels, by the year 2050. [7] Climate data and models have shown that to be consistent with a world with carbon balance, not only 85% of electric power generation has to be carbon-free, but also need to achieve 85% carbon-free buildings and transportation. By end-use sectors, buildings and transportation account for whopping 68% of energy consumption [8] and more than 70% of carbon-dioxide emissions in the U.S. Buildings also account for nearly all of 39% of total energy consumption by residential and commercial end-use sectors in 2017, [9] and more than 35% of total carbon-dioxide emissions from all end-use sectors. [10] Renewable sources like solar and wind are having greater penetration in the power generation market space, with both accounting for nearly 10% of the United States' electrical generation. [11] Both are essential towards carbon neutrality; however, we also need other measures including electrification of buildings and transportation.

Electrification is a strategy for transitioning from carbon-based energy sources to electric. By electrifying buildings, we can transition from natural gas space and hot water heating to electricity, and in the case of transportation from gasoline and diesel to electricity. The lingering question is how we make the transition and what are the associated technological, social and economic costs. At current emission levels, we are likely to exceed 1.5°C carbon budget by 2030 and on track for more than 3.5°C global warming by 2100, a degree above IPCC target. [4] Hence, substantial effort is required from the United States and other industrialized nations to quickly take actions to avert worst effects of global warming. Excluding electricity consumption, most of energy consumed in buildings is for space heating / cooling and hot water.[12] An Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) conducted in 2009 shows that heating accounts for 22% of residential energy use in Texas, and 59% in Massachusetts; while cooling accounts for 19% and 1% respectively.[13] In electrifying buildings towards carbon neutrality, the following key strategies are needed: (1) energy efficiency and demand-response programs; (2) generation and accessibility to clean, carbon-free energy, (3) democratize electricity rates for affordability across all income levels; [14] (4) enact and update building policies, rules and codes to reflect buildings' transition from fossil fuels to electricity; [14] (5) financial incentives and tax breaks for retrofitting and conversion to electricity; and (6) facilitate research and encourage development of energy efficient technologies, including thermal storage and power batteries.

To achieve a carbon-neutral building and reduce cost of switching from fossil fuels to electricity in residential heating, one has to look at current energy sources used in buildings. Most buildings' air-conditioning systems are powered by electricity; however, the heating fuel source is primarily electricity in the South and natural gas in rest of the United States. In colder regions of the U.S., residential households are less reliant on electricity and use more fossil fuels (natural gas, fuel oil, propane) as their primary heating fuel source, resulting in higher direct greenhouse gas emissions. Massachusetts on average used 109 million Btu of energy per home in 2009, 22% more than the national average. [15] For the same year, an average household in Texas used 77 million Btu, about 14% less than national average. [16] Moreover, average electricity consumption per Texas home is 26 percent [16] higher than the U.S. average, while the average electricity consumption per Massachusetts home is about 35% lower than the U.S. average. [15] Since more energy is required for heating than for cooling and majority of heating is from fossil fuel sources, moving to electrify U.S. residential heating at optimal cost gets us closer to carbon-neutral residential dwellings. The ability to forecast, predict and optimize energy usage for space and water heating offers a way for energy consumers and policy makers to gain insights into a real-time usage profile and corresponding improvements in efficiency standards, real-time adjustments in consumption, as well as social and economic costs. In analyzing the heating load of the end-use residential sector, the following three questions are answered in this research thesis:

- What are the tradeoffs with natural gas as primary source of residential heating versus electrified heating?
- What does it take to transition from natural gas to electricity?
- What is the economic cost of electrifying home heating compared to fossil fuel use?

This research focusses on two states in different geographic and climatic regions of the United States – Massachusetts and Texas. The difference in consumption between the two states is that Texas households use electricity mainly as energy source for air conditioning; while Massachusetts residents use more of natural gas and fuel oil as their energy source for heating. [15,16] The research thesis is organized as follows:

- Chapter One is an introduction to the problems being addressed and review of both historical and current statistics related to end-use energy consumption and especially, space heating of buildings.
- Chapter Two presents a review of existing literature on what research have been done related directly or indirectly on electrifying heating in buildings and especially residential dwellings, as well as thermal models of buildings' heating systems.
- Chapter Three describes the methodology employed in modeling, building characteristics, input parameters, as well as assumptions made.
- Chapter Four presents the results of survey and models, including heating demand and associated economic and emission costs.
- Chapter Five analyzes the results by deducing key factors and pathways to electrification of end-use residential sector.
- Chapter Six is a conclusion summarizing key points deduced from the research to help reach target goal of carbon-neutral buildings by 2050.

Citations for Introduction Chapter:

[1] - "Our Paris Carbon Budget May be 40% Smaller than Thought", *The Guardian*, 2018, www.theguardian.com/environment/climate-consensus-97-per-cent/2017/jul/24/study-our-paris-carbon-budget-may-be-40-smaller-than-thought. Accessed 7 March 2019.
[2] – Mulligan James, Ellison Gretchen, and Levin Kelly. "Six Ways to Remove Carbon Pollution from the Sky." *World Resources Institute*, September 2018, https://www.wri.org/blog/2018/09/6-ways-remove-carbon-pollution-sky. Accessed 15 April 2019.
[3] – "C40 Cities – Cities Get The Job Done." https://www.c40.org/cities.
[4] – "There's One Key Take Away from Last Week's IPCC Report." *The Guardian*, 2018, www.theguardian.com/environment/climate-consensus-97-per-cent/2018/oct/15/theres-one-key-takeaway-from-last-weeks-ipcc-report. Accessed 7 March 2019.
[5] – City of Boston. "Carbon Free Boston – A Summary Report." 2019.
[6] – James Temple. "California Advances an Ambitious Climate Policy That Should be a Model for the World." *MIT Technology Review*, August 28, 2018, www.technologyreview.com/s/611945/california-advances-an-ambitious-climate-policy-that-should-be-a-model-for-the-world/. Accessed 7 March 2019.
7] – Burness Alex and Herrick John. "Bold Climate-Action Legislation For Colorado Nears Rollout." *The Colorado Independent*", March 2019, https://www.coloradoindependent.com/2019/03/20/colorado-paris-climate-greenhouse-gas-mandates/. Accessed 18 April 2019.
[8] - "Use of Energy in the United States." *U.S. Energy Information Administration (EIA)*, https://www.eia.gov/energyexplained/index.php?page=us_energy_use.
[9] – "EIA Frequently Asked Questions." *U.S. Energy Information Administration (EIA)*, https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.
[10] – "U.S. Energy-Related Carbon Dioxide Emissions." *U.S. Energy Information Administration (EIA)*, https://www.eia.gov/environment/emissions/carbon/pdf/2017_co2analysis.pdf, September 2018.
[11] – Pickerel Kelly. "Solar and Wind Account For 10% of Nation's Electrical Generation in First Half of 2018." *Solar Power World*, August 2018, https://www.solarpowerworldonline.com/2018/08/solar-and-wind-account-for-10-of-nations-electrical-generation-in-first-half-of-2018/.
[12] – Jeff Desjardins. "Residential Energy Consumption – What Uses Most Energy in Your Home?", *Visual Capitalist*, https://www.visualcapitalist.com/what-uses-the-most-energy-home/, Nov. 2016.
[13] – "Consumption and Efficiency: Data from Residential Energy Consumption Survey (RECS)." *Energy Information Administration (EIA), 2009 & 2015 RECS Survey Data*,
[14] – Harvey Michaels. "Electrification and City Leadership: Five Imperatives for Climate Action." *MIT Sloan*, January 2019.
[15] – "*Household Energy Use in Massachusetts – A Closer Look at Residential Energy Consumption*", U.S. Energy Information Agency (EIA) Residential Energy Consumption Survey, 2009.
[16] – "*Household Energy Use in Texas – A Closer Look at Residential Energy Consumption*", Energy Information Agency (EIA) Residential Energy Consumption Survey, 2009.

2. Literature Review on Electrifying Heat

Energy usage by residential households in the United States have changed over the years and across regions. As a result of climate change and effects of global warming becoming more visible, government and policy makers at the state and federal level are instituting legislation and environmental rules to mitigate its effect. Utility generators are changing their fuel mix in generating electricity. State and local governments are also offering incentives to individuals and companies investing in renewable energy. This has created price dynamics for both power generators and retail consumers and caused shifts in consumer behavior in support of energy management.

More and more, research is focusing on electrifying heating of buildings and transportation. These are end-use sectors with the largest direct consumption of fossil fuels and contributors to greenhouse gas emissions. The United States has proposed reduction targets for greenhouse gas emissions of 17% by 2020, and between 26-28% by 2025 relative to 2005 levels. [1] Transportation and buildings also account for the largest emissions by end-use sector in the European Union. The European Commission is tasked to reduce greenhouse gas emissions by 20% below 1990 levels by 2020 and by 40% below 1990 levels by 2030. [2] Achieving these targets does not solely hinge on having carbon-free transportation and carbon-free utility power plants (i.e., renewable power plants), but also requires having carbon-free buildings. Since most of direct greenhouse gas emissions in buildings is from heating and hot water, reducing use of fossil fuel for space heating and hot water generation is key towards carbon-free buildings in U.S. cities and states. Businesses and households have roles to play in making our building sector energy efficient and carbon-neutral by 2050. Scientists and data analysts are working with various cities in the U.S looking into ways of reducing carbon footprint across all end-use sectors. Scientists using computer modeling and citywide datasets show how New York City can improve the efficiency of its building sector. [3] With technologies and support from businesses and local governments, New York City can improve efficiency of its buildings and reduce their carbon footprint by more than 60%. [3] Technology advances can help increase energy efficiency by improving building envelopes, window insulation to control air flow and moisture, wall materials with better heat resistance, higher performance lighting, and digitalization with better predictive and cost optimization models. [4]

Electrification of end-use sectors is a major pathway to carbon neutrality. Using an ultimately decarbonized energy source, electricity for space heating, cooling, hot water generation, etc. instead of fossil fuels, will greatly reduce buildings' emissions. [4] More efficient heat pump technologies, decarbonizing grid in the Northeast corridor, and aggressive carbon mandates from state and local governments have helped in changing the energy usage and carbon footprints of existing buildings. [5] As example, the Deep Decarbonization Pathways Project (DDPP) established three primary goals by 2050 that affect new buildings: (1) 80% reduction in greenhouse gas emissions from 1990 level; (2) 90% energy from decarbonized electric power in building end-uses; and (3) highly energy efficient buildings. [6] Meeting these goals by 2050 requires almost completely eliminating the use of natural gas in buildings. This will not be an easy process to accomplish, nor an easy proposition to sell to building owners and users as long as electricity rates are still relatively higher than natural gas, and potential costs of making buildings more efficient could be prohibitive. Also, because of the complex interactions of mitigation actions to meet these goals there are tradeoffs involved. For instance, changing the fuel mix such that electricity supply comes from cleaner sources amplifies the reductions that can be achieved by electrifying energy end-uses. However, having cleaner electricity dampens the mitigation effect of energy-efficient equipment. One way of determining the optimal cost-effective decarbonization pathway that will meet the goals is through leveraging of the complexity of these interactions. [7]

The performance metrics and policy goals for energy conservation are changing. Simple energy conservation of past years focused on energy consumption and efficiencies is shifting more towards greenhouse gas reductions. It no longer suffices to gauge performance in energy conservation on how much less electricity and natural gas is consumed, or just on energy efficiencies of appliances; moreso, on the degree of reduction in carbon-based emissions. Hence, there is a growing consensus for 'environmentally beneficial electrification' and a new performance measure on 'emissions efficiency' of end-uses. [8] Efficient technologies exist today that can deliver electric energy for buildings' end uses. Some other direct-fueled end uses such as backup generators, and backup space heaters for extremely cold weather do not have effective electric power substitutes; however, they represent a smaller fraction of building energy usage. [9] The challenge is not an issue of efficient technology; rather, it is primarily economic. An investigation of supply-demand options is conducted to assess California's future energy systems in order to meet its greenhouse gas emissions reduction target of 80% by 2050. [10] Academic studies on electrification pathways have analyzed high percentage rate of electrification in the building sector. Greenblatt et. al. [11] assumes 70% of space heating in California for instance will be electrified by 2050. Weiss et. al. [12] as well as Steinberg et. al. [13] assume all U.S. residential and commercial end uses are electrified by 2050. This is a very ambitious undertaking. We probably do not need to reach 100% electrification to meet 2050 target. If we electrify 85% of buildings and transportation end uses, we will reach the 2050 reduction target.

Understanding household energy profile and usage patterns is an important component of having a proper balance between energy supply and demand. Jaehoon Jeong et. al. [14] identifies U.S. households heating energy usage patterns based on using electricity and natural gas as substitutive and/or complimentary fuel sources. Unlike previous studies where energy consumption was analyzed separately based on heating energy sources and equipment, this study examines the effect of substituting various heating energy sources and heating equipment. The choice of heating fuel tends to be associated with income level. [14] Studies show low income tend to prefer electric heaters and gas furnaces, while high income households tend to prefer electric heating systems over gas. [14] This dichotomy in heating fuel and equipment choices based on income slows the progress of achieving carbon-neutral buildings. In a report by the Rocky Mountain Institute, the economics and carbon impacts of electrifying residential heating is influenced by many scenarios based on building type and heating energy source mix. [15] Emissions tend to be higher in older buildings than new construction because older buildings' construction is less energy efficient and appliances are also less energy efficient. In addition, most of the older buildings that require higher retrofitting costs are mainly in low income neighborhoods. As such, it costs more to retrofit older buildings to switch to electricity. Massachusetts' annual $730 million of investment in energy efficiency is governed by the Green Communities Act, which emphasizes cost-savings for consumers rather than environmental benefits or social equity. [16]

Buildings' energy performance is affected by a number of factors that makes it more complex to generally predict energy load and usage. Analysis of predictions of building energy use have addressed three common methods – engineering, statistical, and artificial intelligence methods. Zhao and Magoules [17] reviewed various prediction methods and the degree of accuracy and performance of each method considering the complexity of factors that influence a building energy load. The complexity of a building problem, ability to model load-influencing factors affects the accuracy of predictions. Because of variability in weather patterns, degree of solar gains, changes in occupancy behavior, and type of construction materials used, predictive energy usage models tend to be scenario specific. The ability to predict building thermal loads and overall energy usage is important to improve energy efficiency and performance, as well as optimize overall usage cost. The usage profile varies if building is an office, residential, commercial or industrial building. And the thermal load behavior depends on weather conditions (outside temperature), buildings' solar gain, building occupancy and behavior, construction materials' thermal resistance and conductance, and to a lesser extent, refrigeration heat expended inside building. Of the various end-uses, residential dwellings consume the highest amount of energy as there are more energy management tools and systems out there that helps to optimize energy needs in commercial and industrial building sectors compared to residential end-use. These systems and tools have broader access to the grid for dynamic demand-response measures; whereas, residential buildings tend to have limited grid access. Thus, improving energy efficiency in residential dwellings by optimizing usage and cost provides an important pathway to reducing greenhouse gas emissions and achieving carbon-neutral buildings.

Research has been carried out to model overall energy consumption by end-use sector and predict loads for heating, ventilation, and air-conditioning (HVAC) systems in both commercial and residential buildings. Model-based design and simulation techniques using MATLAB/Simulink^{TM} have been employed to model residential HVAC systems' energy consumption.[18] A simpler engineering-based approach to residential HVAC systems is modeled to simulate electric and heating load for space-conditioning using limited set of building characteristics and fundamental principles of thermodynamics and heat transfer.[19] Though simpler with limited building and household characteristics, model flexibility enables simulation of various scenarios in different climate but may not easily adapt to complex situations. To reduce a building's peak load and overall energy cost, it is possible to control the HVAC's set-point temperature based on retail electricity price, while at the same time maintaining satisfactory thermal comfort inside the building. By modeling the demand-response controller to adjust interior temperature setting based on changes in electricity price, it is possible to reduce energy usage and cost while maintaining optimal comfort.[20] Other approaches have been proposed using combination of building simulation software and regression techniques to accurately predict energy consumption in order to develop an optimal demand-response strategy. [21] Electricity providers have proposed time-varying rate plans as incentives to retail consumers with the goal of effecting overall demand. [22] Matteo Muratori & Giorgio Rizzoni used energy consumption models to simulate residential demand response to estimate energy usage behavior based on a bottom-up approach. [22] And notable economist Alfred Kahn in his 1970 book argued that end-use electricity consumers should face prices that reflect the time-varying marginal costs of generating electricity. [23]

Citations for Literature Review Chapter:

