Electrification of home heating in Ontario with the air-source heat pump

by

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A thesis submitted to the Department of Mechanical and Materials Engineering in conformity with the requirements for the degree of Doctor of Philosophy

Queen’s University
Kingston, Ontario, Canada
April 2019

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Abstract

Home heating is the primary energy end-use in Ontario homes. Consequently, it is also the largest source of greenhouse gas emissions in the residential sector, particularly because most homes in Ontario use fossil fuels to generate heat. The objective of this thesis is to investigate whether the air-source heat pump is a viable technology to allow the electrification of home heating in Ontario. At stake is considerable potential for energy conservation, reductions of greenhouse gas emissions and cost savings on home heating bills.

Chapter two presents a new system-dynamics-based method for predicting homeowners’ future adoption of heat pumps. Exploring two facets of the development of heat pump technology—low temperature operating limit and increasing coefficient of performance—we predict the extent of future adoption, and find little change is likely by 2025. The main mechanism affecting adoption is the change in operating cost due to technological advancements; however, the method applied in this research accommodates future work that includes other driving forces of adoption.

Chapter three examines the performance potentials for three different types of air source heat pump: single-stage, variable-speed centrally ducted, and variable-speed ductless heat pumps. The last, and most expensive of these three types, realizes the greatest reductions in energy consumption, greenhouse gas emissions, and heating
costs.

Chapter four more closely examines the effects of several time-of-use pricing rate plans on heat pump use in cities in direct competition with natural gas forced-air heating. Homeowners could replace ageing central air conditioning units with single-stage heat pumps at an added cost of approximately $1000. Policymakers can choose rate plan price policies to significantly improve the economic feasibility of running a low-cost, low-performance heat pump, making widespread adoption more likely. Such policies could more than halve energy and greenhouse gas emissions, while saving homeowners hundreds of dollars per year.

Heat pump technology can benefit Ontario homeowners, and society at large, by providing a cost savings to the former and a reduction of energy use and greenhouse emissions for the latter.
Acknowledgments

I would like to thank Prof. Jack Jeswiet for his help over these many years. All the people in the Department of Mechanical and Materials Engineering have been so very helpful and supportive, with special thanks to Ms. Jane Davies for guiding me through the many administrative tasks necessary for degree completion.

Most importantly I would like to thank my family for continuing to support me while I slowly completed this thesis. My wife, Ms. Claire Hooker, has been especially patient. Her suggestions and encouragement have kept me going when I felt I might not succeed.

This thesis is dedicated to my daughter. What we do today will decide her tomorrow.
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<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>air conditioning or air conditioner</td>
</tr>
<tr>
<td>ACH</td>
<td>air changes per hour</td>
</tr>
<tr>
<td>ASHP</td>
<td>air-source heat pump</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigeration and Air-conditioning Engineers</td>
</tr>
<tr>
<td>COP</td>
<td>coefficient of performance</td>
</tr>
<tr>
<td>CWEC</td>
<td>Canadian Weather for Energy Calculations</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy (U.S.)</td>
</tr>
<tr>
<td>DRA</td>
<td>delivery and regulatory adders</td>
</tr>
<tr>
<td>FIT</td>
<td>feed-in-tariff</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gas(es)</td>
</tr>
<tr>
<td>GWP&lt;sub&gt;100&lt;/sub&gt;</td>
<td>global warming potential for 100 years</td>
</tr>
<tr>
<td>HDD</td>
<td>heating degree days</td>
</tr>
<tr>
<td>HSPF</td>
<td>heating season performance factor</td>
</tr>
<tr>
<td>IDF</td>
<td>input data file (for EnergyPlus)</td>
</tr>
<tr>
<td>IESO</td>
<td>Independent Energy Systems Operator</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>LCA</td>
<td>life cycle assessment</td>
</tr>
<tr>
<td>LIDAR</td>
<td>light detection and ranging</td>
</tr>
<tr>
<td>LTEP</td>
<td>long term energy plan</td>
</tr>
<tr>
<td>NEEP</td>
<td>Northeast Energy Efficiency Partnerships</td>
</tr>
<tr>
<td>NRCan</td>
<td>Natural Resources Canada</td>
</tr>
<tr>
<td>OEB</td>
<td>Ontario Energy Board</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>QRAM</td>
<td>quarterly rate adjustment mechanism</td>
</tr>
<tr>
<td>REaCP</td>
<td>reduced electricity and carbon pricing</td>
</tr>
<tr>
<td>SDD</td>
<td>single detached dwelling</td>
</tr>
<tr>
<td>SD</td>
<td>system dynamics</td>
</tr>
<tr>
<td>SS</td>
<td>single-stage (heat pump)</td>
</tr>
<tr>
<td>TLF</td>
<td>total loss factor (electricity)</td>
</tr>
<tr>
<td>TMY</td>
<td>typical meteorological year</td>
</tr>
<tr>
<td>TOU</td>
<td>time-of-use</td>
</tr>
<tr>
<td>UEP</td>
<td>unchanged energy pricing</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>VC</td>
<td>variable speed centrally-ducted (heat pump)</td>
</tr>
<tr>
<td>VD</td>
<td>variable speed ductless (heat pump)</td>
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<th>Units</th>
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<tr>
<td>Ad</td>
<td>households</td>
<td>annual heat pump adoptions</td>
</tr>
<tr>
<td>CBR</td>
<td>$$/ $</td>
<td>cost benefit ratio</td>
</tr>
<tr>
<td>CR</td>
<td>households/households</td>
<td>contact ratio</td>
</tr>
<tr>
<td>HH</td>
<td>households</td>
<td>households without heat pumps</td>
</tr>
<tr>
<td>HP</td>
<td>households</td>
<td>households with heat pumps</td>
</tr>
<tr>
<td>Q</td>
<td>kWh</td>
<td>annual heat energy needs</td>
</tr>
<tr>
<td>A</td>
<td>m$^2$</td>
<td>heated living area</td>
</tr>
<tr>
<td>U</td>
<td>W/m$^2$</td>
<td>heat loss at 99$^{th}$ percentile winter design temperature</td>
</tr>
<tr>
<td>HDDS</td>
<td>$^{\circ}$C days</td>
<td>heating degree days</td>
</tr>
<tr>
<td>WD</td>
<td>$^{\circ}$C</td>
<td>99$^{th}$ percentile winter design temperature</td>
</tr>
<tr>
<td>GHG$_{red.}$</td>
<td>kgCO$_2$e</td>
<td>reduction of GHG emissions</td>
</tr>
<tr>
<td>GHG$_{disp.; heating}$</td>
<td>kgCO$_2$e</td>
<td>displaced GHG emissions from conventional heating</td>
</tr>
<tr>
<td>GHG$_{HP; elec.}$</td>
<td>kgCO$_2$e</td>
<td>displaced GHG emissions from conventional heating</td>
</tr>
<tr>
<td>I$_{(yr)}$</td>
<td>kW/kW</td>
<td>y intercept of average heat pump COP line at year, yr</td>
</tr>
<tr>
<td>I$_{initial}$</td>
<td>kW/kW</td>
<td>initial value of COP at 0$^{\circ}$C outdoors</td>
</tr>
<tr>
<td>I$_{delta}$</td>
<td>kW/kW</td>
<td>annual change in COP at 0$^{\circ}$C outdoors</td>
</tr>
<tr>
<td>yr</td>
<td>years</td>
<td>number of years passed in model, 1 to 20</td>
</tr>
<tr>
<td>S</td>
<td>kW/kW</td>
<td>slope of average heat pump COP line</td>
</tr>
<tr>
<td>S$_{initial}$</td>
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<td>initial slope of COP line</td>
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<tr>
<td>S$_{delta}$</td>
<td>kW/kW</td>
<td>annual change in slope of COP line</td>
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<tr>
<td>COP</td>
<td>kW/kW</td>
<td>coefficient of performance</td>
</tr>
<tr>
<td>Symbol</td>
<td>Units</td>
<td>Description</td>
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<tr>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>T</td>
<td>°C</td>
<td>outdoor temperature</td>
</tr>
<tr>
<td>L</td>
<td>°C</td>
<td>low temperature cut-off</td>
</tr>
<tr>
<td>L_{initial}</td>
<td>°C</td>
<td>initial cut-off temperature</td>
</tr>
<tr>
<td>L_{delta}</td>
<td>°C</td>
<td>annual change cut-off temperature</td>
</tr>
<tr>
<td>HDD_{HP}</td>
<td>°C days</td>
<td>HDDs serviced by heat pump</td>
</tr>
<tr>
<td>HDD_{city}</td>
<td>°C days</td>
<td>total HDDs by city</td>
</tr>
<tr>
<td>Q_r</td>
<td>m^3/s</td>
<td>volume of air exchanged per second</td>
</tr>
<tr>
<td>V</td>
<td>m^3</td>
<td>volume of heated space</td>
</tr>
<tr>
<td>ACH_{50}</td>
<td>—</td>
<td>number of air changes at 50 Pa pressure</td>
</tr>
<tr>
<td>ELA</td>
<td>cm^2</td>
<td>equivalent leakage area</td>
</tr>
<tr>
<td>C_D</td>
<td>—</td>
<td>discharge coefficient</td>
</tr>
<tr>
<td>rho</td>
<td>kg/m^3</td>
<td>density</td>
</tr>
<tr>
<td>deltaP_r</td>
<td>Pa</td>
<td>pressure differential (50 Pa or 4 Pa)</td>
</tr>
<tr>
<td>n</td>
<td>—</td>
<td>empirical pressure exponent</td>
</tr>
<tr>
<td>Inf.</td>
<td>m^3/s</td>
<td>infiltration</td>
</tr>
<tr>
<td>C_s</td>
<td>(L/s)^2/(cm^4K)</td>
<td>stack coefficient</td>
</tr>
<tr>
<td>C_w</td>
<td>(L/s)^2/[cm^4(m/s)^2]</td>
<td>wind coefficient</td>
</tr>
<tr>
<td>v_{wind}</td>
<td>m/s</td>
<td>average wind speed</td>
</tr>
<tr>
<td>E_{price}</td>
<td>¢</td>
<td>electricity price</td>
</tr>
<tr>
<td>E_{consumed}</td>
<td>kWh</td>
<td>electricity consumed</td>
</tr>
<tr>
<td>E_{tax}</td>
<td>—</td>
<td>taxation rate applied to electricity</td>
</tr>
<tr>
<td>TLF</td>
<td>—</td>
<td>total loss factor</td>
</tr>
<tr>
<td>DRA</td>
<td>¢</td>
<td>delivery and regulatory adder</td>
</tr>
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Chapter 1

Introduction

Most appliances in the home have efficiencies of 100% or less. There is, however, one type of machine in perhaps every home in Ontario that can move more energy than it uses: the refrigerator. For every unit of energy used by the heat pump within the refrigerator, many units of heat are driven from inside the refrigerator to the kitchen surrounding it. No other device in the home can claim such extraordinary efficacy, except perhaps the air conditioner, which uses the same vapour compression cycle to move heat from inside the home and deliver it outside the home.

The refrigerator is ubiquitous and the air conditioner is surprisingly common in Ontario homes, yet for home heating we rely most often on burning fossil fuels [3, 1]. We have the refined the process of burning to produce heat to the point where more than 95% of the heat can be retained within the home, while still expelling the dangerous by-products. Such efficiency seems impressive, until we consider the heat pump. Functionally identical to an air conditioner except that it can also operate in reverse. The heat pump can extract heat from the cold outside air and deliver it inside, commonly under most outdoor conditions delivering 2–4 kWh of heat for every 1 kWh of electricity it requires. This astonishing efficacy should make heat pumps
very popular, yet in 2016 only 6.3% of Ontario residences had heat pumps (see Figure 1.1) [3].

Curiously, 69% of households in Ontario have centrally-ducted air conditioning (AC) and many additional homes have portable, window, and through-the-wall AC units [1]. This fact is especially surprising when we consider the relative utility of AC. In Table 1.1 we see that only 2.5% of energy consumption in the residential sector is due to space cooling [2]. Homeowners still value AC, however, because it provides comfort and safety when heat and humidity threaten health and well-being.

Heating in Ontario accounts for most of the energy and greenhouse gas (GHG) emissions for the residential sector. More than 60% of energy use in the residential
Table 1.1: Energy and emissions in the Ontario residential sector, 2014.[5, 2]

<table>
<thead>
<tr>
<th>Secondary Energy Use</th>
<th>Entire Sector</th>
<th></th>
<th>SDDs Only</th>
<th></th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>GHGs</td>
<td>Energy</td>
<td>GHGs</td>
</tr>
<tr>
<td></td>
<td>[PJ]</td>
<td>[%]</td>
<td>[MtCO₂e]</td>
<td>[%]</td>
</tr>
<tr>
<td>Space Heating</td>
<td>404</td>
<td>64.6</td>
<td>16.5</td>
<td>299</td>
</tr>
<tr>
<td>Water Heating</td>
<td>118</td>
<td>18.8</td>
<td>5.0</td>
<td>76</td>
</tr>
<tr>
<td>Appliances</td>
<td>69</td>
<td>11.0</td>
<td>0.2</td>
<td>41</td>
</tr>
<tr>
<td>Lighting</td>
<td>20</td>
<td>3.2</td>
<td>0.0</td>
<td>16</td>
</tr>
<tr>
<td>Space Cooling</td>
<td>15</td>
<td>2.5</td>
<td>0.0</td>
<td>12</td>
</tr>
<tr>
<td>Totals</td>
<td>626</td>
<td>100</td>
<td>21.7</td>
<td>444</td>
</tr>
</tbody>
</table>

The ASHP is therefore the most economically viable technology in terms of initial cost of purchase and installation, and even so only the most affordable of these ASHPs are nearly the same price as a central AC unit. Having the ability to provide both space heating and space cooling makes ASHPs a potential replacement for an AC system, a possibility examined in more detail in Chapter 4.

Having settled upon the readily available ASHP to begin electrifying the existing heating system stock, we turn to examining its viability. The objective of this work is to investigate whether heat pump use can reduce energy consumption and GHGs...
without negatively affecting household finances. The main metrics we apply are a household’s annual energy use for heating, annual GHG emissions, and annual savings as compared to the incumbent heating system’s annual costs.

Secondary goals of this research include:

1. Estimating the effects of improving technology on adoption rates of heat pumps.

2. Determining how different types of ASHP perform relative to changing time-of-use prices and seasonal changes, and how the electricity-generating system affects GHG emissions when heat pumps are used.

3. Determining whether time-of-use (TOU) price policy measures can increase the cost benefits of ASHP use, and how energy consumption and GHG emission levels are affected by diurnal price changes.

After initially considering all residential dwellings in chapter 2, the scope was narrowed to include only single detached dwellings (SDD). SDDs represent a small majority of residential dwellings in Ontario. Being detached, SDDs are exposed to the weather on all sides and also tend to contain larger living areas than do attached dwellings and apartments, and therefore have the greatest heating needs. Although greater heating needs can be a disadvantage when temperatures are low and ASHPs may struggle to supply enough heat, greater overall heating needs provide more opportunity to save on the costs of heating. The level of annual savings is important when we consider payback intervals for ASHPs. In this sense, SDDs are the best candidates for ASHP adoption. If lower-cost ASHPs were available, then attached and apartment dwellings may more easily justify the initial investment with their smaller expected annual savings on home heating costs.
1.1 Adoption and Technology

Heat pumps are not yet common in Ontario’s residences. Their adoption has proceeded slowly, and the proportion of homes with heat pumps rests now at 6.3% across all housing types and at 9.8% amongst SDDs [3, 4]. We ought to look ahead in time and determine whether adoption of heat pumps is likely to proceed quickly, or whether we ought to take action to increase adoption rates.

Province-wide heating system stock data are available, showing annual changes in the number of heat pumps operating in Ontario. These data are critical to developing models for predicting future adoption of heat pumps. Chapter 2 details the creation of a System Dynamics model of adoption that is capable of modelling the exponential increase in the number of heat pumps installed and the eventual decay of the adoption rate due to market saturation. The method is extensible, allowing for almost any driving mechanism to be used to predict adoption and model past trends. The main driving factor chosen in this work is the affordability of ASHP use. Costs are calculated annually. A heating cost savings due to ASHP use is a positive driver of adoption. Future predictions of energy prices are used to predict future rates of adoption of ASHPs.