[1] - Thomas Damassa, Mengpin Ge & Taryn Fransen. "The U.S. Greenhouse Gas Reduction Targets." *World Resources Institute*, December 2014, https://www.wri.org/publication/us-greenhouse-gas-reduction-targets. Accessed 7 March 2018.
[2] – Jose L. Moraga & Machiel Mulder. "Electrification of Heating and Transport: A Scenario Analysis of the Netherlands up to 2050." *Center for Energy Economics Research (CEER) - Policy Papers*, no. 2, May 2018.
[3] – Daniel Wright, et. al. "New York City can Eliminate the Carbon Footprint of its Buildings by 2050." *Energy for Sustainable Development*, vol. 23, December 2014, pp. 46-58.
[4] – Jessica Leung. "Decarbonizing U.S. Buildings." *C2ES Climate Innovation 2050*, July 2018, www.c2es.org/document/decarbonizing-u-s-buildings/. Accessed 8 March 2019.
[5] – Sue Coakley. "Developing A Pathway to Decarbonize Existing Buildings." *Northeast Energy Efficiency Partnerships (NECP)*, November 2018, www.neep.org/blog/developing-pathway-decarbonize-existing-buildings, Accessed 8 March 2019.
[6] – Lee Paddock & Caitlin McCoy. "Deep Decarbonization of New Buildings." *Environmental Law Reporter – News & Analysis*, vol. 48, 2018, pp. 10130-10149.
[7] – Benjamin Leibowicz, et. al. "Opimal Decarbonization Pathways for Urban Residential Building Energy Services." *Applied Energy*, vol. 230, 2018, pp. 1311-1325.
[8] – Keith Dennis, Ken Colburn, & Jim Lazar. "Environmentally Beneficial Electrification: A Dawn of Emissions Efficiency." *The Electricity Journal*, vol. 29, 2016, pp. 52-58.
[9] – Jeff Deason, Max Wei, Greg Leventis, Sarah Smith & Lisa Schwartz. "Electrification of Buildings and Industry in the United States." *Energy Analysis and Environmental Impacts Division – Lawrence Berkeley National Laboratory*, March 2018, www.ipu.msu.edu/wp-content/uploads/201804/LBNL-Electrification-of-Buildings-2018.pdf. Accessed 9 March 2019.
[10] – Max Wei, et. al. "Deep Carbon Reductions in California Require Electrification and Integration across Economic Sectors." *Environmental Research Letters*, vol. 8, 2013, 014038, 10pp.
[11] – Greenblatt, Jeffrey, Wei Max, & McMahon, Jim. "California's Energy Future: Buildings and Industrial Energy Efficiency." *California Council on Science and Technology*, 2011, www.ccst.us/reports/californias-energy-future-the-view-to-2050/. Accessed 9 March 2019.
[12] – Weiss, Jurgen et. al. "Electrification: Emerging Opportunities for Utility Growth." *The Brattle Group*, www.brattle.com/system/news/pdfs/000/174/original/Electrification_white_paper_final_single_pages.pdf?1485532518. Accessed 9 March 2019.
[13] – Steinberg, et. al. "Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization." *National Renewable Energy Laboratory (NREL) – Technical Report*, July 2017, www.nrel.gov/docs/fy17osti/68214.pdf. Accessed 9 March 2019.
[14] – Jaehoon Jeong, Chang Seob Kim, & Jongsu Lee. "Household Electricity and Gas Consumption for Heating Homes." *Energy Policy Journal*, vol. 39, February 2011, pp. 2679-2687.
[15] – Billimoria, Sherri, Guccione, Leia, Henchen, Mike, & Louis-Prescott, Leah. "The Economics of Electrifying Buildings (Report Summary)." *Rocky Mountain Institute*, 2018, www.rmi.org/insight/the-economics-of-electrifying-buildings/. Accessed 9 March 2019.
[16] – Adam Hasz. "Equitable Energy for Massachusetts: How Can Climate Policy Reduce Inequality?" *Master's Thesis, City Planning, Massachusetts Institute of Technology*, June 2018.
[17] – Hai-xiang Zhao & Frederic Magoules. "A Review on the Prediction of Building Energy Consumption." *Renewable and Sustainable Energy Reviews*, vol. 16, 2012, pp. 3586-3592.
[18] – Mahmoud Kassas. "Modeling and Simulation of Residential HVAC Systems Energy Consumption". *Procedia Computer Science*, vol. 52, 2015, pp. 754-763.
[19] – Matteo Muratori, Vincenzo Marano, Ramteen Sioshansi, & Giorgio Rizzoni. "Energy Consumption of Residential HVAC Systems: A Simple Physically-based Model." *IEEE Power and Energy Society General Meeting*, 22-26 July 2012, https://ieeexplore-ieee-org.libproxy.mit.edu/document/6344950. Accessed 6 March 2019.
[20] – Ji Hoon Yoon, Ross Bladick, Atila Novoselac. "Demand Response for Residential Buildings based on Dynamic Price of Electricity." *Journal of Energy and Buildings*, vol. 80, 2014, pp. 531-541.

[21] - Zeya Li, Genke Yang, Changchun Pan, & Qingsong Gong. "Demand Response Based on Dynamic Electricity Price and Energy Consumption of Residential House." *Chinese Automation Congress*, 2015, pp. 1361-1365.
[22] – Matteo Muratori & Giorgio Rizzoni. "Residential Demand Response: Dynamic Energy Management and Time-Varying Electricity Pricing." *IEEE Transactions on Power Systems*, vol. 31, no. 2, March 2016, pp. 1108-1117.
[23] - Kahn, Alfred E. 1970. "The Economics of Regulation: Principles and Institutions." *John Wiley & Sons*, 1970, Vol. 1.

3. Methodology

Two cities were considered as the main focus for comparison and analysis – Boston, Massachusetts and Houston, Texas. The choice of these two cities in conducting this research is because both tend to be similar and contrasting in a number of ways including:

- End users in the two cities cannot be any more different in how they use energy.
- Energy costs in Boston are much higher than they are in Houston.
- There are contrasting weather conditions in winter months with longer heating degree days per year in Boston compared to Houston.
- States of Massachusetts and Texas are one of the most deregulated energy markets in the country.
- Unlike Massachusetts' ISO, Texas electricity regulatory authority ERCOT, offers consumers real-time market pricing options.
- These states have different investment and tax incentives towards renewable energy generation.

3.1. Residential End-Use Energy Survey

In conducting this research, an energy profile survey was created and distributed to some residential households in Massachusetts and Texas. The survey questions are similar to the longer EIA RECS survey [1] and has more than 100 questions in total, ranging from residential household's characteristics to number of appliances in household and their frequency and pattern of use. Appendix A shows results of some of the survey questions. The results help to identify how residential end users consume electricity on a daily basis in these two states and provide insights towards pathways to addressing buildings consumption and emissions. Survey was sent out to 26 recipients with 46% completed responses. Table 3-1 is a summary of responses received over the course of 2 months between January and March 2019. About 45% of respondents in both states completed the residential energy usage profile survey and 35% respondents with partial completion. Some key highlights of survey results are available in Appendix A.

State	# Survey Recipients	Completed Response	Partial Response	No Response
Massachusetts	6	2	3	1
Texas	19	9	7	3
Other	1	1	-	-

Table 3-1: Residential End-Use Energy Profile Survey

In summary, 23% of survey responses where from Massachusetts and 73% from Texas with 81% in single family dwelling (SFD). Average SFD size of survey residential dwelling is 2500 sq. feet, and average number of bedrooms is 3. Also, the average number of household members or occupants per dwelling from the survey is 4. Data from the survey was employed in developing the simulation model. To generate energy consumption for residential household heating in Boston and Houston, thermal model of residential building was developed in MATLAB/Simulink™ using related example available in Simulink library.

3.2. Residential End-Use Thermal Model

For this thesis a MATLAB/Simulink™ thermal model of a building was developed to simulate energy load for residential space heating. It simulates the internal temperature within the building and determines the amount of heating load required to achieve the desired thermal comfort level. The model is developed with some assumptions to reduce complexity. It is implemented to support multiple scenarios involving different building structure and characteristics, occupancy, and weather conditions based on geographic location. Some of the building characteristics employed in model are based on the survey results from participants. Simulating thermal comfort temperature of building requires determining building net heat load based on outside temperature, heat load due to heater, expended refrigerator heat, occupants heat load, and building's equivalent resistance.

The model components and their interactions are illustrated in the schematic diagram below.

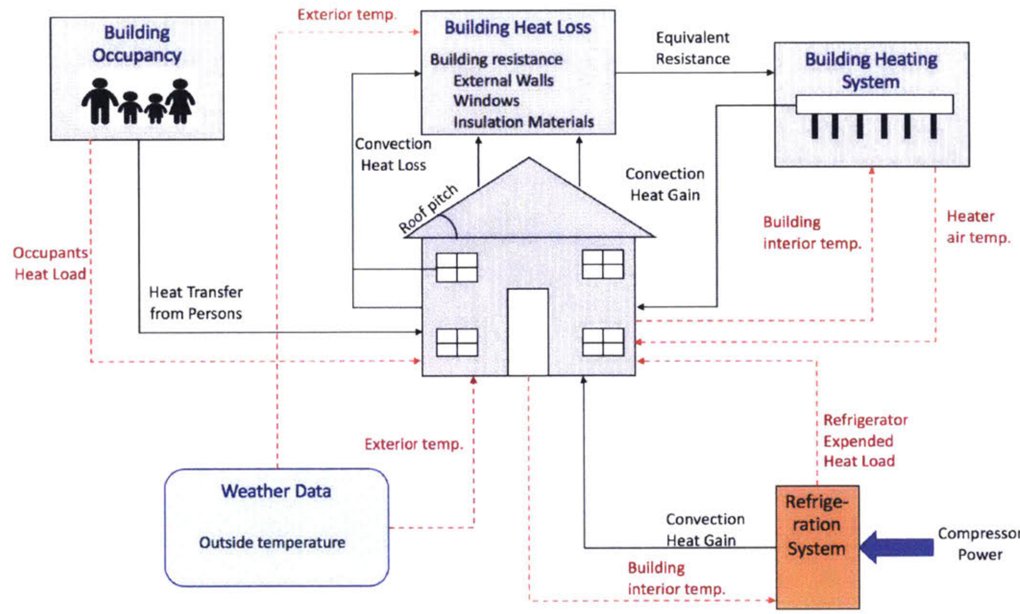


Figure 3-1: Illustration of Model Components and Interactions

3.2.1. Building Characteristics

From survey results, the average square footage of residential dwellings of participants is about 2,503 sq. feet. This is the building size modeled in MATLAB/Simulink^{TM} for both cities. The roof pitch in model is 6:12 pitch with a roof angle of 26.57°. Most common roof pitch types in residential applications are designed with pitch between 4:12 and 9:12. [2] Window area in dwelling is equal to 15% of floor area. [3] Walls are insulated with glass wool having R-11 resistance. The residential building also included layers of insulation of external walls, comprising drywall, siding wood, and sheathing wood and having their respective R-values. [4]

3.2.2. Model Assumptions

The following are assumptions made in developing the thermal simulation model. The assumptions helped simplify the model since the focus is to analyze the need to electrify heat towards carbon-neutral buildings, and not the optimization of building heat load.

1. Heat transfer and dispersion within the building is based on convection and radiation.

2. Heat losses is mainly through radiation by exterior walls, windows, and roofing. [5]
3. No heat loss through interior walls of building.
4. Doors excluded in thermal resistance and losses.
5. Heat transfer through conduction by materials and elements in building is small compared to radiation and convection.[5]
6. Infiltration not considered in model and no heat losses through ground surfaces of building.
7. Heat load due to occupancy is based on sensible heat and kept the same for all building occupants.[6]
8. No solar gains.

3.2.3. Model Description

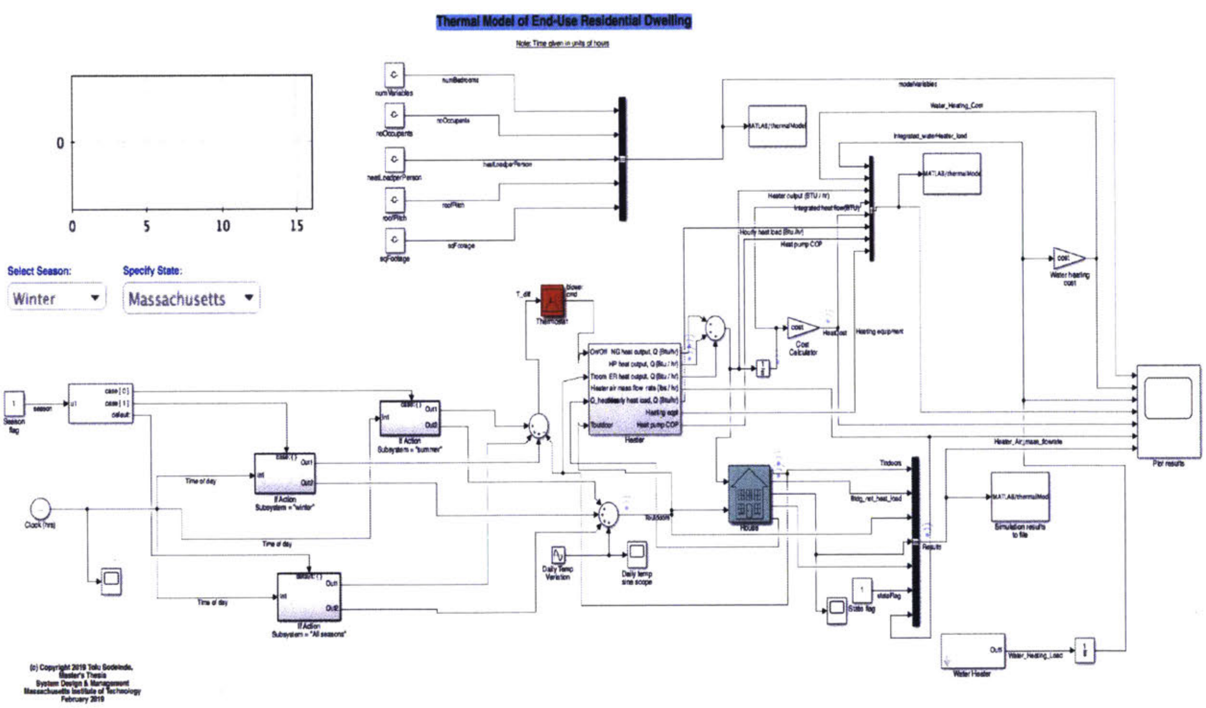


Figure 3-2: Thermal Model Overview of Residential Dwelling

Figure 3-2 is the thermal model of the building and comprises of two sub-systems:

- Heater sub-system – modeling heat generation by heater.
- House thermal sub-system – modeling internal building thermal comfort.

The thermal model analyzes scenarios for Boston and Houston with varied winter conditions and differing electric power prices. It employs historical median monthly winter temperatures for both cities; representing outside temperatures in model scenarios. Historical median temperatures for the above cities are defined in Tables 1 and 2 of Appendix A. In addition, the model simulations use historical winter temperature ranges recorded in a particular day in January 2019 [7] to determine the hourly building heating demand load and required heat pump output capacity at varying outside temperatures in both cities. Daily outdoor temperature variations in the model used the MATLAB/Simulink™ sine wave block, defined as:

Output (t) = Amplitude * Sin(Frequency*t + Phase) + Bias

where:

- Frequency (rad/sec) is 2*π / 24, and
- t represents the simulation time

The thermal model has the following configuration scenarios:

- Geographical scope – models include scenarios for cities of Boston and Houston.
- Heating period – Boston model has winter season coverage between October and May, and Houston model's winter season is between November and April.
- Heating systems – modeled to utilize three types of heating systems: natural gas furnace, electric resistance furnace, and electric air-sourced heat pump.

3.2.3.1 Heater Sub-System

The building's heater model sub-system determines the heat rate, Q of the heater based on temperature differential between interior and exterior temperature of building and mass air flow rate based on air changes per hour (ACH). It assumes air temperature from heater into living space is at 130°F. The building heat load also factored in heat generated from home refrigeration, which is expended inside building. This is employed in model to determine the net heat load for the residential building.

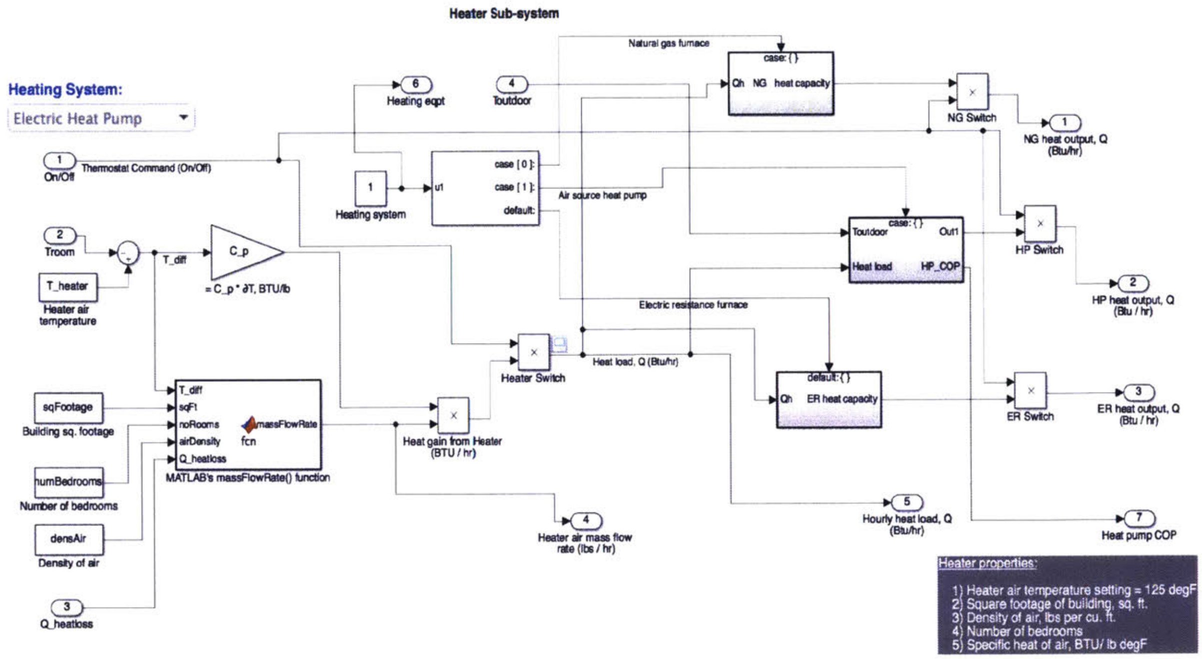


Figure 3-3: The Heater Sub-system

The Heater sub-system is modeled with scenarios using three different heating systems. A dataset is generated for heat pump coefficient of performance (COP) at varying outside temperatures using the regression formula determined for a Mitsubishi, MUZ-FE12NA model heat pump. [8] This model of heat pump with rated capacity of 13,600 BTU/hr. and power consumption of 1.78 kWh was employed in the heater model sub-system. [9]

The heater's heat load for the building is calculated as:

$$Q_h = m_h C_{p\_air} (T_{heater} - T_i) \quad \text{----------} \ (1)$$

where:

- Q_h – heater's hourly heat rate
- m_h – mass flow rate of heated air
- C_{p_air} – specific heat of air
- T_{heater} – outlet air temperature from heater
- T_i – simulated interior building temperature.

The input variables of the heater sub-system are defined in Table 3-2.

Input Parameters	Input Parameter Type	Default Setting
Heater output temperature	Variable constant	-
Air density	Constant	0.0765 lb/ft^3
Building square footage	Constant (From end-use survey results)	2503 sq. ft.
Number of bedrooms	Variable constant	-
Interior temperature of building	Simulated value	-

Table 3-2: Heater Sub-system Input Parameters

3.2.3.2 Residential Building Thermal Sub-system

The thermal sub-system includes components for the calculation of building net heating load and interior building temperature. The building geometry was modeled by defining building structures (walls, roof, windows), occupancy, and building materials resistance. The building ventilation rates and refrigeration heat expended inside the building were calculated to determine net heat load. Varying operating schedules from weekdays, weekends, and holidays were not factored; rather, energy usage profile was kept the same for all simulation periods. The temperature setting for interior thermal comfort was set to be 68°F based on standards. Typical range is between 64°F and 72°F, but it varies by individual.

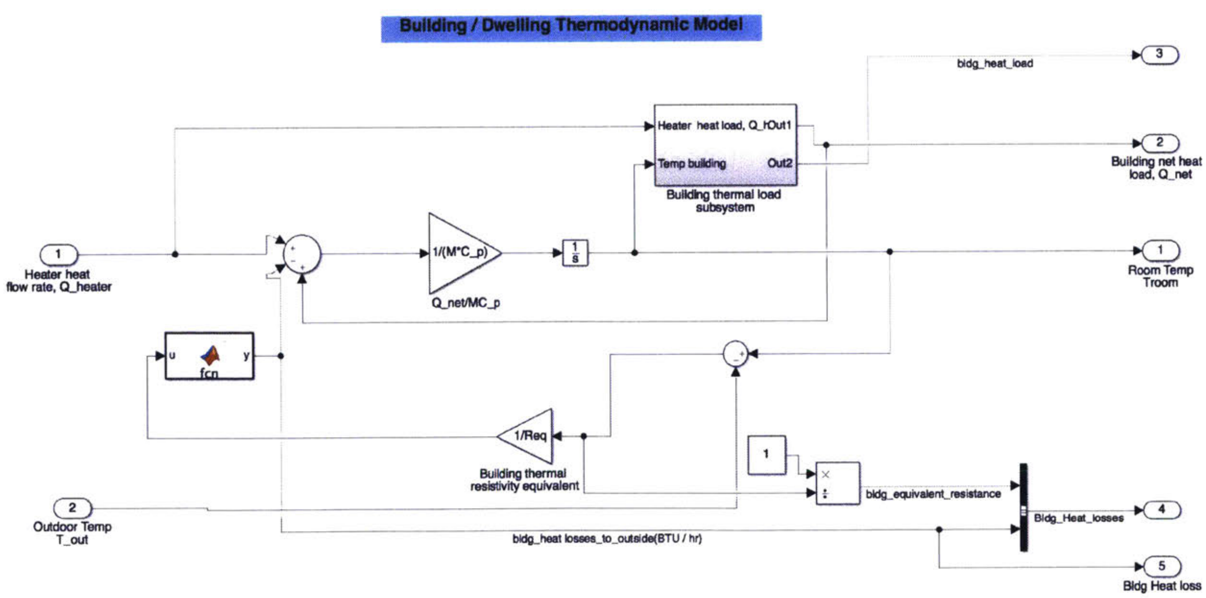


Figure 3-4: Building Thermal Sub-system

The building net load (Btu / hr.) is calculated using following expression:

Building Net load = [Heater load] + [Occupancy load] + [Refrigerator heat expended] – [Building heat loss to environment].

The equation for calculating the building net load is defined as:

$$Q_{\_netload} = m_h C_{p\_air} [T_{heater} - T_i) + (\#Persons * \text{metabolic heat rate per person}) + (COP_{rf} * Efficiency_{rf} * Power_{rf}) - [1 / R_{eq} * (T_i - T_o)] \quad \text{---------- (2)}$$

where:

- $Q_{\_netload}$ – building net load per hour
- COP_{rf} – coefficient of performance based on a Carnot engine
- $Efficiency_{rf}$ – efficiency factor for non-Carnot engine
- $Power_{rf}$ – power usage of refrigerator per hour
- R_{eq} – building equivalent resistance
- T_i – interior building temperature
- T_o – outside temperature
- rf – a subscript representing refrigeration

Input variables for the model's building sub-system are defined in Table 3-3.

Input Parameters	Parameter Type	Default Setting
Building equivalent resistance	Calculated variable	-
Outdoor temperature	Variable constant	Varies based on regional weather
Heater heat rate	Simulated value	-
Climate season	Default is 'winter'	

Table 3-3: Building Thermal Sub-system Inputs

The output of the thermal model is then employed for comparisons of energy usage in space heating using fossil fuels versus electricity. Using results and behavioral data from the end-use energy survey along with outputs from model simulation, the costs of electrifying heat in residential buildings are calculated. This includes switching cost, operating, emissions, and efficiency costs related to fossil fuels and electricity as primary heating source.

3.3. Electrification Cost Model

For the building structure, characteristics and household occupancy described in Section 3.2.1, the thermal model was employed to generate simulated heat load and heating system's energy output over a 24-hour period. It uses the model outputs to determine potential economic costs of electrifying and the tradeoffs involved. The output parameters generated from the thermal model are described in Table 3-4 below.

Simulation Output Parameters	Description	Unit of Measure
Heat load	Building heat load	Btu / hr.
Heating system capacity	Energy output of heating system	Btu / hr.
Integrated heat flow	Heat flow from heater over 24-hour period	Btu / day
Interior building temperature	Simulated temperature inside residential building	^{o}F
Outdoor temperature	Outside winter temperature as sine wave input	^{o}F
Building heat loss rate	Hourly heat loss from building	Btu / hr.
Building thermal resistance	Heat loss by building to outside environment over 24-hour period	Btu / day

Table 3-4: Thermal Model Simulation Output Parameters

The above parameters were later employed in the electrifying cost model spreadsheet to analyze the cost of electrifying space and hot water heating in the residential households.

3.3.1. Cost Model

In building the electrification cost model spreadsheet, the following assumptions were made:

1. Unit costs of heating fuels, electricity and natural gas, are kept constant in determining heating costs.
2. Winter duration in Massachusetts spans 8 months from October to May [10] and 5 months between November and March in Texas. [11]

3.3.2. Electrifying Cost Model Description

Using the thermal building model in MATLAB/Simulink™, the daily heating load was simulated, and results used to develop the economic model in a spreadsheet. In building this model, some key parameters were defined with settings as defined in Appendix B. The economic model is comprised of data for space heating including purchase price, installation costs, and operating costs for space heaters. The following space heating systems were modeled for economic analysis and amount of carbon-dioxide emissions.

- Natural gas furnace
- Electric resistance furnace
- Electric air-source heat pump (ASHP) with resistance backup.

It should be noted that electric ground-soured heat pump (GSHP) was not modelled because of the very high installation cost and space requirement for setup, which makes it not economically viable for a majority of residents of these two states.

The objective for this model is to: (1) define potential economic costs of switching to electrifying residential heat using one of three main types of space heating equipment, and (2) determine amount of greenhouse gas emissions generated by the heating systems. Results were analyzed using following criteria:

- Efficiency of heating equipment
- Cost penalties
- Emission penalties
- Incentivization – customer incentives for energy efficiency and electrification of buildings through program offerings.
- Weatherization / efficiency of building

Citations for Methodology Chapter

[1] – "EIA-Residential Energy Consumption Survey.", U.S. Energy Information Administration (EIA), 2009, https://www.eia.gov/consumption/residential/index.php.
[2] – "*Roof Pitch Angle and Slope Factor Charts*", The Barn ToolBox, https://www.barntoolbox.com/roof-pitch-angles.htm.
[3] – "Review of Cost Effectiveness Analysis. – Table 3" *Energy Star for Windows, Doors, and Skylights – Criteria Revision*, version 6.0, https://www.energystar.gov/sites/default/files/ESWDS-ReviewOfCost_EffectivenessAnalysis.pdf
[4] – "Table 4: Typical Thermal Properties of Common Building and Insulating Materials." *ASHRAE Handbook-Fundamentals (I-P Edition)*, 2009.
[5] "Heat Gain / Loss in Buildings." *Protek-USA*, https://www.protek-usa.com/pdf-new/Heat-Gain-Loss-Buildings.pdf.
[6] – "Table 8: Metabolic Heat Load of Persons." *ASHRAE Handbook-Fundamentals (I-P Edition)*, 2009.
[7] – "Data Tools: Daily Weather Records." *NOAA National Centers For Environmental Information*, https://www.ncdc.noaa.gov/cdo-web/datatools/records.
[8] – Eric Abboud, et. a. "Heat Pump Calculator for CSEC." *Tufts University*, ME-145, April 2016.
[9] – "MUZ-FE12NA Submittal, Manual, Specification, Diagram." *Richair Comfort Solutions*, https://richairductless.com/ductless-mini-split-systems/ductless-ac-and-heat-pumps-technical-data/muz-fe12na/. Accessed 01 April 2019.
[10] – "Boston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Massachusetts/Places/boston-temperatures-by-month-average.php.
[11] – "Houston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Texas/Places/houston-temperatures-by-month-average.php.

4. Data Results

This section provides analyses of information captured from the survey and results from the models. The flow of information in this research thesis is described in the diagram below.

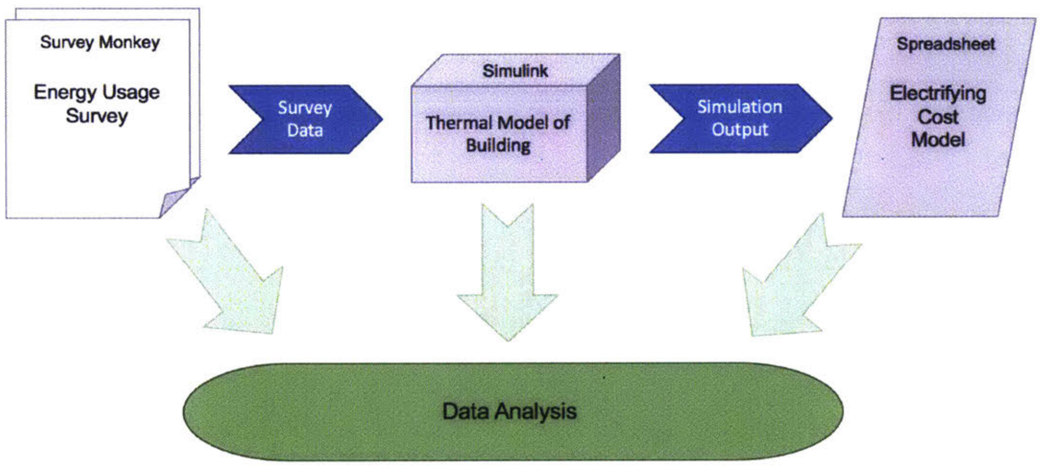


Figure 4-1: Schematic Diagram of Information Flow

4.1. End-use Energy Usage Survey Results

The average square footage of residential buildings from the survey was 2,500 square feet, and average number of occupants per dwelling is four. A plurality of responders uses double-pane windows to reduce solar insolation and improve building's energy efficiency (see Appendix A). About two-third of respondents in Massachusetts and Texas have additional thermal wall insulation and more than 80% have additional attic insulation.

The majority of survey responses indicated no participation in any form of energy programs like net metering and demand-response programs. This may be from lack of awareness of the program in their city or such programs do not exist in their state. Texas for instance does not have net metering [1] and does not allow its residents with roof-top solar panels to sell their excess electricity to the grid, making adoption of solar slow in a state with relatively high solar irradiation. [2] The primary heating system of the majority of survey respondents was gas-fired central warm-air furnace. More than 60% of respondents use this type of space heating system, 15% use steam or hot water system, and another 15% use some form of built-in and/or portable electric heating units. This aligns with the EIA survey results showing most residential households use gas-fired furnace and electricity in Massachusetts [3] and Texas [4] respectively.

The results from the survey were employed in building and configuring the thermal simulation model.

4.2. Thermal Model Simulation Results

The thermal model was implemented for a residential dwelling that is similar to an average residential household as depicted in survey results. Key information collected from survey results and employed in the thermal model are listed in Appendix B.

In addition to survey parameters in Appendix B, additional parameters including building characteristics (number of windows, roof pitch, number of bedrooms, building geometry, etc.), thermal resistances, outside and inside temperatures, conversion factors, specific heats of materials (air and water), simulation duration, etc. where also part of model. The simulation was run with a time period equivalent to an average 16 hours per day of heating to maintain interior set point temperature. The simulated heat load and heat pump's energy outputs is dependent on a number of factors including outside winter temperature. The recorded temperature for specific day in January in Boston and Houston was used in the simulation. The exterior temperature has effects on the "*balance point*" of heat pumps as shown in following charts: plots of heat load, energy output, and heat pump COP against outside temperatures for Boston and Houston. Tables 3 and 4 in Appendix B show sample of simulated results of average daily heat load and system capacity during a winter day in Boston and Houston respectively.

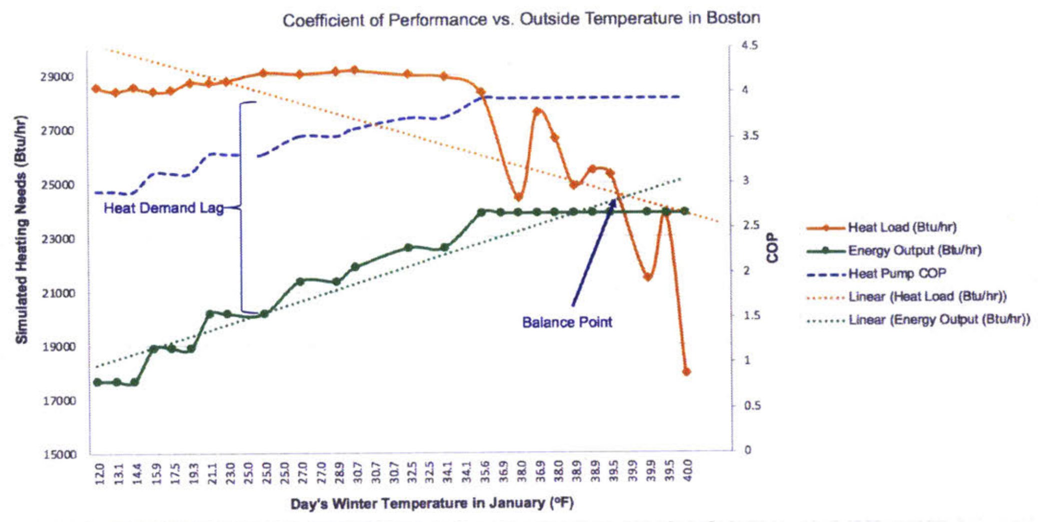


Figure 4-2: Heat Pump Performance in a January Day in Boston

Figure 4-2 is generated from simulation outputs using a Mitsubishi heat pump model MUZ- FE12NA, with a rated capacity of 13,600 Btu/hr. and power consumption of 1.78 kilowatt-hour. At lower temperatures, the heat load representing building het demand is higher than available energy output of the heat pump, thus creating a shortage of heat requirement. As such, supplementary or secondary heating is needed to meet the heating needs to achieve thermal comfort. As temperature increases during the day, heat load drops while energy output increases due to higher COPs at higher temperatures. Thus, assessing the right heat pump for a residential dwelling is dependent on factors such as: expected building load, sizing (or capacity) of heat pump, its performance, and the weather conditions in the region where heat pump is to be installed.

With the same heat pump specification, a similar chart was generated for the Houston scenario as shown below. Because of warmer winter temperatures in Houston, heat pump performance is better compared to Boston, and energy output is consistently higher than heat load required. However, supplemental heating in the form of electric resistance backup may be required in this Houston scenario for very cold winter hours where there may be heat demand lag.

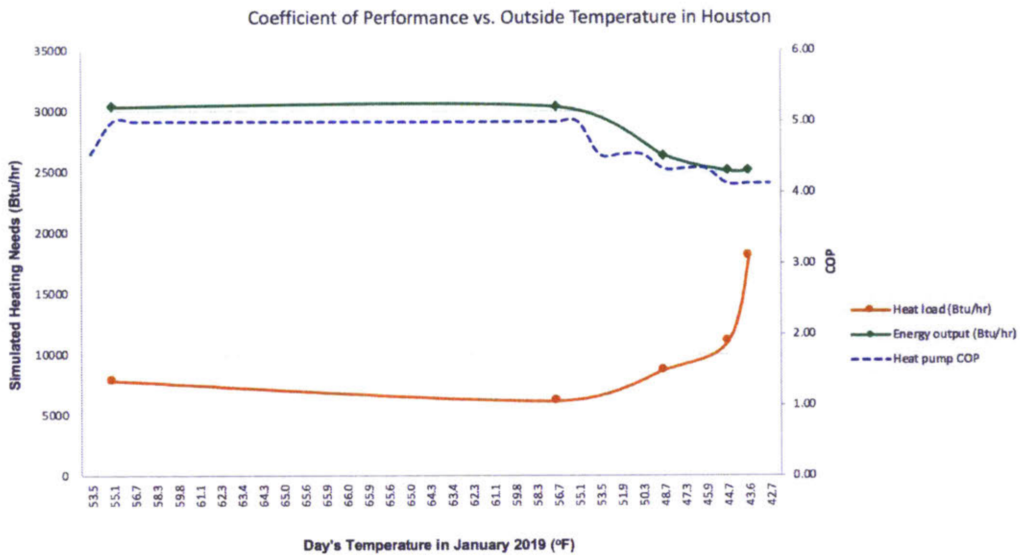


Figure 4-3: Heat Pump Performance in a January Day in Houston

Air-sourced heat pumps (ASHP) perform well and move heat efficiently at moderate weather, rather than freezing weather. Texas tend to have moderate winter conditions (mostly >40°F) and as such heat pumps can be very efficient with COPs above 400% as shown in results in Figure 4-3. Below the freezing point, heat pumps' performance drops as indicated in the Boston model in Figure 4-2. Performance of heat pumps are dependent on outside temperature and related to the amount of heat it can move inside the building relative to its input power. The capacity of the heat pump relative to the heat load indicates the ASHP has the capacity to meet load demand at lower temperatures and thus reducing the balance point. At about 20°F, the COP is above 3.0 for the specified heat pump model (Figure 4-2). At higher winter temperatures as is the case in Texas, ASHPs' performance tend to be higher as the system is able to move larger amount of heat inside building. As shown in above charts, the warmer the outside weather, the higher the COP of the ASHP.