Contributing to the cost benefit of ASHPs is their capacity to provide heat at low temperatures, and also their ability to provide heat efficiently. Higher heating capacity allows a greater proportion of heating needs to be met with ASHPs, and higher efficiencies guarantee and magnify the cost savings by delivering more heat with less electrical energy input. Developments in heat pump technology, captured by their low temperature operating limit and coefficients of performance (COP), are estimated based upon existing ASHP performance data. Three different rates of
1.2. Hourly and seasonal effects

While Chapter 2 reports on a yearly time scale, chapter 3 delves into performance characteristics of ASHPs at the hourly time scale. This examination allows for seasonal and diurnal phenomena to be assessed. To this end, three types of ASHP are tested against weather conditions from seven cities across the province of Ontario. Varying weather and energy prices affect energy consumption, GHG emissions, and annual heating costs. The varying performances of the single-stage, the variable-speed centrally ducted and the variable-speed ductless ASHPs also contribute to the outcomes based on the three metrics of energy, emissions, and cost.

Each of the three types of ASHP in one analysis is assumed to be in use in all the SDDs in Ontario. In these three hypothetical scenarios we see the effects on energy consumption patterns, GHG emissions, and new electricity demand demonstrating how each type of ASHP differs in these respects. Future policy decisions may be influenced by the theoretical outcomes elaborated in chapter 3. If the initial cost of the ASHP is paramount, the single-stage heat pump may be chosen. If energy conservation and GHG emissions are most important, then adoption of the variable-speed ductless ASHP might be encouraged.
1.3 Price policies

Furnace and ASHP technologies become more efficient over time, but it is energy prices that are the most important determinant of the costs of heating. What is more, high-efficiency heating equipment is much more expensive than average or low-performing devices. Chapter 4 endeavours to find an energy price regime that can make low-performing single-stage ASHPs profitable for homeowners to operate. Furthermore, it finds a price policy that allows ASHPs to compete with natural gas furnaces in cities—the toughest competition for ASHP heating.

Chapter 4 begins with an analysis of the historical energy pricing in six cities across Ontario, demonstrating the regional differences in climate and energy price regimes that affect ASHP feasibility. The discovery that most SDDs in cities have natural gas centrally ducted heating with AC systems attached [1], has led to considering the possibility of replacing the AC portion of these systems with ASHPs at an increase in initial cost. Electricity rate plans that are already being investigated by the Ontario Energy Board, which is entrusted with the regulation of electricity and natural gas prices, are tested in cities all across Ontario to determine what effects they may have on heating costs, energy consumption, and GHG emissions.

1.4 Summary

Initially, a method of predicting heat pump adoption within a System Dynamics model is introduced. It is found that in Ontario, ASHP technology already performs well enough to provide significant reductions in energy consumption and GHG emissions, but ASHPs seem unlikely to become a common part of home heating systems in the next decade. We next examine the potential for three categories of ASHP
1.4. SUMMARY

to deliver energy savings, GHG abatement, and cost savings across the province of Ontario. Lastly, the simplest and most cost-effective ASHP is tested as a replacement for AC systems in homes using the most competitive heating fuel, natural gas. Price policy changes are put forward that will help ASHPs lower home heating bills, in the hopes that this may motivate Ontario homeowners to adopt ASHPs in the future.
References


Chapter 2

Effects of technological development and electricity price reductions on adoption of residential heat pumps in Ontario, Canada

Published in Int. J. of Energy and Environmental Engineering
Authors: Alex Szekeres and Jack Jeswiet

Abstract Home heating accounts for most of residential energy use in Canada. While natural gas, oil-fired furnaces, and electric resistance are the dominant heating system choices, heat pumps have become a viable alternative. Heat pumps with lower minimum operating temperatures and better performance are increasing both their effectiveness and their number of hours of useful service. In this study, we apply System Dynamics to analyze the effects of technological development on the rate at which homeowners adopt residential air source heat pumps. We test the effects of low, moderate and high rates of technological development, as well as reduced electricity and carbon pricing on the predicted rate of adoption in Ontario. From the perspective of the use stage in life cycle assessment, we estimate energy savings and greenhouse
gas emissions reductions. We predict that using heat pumps will substantially reduce overall energy consumption, and in Ontario, where electricity is generated with little use of fossil fuels, it will also reduce greenhouse gas emissions.

2.1 Introduction

In cold climates, space heating is a necessity and also one of the largest residential energy needs. In Ontario, Canada, approximately 62% of residential energy consumption was for space heating alone in 2012 [20]. At present this energy is primarily supplied by natural gas, fuel oil, and electricity, with natural gas and oil furnaces making up almost three quarters of heating systems [21]. These fossil fuels accounted for 90.6% of residential greenhouse gas (GHG) emissions in Ontario in 2012 [21]. A reasonable goal is to minimize residential use of natural gas, using instead a greater proportion of electrical energy, which in Ontario results in the emission of less than 100 grams of CO$_2$ equivalent per kWh consumed [8, 28]. Heat pumps provide an effective means of heating homes with electricity, even in cold climates.[29] The objective of this work is to design a System Dynamics (SD) model which can be used to analyze the effects of introducing a modern, green technology, in this case modern heat pumps, and observing the effects of the development of heat pump technology, reductions in electricity costs and the introduction of carbon pricing on heat pump adoption in a cold climate region. A brief introduction to SD is available in Appendix A.1. Objectives in this study include:

- predicting heat pump adoption rates up to 2025 in 10 cities all across Ontario, Canada;
- testing the effects of advancing heat pump technology on the adoption of heat
pumps;

- testing the effects of new electricity price reductions and the simultaneous implementation of carbon pricing;

- using SD to predict adoption rates instead of more common methods; and

- calculating the resultant GHG emissions reductions and energy savings due to heat pump use in Ontario.

The improvement of air source heat pump (ASHP) technology enhances economic and environmental performance by decreasing electrical energy use while providing the necessary home heating. Heat pumps can deliver approximately three (3) times as much heat as the electrical energy used to drive them.[26, 17, 14, 37] Variation in performance occurs due to outside temperature, the need to defrost outdoor heat exchangers, and even the frequency with which the heat pump is cycled on and off, among others. However, if 10% of the heating needs of Ontarians currently supplied by fossil fuels were supplied with heat pumps, we could expect a 6-7% reduction in energy consumption for heating, and an approximate 9% reduction in greenhouse gas (GHG) emissions. But will this technology be adopted, and how can we encourage it? To analyze this problem we propose an SD model.

Three parameters are most important to answering this question. The first is the lowest feasible outside operating air temperature. With lower operating temperatures, modern heat pumps can now be used for more of the heating season. Today, the best commercially available models can operate at temperatures as low as -30°C[19]. However, at these temperatures performance is reduced and operating costs are consequently higher than at more moderate temperatures. Potential users must
therefore consider the balance between energy savings and cost savings.

The second parameter is performance. How effective is a heat pump at a given outside temperature? Manufacturers often state a heating season performance factor (HSPF), which is the heat provided over the entire heating season in BTUs divided by the electricity consumed in kWh. This factor can be translated into a coefficient of performance (COP), which is usually used to measure instantaneous performance, and has the advantage of using the same units in the numerator and denominator (in this case kWh). Over the entire heating season, the COP can average in the range of 2 to 3 or more.[17, 37, 33] Performance can be adversely affected by many factors. When temperatures are high, single speed heat pumps must cycle on and off to deliver only the heating required by the home. Cycling can reduce performance, but is mitigated by new variable speed heat pump technology that allows the heat pump to match output to indoor needs. As temperatures fall, it becomes more difficult to draw heat from the outside air, and while this will reduce the need to cycle on and off, it increases the risk of frost, ice and snow building up on the outdoor heat exchanger. To combat this inevitability, defrost cycles are periodically activated by reversing the refrigerant flow and dumping heat outside to melt any ice or snow that has built up.[30] As temperatures fall further the heat pump will struggle to provide adequate heating and require backup heating from a conventional heating system. In Ontario, even modern variable speed heat pumps may not be able to provide for all of a home’s heating needs throughout the heating season. Despite all of these problems modern heat pumps can operate at very low outdoor temperatures and many can maintain their full heating capacities at a temperature of -15°C.[19, 37, 30] Because the COP varies over both the range of operating temperatures and amongst different
models of heat pumps, an aggregated estimate of performance is necessary to predict energy requirements over the geographic and temporal ranges studied.

The third parameter is the price of energy, in particular the relative cost of electricity with respect to competing fossil fuels. Furnace oil and natural gas prices are typically far less than the price of electricity per unit of energy. While this is a disadvantage for electrification, high average COPs over the heating season can still make heat pumps economically viable.

These three parameters allow an estimation of heat pump operating costs and their comparison with the costs of competing technologies. Expecting that homeowners will act rationally and allow financial considerations to dominate their reasoning, we predict the share of Ontario residences with heat pumps.

Ultimately, the transition to a fossil fuel free heating stock is expected to reduce GHG emissions. Of course, the need for electricity to drive these new heat pumps can have an effect on electricity demand and therefore power generation at the provincial scale. But such a change might only be important as heat pump adoption rates increase. Currently, less than 10% of homes in Ontario have a heat pump, and for now these effects are likely minimal, though they may require future study. Overall, with heat pumps it is possible to achieve large reductions in energy consumption. Life cycle assessment can be used to gauge whether this will yield a net reduction in environmental impacts. This study contributes to the analysis of the GHG emissions and energy consumption during the use (life stage) of heat pumps. In fact only the consumption of fossil fuels or electricity in the home for heating are considered. Even the transportation of oil to the home via truck, and natural gas via underground pipes, are omitted from the calculations of GHG emissions.
Life cycle assessment (LCA) began with single products [12]. In this case the manufacturer could make a change in a product and expect a reduction of environmental impacts based upon maintaining their current production volume. In the case of heat pumps, performance and energy prices are closely tied to their economic viability. It stands to reason that better performance, leading to lower operating costs, will encourage more homeowners to use them. Lower operating costs can also be achieved by reducing the cost of electricity, whether it is absolute or relative to competing fuels.

Much work has been done in the field of LCA to determine which technologies are likely to be favoured in a consequential study. Generally, the least expensive technologies are favoured by consumers in a growing market [43, 44, 5]. This might result in natural gas furnaces being favoured over heat pumps, but variations in heat pump performance and weather conditions can change the cost balance. Market data are often used to determine which is favoured [5], but there may be a need to “include more mechanisms than just the market ones [47].” While this study focuses on the economics of heat pump use for the home owner, the use of System Dynamics enables the integration of the effects of consumer education and marketing on heat pump adoption. Examining the problem more holistically will better aid policy makers.

Although this study firmly sets the LCA system boundaries around the household, thereby restricting the GHG emissions calculations to only those produced by using fuel or electricity within the home, it integrates SD with LCA. This integration allows the use of household economics instead of broad market data, but the method can be employed with both, simultaneously. Even more influences on heat pump adoption may be incorporated in the future. These may include consumer education, simple
2.2. METHODOLOGY

payback times, or the changes in technology discussed here.

In this paper, we apply System Dynamics to analyze the effects of technological development and energy prices on homeowner adoption of heat pumps. That is, the number of heat pumps in service is not prescribed, but rather estimated based on the influence of their improving performance and consequent economic feasibility. Changes over time in the relative economic performance of technologies, the likelihood that people will use them, and the environmental impacts associated with their use, are being tackled with a number of techniques including agent based modelling, behavioural models, and system dynamics, among others [45, 25, 3, 46, 4]. The use of SD constitutes a new and flexible approach to consequential LCA studies. Methods typically used in economics, science, and sociology may all be integrated into a SD model, aligning with Zamagni’s suggestion to add more mechanisms to consequential LCAs [47]. Furthermore, the calculation of energy consumption and heating requirements are also modelled within the same framework. We chose Stella Pro, version 1.3 [16] made by ISEE Systems, as the software for this work.

These inputs can have a firm causal influence on the outcome even when the extent of that influence is unknown. Historical knowledge of both the inputs and outcomes can be used to tune the model and determine the extent of the influence.

2.2 Methodology

System Dynamics is used to model situations where there is feedback in the system contributing to its evolution. In this case, as heat pumps are put into service their share of the heating system stock increases. This share increases at a varying rate every year—the adoption rate seen in figure 2.1. In figure 2.2, this is shown as the
2.2. METHODOLOGY

number of adoptions calculated yearly (Adoptions in figure 2.2 and Ad in equation 2.1). The greater the number of households with a heat pump installed (HP), the greater the likelihood that other home owners (HH) will come into contact with members of these households or learn of their heat pumps in operation. This contact rate (CR) coupled with the economic feasibility of using a heat pump (CBR) affects the number of adoptions (Ad). The CBR, or cost benefit ratio, is calculated directly from energy prices, heating equipment efficiencies, and local weather conditions. Equation 2.2 shows this ratio, where the incumbent heating cost is that of the system displaced, be it a natural gas furnace, oil furnace, or electric resistance heat. The loop is reinforcing. That is, the greater the number of heat pumps, the greater their rate of adoption and in turn the number of heat pumps will rise even more quickly. Equation 2.1 describes the calculation of the number of yearly adoptions (Ad) shown in figure 2.2. Dimensionally, the equation reduces to the number of households adopting heat pumps in the year.

Figure 2.1: Causal loop diagram of heat pump adoption.
2.2. METHODOLOGY

Figure 2.2: Stock and flow diagram of adoption rate model.

\[ Ad = HH \cdot CBR \cdot CR \cdot \frac{HP}{HH + HP} \]  \hspace{1cm} (2.1)

\[ CBR = \frac{Incumbent \ Heating \ Cost}{Heat \ Pump \ Heating \ Cost} \]  \hspace{1cm} (2.2)

These two equations (2.1, 2.2) form the main structure of the model; see figures 2.1 and 2.2. The cost benefit ratio is influenced by the rate of technological development and the price of energy in the forms of electricity, natural gas, and furnace oil. If a large number of households chose to use heat pumps instead of fossil fuels, we would expect a drop in fuel prices to be induced. In this model it is assumed that the shift in heating technology is insufficient to have such an effect.

Figure 2.2, shows the stock and flow diagram of the main feedback loop shown above. This structure and the accompanying equation (2.1) are based upon an epidemiological model of infection rates in a population from Business Dynamics by John Sterman [36]. It exhibits S-shaped growth. There is a slow adoption rate at first, but
it accelerates as the number of heat pumps increases, until finally it slows again due to reduced availability of households where a heat pump can be installed. The latter is unlikely to occur within the timeframe studied, and while this balancing effect is incorporated into the model, it has been omitted from the causal loop diagram in figure 2.1.

2.2.1 Economic Feasibility

In this study, economic feasibility is determined by operating cost alone. It is expected that if operating a heat pump costs more than readily available alternatives, fewer homeowners will install them. If the cost of home heating can be reduced by installing a heat pump, then it is expected that more people will make the initial investment necessary to reap these savings. Two factors influence the operating costs: heat pump performance, and the relative cost of electricity compared to heating fuels.

The most important factor in determining the cost of operation is the price of fuel. While heat pumps use electricity, most furnaces in Ontario use natural gas and furnace oil. Both the historical and forecast prices of these three energy sources are shown in figure 2.3, for the years 2005 through 2025.

The historical pricing for electricity and natural gas are gathered from Statistics Canada census and survey data [35, 34]. Furnace oil pricing is available through Natural Resources Canada (NRCan) [24]. These data are collected for Ontario in aggregate and averaged over each year represented, except in the case of furnace oil where data was available for each city studied.

Electricity price predictions are sourced from the 2013 Long-Term Energy Plan (LTEP) [28] produced by Ontario’s government. However, the forecast shown in figure
2.2. METHODOLOGY

Figure 2.3: Historical and forecast energy prices.

2.3 also includes a price reduction starting on January 1, 2017 of 8% and a further reduction as of May 1, 2017 totalling 25%. These price reductions were implemented by the provincial government, and are detailed in a news release from the Ontario Energy Board (OEB)[27].

Natural gas and furnace oil price predictions are estimated using forecasts obtained from Sproule Associates Incorporated [32]. The price forecast for natural gas is based upon the predicted price at the Dawn Hub, where natural gas is traded, stored, and distributed. This is the price most relevant to assessing the cost of Ontario’s natural gas providers because the bulk of their supply passes through this location. The historical Dawn Hub prices are compared to the Statistics Canada historical prices, and the difference is minimized using the least squares method. The forecast prices...
are shown in a dashed line in figure 2.3.