As outside temperature drops below freezing, the output heat capacity of the heat pump drops below the required heat load of the building. This point is referred to as the "*balance point*" as described in Figure 4-4. [5] The "*balance point*" is a point on the COP curve below which it is not sufficient to operate the ASHP in heat pump mode to achieve thermal comfort inside the building. Additional backup heating is required. In the Boston model in Figure 4-2, at temperatures below 39°F, this model of heat pump may not be able to provide required heat load to maintain thermal comfort. Below this balance point on the COP curve, heat pump users in Boston will need to augment their heating needs with other secondary heating sources such as natural gas and electric resistance backups. The latter is 100% efficient, but costs more to operate since it uses same amount of energy as it supplies and electric power cost more than gas. Most existing homes in Boston and Houston already have gas furnaces that can serve as backup in situations where temperature is below the "*balance point*". However, in most cases, there is no unified control of the ASHP and gas furnace backup to optimize the building's heating demand.

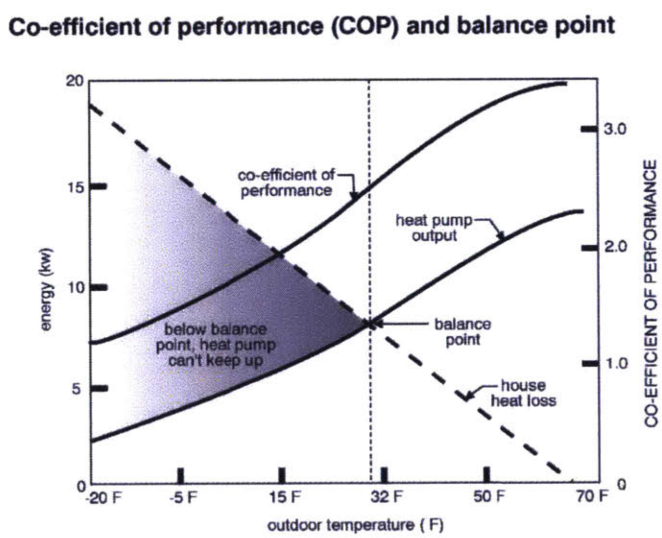


Figure 4-4: Heat Pump Coefficient of Performance and Balance Point [5]

ASHPs have built-in electric resistance coil that acts as supplementary energy source when the heat pump output is not sufficient to meet heating needs. However, operating the pump in this mode could be costly because the electric radiator consumes as much power as the heat it produces. Unlike ASHP, a secondary heater is typically not needed with gas furnace since heat is not being moved from outside cold air into inside. Rather, it generates its own heat by combustion.

The model was again simulated to analyze and compare expected monthly heat load in Boston and Houston with same building characteristics as before but having different historical monthly median temperatures. [6, 7] The median temperatures employed in the model are in Tables 1 and 2 of Appendix B. The thermal model was executed for each month using historical median temperatures from above tables to analyze the heating load for the building. The output is shown in chart below.

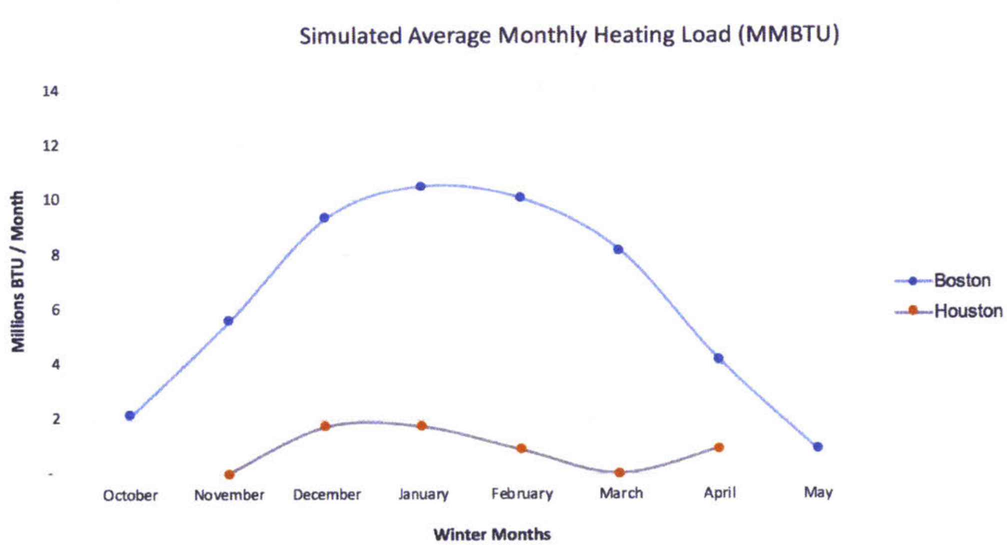


Figure 4-5: Building Simulated Heat Load in Winter Months

The monthly values are based on historical average monthly temperatures recorded in both cities during winter periods. As expected, there is higher need for heating in Boston to achieve thermal comfort of 65°F to 68°F. Reducing amount of heat load in a typically high heating period of December through February may involve temporary changes to improve building warmth and reduce losses. [8] Since they are temporary changes, they tend to be low cost as they may not include structural changes and retrofitting. During winter season in Boston, with average monthly temperatures between October and May ranging between 22°F and 61°F [6] (see Figure B1 in Appendix B), heating demand increases as temperature dips. Also, the average monthly temperatures in Houston ranges between 43°F and 80°F [7] during winter period between November and April (see Figure B2 in Appendix B). Heat pumps are generally more efficient at higher outdoor temperatures as they are able to move more heat from outside to inside with a higher coefficient of performance, COP. Because of warmer Houston winters, heat pump is more efficient and can move more heat inside than in Boston.

Temperature differential (∂T) between thermal comfort setting and outside temperature during winter period is lower in Houston than Boston, implying less heat demand to attain thermal comfort. Lesser heat load implies lower heating output /capacity from heating system resulting in lower heating cost. The simulated average daily kilowatt-hours required in Boston to achieve thermal comfort inside the residential dwelling is shown in Figure 4-6, determined from historical median winter temperatures between October and May (see Table 1 in Appendix B). Each temperature setting in chart represents historical median temperature recorded between October and May in Boston.

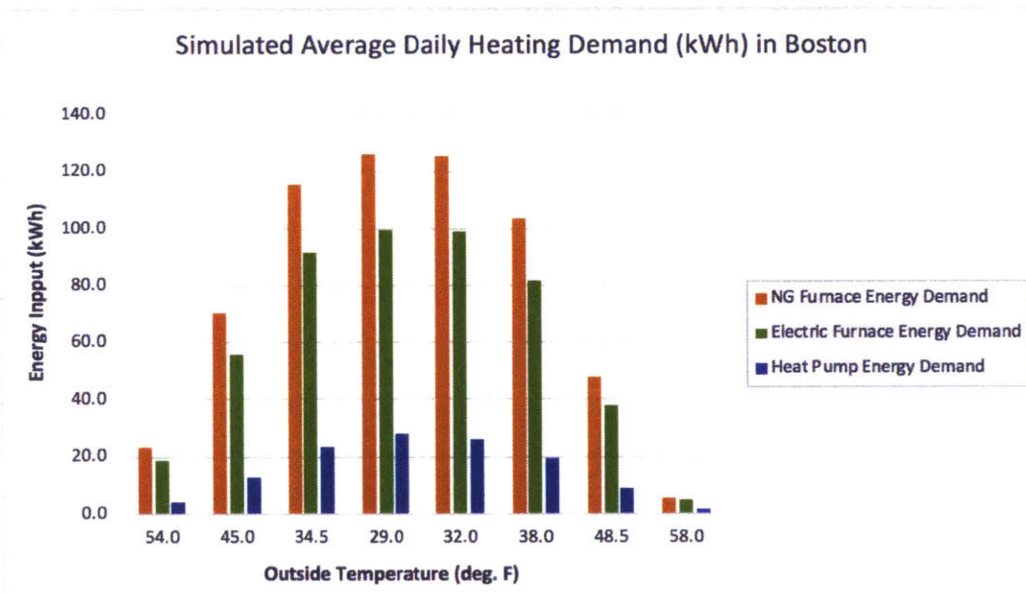


Figure 4-6: Average Daily Heating Demand in Boston, MA

And average daily kilowatt-hours required in Houston is shown below. It is determined using historical median winter temperatures from November through April (see Table 2 in Appendix B). The Houston model did not generate any heating demand for the months of

November and March as indoor temperature did not deviate far from model's thermal set point.

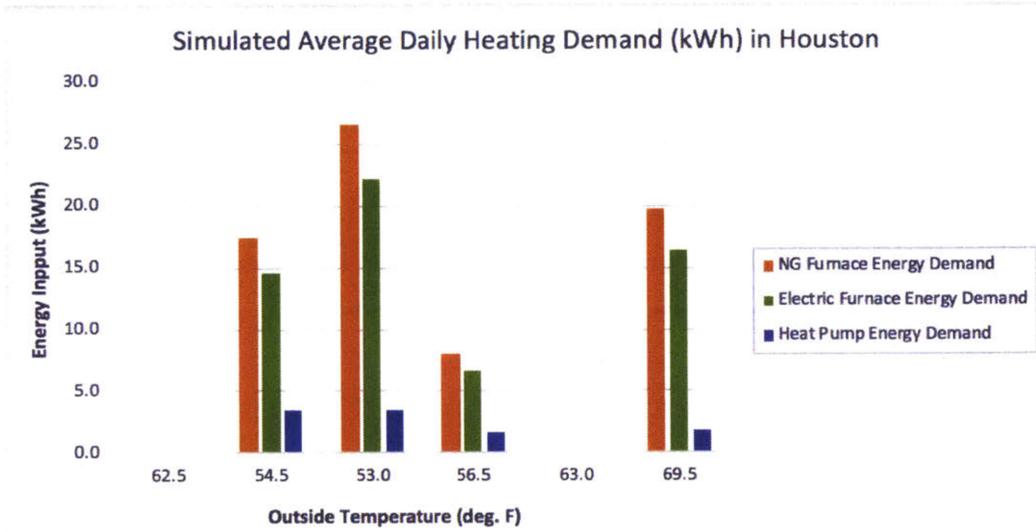


Figure 4-7: Average Daily Heating Demand in Houston, TX

The simulated building heat load and heating system energy output of the building is employed in performing the electrification cost model.

4.3. Electrification Cost Model Results

The thermal model simulation output generates the heating load requirement for an approximately 2500 sq. ft. residential dwelling. This heat load represents the amount of heat required to raise the indoor temperature of the building to thermal comfort model setting of 68°F. In addition, the model also simulates the heating capacity (energy output) of the heating systems in order to determine potential heating gap especially when the outside temperature is at freezing point or below. These outputs from the thermal model, together with the COP of the heating systems (note that COP of ASHP varies with outside temperature), were employed in calculating potential heating costs in Boston and Houston for each system. The economic data output generated from the model is in Appendix C.

4.3.1. Economic Costs

The economic costs are comprised of prices of various heating systems. As expected, electric air-sourced central warm-air heat pump is most expensive with higher installation cost. Heat pump cost is determined based on sizing capacity for a 3-bedroom, ~2503 sq. ft. residential dwelling (see section 4.1). It is more costly for new construction using central warm-air system versus ductless mini-split heat pump. [9]

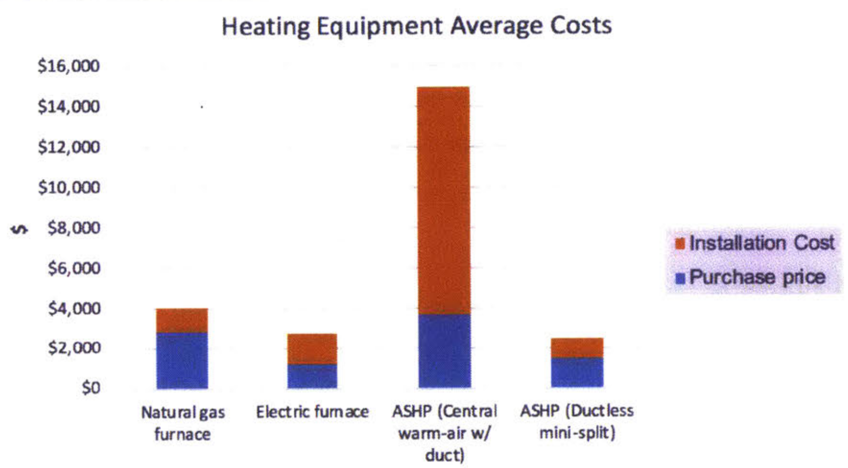


Figure 4-8: Estimated Costs of Heating Systems by Type

Despite a higher operating efficiency of 95% and lower initial purchase price compared to gas-fired furnace and ASHP, the electric resistance furnace is quite expensive to operate because of cost of electric power in Boston. At lower rating capacity with lower energy output (see ASHP model specifications [5]), the ASHP has slightly lower heating cost than natural gas furnace. At higher ratings, ASHP will be more expensive to operate in Boston than gas furnace due to high electricity rates/prices in Boston. However, this is compensated by higher COP and lower carbon emissions from ASHP.

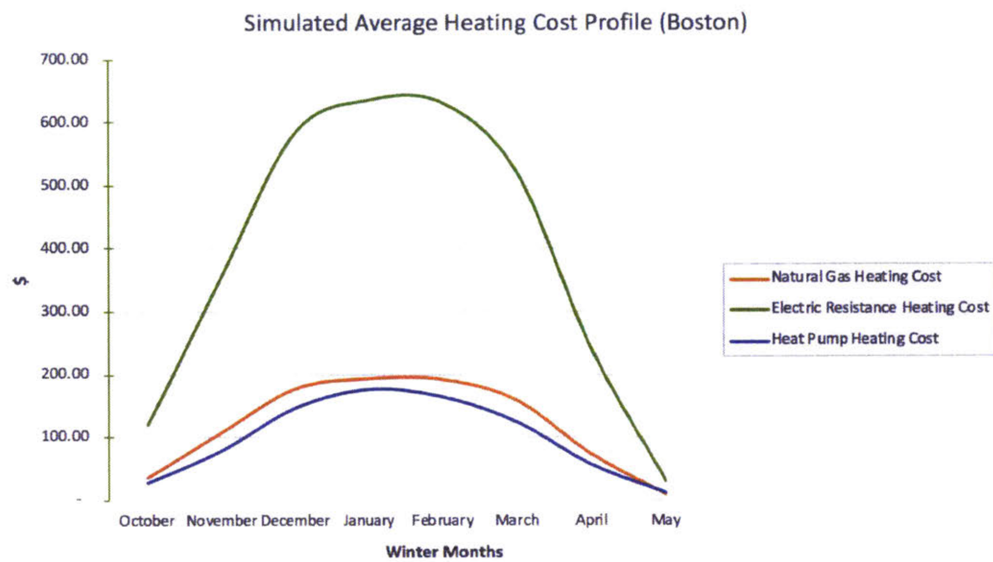


Figure 4-9: Average Operating Costs of Heating in Boston, MA

Figure 4-9 shows heating costs for electric resistance furnace and heat pump in Boston is more than twice (2x) heating cost in Houston (Figure 4-10) as electricity rates are relatively cheaper in Houston. It is more expensive to operate a natural gas-fired furnace than a heat pump in Boston. Texas generally have shorter winter months, implying shorter heating period compared to Massachusetts; thus, it is expected that energy usage for heating and associated operating costs will be higher in Massachusetts than Texas. This cost is reduced with high efficient electric air-sourced heat pump.

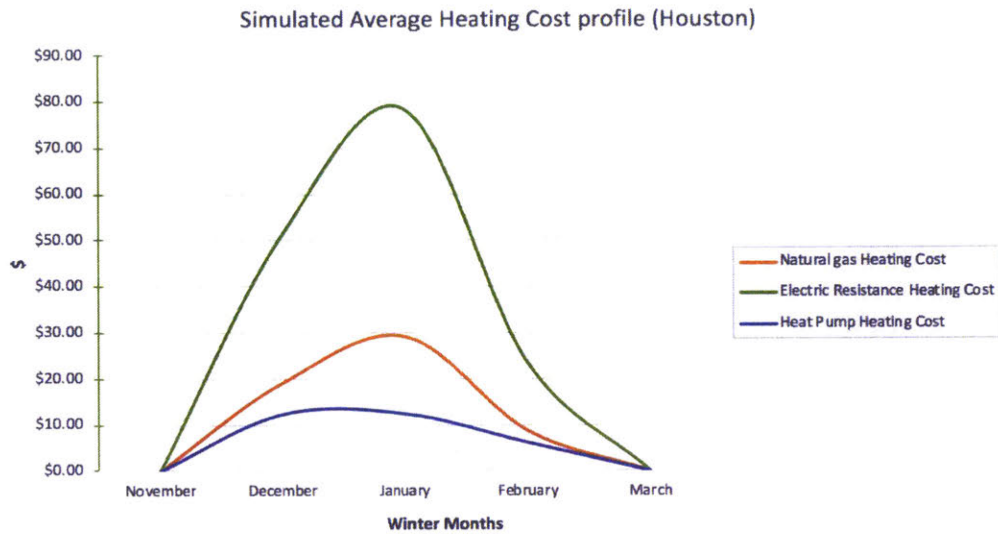


Figure 4-10: Average Operating Costs of Heating in Houston, TX

4.3.2. Carbon Emissions by Heating System

Greenhouse gas emissions measured by amount of carbon-dioxide emissions from residential heating is estimated from the electrifying cost model and results shown in following chart (Figure 4-11). For same building size, structure, and characteristics, yearly carbon-dioxide emissions are higher in the state of Massachusetts than Texas. This is related to having a longer winter season in Massachusetts, resulting in longer heating days. Across heating equipment, electric resistance furnace emits the most since it consumes same amount of energy as it supplies (COP is ~ 1.0). Using the MATLAB/Simulink™ simulation result of daily heat supply into the building, the amount of daily energy demand for heating is calculated as:

[Daily energy demand] = [Daily heat load supply] / [Heating system thermal efficiency]

Indirect carbon-dioxide emission from electric resistance furnace is determined using the emission factor of 0.35 kg-CO_2 / kWh of electricity produced, factoring new generating capacity from solar and wind. [10] It is indirect because there is no greenhouse gas emission from the building by the electric furnace; however, emission exists at the power plant that supplies electricity to the furnace. Same circumstance exists with heat pump where the only source of emission is from the power plant providing electric power to the heat pump. Direct emission of greenhouse gas comes with the use of natural gas-fired furnace. This amount is calculated using the coefficient of 53.04 kg-CO_2 / Million BTU of heat. [11]

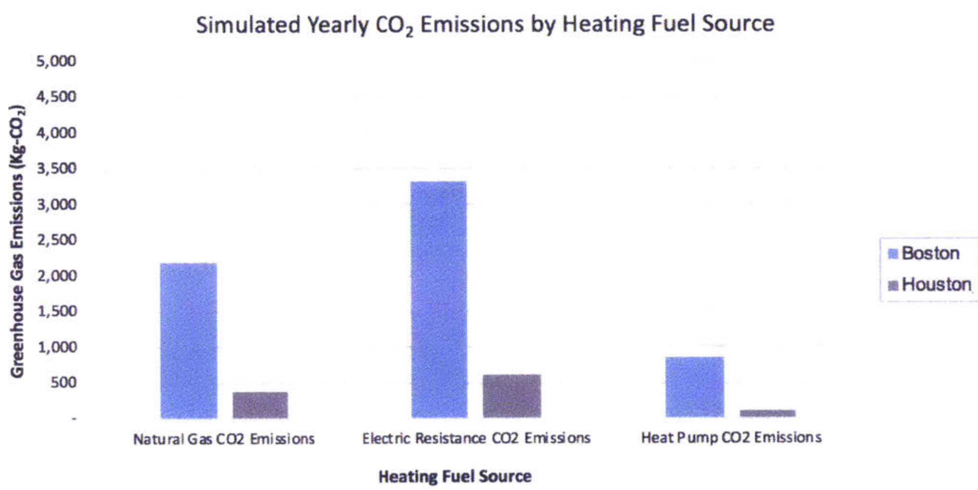


Figure 4-11: Estimated Annual Carbon-dioxide Emissions by Heating System

Using simulated results from the model, annual emissions in Boston from natural gas-fired furnace is about 60% higher than heat pump, and more than 50% lower than electric resistance furnace. And in Texas, annual emissions from gas-fired furnace is about 72% higher than that of electric heat pump, and 60% lower than electric resistance furnace. In the current grid configuration, with fossil fuel still the dominant fuel source in power generation, electric resistance is lower in carbon emissions compared to gas furnace. However, they are not viable economically as primary heating source. With high electricity cost, they are expensive to operate and thus unaffordable. As long as power utilities still use fossil fuel in generating power at their plants, electric resistance furnace heating will continue to be a major indirect source of greenhouse gas emissions.