Similarly, historical furnace oil prices [24] are compared to past oil prices and the difference between the two minimized to obtain a price forecast. That is, furnace oil prices paid by homeowners in the past are compared to the weighted average price at the time of 85% Canadian Light Sweet Crude and 15% Western Canada Select. The latter is a heavy crude oil price. This is the crude oil make-up used by refiners in Ontario according to NRCan [24].

Although energy price forecasts for fossil fuels can change, for this work the forecasts of fossil fuel prices are assumed to be accurate. In the case of the electricity price predictions, the assumption of their accuracy can be made with greater confidence because Ontario’s electricity is produced mainly with nuclear, hydro, and natural gas power plants. Pricing data are published hourly online at the Independent Energy Systems Operator (IESO) website (ieso.ca).[13] Only natural gas powered generation is directly influenced by fossil fuel price volatility. Nuclear, hydro, and renewables, like wind and solar, are usually priced by contractual agreement or regulation. Their pricing should therefore be less volatile, and more easily predicted by those forecasting prices in the LTEP.

Carbon pricing has also come into effect in the jurisdiction of Ontario. A “cap and trade” system is being implemented with a price of $18 per tonne of carbon dioxide equivalent (CO$_2$e) as of January 1, 2017. This price is expected to increase to approximately $19.86 by 2020 [7]. The price increase will however be insufficient to meet the standard being set forth by the federal government. All provinces will be required to introduce carbon pricing by January 1, 2019 with a value of $20 per tonne increasing by $10 every year until reaching $50 per tonne in 2022.[18] The
2.2. METHODOLOGY

federal minimum price is used in this study from 2020 onward, and it is calculated on a per kWh basis according the the global warming potential of each fuel (see section 2.2.6).

As previously stated, heat pump performance is also critical to the operating cost comparison. Operating costs are reduced in proportion to seasonal performance. The cost of electricity can be divided by the seasonal average COP (approximately 3). The average COP is calculated yearly because technology improves every year, and for each city because weather conditions vary across the province. Furnace efficiencies (typically between 0.78 and 0.96) increase the cost of using natural gas and especially oil, whose efficiencies are typically lower. It is the balance of these operating costs that is used to calculate economic feasibility and subsequently adjust the rate of adoption.

2.2.2 Heat Pump Performance

In North America heat pump manufacturers provide standard performance factors to their customers for the purpose of comparison between models. Heat pump performance depends mainly on the outdoor temperature. Air source heat pumps generally have declining performance as the outside temperature falls [2, 1, 10].

Standards have been developed and are elaborated by the United States Department of Energy (DOE) [40, 41]. These require testing of heat pumps at a number of temperatures and conditions. Based upon these laboratory tests, a “heating season performance factor” (HSPF) is calculated. The mathematical form of the HSPF is the total heat provided over the season in British thermal units (Btu) divided by the total electrical energy used by the heat pump in kilowatt hours (kWh) [2].

Total heating needs are based upon the weather conditions in the geographic
2.2. METHODOLOGY

location where the heat pump is to be used. To facilitate standardization, the DOE has divided up the geography of the United States into zones based upon the heating needs measured over the full year. Zones 1-5 are progressively colder as the number increases. Zone 4 was chosen for the purpose of testing and reporting HSPF values [40, 41, 1]. This region roughly spans the middle of the United States from coast to coast, and is warmer than almost every location in Ontario. Some Canadian databases provide zone 5 HSPF values for commercially available heat pumps [22]. In the following sections we describe the methods used in this study to further localize heating needs for each city studied.

2.2.3 Weather

Heating needs can be estimated by using a measure of the weather conditions averaged over a period of 20 or 30 years. The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) provides such data for thousands of locations around the world [2]. 10 cities were selected in Ontario, based upon availability of data in the ASHRAE tables, population, and climate. Larger populations and diversity of climate were given preference when selecting locations. Table 2.1 shows the cities chosen.

The key data provided by ASHRAE are heating degree days (HDD) for each location. These are the sum of the number of days where the temperature is below 18.3°C multiplied by the number of degrees below 18.3°C. This is the temperature at which heating will become necessary for a typical home to maintain an interior temperature of approximately 20°C [2].

Average monthly temperatures and their standard deviations are used to calculate
Table 2.1: Cities, Heating degree days (HDD), heat loss per unit area (U), and winter design temperature (WD).[2]

<table>
<thead>
<tr>
<th>City in Ontario</th>
<th>HDD 18.3 ( \text{days}^{\circ\text{C}} )</th>
<th>U ( \text{W/m}^2 )</th>
<th>99% WD ( \circ\text{C} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamilton</td>
<td>3919</td>
<td>50.1</td>
<td>-15.4</td>
</tr>
<tr>
<td>London</td>
<td>3954</td>
<td>50.1</td>
<td>-15.4</td>
</tr>
<tr>
<td>North Bay</td>
<td>5192</td>
<td>60.9</td>
<td>-24.6</td>
</tr>
<tr>
<td>Ottawa</td>
<td>4441</td>
<td>56.4</td>
<td>-20.8</td>
</tr>
<tr>
<td>Sault Ste. Marie</td>
<td>4950</td>
<td>57.2</td>
<td>-21.5</td>
</tr>
<tr>
<td>Sudbury</td>
<td>5241</td>
<td>61.0</td>
<td>-24.7</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>5594</td>
<td>63.2</td>
<td>-26.6</td>
</tr>
<tr>
<td>Timmins</td>
<td>6017</td>
<td>67.1</td>
<td>-29.9</td>
</tr>
<tr>
<td>Toronto</td>
<td>3533</td>
<td>48.1</td>
<td>-13.7</td>
</tr>
<tr>
<td>Windsor</td>
<td>3444</td>
<td>47.4</td>
<td>-13.1</td>
</tr>
</tbody>
</table>

the likelihood of experiencing a given temperature in a given month. By selecting a minimum temperature below which the heat pump stock will not operate, we can estimate the proportion of heating that will be supplied by heat pumps. The remainder of heating needs are satisfied by backup heating systems, which will be electric resistance heating, natural gas, or oil fired. Fairey et al. developed a system of calibrating HSPF ratings based upon winter design temperatures [10], and it is an alternative method.

\[
Q = \frac{A \cdot U \cdot HDDs \cdot 24 \cdot 0.75}{(18.3 - WD) \cdot 1000} \tag{2.3}
\]

2.2.4 Energy Consumption and Costs

Heating needs for a year, for a home, can be estimated using the number of HDDs at that location, the coldest expected winter temperature and an estimation of the heating needs for the home at that temperature [1]. Ideally, an estimation of heating
2.2. METHODOLOGY

needs would be carried out for each home with attention paid to details of the construction, orientation, number and location of windows, solar radiation and even the elevation. These parameters and many more including the type of dwelling, construction standards, height and shape can influence heating requirements for any particular home in a given climate. However, for a study of this scope average numbers better represent the aggregated home heating needs.

An average Ontario single family home (see table 2.2) as described by Swan et al. [38] is used to calculate $U$, which is heat loss in Watts per square metre of living area per hour of heating at the 99th percentile coldest temperature (99% winter design temperature) for each city studied. The method used is detailed in the ASHRAE Load Calculation Applications Manual [31, chap. 10]. Results ranged between 47 and 67 W/m$^2$ and are shown in table 2.1. Equation 2.3 describes the calculation of heating energy requirements, $Q$ (kWh), for an average home [1, 6]. The average area, $A$, heating degree days for each city, $HDDs$, and local 99% winter design temperature, $WD$, are used to complete the calculation [6]. Approximately half of homes in Ontario have one level above grade with the other half having two levels, and relatively few homes are 1.5 storeys high.[38] An evenly weighted average of 1 and 2 storey homes is used when calculating heat losses through ceilings and basement walls.

Table 2.2: Specifications of average home from Swan et al.[38]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Area</td>
<td>144.7</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Wall Area</td>
<td>141.7</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Window Area</td>
<td>23.1</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Indoor Ceiling Height</td>
<td>2.44</td>
<td>m</td>
</tr>
<tr>
<td>Ceiling Insulation</td>
<td>4.6</td>
<td>$m^2\cdot{\degree}{C}/W$</td>
</tr>
<tr>
<td>Wall Insulation</td>
<td>2.1</td>
<td>$m^2\cdot{\degree}{C}/W$</td>
</tr>
<tr>
<td>Basement Insulation</td>
<td>1.4</td>
<td>$m^2\cdot{\degree}{C}/W$</td>
</tr>
<tr>
<td>Air Changes at 50Pa</td>
<td>6.5</td>
<td>$ACH_{50}$</td>
</tr>
</tbody>
</table>
2.2. METHODOLOGY

Using the number of households that use heat pumps, and the average size of a home in Ontario (144.7m$^2$) [38] we can calculate the approximate energy needs for the year in a particular city. From knowledge of the weather conditions, the proportion of heating provided to a home by heat pump is determined (see equation 2.9). Energy requirements are then calculated by applying efficiencies of the heat pumps (see section 2.2.7) and incumbent heating systems, and from these energy requirements, greenhouse gas emissions can be estimated.

2.2.5 Life-Cycle Assessment

This study does not constitute a full LCA. It is narrowly restricted to the use of energy to heat residences in the 10 cities chosen in Ontario (see table 2.1). The system boundary is placed around the home. Energy requirements described in the preceding sections are used to calculate the needed energy inputs to the home. The three possible inputs are furnace oil, natural gas, and electricity. The fossil fuels are combusted in the home, and the resultant GHG emissions are the outputs. Electricity used for heating is attributed GHG emissions because Ontario’s electrical power generation system emits GHGs, especially when thermal power plants with coal or natural gas inputs are used. In terms of LCA, the GHG emissions (stressors) are assigned a midpoint impact in gCO$_2$ equivalent, that is, the potential for the emitted GHGs to force energy radiating from the planet to remain within the confines of the atmosphere, thus inducing global warming. The calculation of GHGs is elaborated in the following section (2.2.6).

The time period studied begins in 2005 exclusively using historical data inputs to the model up to 2012. The main output, percentage share of homes with heat pumps,
is compared to historical data. After 2012, the model’s predictions of the heat pump share are used to calculate the GHG emissions and energy consumption as they change through time until 2025. The radiative forcing effects of these emissions will be felt for decades and centuries beyond 2025. Therefore, the time horizon in terms of midpoint impacts is greater than the modelling timeframe.

2.2.6 Greenhouse Gas Emissions

Greenhouse gas emissions are calculated first by determining the CO$_2$e emissions for natural gas, furnace oil, and electricity in Ontario. These carbon emissions are shown in table 2.3. First the content of CO$_2$, CH$_4$, and N$_2$O were obtained from Canada’s National Inventory Report [8] and then the Intergovernmental Panel on Climate Change’s (IPCC) fifth Assessment Report was used to find weightings for CH$_4$ and N$_2$O. The global warming potential for 100 years (GWP$_{100}$) was used [15]. This metric is used in the United Nations Framework Convention on Climate Change (UNFCCC)[15] for whom Canada prepares the National Inventory Report. Consequently, GHG emissions from power generating stations in Ontario are also reported using the GWP$_{100}$ as stipulated under Section 46 of the Canadian Environmental Protection Act and in compliance with Decision 24/CP.19 of the Warsaw Climate Change Conference in November, 2013.[11, 39]

<table>
<thead>
<tr>
<th>Heating Energy Source</th>
<th>Carbon Emissions (gCO$_2$e / kWh heat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity*</td>
<td>40</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>215</td>
</tr>
<tr>
<td>Furnace Oil</td>
<td>351</td>
</tr>
</tbody>
</table>

*approximate emissions as projected in 2013 LTEP for the year of 2016
Electricity emissions per kWh consumed in Ontario were provided in the National Inventory Report [8] up until 2012 with some years requiring interpolation. Future estimates of emissions were obtained from the 2013 Ontario government Long-Term Energy Plan (LTEP) [28]. Reductions in GHG emissions due to displaced fuel consumption are calculated within the system dynamics model. For residences with heat pumps, the proportion of heating provided by the heat pumps is calculated. The remainder of heating needs are provided by the backup heating systems (electric, natural gas, or oil). Reductions in GHG emissions are then calculated by summing the displaced emissions for all homes in all cities and subtracting the emissions resulting from the increased use of heat pumps (see equation 2.4). Displaced emissions are those that would have resulted from the combustion of fossil fuels for heating the home or the use of electric resistance heating but were instead replaced by heat pump heating. The emissions from heat pumps are due to the electricity required to provide the displaced heat energy. Section 2.3.3 details the GHG emission reductions as they were calculated for each year.

\[
GHG_{\text{red.}} = GHG_{\text{disp. heating}} - GHG_{HP \text{ elec.}}
\]  

(2.4)

2.2.7 Technological Development

Technology tends to improve over time. For heat pumps these improvements usually mean higher COPs at a given temperature, and also the ability to operate at lower outdoor temperatures. The former means more heat energy is delivered with the same electrical inputs, and the latter means that the heat pumps can remain in operation for more of the heating season. In this section we describe the estimates of
2.2. METHODOLOGY

Current ASHP performance, and three scenarios used in the analysis of sensitivity to technological development (section 2.3.1). These scenarios describe the progression of heat pump performance from the beginning of the simulation, 2005, to the final year modelled, 2025. There is a worst case, model case, and best case scenario. Their effect on heat pump adoption is shown in the results (section 2.3.1). They are defined below.

To help set a lower limit for the expected performance of heat pumps we first examine the minimum standards for ASHPs set at intervals by the DOE in the United States and by NRCan in Canada. These standards require that all heat pumps meet a minimum level of seasonal performance. Table 2.4 below shows the dates these standards were effective and the associated HSPF and average seasonal COP values [42, 23].

Table 2.4: Standards for heat pump performance in Canada and the US.[42, 23]

<table>
<thead>
<tr>
<th>Effective Dates</th>
<th>Split HSPF(COP)</th>
<th>Packaged HSPF(COP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Resources Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After 2006</td>
<td>7.7 (2.25)</td>
<td>7.7 (2.25)</td>
</tr>
<tr>
<td>Before 2010</td>
<td>7.1 (2.08)</td>
<td>7.1 (2.08)</td>
</tr>
<tr>
<td>After 2010</td>
<td>7.4 (2.17)</td>
<td>7.4 (2.17)</td>
</tr>
<tr>
<td>U.S. Department of Energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1992-2006</td>
<td>6.8 (2.00)</td>
<td>6.6 (1.93)</td>
</tr>
<tr>
<td>2006-2015</td>
<td>7.7 (2.25)</td>
<td>7.7 (2.25)</td>
</tr>
<tr>
<td>After 1 Jan. 2015</td>
<td>8.2 (2.40)</td>
<td>8.0 (2.34)</td>
</tr>
</tbody>
</table>

Current cold climate air source heat pumps (CC-ASHP) are best suited to Ontario’s climate because they are designed to operate at very low temperatures (as low as -30°C) [19]. Northeast Energy Efficiency Partnerships (NEEP) maintains a dataset of currently available CC-ASHPs complete with performance data for at least three
2.2. METHODOLOGY

Temperatures (8.3°C, -8.3°C, -15°C) for each heat pump in the dataset.\cite{26} They are the three orange data points from the right shown in figure 2.4. Error bars indicate a 95% confidence interval at each of the three temperatures. From the average performance at these three temperatures a linear curve fit was applied. It is shown in figure 2.4, in black. While it is expected that a normal COP curve would not be linear, we use lines to represent the average performance of these heat pumps in this model.

Manufacturers have provided additional low temperature performance data for some of the 312 heat pumps in the NEEP dataset at the time of writing. These data are shown as a cluster of orange points below -15°C, and left of the three data points used for the linear fit. All the points from this dataset have error bars indicating a 95% confidence interval based upon the standard deviation of the available samples. The purpose of this cluster of points is to describe the cold weather capabilities of very good ASHPs available today.