Figure 4-11 shows cities' annual carbon-dioxide emissions from heating by fuel source. Electrification of heat seeks to eliminate direct carbon emissions from buildings, which is mainly from natural gas, and at the same time increase electricity production by power utilities from renewables to reduce indirect carbon emissions. Electrifying heat in residential dwellings potentially could be expensive. From the electrifying cost model, Table C2 of Appendix C shows cost breakdown of the heating systems. [12] An electric resistance furnace is cheapest to install, but more expensive to operate (Tables C3 and C6, Appendix C). ASHPs are more efficient and cleaner alternatives to gas-fired and electric resistance furnaces. They are cheaper to operate when in heat pump mode and efficient with coefficient of performance (COP) above 400% in milder winter temperatures as shown by the Houston model (Figure 4-3). However, initial construction cost can be prohibitive. Electrifying heat using ASHPs could be expensive for new installations with no existing insulated ductwork. Without a new ductwork, installation could be as low as $7,500. [9] An alternative option is a ductless mini-split air-sourced heat pump, which cost about $1,975 including installation for a 12,000 BTU/hr. (one-ton) unit. [12] A ductless mini-split heat pump is still able to move heat efficiently but has limited heating range. It is typically used to heat a room or a small-size living space in a home. However, to heat a building of 2,500 sq. ft. would require more than one mini-split unit, but a multi-zone system with the ability to run multiple cooling and heating areas in the residential building. The size and capacity of the mini split depends on the amount of cooling required. For the 2,500 sq. ft. residential building employed in the model, the estimated BTU load is about 48,000 BTU per hour (4-tons), [13] having two-zones. The potential cost for this two-zone mini split system with two outdoor condenser units and four indoor wall mount units is about $8,000, [14] which is almost as expensive as an electric ASHP without a new ductwork.

4.3.3. Reducing Carbon Emissions

A larger percentage of Texas households use electricity for home heating and carbon-dioxide emission from indirect source like power generation plants is much higher per kilowatt-hour than direct fuel sources like natural gas, propane and fuel oil. Figure 4-12 reflects higher emission of carbon-dioxide from electric power use. Using EIA's energy demand data for both states, [3] [4] Boston households on average emit about 4,000 kilograms of carbon-dioxide yearly and Houston households emit on average close to 2,500 kilograms of carbon-dioxide per annum (see Tables C9 to C11, Appendix C) This is based on EIA 2009 RECS data with 6.0% and 6.2% renewable energy consumption in Texas and Massachusetts respectively. [15] [16] As more renewables like solar and wind become major part of power generating mix, households' energy consumption from renewables will increase and annual carbon-dioxide emission per household in Boston and Houston is expected to drop.

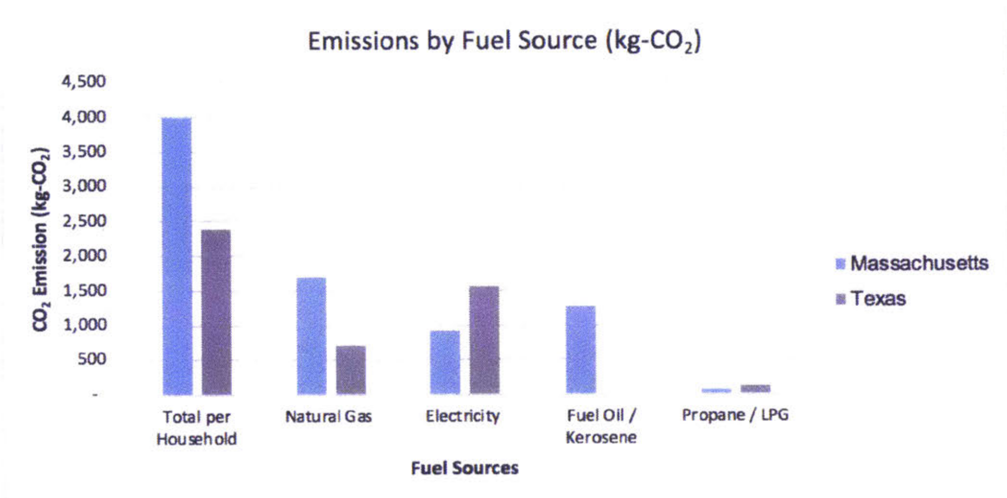


Figure 4-12: Household Carbon-dioxide Emissions by Fuel Source [EIA's 2009 RECS Data]

In order to meet IPCC target of 1.5°C of earth's temperature rise above pre-industrial level by end of century, [17] some drastic actions need to be taken to cut down emissions by reducing demand and consumption of carbon-based fuels both in direct use and power generation. Electrification of buildings is key to cutting direct use of fossil fuel in buildings' space heating and overall energy demand in buildings. It will save households a substantial amount in energy costs due to lower demand. A carbon tax could play significant role in financing the switch to electrifying heat. Putting a price on carbon will adjust behavior and guide consumers towards an economic self-interest to reduce their emission footprints as well as benefiting solar and wind electric generators . [18]

4.3.4. Household Heating Demand

According to the latest U.S. Census data, about 50% of Massachusetts households use utility gas (mainly natural gas) for heating, 27% use fuel oil and kerosene, and 15% use electricity. [19] In fact, outside of Northeast, fewer households choose natural gas as heating fuel. [20] The opposite is the case in Texas with about 43% of households using natural gas as primary heating source, about 51% using electricity, and 6% use propane or liquefied petroleum gas (LPG) based on 2000 U.S. Census data. [21] There are about

263,000 households in Boston city and about 2.6 million in Massachusetts. [22] There are close to 840,000 households in Houston and about 9.4 million in Texas. [22] A large percentage of these households use carbon-based fuels (natural gas, fuel oil, LPG) for heating, resulting in significant amount of greenhouse gas emissions from end-use residential heating alone.

Using simulation outputs from the MATLAB/Simulink™ thermal model, the following table shows energy demand and carbon-dioxide emissions from end-use residential heating in Massachusetts and Texas.

Heating Demand (Million BTU / year)	Massachusetts	Texas
Average per Household	64,310,000	31,570,000
Natural Gas	32,155,000	13,575,100
Electricity	9,646,500	16,100,700
Fuel Oil / Kerosene	17,363,700	-
Propane / LPG	1,028,960	1,894,200

Table 4-1: Estimated Average Household Heating Demand by Fuel Source

The above table is calculated based on 59% and 41% of energy demand is used in residential space heating in Massachusetts and Texas respectively. [6, 7] More energy is used by households in Massachusetts than in Texas and mainly for heating. By electrifying end-use residential dwellings, reduction in direct carbon emissions in buildings is achieved to meet the goal for carbon-neutrality by 2050. [23]

Citations for Data Results Chapter:

[1] – "Why Texas Don't Mess With Solar.", *Solar Power Rocks*, https://www.solarpowerrocks.com/texas-solar-power/why-texas-dont-mess-with-solar/.
[2] – "*Direct Normal Solar Resource of Texas*", National Renewable Energy Laboratory, NREL, https://www.nrel.gov/gis/solar.html., April 2017.
[3] – "Household Energy Use in Texas – A Closer Look at Residential Energy Consumption." *U.S. Energy Information Agency (EIA) Residential Energy Consumption Survey*, 2009, https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/tx.pdf.
[4] – "Household Energy Use in Massachusetts – A Closer Look at Residential Energy Consumption." *U.S. Energy Information Agency (EIA) Residential Energy Consumption Survey*, 2009, https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ma.pdf.
[5] – Heat Pump Efficiency, COP." *InspectAPedia – Encyclopedia of Building & Environment Inspection, Testing, Diagnosis, Repair*, https://inspectapedia.com/aircond/Heat_Pump_COP.php.
[6] – "Boston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Massachusetts/Places/boston-temperatures-by-month-average.php.
[7] – "Houston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Texas/Places/houston-temperatures-by-month-average.php.
[8] – Tom Hayden. "Low Tech Ways to Keep House Warm During Winter." *BBC News Magazine*, October 2013, https://www.bbc.com/news/magazine-24757144. Accessed 26 March 2019.
[9] – "Heat Pump Buying Guide – Prices, Reviews and Tax Credits 2019." *PickHvac – Cooling & Heating Guide*, https://www.pickhvac.com/heat-pump/.
[10] – "Table 11 – CO2 Emission Factors for Heating Fuels." *Heating Systems and CO2 Emissions, OpenLearn*, https://www.open.edu/openlearn/nature-environment/the-environment/energy-buildings/content-section-3.5. Accessed 25 March 2019.
[11] – "Carbon Dioxide Emissions Coefficient.", *U.S. Energy Information Administration*, February 2016, https://www.eia.gov/environment/emissions/co2_vol_mass.php.
[12] – "Cost of Ductless heat Pump Systems." *Remodeling Expense*, https://www.remodelingexpense.com/costs/cost-of-ductless-heat-pump-systems/.
[13] – "How Many BTU's DO I Need For My Mini Split?" *Comfort Up Learn Center*, https://learn.comfortup.com/how-many-btus-do-i-need-for-my-mini-split/.
[14] – "How Much Does It Cost To Install A Ductless Mini-Split A/C System?" *Home Advisor*, https://www.homeadvisor.com/cost/heating-and-cooling/ductless-mini-split-ac/.
[15] – "Texas State Profile Data.", *EIA's Texas State Profile and Energy Estimates*, https://www.eia.gov/state/data.php?sid=TX#SupplyDistribution.
[16] - "Massachusetts State Profile Data., *EIA's* Massachusetts State Profile and Energy Estimates", https://www.eia.gov/state/data.php?sid=MA#SupplyDistribution.
[17] – Peter Frumhoff. "The IPCC Gets Real About the 1.5°C Target." *Union of Concerned Scientists Blog*, October 2018, https://blog.ucsusa.org/peter-frumhoff/the-ipcc-gets-real-about-the-1-5c-target. Accessed 26 March 2019.
[18] – Kaufman Noah, Obeiter Michael, & Krause Eleanor. "Putting a Price on Carbon: Reducing Emissions." *World Resources Institute*, https://www.wri.org/sites/default/files/Putting_a_Price_on_Carbon_Emissions.pdf. Accessed 03 April 2019.
[19] – U.S. Census Data. "How Massachusetts Households Heats Their Homes." *Energy Policy Planning & Analysis*, https://www.mass.gov/service-details/how-massachusetts-households-heat-their-homes.
[20] – "Primary Heating Fuel [2005-2013]", *U.S. Energy Information Administration (EIA), 2014*, https://www.eia.gov/todayinenergy/detail.php?id=18131.
[21] - 2000 U.S. Census Data. "Census of Housing – Historical Census of Housing Tables." *United States Census Bureau*, 2000, https://www.census.gov/hhes/www/housing/census/historic/fuels.html.
[22] – "Census Quick Facts." *United States Census Bureau*, https://www.census.gov/quickfacts/fact/table/tx/PST045218. Accessed 26 March 2019.
[23] – City of Boston. "Carbon Free Boston – A Summary Report." 2019.

5. Analysis for Electrifying Heat

5.1. Thermal Model Analysis

The key results from the model and research show that electrifying heat in Boston and Houston offers pathways to reducing carbon emissions in residential buildings. Switching from carbon-based heating systems like gas-fired furnaces to electric air-sourced heat pumps (ASHPs), operating in heat pump mode, reduces heating costs for households while at the same time eliminating direct carbon emissions. At very cold temperatures below "*balance point*", the electric resistance backup is in use to keep thermal comfort and this will potentially increase heating cost. A gas system as opposed to electric resistance is a more economical heating backup in situations where the ASHP is not able to meet the heating load of the building. A gas-fired furnace cost less to operate than an electric resistance heater. This assumes that supplemental heat provided by gas backup is cheaper than electric resistance backup.

5.1.1. ASHP Energy Outputs Dependency

The results of the heating scenarios modeled with ASHP shows higher energy outputs in the Houston than Boston model. ASHP is able to move more warm air from the outside into residential dwelling at higher COP to generate more energy outputs. ASHP is very efficient for space heating in a city like Houston, with temperatures ranging from low-40s to mid-60s in a winter day. When the model was configured for Boston scenario, the heat output of the ASHP drops with decreasing outside winter temperatures. This is because the COP of ASHP drops with outside air temperature as shown in Figure 4-2. ASHP tend to be more common in southern climate in the U.S. where median winter temperatures are mild. Houston is a good location to use ASHP for heating to get a high COP. The simulated heat load of building drops as outside temperatures in Boston increased while heat pump's energy output increased with outside temperatures and COP. When outdoor temperature drops below 39°F, the ASHP unit tend to lack sufficient output to meet demand. [1] The relatively high "*balance point*" generated by the thermal model is due to a number of factors, including low COP for the ASHP model and the building's heat losses. And the fact that the ASHP model is not well-sized to fit the cooling requirement of the building results in the heat pump's capacity not meeting the building's heating demand. This is a lag on demand output to heat the building as seen in the model at temperatures below 39°F. Thus, in this scenario, supplemental heating is needed to provide heating when the outside winter temperature drops below this temperature. The "*balance point*" determined from the model and captured in Figure 4-2 is due to a number of factors including: efficiency of heat pump (COP), heat pump's sizing / capacity in relation to the building's thermal resistance and heat loss.

Supplementary heating can be achieved through the use of gas backup heating systems, electric backup heating in heat pumps, and even portable electric heaters. These secondary heating options are not modeled in this research; however, households with existing gas infrastructure of pipeline and gas-fired furnaces may be able to supplement their heating demand at relatively low cost using "*off-the-shelf*" hybrid gas/electric system. A hybrid electric ASHP / gas system with "*off-the-shelf*" controller enables automatic switch-on of gas system backup for supplemental heating. Homes without existing gas infrastructure have the option of propane or electric space heaters. This backup options do not support "*off-the-shelf*" combined technology. With proper control, ASHPs with backup electric heat strips are better controlled such that only the amount of energy needed to meet heating demand is utilized. [1] A two-stage ASHP with thermostat controls set at some temperature differentials will initiate the first stage of the heat strips. A further drop in temperature differential from thermostat setting will initiate the second stage of heat strip for additional heat above the first stage. Electric resistance system tend to use same amount of energy as its outputs, but costs more to operate as shown in the electrification cost model (see Figure 4-9 and Figure 4-10). An ASHP with thermostat controls for stage heating controls the amount of supplemental energy needed to meet heating demand at each stage.

5.1.2. Heat Demand Gap and ASHP Capacity

The capacity and performance of the ASHP is key in reducing the gap between building heat load and heating system's energy output. At low COP and below freezing temperatures, a larger sizing of ASHP is able to move more warm air inside the building and carry the load without as much electric resistance supplement as shown in Figure 5-1. Using a higher ASHP specifications (Mitsubishi MUZ-FE18NA model with load capacity of 21,600 Btu/hr. and power rating of 2.62 kilowatt-hours [2]) in the thermal model resulted in a heat demand gap that is narrower than in previous scenario (Figure 4-2). The balance point is now at 27°F (Figure 5-1) compared to results in Figure 4-2. Less amount of supplementary electric resistance heat is needed from the ASHP with higher load capacity unit. But there is still sufficient heat demand lag even with this higher ASHP model because it may not be properly sized to fit the cooling requirement of the building.

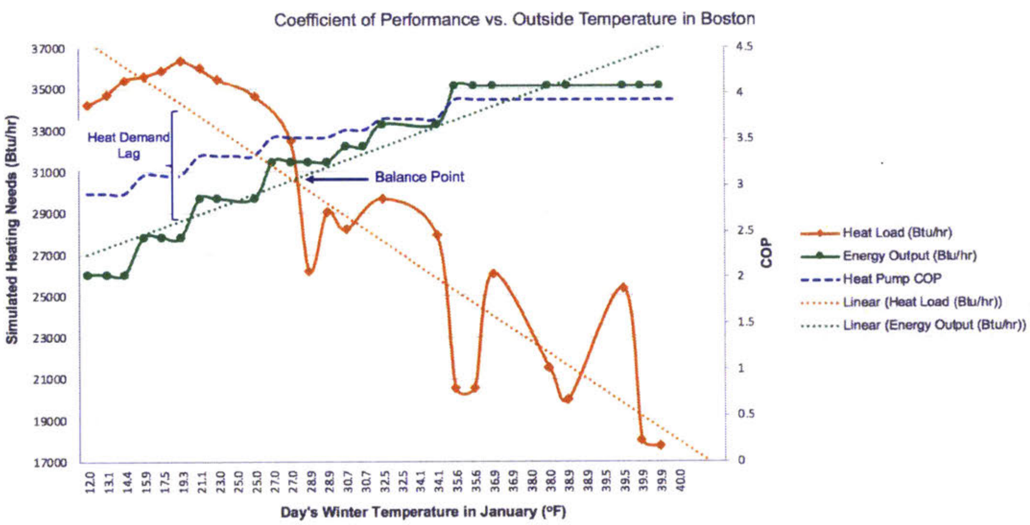


Figure 5-1: Higher Capacity ASHP Performance in a January Day in Boston

An electric ground-source heat pump (GSHP) is very effective in moving heat in cold climate like Boston. GSHP uses the constant temperature that exists below ground to move heat into buildings. [3] And since the temperature is constant below ground, GSHPs are not subject to varying COP and are independent of outside air temperature. Compared with ASHPs, GSHP units are more expensive to install; however, they deliver more energy per unit consumed. It should be noted that a GSHP scenario is not modeled in this research.

5.2. Efficiency and Weatherization

Median age of homes in Houston is between 20 and 29 years old while Boston is between 49 and 59 years old. [4] Older buildings tend to be less energy efficient compared to newer homes. It will cost more to retrofit older homes with electric heating than newer ones because in addition to replacing older furnaces, such buildings may also need to be weatherized for efficiency. Electrifying heat in residential households without cutting power usage could increase electricity needs. And improving efficiency without electrifying keeps fossil fuel in place and does not move towards carbon-neutral buildings. It is therefore imperative to combine efficiency and electrification of buildings towards cost-effective carbon-neutrality. [5] Improving building efficiency requires focusing on reducing demand. Reducing household energy demand significantly is a driver towards reducing carbon footprints in the end-use residential sector. Efficiency involves the following aspects:

- Weatherization of buildings – as a way of reducing ventilation and/or infiltration rates.
- Efficient building materials – use of thermal resistance building materials to reduce both heat loss to environment and buildings solar gain.
- Energy efficiency programs – with the goal of reducing energy usage and costs in residential dwellings.

5.2.1. Weatherization

Reducing energy demand as part of climate change mitigations requires reduction in ventilation rates in buildings (infiltration of residences without ventilation). Ventilation affects effectiveness of heating systems and thermal comfort of dwellings. [6] Weatherization involves steps taken in building design or retrofit to increase energy efficiency by reducing air infiltration in homes and unintended heat exchange between interior and outside environments. Residential dwellings can be "*tightened*" to reduce unintended air leakage and infiltration. [7] This can be achieved by caulking / sealing cracks and holes in the building, resulting in savings in energy. The average cost of sealing air leaks in homes is $350 - $600. [8]

Retrofitting homes with thermal resistance materials and fixtures can help improve energy efficiency in residential buildings. Use of double or triple-glazed windows can reduce solar gain. The smaller a window's total glazing area, the smaller amount of solar energy captured. A double-glazed window has potential of reducing amount of solar gain into a building by 10%, and this could be doubled with a triple glaze window. Proper insulation of exterior walls of buildings and attic is also key to reduce heat loss to exterior environment, while at same time limits solar gain in summer.

5.2.2. Energy Efficiency Programs

There are several government and private programs aimed at reducing energy consumption in residential buildings, including energy audits, specific building upgrades and recommendations, special assistance towards building remediations, and financial assistance for energy-efficient home appliances (ENERGY STAR). The National Weatherization program for instance offered services to low-income households in response to increased fuel prices during the oil embargo of the 70s. [6] ENERGY STAR launched by U.S. Environmental Protection Agency (EPA) was aimed to identify and promote energy-efficient products to reduce energy usage and amount of greenhouse gas emissions. Rate-payer funded programs now exist in various states through what is called "*system benefits charge*" in order to fund certain public benefits that are in risk of losing out in a competitive industry. [9] Massachusetts in 1997 created separate public benefits funds to promote renewable energy and energy efficiency. These funds are used to provide energy audits, subsidies to low-income and zero-interest loans for weatherization and insulation. An example is the Mass Save® energy assessment program sponsored by utility and energy efficiency providers and available to renters, homeowners and businesses in Massachusetts. Utility companies and appliance manufacturers also provide financial incentives in form of discounts and rebates to consumers that purchase specific home products and appliances with the ENERGY STAR label. Residential households in Massachusetts and Texas are able to take advantage of some of the above energy efficient improvements to cut down on their energy use and heating bill. And combining these improvements with electrification of residential heating is a cost-effective solution towards carbon-neutral buildings.

Reducing energy demand is achieved through efficiency and carbon-neutrality is achieved through electrification and carbon-free grid. Efficiency and electrification can [and should] be implemented in parallel. The common premise that efficiency has to be achieved prior to electrification may not be logical as this only reduces heating needs and does not move us towards a carbon-free building. Energy demand is lowered through efficiency resulting in electricity becoming more affordable. While electrification moves us towards zero emissions in buildings, the use of ASHPs, heat storage technologies, demand-response schemes with dynamic pricing of electricity are means of managing peak electricity demand. As grid becomes carbon-free and buildings are becoming carbon-free through electrification, though inefficient in terms of energy use, then energy efficiency programs are expected to make electrification more affordable.

5.3. Demand Response Management

Majority of research survey respondents do not participate in any form of energy savings programs like demand-response and net metering with solar roof tops. Demand-response schemes can help lower their energy bill by reducing usage at peak times. Both Massachusetts and Texas have deregulated power markets. Though not fully deregulated, both states have their electric power markets set by supply and demand. Demand response can be achieved in multiple of ways including simple off-peak metering, where power is cheaper at certain times in the day and consumer move usage of power consuming tasks to periods of off-peak; and smart metering in which requests or price changes is communicated by power utility companies to their customers. Responding to these request and price changes affords the consumer to lower usage or shift usage to off-peak periods. In both scenarios, consumer saves on electricity bill. By shifting demand to off-peak periods, the power utility is able to throttle production by taking generating units that are more expensive to operate, as well as high-polluting generating units, off line during peak. Consumers may allow power providers to take control of their thermostat as part of demand response management to regulate peak and off-peak periods.

The installation of smart thermostat controls in homes offers consumers dynamic control of energy usage based on accessibility to hourly power changes. A smart thermostat can dynamically make decisions based on real-time electricity prices. In addition, consumers can give access to power utilities to remotely regulate thermostats in return for price discounts on their electric power rates. Demand response management applies where electricity is the primary source for heating and cooling. Demand response does not work for indirect heating where fossil fuel is the primary heating source.

5.4. Dynamic Electricity Rates

Improvements in buildings' energy efficiency and electrification is key towards carbon-free buildings. But as long as electricity is still expensive in states like Massachusetts, it would be difficult to convince homeowners to make the switch from fossil fuel to electricity. In the electrification cost model, use of electric resistance furnace results in high heating cost of more than $2,000 for an average sized residential building (2,500 sq. ft.) in a year compared to Texas with heating cost of just above $200 per year. However, compared to other heating systems, it is still the most expensive to operate and not an economically viable option in electrifying heat. An electric ASHP with resistance backup is a viable and efficient heating system and offers lower electric power consumption when in heat pump mode. Alternate option is an ASHP with gas furnace backup for homes that already have gas line and furnace installed. The gas furnace serves as backup in situations where a building's heating demand is more than the heat pump output due to very cold winter temperatures. A gas backup is a cheaper and effective alternative to electric resistance backup. The use of ASHPs with gas backups especially for existing homes enables a smooth transition from full 100% carbon-based heating to less use of fossil fuel; thus, a cheaper, more efficient, and cleaner alternative for residential heating .

Electricity rates need to be dynamic priced to make electrification of heat more affordable. It is an easier decision for consumers to electrify buildings for heat in Texas were electricity prices averaged at 10 - 11 cents per kWh compared to Massachusetts at 22 cents per kWh. Most electricity consumers pay for electricity based on contractual rates averaged over the course of the year by power utilities. But in some deregulated markets like Texas, opportunity exist to take advantage of hourly variations in electricity prices using "*real-time pricing*" rates. With real-time pricing, consumers can take advantage of the opportunity to purchase when prices are low by knowing prices, planning ahead, and controlling load. However, engaging in real-time pricing may require understanding your electric power usage pattern. Having smart meters can help in this regard to capture and track usage over time on a daily basis. To take advantage of real-time pricing requires flexibility in behavior and control of appliances based on price awareness, understanding of how and when prices vary, flexibility to purchase at lower prices, and smart metering that helps keep track of how much power is consumed. The decision to pursue real-time pricing management versus other forms of time-based rate programs needs to be further quantified as this is not included in this research.

In Texas, the retail rates of electricity can range between $0.065 to $0.12, [10] making heat pumps cheaper to operate (Table C6, Appendix C). In both states, electric resistance furnace is not cost effective to operate, though they cost less than other systems to install. Electric resistance heat consumes lots of electricity which is all converted to heat. They generate higher energy demand from power utility, thereby straining the grid. However, with proper financial incentives such as low-income subsidies on electric rates, progressive carbon penalties, and demand response management rebates, the cost of switching to carbon-free alternative could be cheaper for low-income households.

5.5. Renewable Energy and Distribution Investments

The pathway to electrification of residential buildings involves carbon-free power generation, and expansion of distribution networks as more electricity is needed to replace displaced gas infrastructure and steam / oil boiler investments. As more renewable sources enter the market and replace old and expensive power generating units, cost per kilowatt-hour is expected to drop making electrifying heat more viable financially. Investments in power distribution network is also important to ensure there is no strain on the system as more people switch to electricity from fossil fuels. Building smart grid distribution network infrastructure is a robust and reliable way of managing high demand and changes in load patterns from electrifying heat. [11]

Heat storage is a great way of capturing heat to be used or distributed at later times. In residential buildings, heat storage media include hot water tank, rocks and concrete, underground storage aquifers, ground earth, as well as heat pumps producing heat during off-peak times. Ability to store heat for later use offers flexibility in peak and off-peak electricity usage. Heat can be captured and stored during off-peak period for use at peak times. Summer heat can be captured for use in winter heating. Use of heat storage helps reduce load demand on the power grid especially in winter season and way to optimize power generation by shutting off more costly units.

5.6. Policies, Regulations and Incentives

For cities like Boston to achieve its goal of carbon neutrality by 2050 requires the city and state, in addition to updating policies and regulations, also provide financial incentives such as tax credits and subsidies to households for retrofitting their homes and electrifying heat. Replacing old gas-fired and oil furnaces with electric heat pumps and electric resistance furnaces will be costly. The carbon-free Boston report offers strategies and pathway towards having carbon-neutral buildings by 2050. [5]

For low-income neighborhoods, cities like Boston and Houston need to lead initiatives that provides incentives, financing, and support for the retrofitting and conversion to electric heat that lowers initial capital costs, heating bill, and also ensures thermal comfort. Of the three heating systems analyzed in this research, it costs more to operate an electric resistance furnace (Tables C3 and C6, Appendix C on heating costs in both Boston and Houston respectively). ASHPs operating only in heat pump mode use less energy to move more heat and model scenarios show lower heating cost than gas-fired furnace in both Boston and Houston. Larger capacity ASHPs may have higher operating cost than gas-fired furnace because of higher electric power rate in Boston. In addition, initial cost of switching from carbon-based heating source to electricity and retrofitting of the building is cost prohibitive for which many consumers might need some form of financial assistance.

Enacting policies and providing incentives that facilitate more renewable power generating units to come online will help lower electricity prices in cities like Boston. There are currently incentives like Net metering in place for solar roof tops in Massachusetts and Investment tax credits (ITC) for utility solar and wind power plants. Tax credits for residential energy efficiency and builders of energy efficient homes have expired. [12] Government should reactivate these credits to facilitate the switch to electrified buildings. Tax credits for renewable energy products are still available till December 31, 2021, [12] but does not cover ASHPs. Extending these credits to include ASHPs will provide significant savings for consumers looking to electrify.

Citations for Analysis Chapter:

[1] – "Heat Pump Electric Backup Heating." *HP-HVAC: Heating & Cooling*, https://highperformancehvac.com/heat-pump-electric-backup-heating/. Accessed 03 April 2019.
[2] – "MUZ-FE12NA Submittal, Manual, Specification, Diagram." *Richair Comfort Solutions*, https://richairductless.com/ductless-mini-split-systems/ductless-ac-and-heat-pumps-technical-data/muz-fe12na/. Accessed 01 April 2019.
[3] – "Air and Ground Source Heat Pumps." *Mass.gov*, https://www.mass.gov/service-details/air-and-ground-source-heat-pumps.
[4] – Na Zhao. "Age of Housing Stock by State." *National Association of Home Builders (NAHB) – Eye on Housing*, January 2017, http://eyeonhousing.org/2017/01/age-of-housing-stock-by-state/.
[5] – City of Boston. "Carbon Free Boston – A Summary Report." 2019.
[6] – The National Academies of Sciences, Engineering & Medicine. "Building Ventilation, Weatherization, and Energy Use." *The National Academies Press*, pp. 209-238, https://www.nap.edu/read/13115/chapter/10. Accessed 27 March 2019.
[7] – "Air Sealing Your Home." *Energy.Gov*, https://www.energy.gov/energysaver/weatherize/air-sealing-your-home.
[8] – "Home Air Sealing Cost." *Fixr*, https://www.fixr.com/costs/air-leaks-sealing.
[9] – Fisher, Sheehan & Cotton. "Electric Utility Restructuring and the Low-Income Consumer." *Public Finance and General Economics*, October 1997, File no. 14.
[10] – "Table 5.6.A: Average Price of Electricity to Ultimate Consumers by End-Use Sector." *Electric Power Monthly*, March 2019, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a.
[11] – Brendan Coyne. "Electrifying Heat: Too Expensive, or Too Little Ambition?" *The Energyst*, https://theenergyst.com/electrifying-heat-too-expensive-or-too-little-ambition/.
[12] – "Federal Income Tax Credits and Other Incentives for Energy Efficiency." *Energy Star*, https://www.energystar.gov/about/federal_tax_credits.

6. Conclusion

Electrification of residential households is key to reducing greenhouse gas emissions in buildings and achieving the goal of carbon neutrality by 2050. Space heating is the largest energy consumption by end-use in Massachusetts with natural gas as the primary heating fuel source. And it is second largest by residential end-use in Texas with about 43% of households using natural gas as main heating fuel. Electrifying residential heating eliminates direct carbon-dioxide emissions in space heating. Electrification has to be combined with energy efficiency to not only cut emissions in buildings, but also reduce energy costs.

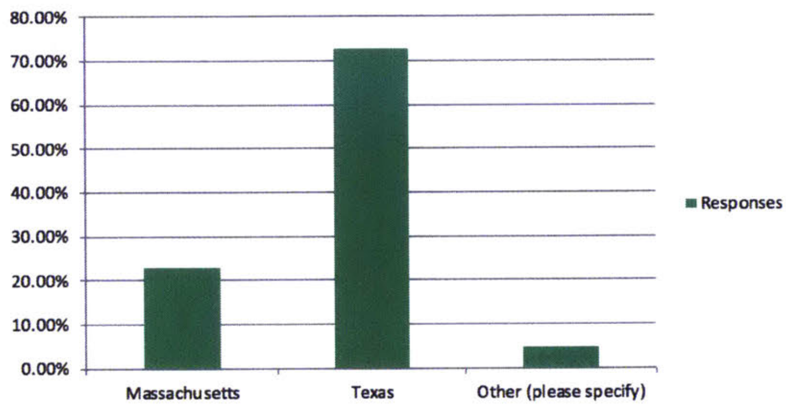
Decarbonization of residential buildings depends on improving their energy performance. With effective energy efficiency strategies including weatherization, demand response schemes, and retrofitting homes with better insulating and thermal resistance materials, we can cost-effectively reduce end-use energy consumption and lower energy costs for consumers in Boston and Houston. The cost of retrofitting homes could be expensive to home owners as shown and discussed in model results and analysis. Large urban cities like Boston and Houston should offer financial assistance programs, *carbon-free* energy initiatives ,and outreach to residential households for the switch to electrify heat. These programs should be cost-effective in the sense that it helps to lower households' power bills while maintaining buildings' thermal comfort.

By electrifying buildings, expanding investments in network infrastructure, updating building policies, and deploying newer and efficient technologies, we can reduce end-use energy consumption, effectively manage demand response, and eliminate direct carbon-dioxide emissions in residential dwellings, while also lowering energy costs for consumers.

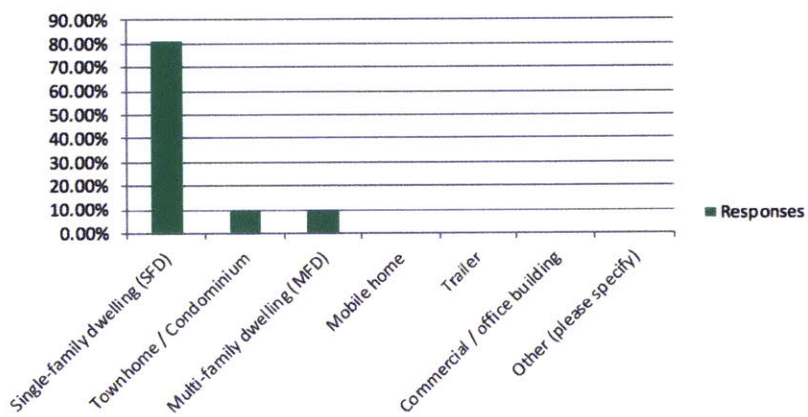
APPENDIX A: Results of Residential End-Use Energy Profile Survey

Total number of responses is 22. The following are subset of responses from the survey. Not all the responses are documented in this section because of sizable amount of response data.

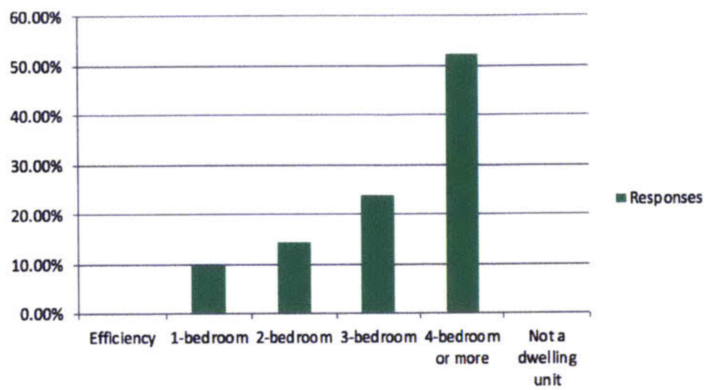
1. Location of survey participants.