Figure 2.4 also shows three pairs of linear performance curves. In solid green are the COP curves used for sensitivity testing in the model for 2005(lower) and 2025(upper). It should be noted that the upper green line, denoting heat pump performance in 2025 for the model scenario, is often near to the mean performance, or within reach of the 95% interval of currently available ASHPs. The lower green line denotes performance in 2005 for the model scenario. A new COP curve is calculated for every year in between, but not shown in figure 2.4. The improvement in performance from year to year is linear. That is, the slope and intercept with the y axis (COP at 0°C) of the COP line increases linearly every year as described in equations 2.5 and 2.6. Coefficients for intercepts, I, and slopes, S, are shown in table 2.5. Similarly, in dashed blue lines we see a “worst case” scenario for heat pump performance, and in
2.2. METHODOLOGY

Figure 2.4: Technological development of heat pump performance [26].
2.2. METHODOLOGY

In all scenarios—model, worst, best, and worst to best cases—both the level of performance (intercept) and the consistency as temperatures drop (slope) change from 2005 to 2025. The level of performance increases and the slope becomes flatter, indicating that performance is better maintained at lower temperatures as heat pump technology improves. Equation 2.7 shows the relationship between performance (COP) at outdoor temperature, T, using the yearly calculated intercepts (I) and slopes (S).

\[ I(\text{yr}) = I_{\text{initial}} + I_{\text{delta}} \cdot \text{yr} \] \hspace{1cm} (2.5)

\[ S(\text{yr}) = S_{\text{initial}} + S_{\text{delta}} \cdot \text{yr} \] \hspace{1cm} (2.6)

\[ \text{COP}(T) = S(\text{yr}) \cdot T + I(\text{yr}) \] \hspace{1cm} (2.7)

Table 2.5: Coefficients for calculating the heat pump performance during each year modelled. These are used in equations 2.5 and 2.6. The resulting lines are shown in figure 2.4.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Intercepts (I)</th>
<th>Slopes (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial (°C)</td>
<td>Delta (°C/yr)</td>
</tr>
<tr>
<td>Model</td>
<td>2.25</td>
<td>0.875</td>
</tr>
<tr>
<td>Worst</td>
<td>1.50</td>
<td>0.070</td>
</tr>
<tr>
<td>Best</td>
<td>2.75</td>
<td>0.100</td>
</tr>
<tr>
<td>Worst to Best</td>
<td>1.50</td>
<td>0.163</td>
</tr>
</tbody>
</table>

For every year modelled (and for every scenario) the generated linear average COP performance curve is used to calculate the average yearly performance for each city.
studied. This is done by testing against 30 years of hourly climate data for each city. The data from 1981-2010 inclusive is available from Environment Canada’s database of climate normals [9]. The frequency with which every outdoor temperature occurs is used to weight the heat pump performance at that temperature as calculated using the COP performance curve. The weighted performance is divided by the total number of hours in the 30 year dataset. These weighted performance factors are summed for all temperatures. The resultant average performance for the heating season is used to calculate both the cost of heating and the electrical energy requirements for the heat pumps in service in each city in that year.

2.3 Results & Discussion

This system dynamics model (see figures 2.1 and 2.2) is intended to show the potential for predicting adoption of technologies that may be more energy efficient. Despite lacking data to fully support some of the inputs, it is possible to produce a model that closely tracks historical adoption of heat pumps. Shown in figure 2.5 is both the actual share of heat pumps as tabulated by Statistics Canada and the predicted share from 2005 to 2012.

2.3.1 Sensitivity Analysis

Sensitivity analysis was carried out for two parameters: the lowest operating temperature for heat pumps, and their performance when operating. It was difficult to find historical data for these two parameters that would allow the construction of a trend to extrapolate into future years. We show in Table 2.6 and Table 2.7 that these two
parameters do not have a significant impact on the rate of adoption. Sensitivity analysis was carried out for both the unchanged energy pricing (UEP) and the reduced electricity and carbon pricing (REaCP) regimes.

**Low Temperature Cut-Off**

The lowest temperature at which heat pumps cease to be useful is used to determine what portion of the seasonal heating can be supplied by heat pumps. In Table 2.6 we show the results of the chosen model parameters, including the best and worst case scenarios. The initial condition is the temperature at which the average heat pump would cease to operate in 2005. The “delta” indicates how many degrees Celsius per year this temperature would change. This change is linear and the final temperature in 2025 is also shown for each scenario. Using the values in Table 2.6, Equation 2.8 describes how the low temperature cut-off is calculated for each year. Equation
2.3. RESULTS & DISCUSSION

2.9 describes how the low temperature cut-off \((L)\) affects the proportion of heating, measured in heating degree days (HDD), provided by heat pump. \(T\) is the outdoor temperature and \(HDD_{city}(T)\) is the average number of heating degree days per year occurring at temperature \(T\).

\[
L(\text{yr}) = L_{\text{initial}} + L_{\text{delta}} \cdot \text{yr} \tag{2.8}
\]

\[
HDD_{HP}(\text{yr}) = \sum_{T=L(\text{yr})}^{T=18.3} HDD_{city}(T) \tag{2.9}
\]

Table 2.6: Sensitivity testing of the low temperature cut-off.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Low Temp. Cut-Off (L)</th>
<th>Heat Pump Share</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial (°C)</td>
<td>Delta (°C/yr)</td>
</tr>
<tr>
<td>Model</td>
<td>-7.5</td>
<td>-1.125</td>
</tr>
<tr>
<td>Worst</td>
<td>0</td>
<td>-0.5</td>
</tr>
<tr>
<td>Best</td>
<td>-15</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

Table 2.7: Sensitivity testing of heat pump performance.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>UEP(%)</th>
<th>Heat Pump Share</th>
<th>REaCP(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7.966</td>
<td></td>
<td>8.896</td>
</tr>
<tr>
<td>Worst</td>
<td>7.990</td>
<td></td>
<td>8.931</td>
</tr>
<tr>
<td>Best</td>
<td>7.974</td>
<td></td>
<td>8.286</td>
</tr>
<tr>
<td>Worst to Best Cases</td>
<td>8.862</td>
<td></td>
<td>10.323</td>
</tr>
</tbody>
</table>

Under the original energy price conditions (UEP) and the worst case scenario, the predicted share of heating systems with heat pumps in 2025 is 7.781% whereas the chosen model scenario result is 7.966%. This is a difference in magnitude of 2.3%. The best case scenario leads to an outcome of 8.006% or 0.5% greater than the model.
2.3. RESULTS & DISCUSSION

scenario. Similarly, under reduced electrical energy prices and increasing carbon pricing (REaCP), we see 8.896%, 8.723% (-2.1%), and 8.904%(+0.1%) for the model, worst, and best case scenarios, respectively. The effect of changing low temperature cutoffs can induce a 2.3% change in the final heating system share, whereas energy price effects induce an 11.7% increase in the predicted heat pump share by 2025.

The very small improvement in adoption in the best case scenario suggests that in southern Ontario, the most populous region, residents are already very well served by today’s heat pump technologies. Even in Northern Ontario, well over 80% of the hours requiring heating are at -15°C or warmer. In Toronto, where millions of people reside, over 98% of the heating hours are at or above this temperature [9].

Technological Development

The effect of improving heat pump performance was also tested. Table 2.7 shows results that are insignificant to the ultimate outcome. For each scenario the model was tuned to ensure it closely replicates the historical data shown in figure 2.5. Figure 2.4 shows best, worst and model scenarios. Only when we begin with the abysmal worst case performance in 2005 and end with the highly unlikely best case scenario performance curve in 2025 do we see an 11% increase over the model scenario. While this is a much larger increase in adoption than that of all the other scenarios, it is not the sort of overall improvement that might significantly reduce energy consumption and GHG emissions in this sector. It seems far more likely that policy makers should focus on the relative costs of natural gas, oil and electricity, if they intend to encourage homeowners to use heat pumps. The increase in predicted heat pump share from 7.966% (UEP) to 8.896% (REaCP) due to a decrease in electricity prices
and implementation of carbon pricing supports this assertion (see table 2.7 and figure 2.6).

The portion of the System Dynamics model that uses technological development to calculate operating costs for different fuel based heating systems was not altered by the addition of any correction factors. The heat pumps available in any given year are simply expected to be less expensive or more expensive to operate than the alternatives due to the state of the technology and the prices of energy. However, the model was made to accurately follow the historical dataset by changing the contact rate (see figure 2.2). Conceptually, this factor influences the frequency at which potential adopters come into contact with those who have already installed heat pumps. The cost benefit ratio of operating a heat pump – as affected by the rate of technological development, energy prices, and weather conditions – influences the number of those “contacts” that result in the adoption of a heat pump.

Changes to the contact rate on the order of single percentage points can have significant effects on adoption, which indicates that consumer education may have a role to play in the electrification of heating in Ontario. The baseline scenario fit closest with historical data using a contact ratio, CR, of 0.166. The contact ratio remains constant through all years of model run, and it serves as the only factor used to align the model with historical data.

### 2.3.2 Predicted Heat Pump Share

The model behaviour follows trends in pricing of fuels and the performance of the technology. Shown in figure 2.6 is the predicted share of residences with heat pumps. A dashed line represents the predicted heat pump share with unchanged energy prices.
Figure 2.6: Effect of electricity price reductions and carbon pricing on the share of households with heat pumps.

as forecasted prior to the introduction of carbon pricing and electricity price reductions. These energy price changes take effect in 2017 and by 2025 increase the share of heat pumps from approximately 8% to nearly 9% (solid line in figure 2.6).

This change demonstrates the significance of the relative difference between energy prices. Electricity prices were originally forecast to rise over the medium to long term, but are now forecast to drop over the coming years (see figure 2.3). Furnace oil and natural gas prices still promise to stay low in the coming years, while carbon pricing will increase prices over time. Carbon pricing is likely to add more than a full cent (1.07 cents, total price 4.7 cents/kWh) to the cost of natural gas per kWh in 2022 and beyond. These new energy price changes enacted by the provincial and federal
governments are very likely to increase the rate of adoption for heat pumps.

We see in figure 2.7 the effects of reduced electricity prices and increasing carbon prices significantly increases the rate at which heat pumps are adopted. Technology is forecast to improve steadily over the forecast time period as seen in figure 2.4. It is still a contributing factor because even with unchanged prices (UEP) the number of heat pumps added each year increases from 2016 onward.

![Figure 2.7: Number of heat pumps installed each year.](image)

### 2.3.3 Energy Savings and Greenhouse Gas Emissions

The reduction of electricity prices by 25% and the introduction of carbon pricing has improved the likelihood that Ontario home owners will choose to supplement their heating with a heat pump. Bringing the price of electricity closer to those
of competing fossil fuels increases the cost benefit ratio used to calculate the future potential for adoption of heat pumps. Figure 2.7 demonstrates a pattern of heat pump adoption greatly increased by the new energy price policies and aided by improved heat pump performance.

Figure 2.8 demonstrates the effects of improving heat pump technology on energy efficiency. As more heat pumps are brought into service, the heat energy delivered by heat pumps increases. However, the electrical energy required by the heat pumps increases less quickly, because newly installed and upgraded heat pumps are expected to have higher average coefficients of performance. That is, the collective heat pump stock is expected to become more efficient as older heat pumps are retired and replaced with higher efficiency models. The resultant energy savings are shown in green. Heat pump induced electricity demand is shown in grey. Together these two values make up the total of the home heating energy provided by heat pumps in the ten Ontario cities in the model.

GHG emissions reductions (figure 2.9) show the same pattern seen for energy savings. This similarity is natural since the two are causally linked. Greater use of heat pumps results in lower overall GHG emissions. The prescribed improvement in heat pump technology (see figure 2.4) helps to effect increases in energy savings and GHG emission reductions. The reduced electricity prices and carbon pricing contribute to the higher values shown in green (see figure 2.9).

The total electrical energy demanded by heat pumps in the ten cities studied for heating in one year is typically 0.5% or less of the overall electrical energy demand for Ontario (153 TWh in 2015)[13]. The ten cities studied have approximately 42% of the dwellings in Ontario. The predicted GHG emissions reduction are approximately
2.4. CONCLUSIONS

Figure 2.8: Heating energy provided and energy savings by year.

4% (0.6 MtCO$_2$e) of the total residential GHG emissions due to home heating in 2013 (15 MtCO$_2$e) [21].

2.4 Conclusions

A System Dynamics model has been designed to analyze the effects of technological development, reduced electricity prices and new carbon pricing on heat pump adoption in Ontario. In this specific case, this model allows for a better understanding of the effect on energy consumption due to the increased use of heat pumps in the province of Ontario. A prediction of the number of heat pumps to be put into service is used, instead of a prescribed number. The performance of future heat pumps can be extrapolated from historical data instead of assuming today’s best available
technology will be put into use without subsequent improvement.

From the sensitivity analysis carried out, it seems that technological development does not have a sufficient effect on adoption rates to bring about large-scale change in home heating. This may be because modern heat pumps are already capable of providing heat for most locations in Ontario throughout most of the heating season. It does, however, seem likely that energy pricing has greater potential to encourage heat pump use and ensure the reduction of energy consumption and GHG emissions due to residential heating in Ontario and perhaps elsewhere. While Ontario’s climate is generally cold, it does vary significantly from Windsor in the south to Timmins in the north. Specific cities in Ontario can be comparable to almost any city in Canada and some in the northern parts of the United States or cold regions of the world.[30, 29, 17]
2.4. CONCLUSIONS

We may conclude that heat pumps are physically capable of supplying heat to many populated regions in the world, but the economic feasibility of this technology can be regionally specific. Even within the province of Ontario energy prices can vary from city to city. Applying this modelling methodology to other regions therefore requires not only knowledge of local weather conditions, but also of energy prices and housing specifications.

Future work might investigate the effects of consumer education and marketing on adoption rate since small changes to the contact ratio (see section 2.3.1) can have a strong effect. Governments might fund such education programs, while industry can directly benefit from investment in marketing campaigns. In addition government incentives will increase the uptake of heat pumps just as they have for photovoltaic solar collectors.

The authors acknowledge the support of the Natural Science and Engineering Research Council of Canada.

Conflict of Interest The authors declare that they have no conflict of interest.
References


[34] Statistics Canada. Table 129-0003 - Sales of natural gas, monthly, 2015. [dataset].

[35] Statistics Canada. Table 127-008 - Supply and disposition of electric power, electric utilities and industry, annual, 2016. [dataset].


Chapter 3

Heat pumps in Ontario: Effects of hourly temperature changes and electricity generation on greenhouse gas emissions

Published in Int. J. of Energy and Environmental Engineering
Authors: Alex Szekeres and Jack Jeswiet

Abstract More than 60% of household energy consumption in Ontario is for heating. Home heating needs in Ontario are driven by exterior temperatures that fluctuate throughout the day. Ontario’s electricity is generated from a different mix of primary energy sources from hour to hour. Using average hourly data for the electricity generation mix and hourly outside temperature data for each month of the year, we estimate residential heating loads and the electricity demands due to the use of three models of heat pump. Then we calculate the resultant greenhouse gas emissions and compare them to emissions if heat pumps are not used. We determine heating needs of single detached dwellings using prototypical average Ontario homes and building
simulation software. Using heat pumps in all of these dwellings can reduce heating-related greenhouse gas emissions between 15% and 85% during January, the harshest month of the year. Using heat pumps could also reduce energy consumption for heating by between 12% and 68%, while requiring an approximate 5%–25% increase in electricity demand. Heat pumps can provide a significant portion of home heat needs whilst reducing energy consumption and greenhouse gas emissions. Operating costs are lower than that of electric and oil heating, but similar to natural gas heating.

3.1 Introduction

Methods of home heating in Ontario, Canada’s most populous province, are fossil fuel dependent and inefficient, and electrifying residential heating is the likeliest means of avoiding fossil fuel emissions. Heat pumps are currently the most effective commonly available method of heating a home with electricity, but cold weather reduces their efficacy. While research has been conducted into the design of heat pumps for cold climates, little research has focused on the financial and environmental consequences of residential use of commercially available heat pumps. Few populous regions have more difficult climates than that of northern Ontario, making it an excellent location to test heat pump viability in cold climates. We set out to model a variety of heat pump technologies varying in capability and cost, in seven Ontario cities that provide different climates and energy prices.

While it seems reasonable to argue that improved building design is the key to reducing energy needs, it is difficult and costly to renovate older homes to modern or better standards. Insulating and air sealing a home are still best, but for most homes there will remain a need for significant heat energy input during the cold months of
3.1. INTRODUCTION

winter. Homeowners fullfilling this need with low-emitting electricity generated in Ontario will reduce greenhouse gas (GHG) emissions. Homes using heat pumps will be the most energy efficient. The most economical heat pump to install is the air source heat pump (ASHP), which extracts heat from the outdoor air and pumps it into the interior of the home. ASHPs can effectively achieve over 300% efficacies, because they use electricity to move heat, rather than burn a fuel to liberate the heat within its chemical structures and then struggle to transfer as much of it as possible to the interior of the dwelling. Even electric resistance heating can achieve only 100% efficiency.

Some heat pumps transfer heat from below the ground instead of from outside air. Such heat pumps are referred to as ground source heat pumps. However, these require either that at least one deep well is dug or that a large area be excavated in order to place large coils of piping under ground at a depth of approximately 1–2 metres. This approach allows heat to be extracted from underground, where temperatures fluctuate much less than those in the air above. In contrast, it is far less expensive to install an ASHP, because there is no need to excavate or dig a well. It can be installed just outside the home with one or more heat exchangers delivering heat indoors. ASHPs are today able to extract heat from air at temperatures as low as $-30^\circ C$ [37, 49]. Of course, performance at these temperatures is much reduced, but it is, nevertheless, more energy efficient than conventional heating technologies and less costly to install than ground source heat pumps.

Heat pumps, and specifically ASHPs, are becoming more capable and efficient. A study of 128 heat pumps installed in Icelandic homes found an energy savings of approximately 30% annually [5]. Average temperatures in Reykjavik are a few degrees
Celsius warmer than those in Windsor or Toronto, Ontario [5, 17]. ASHPs studied in Alaska were found to require backup heating only at very low temperatures and to have operating ranges extending to $-27^\circ \text{C}$ [56]. Such low temperatures make up a small portion of the heating season in Ontario’s cities [17].

Why then are heat pumps in use in only 9.8% of Ontario’s single detached dwellings (SDD) [43]? The reason is likely the cost of electricity relative to the cost of natural gas, the most popular heating fuel. Natural gas can be more than four times less expensive than electricity, making it necessary for heat pumps to be more than four times more energy efficient than natural gas furnaces just to remain competitive.

In another study, Kegel et al. [34] simulated ASHP performance in five cities across Canada, including one city in Ontario: Toronto. They found that heat pumps were rarely cost-effective when paired with natural gas heating, despite a more than 50% reduction in both energy consumption and GHG emissions [34]. This study by Kegel et al. simulates a year prior to the removal of coal from Ontario’s generating mix; emissions from electricity generation are now much lower [53], making these results less relevant today.

### 3.1.1 Objectives

The objective of this study is to determine whether we can use heat pump technology to reduce energy consumption and GHG emissions in the province of Ontario. We concentrate on residential heating in SDDs. The study is limited to Ontario in that the electrical generating system is unique to the province, but any location with similar low-emitting generators should see reduced emissions due to the electrification of home heating. For the homeowner, operating costs will affect the feasibility of installing a
heat pump and, for this reason, we also estimate the annual heating costs and savings for three different heat pumps of varying performance.

### 3.1.2 Home Heating in Ontario

Residential energy consumption in Ontario is dominated by the need to maintain a comfortable indoor climate during long cold winters. More than 60% of household energy use is employed for space heating alone [41]. This much-needed heat is delivered via central furnaces in most cases, and these are powered most often by natural gas (64.5%), electric resistance heating (10.7%), or furnace oil (5.5%) [43]. With natural gas furnaces being the most common, it is not surprising that 62.8% of GHG emissions in the residential sector are due to space heating [41].

Energy used for home heating is supplied either by natural gas piped to the home, furnace oil delivered via truck, or electricity transmitted over wires. For the purposes of this study, the demand refers to the energy required to provide the heat energy needed to warm the home. If fossil fuels are needed, this demand will be greater than the heat energy because efficiencies are lower than 100%. If electricity is the energy source, then demand will be the same for electric resistance heating, or much lower when a heat pump is used (usually 2–4 times lower). The energy demand may be stated for a single home as is the case in section 3.3.4. Energy demand may also refer to a large number of homes as is the case in sections 3.3.1 and 3.3.2.

The supply of fossil fuels remains unchanged in this analysis as a consequence of any changes in demand. Large-scale shifts in demand, should they occur, could affect the economics of fossil fuel distribution, but they are not considered here. Electricity is supplied by a number of generators across the province of Ontario. These may
be nuclear, hydroelectric, natural gas thermal, solar, wind, or biomass generating stations. The proportions of the supply provided by each vary with the season and the time of day. We use an average day with hourly time resolution for each month to calculate the GHG emissions due to electricity production, and also to estimate the effects of increased demand on GHGs emitted due to electricity generation.

Ontario has recently achieved significant reductions in GHG emissions from electricity generation by eliminating the use of coal fired generators [53]. Natural gas generators are now almost exclusively the only sources of GHGs from electricity generation in Ontario [15], and also tend to provide much of the supply’s ability to modulate output to compensate for changes in demand.

Electricity generation is central to the analysis of home heating-related GHG emissions because it is the source of energy for operating heat pumps. When an ASHP is used in a home that normally uses electric heating, less electricity will be used. This guarantees that less energy is consumed and fewer GHGs are emitted. In a home that uses natural gas or oil for heating, we need to first consider the energy and GHG emission intensity of the fuels burned in those furnaces. Then we must compare that to the electricity used by an ASHP, considering how this new electricity demand is met.

### 3.1.3 Ontario’s electricity generators

For the single household, we know that displacing fossil fuel-based heating with ASHP heating will result in an increased demand for electricity. It is therefore important to consider the source of this newly-needed electricity. The question of how this new demand is met—from what source—is central to calculating GHG emissions.
Ontario is nearly always a net exporter of electricity [29]. Therefore, adjacent markets are rarely relevant to the determination of the marginal electricity generator [3]. The types of generators used in Ontario are varied; nuclear, hydroelectric, wind, and solar do not contribute to the annual calculations of GHG emissions [28], while natural gas electricity generators are the only generators in Ontario whose emissions are reported yearly [15]. Any new demand for electricity due to heat pump use will be met by one of the following three possibilities.

1. The generating mix remains constant.

2. The demand is met by a single technology, or

3. It is met by a combination of technologies.

Possibilities 1 and 3 may come to pass because heat pump use is predictable, and could therefore be integrated into models for day-ahead bidding on electricity generation. The result would be that some supply would be met with hydro, other renewables, or even nuclear power. Of course, fast-reacting natural gas generators would likely provide for some of the increased demand, which may result in virtually the same generating mix (1) or a new mix (3).

Possibility 2 assumes a single technology is favoured to respond to any increased demand. This is a strategy previously used by researchers [71, 70, 13]. The only GHG emitting generators in Ontario are natural gas fired. Therefore, the worst case for carbon emissions would be that all new electricity demand is met by natural gas generating stations. For this worst-case scenario, we entertain two methods of attributing GHG emissions generated by meeting the net demand increase due to heat pump use.
3.1. INTRODUCTION

a) The new GHG emissions are attributed to heat pump use.

b) The demand is met by natural gas, but we attribute the average emissions for all electricity generation to heat pump use.

Case (a) where only natural gas electricity generators are used to meet new demand and all resulting emissions are attributed to the new energy needs of the heat pumps is the worst case possible. It will result in the highest emissions due to heat pump use. Case (b) provides a more charitable view of the effects of heat pump use. We will show the result of scenarios 1, 2a, and 2b in section 3.3.3. In doing so, we hope to present the range of possibilities, expecting that the result is likely between the virtual best case, 1, and the worst case, 2a.

3.1.4 Hourly effects

Because heat pump electricity demand will likely change from hour to hour depending on outdoor weather conditions, we examine the effects of these changes in demand and make an hourly estimate of energy consumption and GHG emissions. However, the mix of electricity generators also varies from hour to hour and can influence the carbon intensity of each kWh of electricity consumed.

We therefore estimate the hourly heating needs of the average SDD in seven Ontario cities, and determine how much of that need can be met with each of three modern ASHPs of varying capability. We then calculate the potential reduction in energy consumption and GHG emissions compared to conventional natural gas, oil, and electric heating. We test GHG emissions against hourly electricity generation emission profiles for the average day of each month in the year. We did this modelling on an hourly basis throughout the year, but presented results for the average day in
January to allow the reader to see the average daily effects during the coldest month of the year. We also present energy, GHG emissions, and operating costs for the individual home on a yearly basis in each city analyzed. Operating cost is one force driving heat pump adoption [64]. To answer the questions of whether and when there is a net increase in electricity demand we model a hypothetical scenario of full adoption of heat pumps in all the available SDDs in the 7 chosen cities. Effects on energy consumption, GHG emissions, and the three previously mentioned methods of attributing GHG emissions are also calculated for this scenario. This large-scale adoption scenario is presented first in the results while the effects on individual homes are presented last.

Heat pumps may also provide an advantage in managing the variability of electrical demand and generation. Parkinson et al. created a model in which heat pumps could respond to changes in grid level electricity demand [54]. By slightly delaying or hastening the call for heat made by individual thermostats, a large number (1000 in the study) of heat pumps can provide demand response [54, 69]. Other models have been developed with similar aims in mind but without strict consideration for comfort [19, 7]. Modelling both the demand from heating systems and the supply of electricity may be necessary to predict future energy price effects or other effects that demand may have on the supply side [55]. Expanding our understanding of the “benefits for consumer[s]” of active demand response systems is needed before these systems become ubiquitous [55]. One focus of this work is on quantifying the net financial benefit to the consumer of operating a heat pump, and estimating the potential energy savings and GHG emission abatements from heat pump use. This work endeavours to understand heating demand, when that demand will be needed,
3.1. INTRODUCTION

and the cost to the Ontarian providing for that demand with heat pumps.

Our aim is to guide policy makers. Changes in hourly energy consumption patterns may have consequences for electricity generation and GHG emissions, and also influence the cost of heating for individual homeowners. Weighing these outcomes can help policy makers choose amongst available technologies and economic incentives, while pro-actively preparing to mitigate any consequences of increased heat pump use.

3.1.5 Assumptions

Given this aim, it is important to consider the key assumptions under which the study is conducted.

Weather data used is representative of an average year, yet from 1990 to 2015 winters have nearly always been warmer than usual [46]. The assumption is that average weather is relevant to future decision making, which may not be the case [12]. This assumption may provide more conservative results than the future holds because warmer weather allows for better heat pump performance.

Heat pump performance itself is estimated using manufacturer performance data. This is likely a best case scenario as heat pumps installed in homes would have to be installed in nearly ideal conditions to achieve manufacturer stated performance. Manufacturer supplied data is more readily available than independent experimentally obtained datasets. It would be prohibitively costly and time-consuming to purchase heat pumps of all the types to be investigated, install them in appropriate dwellings, set up instrumentation, and verify their performance curves. This assumption has
potential to cause overstatement of the predicted heat pump performance.

**Average building data and building energy simulation** (EnergyPlus™ software) is used to predict heating needs for the average home. There is little choice but to use the data [62] available describing the average Ontario home. Parameters that are normally adjusted in an effort to calibrate a model [2, 10, 14] are already set at their known quantities and cannot be changed. Furthermore, we have only average data (see section 3.2.1) for the whole province of Ontario with which to compare, when we would ideally have average homes constructed and instrumented in as many locations as possible across the province. However, it appears that the energy simulation of the average home produces results similar to Ontario-wide averages in cities with near average weather for Ontario (see section 3.2.1). We rely upon the accuracy of the building parameters used, and the building simulation software that has undergone validation against other building simulation software [2, 31, 6, 66] and also been tested against existing homes and buildings [32, 50]. This assumption could lead to predicted heating needs that are either higher or lower than the true values.

### 3.2 Methodology

Three metrics are used to test heat pump technologies. These are energy conservation, GHG emissions, and cost of operation. Are we assured a reduction of energy consumption? Will GHG emissions be reduced at all hours of the day? Can the homeowner afford to operate a heat pump? In an effort to thoroughly answer these questions, three heat pumps of varying capabilities and costs are simulated in operation throughout one typical year in seven cities across Ontario. These cities are
chosen because of their varied climates and energy costs. To determine whether operating costs can be further reduced we employ an advanced control system aware of the changing costs of heating and compare it to a more conventional method of heating system control. Between the three heat pumps and two control systems, six scenarios are tested in each of the seven cities. All of these simulations are built upon an estimation of the hourly heating needs for an average Ontario SDD.

To determine what effect hourly heating demands place on heat pumps, electricity generation, and the user’s finances, we must first have an estimate of hourly heating needs for the average Ontario home. Second, we need an estimate of how that demand might be met by heat pumps and conventional heating. Third, we need an estimate of the combination of electricity generating methods used on an hourly basis. Finally, the costs and consequences of using these energy resources are calculated based upon current energy-price data and emissions data. These steps (See Fig. 3.1) are detailed in the following sections.

![Simplified flow diagram of the process followed in this study.](image)

Figure 3.1: Simplified flow diagram of the process followed in this study.

### 3.2.1 Estimation of hourly heating needs

For the purposes of determining heating needs on an hourly basis, EnergyPlus™ is employed. The geometry of the home is generated using SketchUp™ and a plug-in allowing the generation of an EnergyPlus™ input data file (IDF). Performance in
3.2. METHODOLOGY

Each city is analyzed using a type three typical meteorological year (TMY3). For Kingston, only the older type two (TMY2) was available. The IDF is then edited either manually in EnergyPlus™ or through the graphical interface, Euclid™, within SketchUp™ to obtain a model consistent with Ontario dwellings. The general and specific configurations of the modelled dwellings are discussed in sections Dwellings and their construction through to Heat loss estimation in EnergyPlus.

Nearly all parameters defining the building are determined by average home data collected by Swan et al. [62]. It is therefore impossible to follow a calibration procedure without deviating from the known values. Ideally, a perfectly average home would be constructed and instrumented in every location. Measurements would be taken for each, and an EnergyPlus™ model would be calibrated using a process similar to the one put forth by Egan et al.[14]. As this seems impractical, we are proceeding with building energy simulations and relying upon the validation of EnergyPlus™ against other building energy simulation software [2, 31, 6, 66].

The output from this stage of modelling is the total heating energy required per hour per SDD. Because SDDs can be 1 or 2 storeys high, a weighted average of heating needs is generated according to the share of dwellings of each type. On average throughout the province, approximately half of dwellings have two levels above ground and the other half have only one level above ground [62]. The two are therefore averaged. This final number along with the outdoor temperature from the TMY3 for each city is imported into a model responsible for simulating the heating system response to these heating needs. It is assumed that for each hour the heating system is able to provide for the full needs of the home. A combination of heat pump provided heating and conventional heating is used. The cost of electricity during the
hour, and both the heating capacity and efficiency of the heat pump at the outdoor temperature during that hour determine the proportion of heat energy delivered via heat pump. The heating system control strategies are elaborated in section 3.2.4.

**Climate**

Table 3.1 contains a list of the cities examined and a measure of the hours below 18.3°C converted to days. These heating degree-days (HDD) are as few as 3444 in Windsor, and as many as 6017 in Timmins. Also listed are the normal daily minimum, average, and maximum temperatures in the month of January. January is typically the coldest month of the year. Warmest temperatures usually occur during the mid afternoon, and coldest temperatures usually occur in the very early mornings prior to sunrise. Wind can have a more significant effect on heating needs in cities like Kingston than in Ottawa or Timmins, but all of these particulars are captured in the TMY created for the city by Environment Canada.

It is assumed that the climate data used will result in average heating needs. However, it should be noted that, in Ontario, from 1990 to 2015 inclusive the HDD index has been 8% lower on average with a 95% confidence interval of 2.7%[46]. Warmer weather usually results in better heat pump performance, resulting in a greater proportion of heating supplied by heat pump, but may or may not result in greater economic benefit as there may be less opportunity to provide heat overall.
Table 3.1: Usual number of HDDs (°C) per year, and normal daily average, minimum and maximum temperatures in January in the seven cities investigated [4, 17].