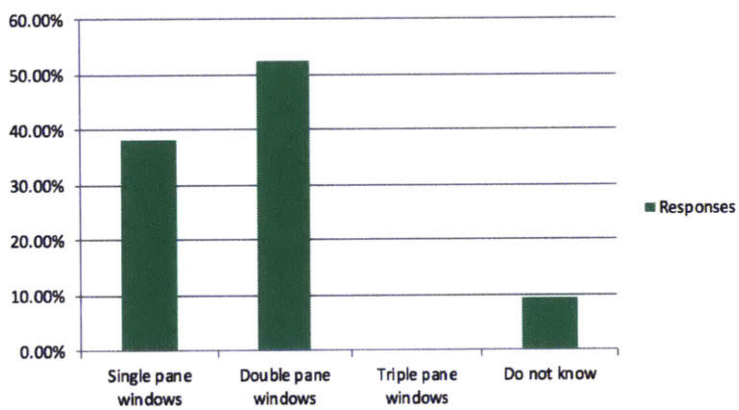
2. Type of housing or building of participants.



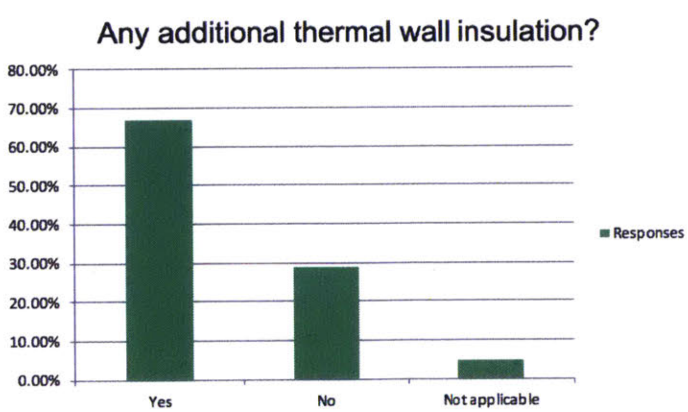
3. Type of dwelling.



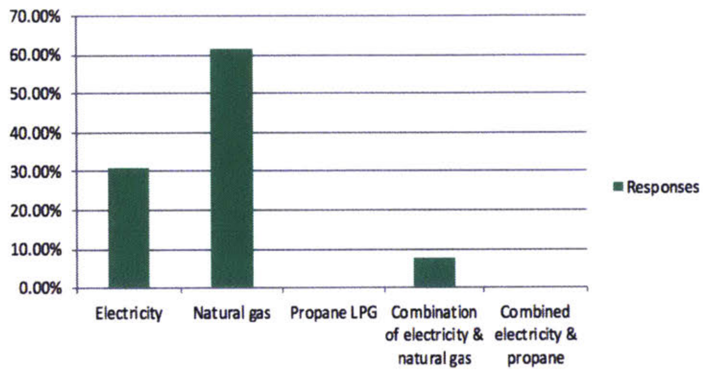
4. Type of Window in Building.



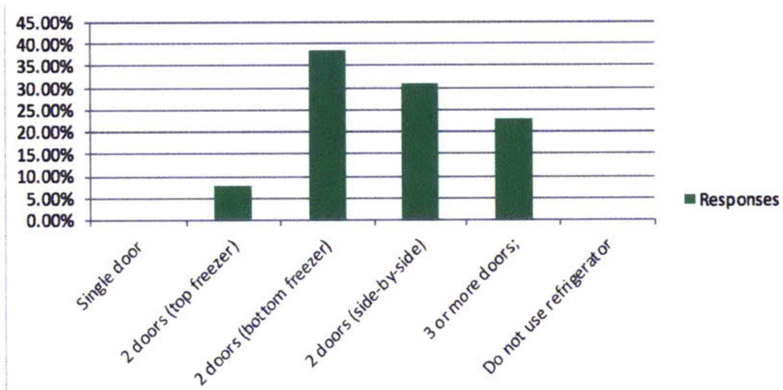
5. Thermal wall insulation in dwelling.



6. Cooking fuel used.

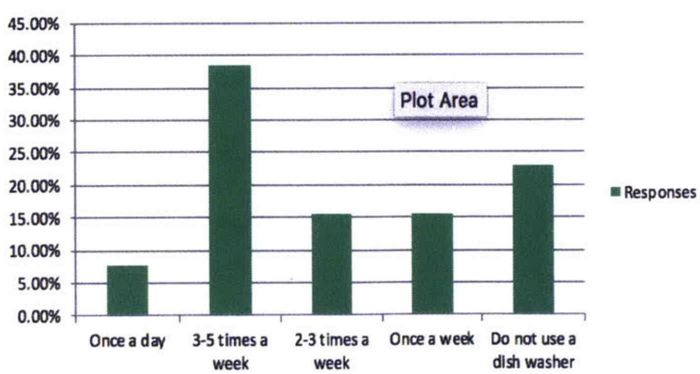


7. Primary refrigerator in use in dwelling

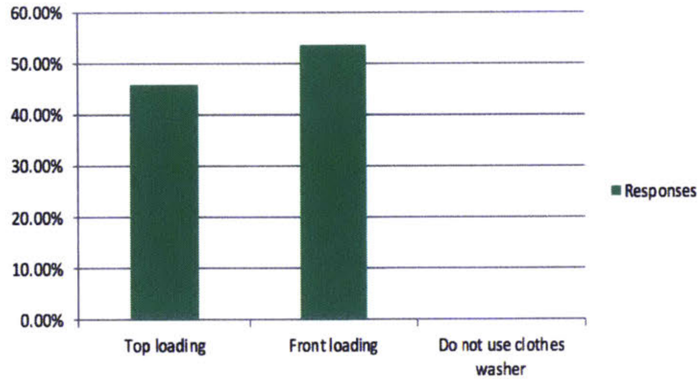


Note: Majority of survey responders indicate they do not have a secondary refrigerator.

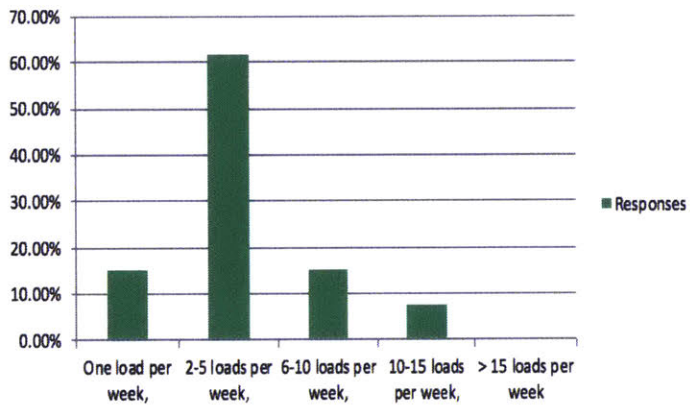
8. Average duration of dishwasher in use.



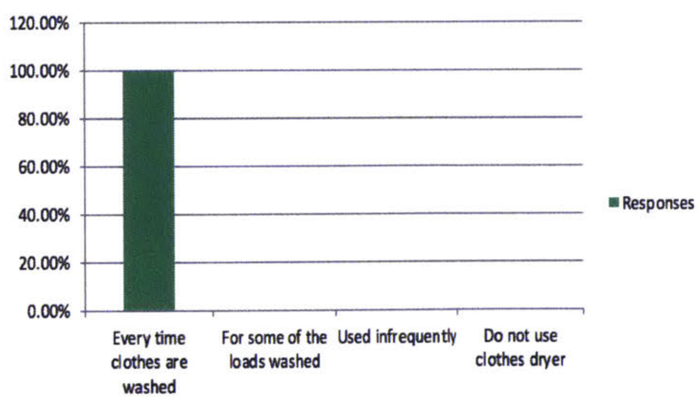
9. Clothes washing appliance type.



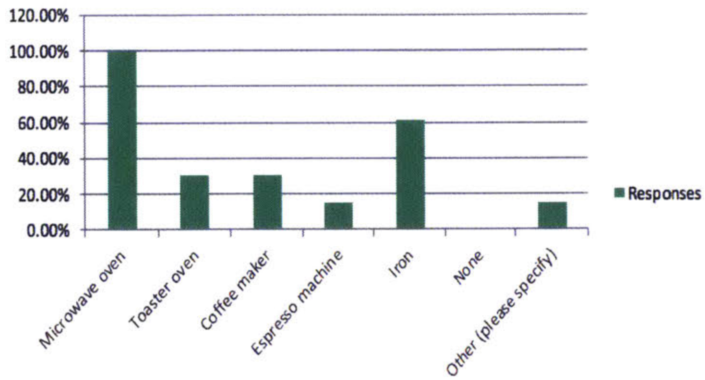
10. Clothes washer utilization.



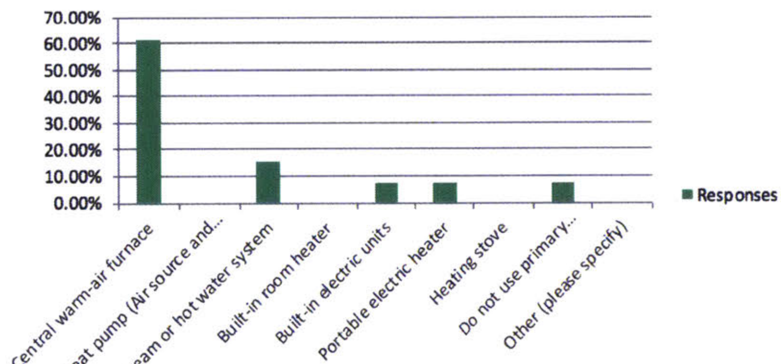
11. Duration of use of clothes dryer.



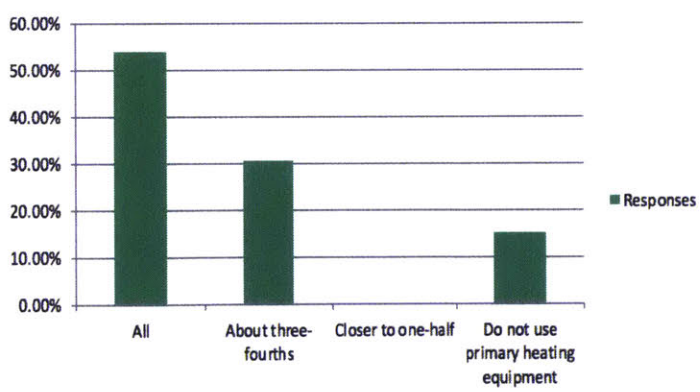
12. Other appliances in use.



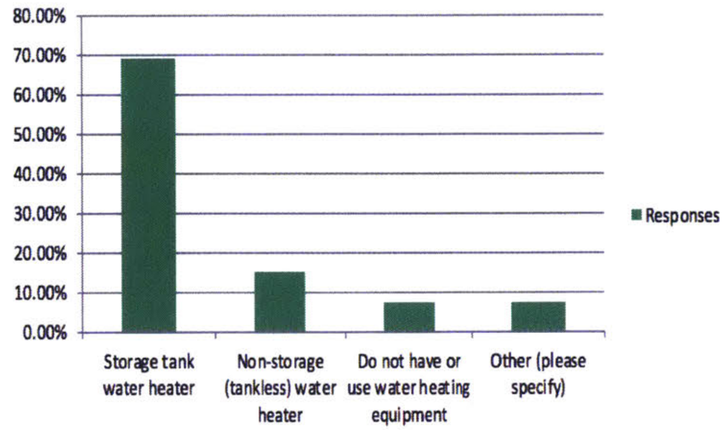
13. Primary heating equipment.



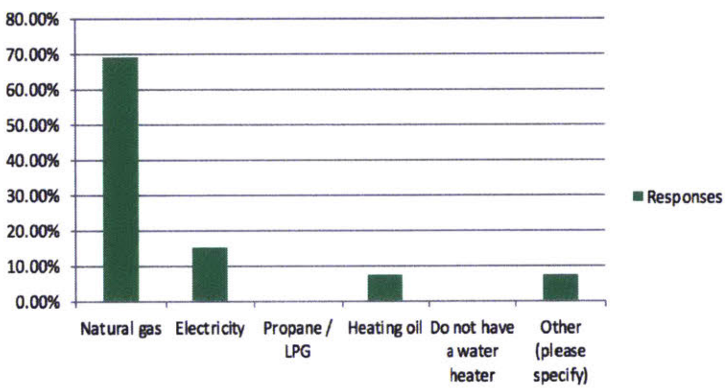
14. Proportion of heat provided by primary heating equipment.



15. Primary water heating equipment.



16. Main fuel source of primary water heater



APPENDIX B: Thermal Building Model Parameters and Results.

Some of the survey data were used in building the thermal model. The following survey parameters and data were employed in the simulation model.

Table B1: Model Parameter Settings for the Thermal Building Model.

Survey Data	Model Parameter	Setting
Average building size	Building square footage	2503 sq. ft.
Type of window pane	Window thermal resistance	Double-pane windows
Number of household members	Occupancy in building	4 persons
Primary heating equipment	Heating system	Central warm-air furnace
Primary heating fuel	Fuel source	Default = Natural gas
Water heating equipment	Water heating system	Storage tank
Primary water heating fuel	Water heater fuel	Default = Natural gas

Table B1: Thermal Building Model Parameters

Simulated average daily heat load supplied to achieve thermal comfort in building at 68°F is shown in following tables for the state of Massachusetts and Texas. This is based on an average daily winter temperature per month during the winter season.

Table B2: Average Daily Temperatures for Winter Months in Massachusetts as available from historical data.

The temperature range was determined from the high and low values and used in the Massachusetts thermal building model.

AVERAGE BOSTON DAILY TEMPERATURES. (°F) [46]				
	High	Low	Median	Temp Range (+/-)
October	61	47	54.0	7.0
November	52	38	45.0	7.0
December	41	28	34.5	6.5
January	36	22	29.0	7.0
February	39	25	32.0	7.0
March	45	31	38.0	7.0
April	56	41	48.5	7.5
May	66	50	58.0	8.0

Table B2: Historical Average Monthly Temperatures in Boston

Table B3: Average Daily Temperatures for Winter Months in Texas available from historical data.

The temperature range was determined from the high and low values and used in the Texas thermal building model.

AVERAGE HOUSTON DAILY TEMPERATURES. (°F) [47]				
	High	Low	Median	Temp Range (+/-)
November	73	52	62.5	10.5
December	64	45	54.5	9.5
January	63	43	53.0	10.0
February	66	47	56.5	9.5
March	73	53	63.0	10.0
April	80	59	69.5	10.5

Table B3: Historical Average Monthly Temperatures in Houston

The following tables are simulation results generated for various scenarios using the MATLAB/Simulink™ thermal model.

Table B4: Simulated Results of Heat Load and Heat Pump Energy Output in Boston.

This table shows result of simulation for specific winter day in January 2019 using outside temperature from National Oceanic and Atmospheric Administration (NOAA). [1] The table below was generated using the following temperature data from NOAA.

- Day's low temperature – 9 deg. F
- Day's high temperature – 39 deg. F

- Day's median temperature – 24 deg. F

Simulation Time	Hourly heat load (Btu/hr)	Integrated_heater_flow(BTU)	Heater_output_rate(BTU/hr)	COP	StateFlag	Tindoors (°F)	Toutdoors (°F)
0	0	0	0	3.32	0-Massachusetts	68	25.000000
0.5	22869.43819	0	21379.10438	3.52	0-Massachusetts	55.1600918	26.957893
1	22825.18614	10689.55219	21379.10438	3.52	0-Massachusetts	57.02991372	28.882286
1.5	22719.76415	21379.10438	21864.99312	3.6	0-Massachusetts	58.75787495	30.740251
2	22788.47628	32311.60094	22593.82622	3.72	0-Massachusetts	60.60235808	32.500000
2.5	23085.86097	43608.51406	22593.82622	3.72	0-Massachusetts	62.60050921	34.131421
3	23311.45498	54905.42717	23869.28416	3.93	0-Massachusetts	64.35388816	35.606602
3.5	23961.55997	66840.06925	23869.28416	3.93	0-Massachusetts	66.44928487	36.900300
4	24466.42164	78774.71132	23869.28416	3.93	0-Massachusetts	68.16195257	37.990381
4.5	24904.16346	90709.3534	23869.28416	3.93	0-Massachusetts	69.5695802	38.858193
5	25318.57419	102643.9955	23869.28416	3.93	0-Massachusetts	70.71131881	39.488887
5.5	0	114578.6376	0	3.93	0-Massachusetts	71.60517728	39.871673
6	17939.90031	114578.6376	23869.28416	3.93	0-Massachusetts	62.12317735	40.000000
6.5	21446.28405	126513.2796	23869.28416	3.93	0-Massachusetts	66.31886256	39.871673
7	23803.22033	138447.9217	23869.28416	3.93	0-Massachusetts	68.84261043	39.488887
7.5	25457.19991	150382.5638	23869.28416	3.93	0-Massachusetts	70.25157527	38.858193
8	26669.79039	162317.2059	23869.28416	3.93	0-Massachusetts	70.87910912	37.990381
8.5	27598.52093	174251.8479	23869.28416	3.93	0-Massachusetts	70.93432274	36.900300
9	28339.09957	186186.49	23869.28416	3.93	0-Massachusetts	70.55389323	35.606602
9.5	28949.78815	198121.1321	22593.82622	3.72	0-Massachusetts	69.83180362	34.131421
10	29026.61132	209418.0452	22593.82622	3.72	0-Massachusetts	68.29511921	32.500000
10.5	29195.41782	220714.9583	21864.99312	3.6	0-Massachusetts	66.74353998	30.740251
11	29160.11949	231647.4549	21379.10438	3.52	0-Massachusetts	64.84204487	28.882286
11.5	29071.66746	242337.0071	21379.10438	3.52	0-Massachusetts	62.80857455	26.957893
12	29109.0198	253026.5593	20164.38254	3.32	0-Massachusetts	60.89674394	25.000000
12.5	28806.04128	263108.7505	20164.38254	3.32	0-Massachusetts	58.56522314	23.042107
13	28711.41003	273190.9418	20164.38254	3.32	0-Massachusetts	56.52413271	21.117714
13.5	28746.47586	283273.1331	18888.92461	3.11	0-Massachusetts	54.70940948	19.259749
14	28448.64876	292717.5954	18888.92461	3.11	0-Massachusetts	52.5823857	17.500000
14.5	28413.50497	302162.0577	18888.92461	3.11	0-Massachusetts	50.90762554	15.868579
15	28547.09048	311606.52	17674.20277	2.91	0-Massachusetts	49.59718062	14.393398
15.5	28420.15877	320443.6214	17674.20277	2.91	0-Massachusetts	48.14695222	13.099700
16	28580.4133	329280.7228	17674.20277	2.91	0-Massachusetts	47.25449441	12.009619

Table B4: Boston Model's Simulation Results of Heat Load and ASHP Energy Output

<u>Table B5:</u> Simulated Results of Heat Load and Heat Pump Energy Output in Houston.