<table>
<thead>
<tr>
<th>City</th>
<th>HDDs (°C days)</th>
<th>Daily Normals in January (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>Kingston</td>
<td>3976</td>
<td>−11.4</td>
</tr>
<tr>
<td>Ottawa</td>
<td>4441</td>
<td>−14.8</td>
</tr>
<tr>
<td>Sudbury</td>
<td>5241</td>
<td>−17.9</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>5594</td>
<td>−18.9</td>
</tr>
<tr>
<td>Timmins</td>
<td>6017</td>
<td>−23.0</td>
</tr>
<tr>
<td>Toronto</td>
<td>3533</td>
<td>−6.7</td>
</tr>
<tr>
<td>Windsor</td>
<td>3444</td>
<td>−7.3</td>
</tr>
</tbody>
</table>

Dwellings and their construction

Heating demand is profoundly affected by building construction, and we therefore lay out in detail the average prototypical SDD. Homes in Ontario are typically constructed using wood frames with exterior cladding and gypsum wall board on the interior wall. The cavities left between wood studs in the frame are hopefully filled with insulation. However, the average level of insulation taken from Swan and Ugursal et al. [62] results in a partially filled wall cavity if fibreglass batt insulation is used. Most homes have basements [62] with less wall insulation than upper levels, and an asphalt shingle covered peaked roof. The greatest level of insulation found in the home is usually at the juncture between the attic and upper living area. Table 3.2 enumerates the basic properties of the prototypical SDDs used in this study.

Dwellings can be SDDs, semi-detached duplexes, townhouses or row-houses, low-rise apartments, or even high-rise apartments and condominiums. Only SDDs are considered in this work. This narrow scope reduces the number of results to present while still showing the benefit of heat pump use for the majority (54.3%, see Table
3.2. METHODOLOGY

3.3) of dwellings in Ontario [42, 59]. SDDs are often built by similar methods, the details of which are summarized in table 3.2 and elaborated in the following sections. Table 3.3 shows the share of housing by type and average floor areas.

Table 3.2: Properties of prototypical average SDD in Ontario. [62, 39, 40]

<table>
<thead>
<tr>
<th>Building Properties</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living Area</td>
<td>173.0</td>
<td>$m^2$</td>
</tr>
<tr>
<td>Wall Heights</td>
<td>2.4</td>
<td>m</td>
</tr>
<tr>
<td>Window (% living space wall area)</td>
<td>15.7</td>
<td>%</td>
</tr>
<tr>
<td>Wall Insulation (RSI)</td>
<td>2.1</td>
<td>$m^2 K/W$</td>
</tr>
<tr>
<td>Ceiling Insulation (RSI)</td>
<td>4.6</td>
<td>$m^2 K/W$</td>
</tr>
<tr>
<td>Basement Wall Insulation (RSI)</td>
<td>1.4</td>
<td>$m^2 K/W$</td>
</tr>
<tr>
<td>Air Changes per Hour at 50Pa</td>
<td>6.5</td>
<td>$ACH_{50}$</td>
</tr>
<tr>
<td>Interior Temperature (+/- 0.2°C)</td>
<td>21.0</td>
<td>°C</td>
</tr>
</tbody>
</table>

Two SDDs were used in the weather simulations—a one-storey and a two-storey building. These both had square footprints and a living area of 173 $m^2$ (see table 3.3) was maintained for both. As a result, the footprint of the two-storey building was reduced. The four walls (section 3.2.1) of the structures are oriented to face the cardinal directions: north, south, east, and west. All features like windows and doors (see fenestration, 3.2.1) are spread evenly across all the walls. The roof is a hip roof enclosing an attic space. Both are described in section 3.2.1. The effects of all weather conditions, including solar insolation, are calculated by Energyplus™ for each city using the appropriate TMY weather file (see sections 3.2.1, 3.2.1, 3.2.1). Both prototypical homes have a basement extending 1.5 m below grade that is not considered part of the conditioned living area.
3.2. METHODOLOGY

Table 3.3: Housing share and average area of dwellings by type in Ontario. Data from Statistics Canada 2016 Census [59] and National Energy Use Database 2014 [39, 40].

<table>
<thead>
<tr>
<th>Type of Dwelling</th>
<th>Housing Share (%)</th>
<th>Floor Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Detached</td>
<td>54.3</td>
<td>173</td>
</tr>
<tr>
<td>Single Attached</td>
<td>17.9</td>
<td>131</td>
</tr>
<tr>
<td>Low-Rise Apartments</td>
<td>10.1</td>
<td>90</td>
</tr>
<tr>
<td>High-Rise Apartments</td>
<td>17.2</td>
<td>90</td>
</tr>
</tbody>
</table>

Walls

Walls are a wood-frame wall common to North American home construction [1, 36, 4]. Wood studs are 39 mm wide by 90 mm deep and spaced on 400 mm centres (2x4 on 16 inch centres). The wall interior has a gypsum wall board 12.7 mm (0.5 in) thick and the exterior consists of a 25.4 mm (1 in) wood board sheathing, a 12.7 mm(0.5 in) felt air gap and finally a 12.7 mm(0.5 in) hardboard wood siding.

Attic and roof

A roof and attic was added to more accurately model common residential building designs. A 6/12 roof pitch was used. This denotes a 6 unit rise per 12 units of length, or a rise of 26.6°C. The roof is covered with asphalt shingles on top of 19 mm wood sheathing. These are supported by 39x140 mm rafters. Details of the thermal modelling are shown in table 3.4. Not shown in the table is attic ventilation. This was modelled as a leakage area of 5000 cm² for the single storey detached home as per the work of Kneifel and Hendron et al. [36, 22] where 1 unit of ventilation is added for every 300 units of attic floor area. A two storey home requires half this leakage area because it has half the attic area due to the fact that the interior living
Table 3.4: Properties of walls and their components [4, 27, 9].

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Thickness (mm)</th>
<th>RSI (m²K/W)</th>
<th>U (W/m²K)</th>
<th>Conductivity (W/mK)</th>
<th>Density (kg/m³)</th>
<th>Spec. Heat (J/kgK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mainfloor Exterior Walls</td>
<td>1 Gypsum Wall Board</td>
<td>12.7</td>
<td>0.075</td>
<td>13.4</td>
<td>0.17</td>
<td>800</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>2 Wood-Frame Wall</td>
<td>90.0</td>
<td>1.3</td>
<td>0.78</td>
<td>0.07</td>
<td>119</td>
<td>766</td>
</tr>
<tr>
<td></td>
<td>Wood Studs 39x90mm</td>
<td>90.0</td>
<td>0.82</td>
<td>1.2</td>
<td>0.11</td>
<td>420</td>
<td>1380</td>
</tr>
<tr>
<td></td>
<td>Fibreglass Insulation</td>
<td>60.5</td>
<td>1.6</td>
<td>0.42</td>
<td>0.038</td>
<td>28</td>
<td>835</td>
</tr>
<tr>
<td></td>
<td>3 Wood Sheathing</td>
<td>19.0</td>
<td>0.35</td>
<td>2.9</td>
<td>0.055</td>
<td>290</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>4 Felt/Air Gap</td>
<td>12.7</td>
<td>0.26</td>
<td>3.9</td>
<td>0.05</td>
<td>330</td>
<td>1360</td>
</tr>
<tr>
<td></td>
<td>5 Wood Siding</td>
<td>12.7</td>
<td>0.14</td>
<td>7.4</td>
<td>0.094</td>
<td>640</td>
<td>1170</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>155.8</td>
<td>2.1</td>
<td>0.477</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement Exterior Walls</td>
<td>1 Concrete (heavy)</td>
<td>203.2</td>
<td>0.1</td>
<td>9.6</td>
<td>1.95</td>
<td>2240</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>2 Insulation Board</td>
<td>39.0</td>
<td>1.3</td>
<td>0.77</td>
<td>0.03</td>
<td>43</td>
<td>1210</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>242.2</td>
<td>1.4</td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basement Floor</td>
<td>1 Concrete (light)</td>
<td>101.6</td>
<td>0.19</td>
<td>5.2</td>
<td>0.53</td>
<td>1280</td>
<td>840</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>101.6</td>
<td>0.19</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Ceiling / Attic Floor</td>
<td>1 Gypsum Wall Board</td>
<td>12.7</td>
<td>0.075</td>
<td>13.4</td>
<td>0.17</td>
<td>800</td>
<td>1080</td>
</tr>
<tr>
<td></td>
<td>2 Wood-Frame Ceiling</td>
<td>140</td>
<td>2.5</td>
<td>0.40</td>
<td>0.036</td>
<td>126</td>
<td>971</td>
</tr>
<tr>
<td></td>
<td>Wood Studs 39x140mm</td>
<td>140</td>
<td>1.27</td>
<td>0.79</td>
<td>0.11</td>
<td>420</td>
<td>1380</td>
</tr>
<tr>
<td></td>
<td>Fibreglass Insulation</td>
<td>140</td>
<td>3.68</td>
<td>0.27</td>
<td>0.038</td>
<td>28</td>
<td>835</td>
</tr>
<tr>
<td></td>
<td>3 Fibreglass Batt Insulation</td>
<td>77.0</td>
<td>2.03</td>
<td>0.49</td>
<td>0.038</td>
<td>28</td>
<td>835</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>229.7</td>
<td>4.6</td>
<td>0.217</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>1 Wood Rafters</td>
<td>140</td>
<td>0.32</td>
<td>3.15</td>
<td>0.44</td>
<td>105</td>
<td>345</td>
</tr>
<tr>
<td></td>
<td>Wood Studs 39x140mm</td>
<td>140</td>
<td>1.27</td>
<td>0.79</td>
<td>0.11</td>
<td>420</td>
<td>1380</td>
</tr>
<tr>
<td></td>
<td>2 Wood Sheathing</td>
<td>19.0</td>
<td>0.35</td>
<td>2.9</td>
<td>0.055</td>
<td>290</td>
<td>1300</td>
</tr>
<tr>
<td></td>
<td>3 Asphalt Shingles</td>
<td>12.7</td>
<td>0.077</td>
<td>13.0</td>
<td>0.17</td>
<td>1100</td>
<td>1260</td>
</tr>
<tr>
<td></td>
<td>Totals</td>
<td>171.7</td>
<td>0.747</td>
<td>1.34</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

area remains constant and is spread across two levels.

**Fenestration**

Fenestration consists often of only one or two windows per room. For this reason windows are assumed to be operable. In the event that some windows are in reality inoperable this assumption results in a slightly conservative (higher) estimate of heating
3.2. METHODOLOGY

needs (inoperable windows have a slightly lower heat loss–$U = 2.24 \text{ W/m}^2\text{K}$). Table 3.5 details the properties used to model fenestration. These properties are sourced from ASHRAE Fundamentals 2013, Chapter 17 [4].

Table 3.5: Fenestration modelling properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glazing Layers</td>
<td>2</td>
</tr>
<tr>
<td>Framing Material</td>
<td>Wood/Vinyl</td>
</tr>
<tr>
<td>U-factor</td>
<td>2.39 (W/m²K)</td>
</tr>
<tr>
<td>Solar Heat Gain Coefficient</td>
<td>0.52</td>
</tr>
</tbody>
</table>

**Air infiltration**

Infiltration of air into the home’s heated volume is an important factor in the overall heat load calculation. From Swan et al. the average number of air changes per hour at a 50 Pa (ACH$_{50}$) wind-induced pressure differential is 6.5 ACH$_{50}$ [63]. From the ACH$_{50}$ value we can calculate an equivalent leakage area (ELA)–the sum total area of all the openings in the building envelope that would produce an equivalent ACH at that pressure (50 Pa)–using Equation 3.2.

$$Q_r = ACH_{50} \cdot V \cdot \frac{1}{\text{hr} \cdot 3600 \text{s}}$$

$Q_r$ is the volume of exchanged air per second for the heated volume (V) in question, and it is calculated using equation 3.1 [4].

$$ELA = \frac{10000 \cdot Q_r \sqrt{\rho / \Delta P_r}}{C_D}$$

ELA is calculated using a discharge coefficient, $C_D$, which can be approximately
0.611 for a sharp-edged orifice or 1.0 as used by Sherman and Grimsrud [57]. We use $C_D = 1.0$ for both equations 3.2 and 3.3. The density of air in equation 3.2 is represented by $\rho$, and $\Delta P_r$ is the pressure differential of either 50 Pa or 4 Pa.

$$ELA_{4Pa} = ELA_{50Pa} \left( \frac{CD_1}{CD_2} \right) \left( \frac{\Delta P_{r2}}{\Delta P_{r1}} \right)^{n-0.5} \quad (3.3)$$

The lower pressure of 4 Pa is used in Energyplus™ to model normal wind loading conditions, and the $ELA_{4Pa}$ is determined using equation 3.3 also from ASHRAE Fundamentals [4]. As previously mentioned $C_{D1} = C_{D2} = 1.0$ and $n$ is a pressure exponent found empirically to be 0.65 [4].

From this starting point the $ELA_{4Pa}$ is used to calculate infiltration induced heat loss according to weather conditions—wind speed $v_{wind}$ and the difference between indoor ($T_{in}$) and outdoor ($T_{out}$) temperatures (see equation 3.4). The coefficients $C_s$ and $C_w$ modify the stack effect and wind effects, respectively. The infiltration model described is based upon the work of Sherman and Grimsrud [57] elaborated within chapter 16 of the ASHRAE handbook of fundamentals [4]. $C_s$ varies depending on the height of the building. Single-storey buildings have a $C_s$ of 0.000145, and two-storey buildings 0.000290. The wind speed coefficient $C_w$ is based upon the level of sheltering to be expected and again the height of the building. Coefficients corresponding to an urban setting, “where obstacles are more than one building height away” 0.000104 and 0.000137 are used for buildings of 1 and 2 storey heights respectively [4].

$$Inf. = \frac{ELA_{4Pa}}{1000} \sqrt{C_s(T_{in} - T_{out}) + C_w(v_{wind}^2)} \quad (3.4)$$
Heat loss estimation in EnergyPlus™

As previously mentioned, EnergyPlus™ modelling software is used to estimate the hourly heating needs of the average SDD in each of the seven cities analyzed. The particulars of construction of the home as described in the preceding sections are inputs to the EnergyPlus™ IDF files used to define the dwelling in each city. Weather is also specified in the IDF, using a TMY file for each location. Outputs from the model include heat losses and outdoor temperatures. With the knowledge of these two pieces of information and the interior set point, the heating system response is calculated from manufacturer-provided performance data elaborated in the following sections.

Table 3.6 shows the resultant yearly heating needs in kWh for the average SDD in each city, alongside the average residential heating needs gleaned from Statistics Canada natural gas consumption data [60] for 2014 (latest year with HDD index of 1,00–heating needs similar to the expected average), and also from Natural Resources Canada’s Comprehensive Energy Use Database for SDDs in Ontario in 2014 [47, 39, 44, 45]. The Statistics Canada average applies to all residential natural gas customers. These data are a proxy for estimating heating needs. It is assumed that natural gas consumption in July (672 kWh per household) is not for home heating, but instead represents a base energy need for cooking and hot water. We have therefore subtracted this value from all months of the year to arrive at the average in table 3.6. 31,420 kWh/year is the estimate without subtracting July consumption. No heating system efficiencies were applied to the Statistics Canada dataset, as there are no such data available. In the case of the NRCan estimate, efficiencies for heating system types are applied because NRCan provides heating system efficiencies that
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can be weighted by secondary energy consumption \cite{44}. The weighted efficiency is multiplied by the total energy used for heating to arrive at the approximately 25 MWh/year in Table 3.6. While these estimates are not used for calibration of the simulations, the resultant heating needs are reasonably close to the province-wide averages in cities like Kingston, Ottawa, and Sudbury. In much colder, but less populous cities like Thunder Bay and Timmins the deviation is between 17% and 38%. More concerning is the fact that heating needs in Toronto, the most populous city in Ontario, are estimated to be 15% to 20% lower than the average, although there are relatively fewer SDDs and more apartments in Toronto than in other cities \cite{59}.