This table also shows result of simulation for specific winter day in January 2019 using outside temperature from National Oceanic and Atmospheric Administration (NOAA). [1] The table below was generated using the following temperature data from NOAA.

- Day's low temperature – 40 deg. F
- Day's high temperature – 65 deg. F
- Day's median temperature – 52.5 deg. F

Simulation Time	Hourly heat load (Btu/hr)	Integrated_heater_flow(BTU)	Heater_output_rate(BTU/hr)	COP	StateFlag	Tindoors (°F)	Toutdoors (°F)
0		0		4.54	2-Texas	68	53.5
0.5	7853.750084	0	30368.046	5.00	2-Texas	64.8166873	55.131577
1		15184.023		5.00	2-Texas	76.28435708	56.735238
1.5		15184.023		5.00	2-Texas	71.13697033	58.283543
2		15184.023		5.00	2-Texas	68.40429796	59.75
2.5		15184.023		5.00	2-Texas	67.17323353	61.109518
3		15184.023		5.00	2-Texas	66.84546069	62.338835
3.5		15184.023		5.00	2-Texas	67.03392531	63.416917
4		15184.023		5.00	2-Texas	67.4898934	64.325318
4.5		15184.023		5.00	2-Texas	68.05308821	65.048494
5		15184.023		5.00	2-Texas	68.61913369	65.574073
5.5		15184.023		5.00	2-Texas	69.11905964	65.893061
6		15184.023		5.00	2-Texas	69.5067031	66.0
6.5		15184.023		5.00	2-Texas	69.75109739	65.893061
7		15184.023		5.00	2-Texas	69.83196013	65.574073
7.5		15184.023		5.00	2-Texas	69.73708417	65.048494
8		15184.023		5.00	2-Texas	69.46086859	64.325318
8.5		15184.023		5.00	2-Texas	69.00349105	63.416917
9		15184.023		5.00	2-Texas	68.37039031	62.338835
9.5		15184.023		5.00	2-Texas	67.57184367	61.109518
10		15184.023		5.00	2-Texas	66.62251262	59.75
10.5		15184.023		5.00	2-Texas	65.54090169	58.283543
11	6173.855486	15184.023	30368.046	5.00	2-Texas	64.34873075	56.735238
11.5		30368.046		5.00	2-Texas	75.95295048	55.131577
12		30368.046		4.54	2-Texas	69.7853514	53.5
12.5		30368.046		4.54	2-Texas	65.33937159	51.868423
13		30368.046		4.54	2-Texas	62.02230178	50.264762
13.5	8709.449631	30368.046	26359.46393	4.34	2-Texas	59.45680099	48.716457
14		43547.77796		4.34	2-Texas	68.46924042	47.25
14.5		43547.77796		4.34	2-Texas	62.42721584	45.890482
15	11040.53761	43547.77796	25084.006	4.13	2-Texas	58.27616684	44.661165
15.5	18083.27052	56089.78096	25084.006	4.13	2-Texas	65.88306229	43.583083
16		68631.78396		4.13	2-Texas	70.2540032	42.674682

Table B5: Houston Model's Simulation Results of Heat Load and ASHP Energy Output

<u>NOTE</u>: The blank cells indicates the model did not have a heat load for simulated building conditions since indoor temperature in building is near or above thermal comfort setting of 68°F.

<u>Figure B1:</u> Monthly Median Temperatures in Boston

The chart shows historical monthly median temperatures during winter season in Boston, Massachusetts.

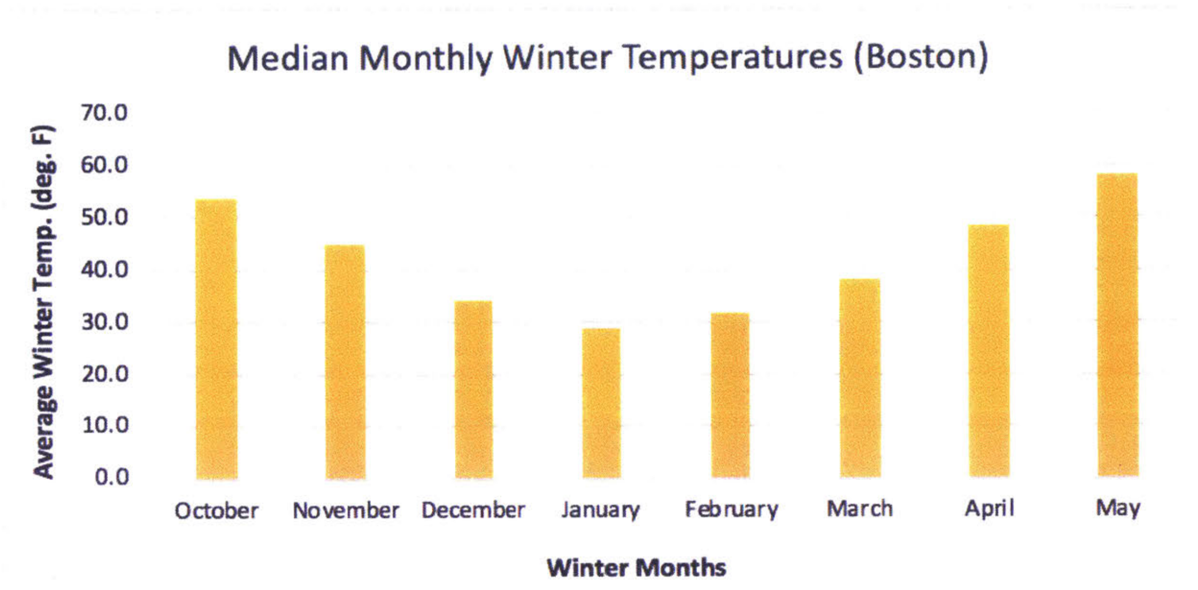


Figure B1: Monthly Median Temperatures in Boston [2]

<u>Figure B2:</u> Monthly Median Temperatures in Houston

The chart shows historical monthly median temperatures during winter season in Houston, Texas.

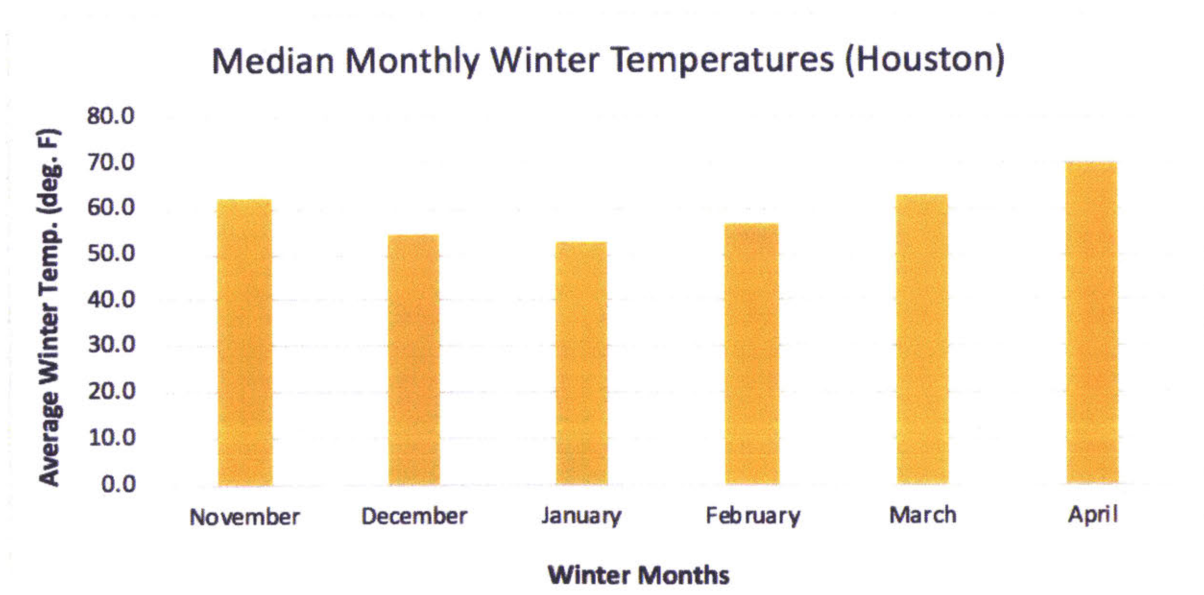


Figure B2: Monthly Median Temperatures in Houston [3]

Citation for Appendix B:

[1] – "Winter temperature For Every State." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/US/average-state-temperatures-in-winter.php.
[2] – "Boston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Massachusetts/Places/boston-temperatures-by-month-average.php.
[3] – "Houston Temperatures: Averages By Month." *Current Results – Weather and Science Facts*, https://www.currentresults.com/Weather/Texas/Places/houston-temperatures-by-month-average.php.

APPENDIX C: Electrifying Cost Model Parameters and Results Output.

Table C1: Cost Model Parameters for Electrifying Heat

Model Parameter	Description	Setting
Natural gas furnace efficiency	Efficiency of gas-fired furnace	75%
Electric furnace efficiency	Efficiency of electric resistance furnace	95%
Heat pump efficiency	Efficiency of air-sourced heat pump	Varies with outside temperature
Building square footage	Square footage of residential dwelling	2503 sq. feet
Seasonal energy efficiency rating (SEER)	Varies by climate zone of various regions in the U.S.	16
Purchase price of furnaces and heat pump	Based on sizing of equipment	Varies based on load
Installation costs of furnaces and heat pump	Based on type of heating equipment and whether it is new or replacement	Dependent on if new vs. replacement
Unit cost of fuel sources	Cost of natural gas per BTU, and cost of electricity per kWh	Varies by state

Table C1: Cost Model Parameters for Electrifying Heat

Result outputs from model are captured below. Table C2 shows the purchase price and installation cost of various heating equipment options. Tables C3 to C5 represents economic data for Boston based on simulated outputs for building heat load; while Tables C6 to C8 represents similar data set for Houston.

Table C2: Heating Equipment Estimated Installation Costs

Heating Equipment	Purchase Price	Installation Cost	Total Cost ($)
Natural gas furnace	$2,900.00	$1,150.00	$4,050.00
Electric furnace	$1,250.00	$1,500.00	$2,750.00
ASHP (Central warm-air w/ duct)	$3,735.00	$11,224.00	$14,959.00
ASHP (Ductless mini-split)	$1,550.00	$975.00	$2,525.00

Table C2: Heating Systems Estimated Purchase Cost

Table C3: Heating Costs in Boston, Massachusetts

Table 6	MASSACHUSETTS	Heating Cost$		
Month [2]	Median Temperature (°F)	Natural Gas Furnace ($)	Electric Resistance Furnace ($)	Heat Pump ($)
October	54.0	36.47	119.33	27.47
November	45.0	108.86	356.22	79.37
December	34.5	178.50	584.11	147.72
January	29.0	194.24	635.63	177.17
February	32.0	192.87	631.13	165.10
March	38.0	159.21	520.99	124.45
April	48.5	73.70	241.16	56.50
May	58.0	8.86	29.01	10.98
	Simulated Average Monthy Costs:	**$125.77**	**$411.58**	**$106.84**
	Simulated Yearly Heating Costs:	**$628.87**	**$2,057.92**	**$534.19**

Table C3: ASHP Heating Cost for Boston's Model Scenario

Table C4: Daily Energy Demand during Heating Period

Table 7	*Daily Energy Inputs*			
Month	Median Temperature (°F)	Natural Gas Power Input (kWh)	E.R. Power Input (kWh)	H.P. Power Input (kWh)
October	54.0	23.7	18.7	4.3
November	45.0	70.6	55.7	12.4
December	34.5	115.8	91.4	23.1
January	29.0	126.0	99.5	27.7
February	32.0	125.1	98.8	25.8
March	38.0	103.3	81.5	19.5
April	48.5	47.8	37.7	8.8
May	58.0	5.7	4.5	1.7

Table C4: Daily ASHP Energy Demand for Boston's Model Scenario

Table C5: Daily CO_2 Emissions during Heating Period

Month [4]	Median Temperature (°F)	[1] NG CO2 Emissions (kg-CO2)	[3] NG CO2 Emissions (kg-C/ kWh)	E.R. CO2 Emissions (kg-CO2)	H.P. CO2 Emissions (kg-CO2)
October	54.0	4.3	5.2	6.5	1.5
November	45.0	12.8	15.5	19.5	4.3
December	34.5	21.0	25.5	32.0	8.1
January	29.0	22.8	27.7	34.8	9.7
February	32.0	22.7	27.5	34.6	9.0
March	38.0	18.7	22.7	28.5	6.8
April	48.5	8.7	10.5	13.2	3.1
May	58.0	1.0	1.3	1.6	0.6
	Total Yearly CO2 Emissions:	**2,184.86**	**2,654.42**	**3,333.90**	**859.73**

Table C5: Calculated Carbon-dioxide Emissions for Boston's Model Scenario

Table C6: Heating Costs in Texas

Table 9	TEXAS	Heating Cost$		
Month [4]	Median Temperature (°F)	Natural Gas Furnace ($)	Electric Resistance Furnace ($)	Heat Pump ($)
November	62.5	$0.00	$0.00	$0.00
December	54.5	$19.18	$51.42	$12.23
January	53.0	$29.22	$78.33	$12.31
February	56.5	$8.79	$23.57	$6.13
March	63.0	$0.00	$0.00	$0.00
April	69.5	$21.73	$58.24	$6.30
	Simulated Average Monthy Costs:	**$13.15**	**$35.26**	**$6.16**
	Simulated Yearly Heating Costs:	**$78.92**	**$211.57**	**$36.97**

Table C6: ASHP Heating Cost for Houston's Model Scenario

Table C7: Daily Energy Demand during Heating Period

Table 10	Daily Energy Inputs			
Month [4]	Median Temperature (°F)	NG Power Input (kWh)	E.R. Power Input (kWh)	H.P. Power Input (kWh)
November	62.5	0.0	0.0	0.0
December	54.5	17.4	14.5	3.5
January	53.0	26.6	22.1	3.5
February	56.5	8.0	6.7	1.7
March	63.0	0.0	0.0	0.0
April	69.5	19.7	16.5	1.78

Table C7: Daily ASHP Energy Demand for Houston's Model Scenario

Table C8: Daily CO_2 Emissions during Heating Period

Table 11	Daily CO_2 Emissions				
Month [4]	Median Temperature (°F)	[1] NG CO2 Emissions (kg-CO2)	[3] NG CO2 Emissions (kg-c / kWh)	E.R. CO2 Emissions (kg-CO2)	H.P. CO2 Emissions (kg-CO2)
November	62.5	-	-	-	-
December	54.5	3.2	3.8	5.1	1.2
January	53.0	4.8	5.8	7.7	1.2
February	56.5	1.4	1.8	2.3	0.6
March	63.0	-	-	-	-
April	69.5	3.6	4.3	5.8	0.6
	Total Yearly CO2 Emissions:	**389.60**	**473.34**	**627.53**	**109.67**

Table C8: Calculated Carbon-dioxide Emissions for Houston's Model Scenario

Table C9: Household Energy Use in Massachusetts and Texas [1] [2]

The table below shows the amount of energy consumed by households in Massachusetts and Texas based on data from EIA's Residential Energy Consumption Survey (RECS) performed in 2009.

EIA 2009 RECS Survey Data	Energy Demand (Btu / year)	% Space heating
Massachusetts	109,000,000	59%
Texas	77,000,000	41%

Table C9: EIA's 2009 Residential Energy Consumption for MA and TX

Table C10: Heating Demand (Million Btu / year) in Massachusetts and Texas

Heating Demand (Milion BTU / year)	Massachusetts	Texas
Average per Household	64,310,000	31,570,000
Natural Gas	32,155,000	13,575,100
Electricity	9,646,500	16,100,700
Fuel Oil / Kerosene	17,363,700	
Propane / LPG	1,028,960	1,894,200

Table C10: Heating Demand in Massachusetts and Texas Based on EIA's 2009 RECS Data [1][2]

Table C11: Carbon-dioxide (kg-CO2 / year) in Massachusetts and Texas based on the Heating Demand

The table below shows the amount of Carbon-dioxide emission per year in each state based on the heating demands in Table C10. The emissions amount for power generation considered 6.2% and 6% comes from households' renewable energy consumption in Massachusetts and Texas respectively. [3] [4]

CO2 Emissions (kg-CO2 / year) [5]	Massachusetts	Texas
Total per Household	3,983	2,393
Natural Gas	1,706	720
Electricity	928	1,552
Fuel Oil / Kerosene	1,273	
Propane / LPG	75	120

Table C11: Carbon-dioxide Emissions from Heating Demand Using EIA's 2009 RECS Data [1][2]

Citation for Appendix C:

[1] – "Household Energy Use in Massachusetts." *EIA's 2009 Residential Energy Consumption Survey*, https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ma.pdf.
[2] – "Household Energy Use in Texas." *EIA's 2009 Residential Energy Consumption Survey*, https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/tx.pdf.
[3] - "Texas State Profile Data.", *EIA's Texas State Profile and Energy Estimates*, https://www.eia.gov/state/data.php?sid=TX#SupplyDistribution.
[4] - "Massachusetts State Profile Data., *EIA's* Massachusetts State Profile and Energy Estimates", https://www.eia.gov/state/data.php?sid=MA#SupplyDistribution
[5] – "How Much Carbon-dioxide is Produced When Different Fuels are Burned?" *EIA's Frequently Asked Questions*, https://www.eia.gov/tools/faqs/faq.php?id=73&t=11.