Table 3.6: Simulated annual heating needs in kWh for each city. Average province-wide residential heating needs in 2014 according to Statistics Canada, and average heating needs per SDD in Ontario, also in 2014, according to Natural Resources Canada \cite{60, 47, 39, 44, 45}

<table>
<thead>
<tr>
<th>City</th>
<th>Annual Heating Needs (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingston</td>
<td>23,873</td>
</tr>
<tr>
<td>Ottawa</td>
<td>23,588</td>
</tr>
<tr>
<td>Sudbury</td>
<td>27,171</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>29,331</td>
</tr>
<tr>
<td>Timmins</td>
<td>32,218</td>
</tr>
<tr>
<td>Toronto</td>
<td>19,935</td>
</tr>
<tr>
<td>Windsor</td>
<td>17,579</td>
</tr>
<tr>
<td><strong>Ontario Averages</strong></td>
<td></td>
</tr>
<tr>
<td>Statistics Canada (per Household)</td>
<td>23,369</td>
</tr>
<tr>
<td>NRCan (per SDD)</td>
<td>24,966</td>
</tr>
</tbody>
</table>
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3.2.2 Heat pump performance

Heat pump performance is dependent primarily upon outside temperature. As the temperature becomes lower, heat pump performance declines. At temperatures near to 0°C there is a tendency for water in the air to freeze on the outdoor heat exchanger. Some heat pumps employ a small heating coil to prevent water from collecting and freezing in the bottom pan of the outdoor unit, and all heat pumps can periodically reverse the direction heat is pumped to defrost the outdoor unit. Defrosting reduces the overall system performance, especially within about 5°C of 0°C [58]. Specific ASHPs monitored in Alaska were found to both exceed, and fail to meet, manufacturer specifications, depending upon circumstance and performance of the particular heat pump [61].

This study employs three different heat pumps of varying capability. All have a rated capacity of 36,000 Btu or 10.6 kW. This capacity is sufficient for the average homes modelled in this study. However, the best of the three heat pump technologies is far more capable of providing heat at lower temperatures than the simplest heat pump in the study.

The first is a single-stage heat pump. This means that the compressor, present in all heat pumps, is capable of running at just one speed. It is the simplest and least effective technology available today. Single-stage heat pumps must be on at full capacity or off. Figure 3.2 shows the performance curve for the chosen single-stage heat pump—a Coleman TH4B36 heat pump [49, 11]. The rated capacity is only available down to about 8–10°C. At −12.2°C the heat pump has reached its normal low-temperature operating limit, ceasing operation and deferring to the backup heating system.
Both the second and third heat pumps chosen are variable speed heat pumps. The compressor can operate at a variety of speeds because it is driven by an inverter. The inverter is an electronic device capable of providing an alternating current within a range of frequencies instead of just the usual 60 Hz used in North America. At higher frequencies the compressor runs faster, and at lower frequencies it runs more slowly. This allows the heat pump to run continuously by matching the heat output to the heating needs of the home. Consequently, the indoor temperature can be maintained more closely and efficiencies are usually higher than with a single-stage or two-stage heat pump.

A Carrier 25VNA036 centrally ducted heat pump is the second heat pump studied. It is denoted in all figures and results as “VC” for “Variable Centrally ducted”.

Figure 3.2: Single-stage heat pump performance curves–SS [49, 11].
Centrally ducted means that these heat pumps can be attached to existing ductwork in one central location where a fan forces the air past the heat pump’s heat exchanger and through the ducts to all the rooms in the home. This simplifies installation because, in many households, ducting and furnaces complete with circulating fans are often already present. When the heat pump is no longer capable of supplying all the heating needs of the home, the conventional home furnace takes over and heats the air travelling through the very same ducts. The performance curves for this heat pump are shown in figure 3.3 [49, 8]. There are two curves each for capacities and COPs. These show the maximum (blue) and minimum (red) heat output and corresponding COPs varying by outdoor temperature. This particular heat pump can operate at temperatures as low as –19.4°C.

![Figure 3.3: Variable-speed centrally-ducted heat pump performance–VC](image)
Third is a Mitsubishi MXZ4C36NAHZ variable speed ductless heat pump system. This heat pump can deliver heat to as many as four interior units that are ductless. Each ductless unit contains a fan and refrigerant coil to deliver heat to the room in which it is situated. There are no ducts used. These are the most efficient heat pump systems, but often require the most effort to install because there are several indoor units to run piping and electrical wiring to. The ductless heat pump is denoted by VD in all figures and results. Figure 3.4 shows the impressive performance of this heat pump system, with a minimum outdoor operating temperature of \(-25^\circ\text{C}\) and full heating capacity maintained at \(-15^\circ\text{C}\) [49, 37].

![Figure 3.4: Variable-speed ductless heat pump performance–VD [49, 37].](image)

All three heat pump configurations are available in the NEEP data set [49], but data for figures 3.2, 3.3, and 3.4 are generated from manufacturer performance data
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[11, 8, 37]. The single-stage heat pump is the least expensive. Units of this type can often be installed for approximately $5-6k. The variable speed systems are more expensive, with costs varying between $8k and $15–20k including installation. The third and best performing heat pump in figure 3.4 is likely to be priced in the $15–20k range, especially when retrofitted, because each indoor unit will need to have piping and wiring fed through existing walls and ceilings.

3.2.3 Conventional heating system performance

Home heating is usually accomplished with a single furnace. These will either heat air and force it through ducts, or heat water and pump it through pipes and radiators. Furnaces can be fueled with natural gas, furnace oil, or electric heat. Electric heat can also be delivered by electric resistance heaters located in each room of the home. This study employs a 100% efficiency for all electric heating systems regardless of type. Natural gas furnaces are modelled to be 96% efficient, better than the 90% used in the National Energy Use Database [44]. Oil fired furnaces are given an efficiency rating of 80%, which is slightly higher than the 78% average seen in NRCan and Statistics Canada datasets [44].

3.2.4 Heating system control

Typical control systems in homes have one single thermostat. When the indoor temperature falls below the set point, heat is required and requested. For conventional heating systems this means that the electric, natural gas, or oil-fired furnace is asked to supply heat. When a heat pump is added to the system, the call for heating is first put to the heat pump. Within a range of exterior temperatures the heat pump is able
to deliver its full heating capacity and needs no additional heat from the conventional furnace. Only when below this temperature range will the heat input to the home fall below full capacity and backup heat may be required from the main furnace. Older heat pumps might reach this point at 5°C [33]. Many modern cold climate heat pumps can maintain 100% of their rated capacity down to –15°C while still providing some heating at temperatures below –25°C [61, 49, 37]. Backup heating is typically requested when the set point temperature cannot be maintained with the heat pump alone and the thermostat registers a temperature 2–5 degrees below the set point, or a set exterior temperature like –15°C is reached and the heat pump is turned off.

This form of control does not take into account exterior temperatures and the resultant heating capacity of the heat pump. Nor does it take into account the cost of electricity at the time heat is needed. In our SD model we are able to simulate an advanced control system capable of delivering heat via heat pump at times when electricity prices are low enough and at temperatures when the COP is high enough to ensure heat pump use is cost-effective. Furthermore, the control system simulated will choose to provide less heat via heat pump at a higher COP to ensure heat delivered is cost-effective, even though it means providing more heat via the conventional furnace. This method of control appears to have not yet been implemented for residential heat pump systems. A flow diagram of the advanced control strategy is shown in figure 3.5. Table 3.7 lists the differences in inputs between the advanced and balanced (described below) control methods.

We compare the advanced control system performance to the conventional strategy of providing as much heat as possible via heat pump, even if it increases the cost of operation. This type of control is depicted in a flow diagram in figure 3.6. We
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Low Temp. Cut-Off ($T_{\text{low}}$)

Temperature Outside ($T_{\text{out}}$)

Heat Pump Capacity Data

Heat Pump COP Data

Energy Price Data

Hourly Heat Loss (HL)

Determine at $T_{\text{out}}$:

- [HP_{\text{MaxCOP}}$^{\text{HP}}$, $\text{HP}_{\text{MinCap}}$]
- [HP_{\text{MinCOP}}$^{\text{HP}}$, HP_{\text{MaxCap}}$]

If HP_{\text{MaxCap}} ≤ HL
- Set HP_{\text{output}} = HL, Else
- HP_{\text{output}} = HP_{\text{MaxCap}} - \text{Time Penalty}

Calculate HP_{\text{COP}}

HP_{\text{Price}} at HP_{\text{COP}}

HP_{\text{Low Price}} at HP_{\text{MaxCOP}}

Backup_{\text{Price}}

HP_{\text{Price}} ≤ Backup_{\text{Price}}

HP_{\text{Low Price}} ≤ Backup_{\text{Price}}

HP_{\text{output}} = 0
Backup_{\text{output}} = HL

HP_{\text{output}} = 0
Backup_{\text{output}} = HL

HP_{\text{output}} = HP_{\text{MinCap}}
Backup_{\text{output}} = HL - HP_{\text{output}}

HP_{\text{output}} = HP_{\text{MaxCap}}
Backup_{\text{output}} = HL - HP_{\text{output}}

Figure 3.5: Advanced heat pump control system flow diagram.
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Table 3.7: Table of inputs and outputs for balanced and advanced control strategies. Control decisions are made hourly.

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balanced and Advanced</td>
<td>Building Heat Loss (kWh/h)</td>
<td>Heat Pump Output (kWh)</td>
</tr>
<tr>
<td></td>
<td>Temperature Outside (°C)</td>
<td>Backup Heating System Output (kWh)</td>
</tr>
<tr>
<td>Balanced Only</td>
<td>Heat Pump Capacity (kWh/h)</td>
<td></td>
</tr>
<tr>
<td>Advanced Only</td>
<td>Heat Pump Balance Temperature (°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Temperature Cut-Off (°C)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Time of Use (Off–Mid–Peak)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy Prices ($/kWh)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat Pump COP</td>
<td></td>
</tr>
</tbody>
</table>

refer to it as “balanced” control due to the use of a balance point temperature, the temperature at which the heat pump can no longer supply adequate heat energy to maintain the interior temperature (21°C). If the heat pump is used only when the cost is the same or lower than conventional heating, we could expect the homeowner to save money over the heating season. Only the advanced control is aware of the financial implications of choosing to use one heating system over the other.

3.2.5 Price of energy

Energy costs in each city are based upon current (as of July 2017) costs of electricity, natural gas and furnace oil. Notably Ontario has mandated a cost reduction of approximately 25% for residential electricity. This price reduction has a positive effect on the relative difference in cost between fossil fuel energy sources and electricity. Prices for electricity and natural gas are established by the Ontario Energy Board (OEB), an independent regulator [51].
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Heat Pump Capacity Data
Heat Pump COP Data

T_{\text{out}} > T_{\text{bal}}
HP_{\text{output}} = 0
Backup_{\text{output}} = HL

NO

YES

Determine at T_{\text{out}}
[HP_{\text{MaxCOP}}^*, HP_{\text{MinCap}}^*]
[HP_{\text{MinCOP}}^*, HP_{\text{MaxCap}}^*]

If HP_{\text{MaxCap}} \leq HL
Set HP_{\text{output}} = HL, Else
HP_{\text{output}} = HP_{\text{MaxCap}} - \text{Time Penalty}

Backup_{\text{output}} = HL - HP_{\text{output}}

Calculate HP_{\text{COP}}

Figure 3.6: Balanced heat pump control system flow diagram.

Electricity prices

Electricity is subject to time-of-use (TOU) pricing. This means that during winter months the price is lowest during the evening hours of 7pm to 7am. It is moderately priced between the hours of 11am and 5pm, and most costly from 7am to 11am and 5pm to 7pm. Prices are 6.5, 9.5 and 13.2 cents per kWh. Saturdays, Sundays and holidays are billed at the lowest rate for all hours of the day.

All electrical consumption measured at the meter is multiplied by a total loss factor (TLF) intended to account for losses in transmission and some of the costs
of maintaining the grid system. The TLF is different for each utility and regulated by the OEB. Costs tend to be higher for medium- and low-density populations, and lowest for those living in higher density urban environments. All cities analyzed are urban in terms of population density and are therefore treated as high density for calculating the TLF.

Beyond the TLF, charges are applied per kWh consumed to compensate utilities for delivery and regulatory costs. These are shown in table 3.8 as a Delivery and Regulatory Adder (DRA). Again, the OEB approves applications made by the utilities to adjust these prices and also applies reductions or increases where it is demonstrated that the true costs were different than expected. The total cost of electricity per kWh consumed at offpeak, midpeak and peak times is shown in table 3.9.

Table 3.8: Added costs for electricity consumption. TLF is multiplied by consumption in kWh and delivery and regulatory adders (DRA) are added per kWh consumed [35, 24, 21, 65, 23, 67, 18].

<table>
<thead>
<tr>
<th>City</th>
<th>TLF (multiplier)</th>
<th>DRA c/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingston</td>
<td>1.0393</td>
<td>2.620</td>
</tr>
<tr>
<td>Ottawa</td>
<td>1.0335</td>
<td>2.938</td>
</tr>
<tr>
<td>Sudbury</td>
<td>1.0540</td>
<td>1.940</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>1.0342</td>
<td>2.380</td>
</tr>
<tr>
<td>Timmins</td>
<td>1.0570</td>
<td>2.527</td>
</tr>
<tr>
<td>Toronto</td>
<td>1.0376</td>
<td>3.020</td>
</tr>
<tr>
<td>Windsor</td>
<td>1.0377</td>
<td>2.574</td>
</tr>
</tbody>
</table>

Charges applied monthly at fixed rates are not included in the calculations because the homeowner would have to cease all use of electricity to avoid them. This is rarely feasible and would render the discussion of economic feasibility here within moot. However, for reference a fixed delivery charge of approximately $21 per 30 days of
service is applied alongside a $0.25 regulatory administration fee and a $0.79 smart metering charge [35, 24, 21, 65, 23, 67, 18].

Table 3.9: Energy prices in c/kWh [35, 24, 21, 65, 23, 67, 18].

<table>
<thead>
<tr>
<th>City</th>
<th>Electricity (Off — Mid — Peak)</th>
<th>Natural Gas</th>
<th>Furnace Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingston</td>
<td>9.80 — 13.1 — 17.2</td>
<td>4.5</td>
<td>11.3</td>
</tr>
<tr>
<td>Ottawa</td>
<td>10.1 — 13.4 — 17.4</td>
<td>3.5</td>
<td>11.3</td>
</tr>
<tr>
<td>Sudbury</td>
<td>9.20 — 12.6 — 16.6</td>
<td>3.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>9.60 — 12.8 — 16.8</td>
<td>3.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Timmins</td>
<td>9.90 — 13.2 — 17.3</td>
<td>3.8</td>
<td>11.2</td>
</tr>
<tr>
<td>Toronto</td>
<td>10.3 — 13.5 — 17.6</td>
<td>3.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Windsor</td>
<td>9.80 — 13.1 — 17.1</td>
<td>3.2</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Natural gas prices

Fossil fuel prices are often subject to similar fixed monthly costs. Natural gas in particular tends to have an identical $21 per month delivery charge. Energy consumption costs are generally calculated per cubic metre of gas volume, but for this study all pricing is shown per kWh of energy consumed at the meter. The conversion factor used is 10.361 kWh/m³ [48]. Delivery, transportation, storage and other consumption related fees are shown in table 3.9 to allow direct comparison of costs with other energy sources.

Furnace oil prices

Furnace oil prices are collected per jurisdiction; an average of the monthly prices over the year preceding July 2017 are used in this study. These prices are also shown in Table 3.9 [38].
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3.2.6 GHG emissions calculations

GHG emission abatement is measured using the global warming potential 100 year time horizon (GWP$_{100}$) as specified in the Intergovernmental Panel on Climate Change 2013 report on climate change [30]. This time horizon is chosen to allow comparison with Government of Canada carbon emissions reporting to the United Nations Framework Convention on Climate Change [68]. This standard is also used to report emissions from electricity generation all across Canada [20]. Table 3.10 shows the GWP$_{100}$ GHG emissions due to consumption of one kWh$_{th}$ of either natural gas, furnace oil, or electricity [26, 15].

Table 3.10: CO$_2$e emissions by fuel type (GWP$_{100}$) [16, 30, 52].

<table>
<thead>
<tr>
<th>Heating Energy Source</th>
<th>Carbon Emissions (gCO$_2$e / kWh heat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (varies by hour &amp; month)</td>
<td>24-68</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>215</td>
</tr>
<tr>
<td>Furnace Oil</td>
<td>351</td>
</tr>
</tbody>
</table>

**Electricity GHG emissions**

As shown in table 3.10, GHG emissions due to the use of electricity varies hourly. This variability occurs because of the number and type of generators supplying electricity changes throughout the day. Data obtained from the Independent Electricity System Operator (IESO) provides historical generator output by type and hour [26].

Emissions from all electricity generators in Ontario are available from Environment and Climate Change Canada [15]. GHG emissions reported are exclusively for natural gas (and a few oil) fired generators. Taking the reported emissions for these generators and dividing by the electricity output of these same natural gas generators
for the year, an average GHG emission intensity per kWh generated is calculated (560 gCO$_2$e/kWh$_e$). The hourly generating mix for each month is averaged over the whole month to produce an average day.

### 3.2.7 Single dwelling calculations

For each city the results of the EnergyPlus simulation are used to determine the proportion of heating provided by heat pumps and also by the backup heating systems. During any hour that a heat pump is used there is a reduction in energy consumption as compared to using the backup heating system exclusively. Electricity needed to operate the heat pump is subtracted from the displaced backup heating energy to arrive at a net reduction in energy consumption.

Similarly, supplying all heating needs with the backup heating system results in GHG emissions that are considered the baseline estimate. Any heating displaced by heat pump use in a given hour results in the equivalent abatement of GHG emissions. The emissions resulting from electricity consumed by the heat pump is subtracted from the GHG emission reductions to arrive at a net value.

Costs of heating are calculated by tallying the cost of the source of energy for backup heating. This baseline cost is measured against the displaced backup heating cost minus the cost of electricity needed to power the heat pump when it is in operation. The costs of natural gas and furnace oil are constant, whereas the cost of electricity varies hourly due to TOU pricing (elaborated in section 3.2.5).

Results for these three metrics are shown for the average house in each of the seven cities studied for all six scenarios tested in sections 3.3.4, 3.3.5 and 3.3.6.
3.2.8 Full adoption estimates

The results from the single home models are extrapolated to all the available SDDs in the 7 cities studied. Available homes are those with either natural gas, electric, or oil heating. The possibility of full adoption of heat pumps in all of these homes is investigated. Energy consumption changes and GHG emissions abatement are considered. The purpose of these calculations is to inform the reader as to the consequences of the hypothetical scenario, where one heat pump technology becomes ubiquitous. In reality, it is likely that a blend of technologies similar to the three heat pumps studied will be adopted in much smaller numbers over the coming decades.

The total number of homes selected to use heat pumps is 480,330 across the 7 cities. These represent 9.3% of the total number of dwellings in Ontario, and about 1/6th of all SDDs. Scaling these results to cover the whole province is inaccurate because weather conditions vary so widely, and it is not likely that the proportion of homes selected in each city will accurately represent the number of adopters in similar climates.

3.3 Results and discussion

Each of the three heat pumps has been modelled, with the average home described above, in each of the seven cities and subjected to two control systems. These six scenarios are denoted with prefixes “SS,” “VC,” and “VD” for single stage, variable speed centrally ducted, and variable speed ductless, respectively. The balance point control is denoted by a “-B” suffix and the advanced control is denoted by a “-A”.

These scenarios are intended to estimate the effects of full adoption of each type of heat pump system in every available SDD in the seven chosen cities. Estimates
of the aggregate effects on energy consumption and GHG emissions are made. The net effect on electricity demand for every hour of the day is calculated and shown in figure 3.14. GHG emissions are also estimated based upon three different generating mixes resulting from the net change in electricity demand.

The dwellings available include those with primary heating that is electric (10.7%), natural gas (64.5%) or oil-fired (5.5%). Any SDDs that already have heat pumps (9.5%) and those with other heating systems (1.1%) are not included. All homes with dual fuel systems (remaining 8.7%), including wood fired heating, are excluded from these estimates.

The results of these estimates are provided for an average day in the month of January (the complete year is available in Appendix B). Results are for each hour of the day, with the goal of showing when heat pumps are used during the day and when they contribute to reduced energy consumption, increased electricity demands, and reductions of GHG emissions. These scenarios are a best case where full adoption of heat pump technology has occurred. The objective is to inform the reader as to what the results may be if a particular policy measure is pursued in an effort to stoke heat pump adoption. Similarly, we can see the merits of each technology and control system in terms of energy, GHGs and electricity demand during the coldest month of the year.

Following these aggregated results are the results for single dwellings in each city. These results provide estimates of energy consumption, GHG emissions, and operating costs for the homeowner for an entire year. Because cities are investigated individually, the differences in climate and energy prices reveal some of their effects.
3.3. RESULTS AND DISCUSSION

3.3.1 Hourly energy consumption

The following figures 3.7 through 3.12 show heating energy consumption for all the available SDDs in the seven cities studied. If the available homes did not have any heat pumps operating, the energy represented by the total coloured area on each chart would be consumed for home heating. However, since we are simulating full adoption, the energy represented by the area in dark green (Energy Savings) at the top of each chart is saved. In order to save this amount of energy, electricity was used to operate the heat pumps, and this is represented by the area shaded in light green (HP Electricity Demand). Energy used to operate the conventional heating systems when the heat pumps are not able to provide heat is shown in gray (Conventional Heating). Again, the entirety of each chart would be gray without the use of any heat pumps, which is the current state of affairs.

In the month of January temperatures are at their coldest in the year and so every heat pump system will be stressed to its limits of operation for at least part of the month. The differences between the usual balance point control and the advanced control system that considers operating costs is not very large. Consequently, we can conclude that the SS-B and SS-A scenarios (figures 3.7 and 3.8) are limited by heat pump performance. It should be noted that even this single stage heat pump can provide for nearly all of the heating needs in more moderate months like March or October. Overall energy savings are on the order of 10% using the SS heat pumps for the month of January.

The variable speed heat pumps are often much more capable and can be used over a greater temperature range, especially when there is complete disregard for the cost of operation. Figure 3.9 confirms this for the variable speed centrally ducted heat
3.3. RESULTS AND DISCUSSION

Figure 3.7: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–SS-B.

Figure 3.8: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–SS-A.
pump systems. There are much greater energy savings possible with this technology. Approximately a third of energy consumption can be eliminated in the VC-B scenario. Unfortunately, these systems are hampered by less economical performance in the cold weather than the best ductless heat pump systems (see figures 3.3 and 3.4). The result is that we see energy savings (VC-A shown in figure 3.10) not much greater than that of a single stage heat pump (figure 3.8) when advanced control is applied.

![Figure 3.9: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–VC-B.](image)

Performance is best with a ductless heat pump system. Figures 3.11 and 3.12 show that, despite the month of January being the coldest in the year, the variable speed ductless heat pump systems are able to supply most of the heating needs in these seven cities, at least as a whole. The balanced control shows an energy savings of approximately 2,000 MWh throughout the day. This is equivalent to an almost 60% energy saving during most of the day. The conventional heating needs become
3.3. RESULTS AND DISCUSSION

Figure 3.10: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–VC-A.

almost negligible during the warmest and sunniest hours of the day.

Figure 3.12 shows the effect economics can have on good technology. It is crippling, and the pattern is pronounced. When electricity prices are highest in the mornings and evenings, very large peaks of conventional heating emerge because natural gas furnaces are less costly to operate than ASHPs. These peaks are present in figures 3.8 and 3.10 as well, but they are much less pronounced because they are hidden by the lower performance capabilities of the other heat pumps under the harsh conditions of January in Ontario. Under more moderate weather conditions these peaks become apparent for the less performant heat pumps, as well.
3.3. RESULTS AND DISCUSSION

Figure 3.11: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–VD-B.

Figure 3.12: Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities–VD-A.
3.3. RESULTS AND DISCUSSION

3.3.2 Hourly net change in electricity demand

Most heating is accomplished with natural gas. Using a heat pump in conjunction with a natural gas furnace results in less natural gas being used and more electricity being used in its place. It is therefore natural to consider whether use of heat pumps in these six scenarios will result in a net increase in the demand for electricity. The use of electricity to drive the heat pump systems is an increase in demand, whereas the displacement of conventional electric heating constitutes a reduction in demand.

Even though only 10.7% of all the SDDs use electric heating, adding heat pumps to all of these homes causes a significant decrease in electricity demand (see figure 3.14). In the advanced control scenarios we can see that this results in a demand reduction for part of, or all of the day. The VD-A scenario shows that it remains economical to run during offpeak electricity times and less so during peak and midpeak billing hours. No scenario exceeds approximately 600 MWh/h of increased demand.

The full electricity generation supply breakdown can be seen in figure 3.13. We see that in January between 17,000 and 21,000 MW of generation are online at anytime during the day. These six scenarios representing full adoption amongst the 480,330 SDDs in seven cities produce an increase in demand of at most 3% and at the least a slight reduction in demand. Scaled to the full number of SDDs in Ontario, this might mean as much as an 18% demand spike, but more likely we would see somewhere around 3-5% increase in demand due to the least expensive heat pump being favoured along with the common balanced control (corresponding to scenario SS-B). Most importantly, we cannot expect full adoption of heat pumps amongst all SDDs in Ontario to occur anytime soon. The very significant effect of TOU pricing should also be noted as an effective method of managing heat pump electricity demand if
energy-price-aware (advanced) controls are installed in most homes.

Figure 3.13: Electricity generation by fuel type for each hour of the average day in January 2016.

Figure 3.14 does show increases in demand for electricity occurring in the early evening for scenarios VC-B, VD-B, and VD-A. These increases coincide with increases in demand that already occur at these times (see figure 3.13). However, the large dips in the VD-A net demand curve due to higher TOU prices from the 17th-19th hours demonstrate the potential effect high electricity prices can have in preventing peak heat pump use when needed. Higher electricity demand late at night may even be beneficial, since demand is typically lower at these times.

It seems likely that in the next 5 to 10 years we will see very small changes in electricity demand due to heat pumps regardless of the scenario chosen because adoption of heat pumps will not be significant [64, 25, 26]. Policy makers might
3.3. RESULTS AND DISCUSSION

for this reason consider the pursuit of the electrification of home heating with heat pumps separately from any concerns for electricity generation. By the time a mix of the six scenarios presented materializes, electricity generation will be approximately as carbon intensive as the current mix or better [52]. This means GHG emissions may not be affected significantly by increased demand. Furthermore, any spikes in residential electricity demand seem to be easily mitigated by TOU pricing. However, this mitigation does require controls like the advanced control system proposed in this study.
3.3. RESULTS AND DISCUSSION

3.3.3 Hourly greenhouse gas emissions reductions

GHG emissions are calculated on an hourly basis for each scenario just as has been done for the previously analyzed quantities. The emissions from electricity generation are based upon the average mix for the month of January shown in figure 3.13. All the emissions from electricity generation are a consequence of burning natural gas. Life-cycle emissions are not used in the calculation of GHG emissions. That is, we do not consider the carbon emissions associated with the construction of the facilities, their annual maintenance, or future emissions due to decommissioning.

Because natural gas generators represent a small proportion of the generating mix (shown in light blue and labelled “Gas” in figure 3.13), the emissions in January are very low. This is due in part to the increased availability of wind power generation during the winter months. It is shown as a near constant in this chart, but on a daily basis it is highly variable. While the wind often blows strongest in the evenings and at night, it is not guaranteed. Nevertheless, we use the average day for each month of the year in our analysis.

The outcome for an average day in January is shown in figure 3.16. Higher numbers represent a greater reduction in GHG emissions. The exception is the “conventional” emissions shown in black. These are the baseline GHG emissions expected from the current heating system stock. We can expect the greatest reductions with the best heat pump technologies and not much less than 100 tonnes of CO$_2$e eliminated per hour of each day in January with even the least effective (and least costly) heat pumps.

It should be noted that these GHG reductions are also calculated for a total of 480,330 SDDs in the 7 cities chosen. This represents almost $\frac{1}{6}$ of the total number
of SDDs in Ontario, and about $1/10^{th}(9.3\%)$ of the total number of dwellings of all types in Ontario in 2016 [59].

A fundamental assumption in this study is that the electricity generating mix will remain constant despite any increases in electricity demand due to heat pump use. This assumption may be correct because heat pump use is predictable one day in advance, and one hour in advance. This predictability of heat pump use allows for electricity demand to be predicted early enough for all types of generators to bid to fill that need. However, in figure 3.15 we consider the implications of a worst case scenario: all new demand is met by natural gas generators. Natural gas generators produce on average 560kgCO$_2$e emissions per MWh of electricity consumed in Ontario [15]. Figure 3.15 depicts in dark blue the outcome of maintaining a constant generating mix. If all new demand is met by natural gas generators but the overall generating mix is attributed to the electricity used by heat pumps, fewer GHG emissions will be avoided. These results are shown in orange and labelled "NG Mix". If all new demand for electricity is met with natural gas generators and the full brunt of these new emissions are attributed to the heat pumps, far fewer GHG emissions are avoided, shown in teal and labelled "NG" in figure 3.15.

First, it is important to note that GHG emissions are always reduced regardless of the scenario chosen. Any heat pump with any control scheme subjected to any of the three electricity generation attribution schemes will still result in a net improvement. Second, it is somewhat interesting to note that under scenarios SS-A and VC-A, GHG abatement increases under the worst case scenario where natural gas generators provide for all new electricity demands. This is because it is assumed that natural gas generators are also the first to cease operating when demand for
electricity decreases. Because SS and VC are unable to compete economically with natural gas fired furnaces, they are not as often used under the advanced control strategy. Electric furnaces however will always be out-competed by heat pumps and will therefore always be displaced by heat pumps. This displacement results in a net decrease in electrical demand under scenarios SS-A and VC-A (see figure 3.14). The resultant reduction in GHG emissions for electricity generation is therefore attributed to the heat pumps used in those two scenarios and GHG abatement increases relative to the status quo scenario.
3.3.4 Energy

The best possible energy efficiency achievable by a conventional heating system is 100%. This is the absolute worst possible performance that we can expect from a heat pump. A 100% efficiency corresponds to a COP of 1.0 and most heat pumps seem to reach their minimum operating temperature while still achieving a COP of 1.2–1.8 [49]. Because of this fact we will never see energy requirements for heating with heat pumps that exceed those of conventional heating systems.

Electric backup heat

Electric conventional furnaces or baseboard heaters are the only conventional heating systems capable of achieving 100% efficiency. In this study we attribute this high
efficiency to all-electric heating systems. The electrical energy consumptions shown in the figure 3.17 are therefore equivalent to the heating needs of our prototypical average home in each city (shown on the left).

![Energy consumption per home of heat pumps compared to electric heating by city.](image)

We see in figure 3.17 that Timmins has the greatest heating requirements and Windsor has the least heating required. It is apparent that all heat pumps, whether controlled with a balance temperature point or the advanced regime, use less energy over the year than conventional electric heat. Energy reductions are substantial, ranging between 21% in Timmins using the single stage heat pump to nearly 80% in Windsor with the variable ductless heat pump.

The advanced control system seems to provide greater reductions in energy consumption than the usual balance point control. This is because both the heat pumps
and the electric backup heating system are powered with electricity and any time a heat pump can be operated it will cost less than electric heat. Balance point control switches over to the conventional furnace when the heat pump can no longer provide the full heating. This switch occurs once the outdoor temperature is low enough that the home’s heat loss exceeds the heat pump’s capacity. While this is a simple control strategy to implement, it prevents energy from being saved due to the fact that the heat pump could still provide for part of the heating demand while the electric furnace can supply the remainder. Simultaneous operation is possible if the heat pump indoor heat exchanger is installed before the electric furnace coils.

**Natural gas backup heat**

Natural gas prices are far lower per unit of energy than electricity. This has no effect on energy consumption for the balance point controlled heat pump results, but has a significant effect on those using the advanced controls. It is simply not economical to use a heat pump as often when natural gas backup heat is available. Because of this trade-off between cost and energy savings we see that in figure 3.18 the energy consumption is nearly always greater under advanced control.

Despite the negative effects of energy prices we see that energy consumption can still be reduced by using heat pumps instead of conventional natural gas heating. Depending on the city and control strategy chosen, energy consumption can be reduced by approximately 20–80%. These significant energy consumption reductions will necessarily lead to fewer GHG emissions in a jurisdiction like Ontario, where electricity is generated with few fossil fuel inputs.
3.3. RESULTS AND DISCUSSION

Figure 3.18: Energy consumption per home of heat pumps compared to natural gas heating by city.

**Furnace oil backup heat**

Oil furnaces tend to have the lowest energy efficiency of any type of heating system. We used 80% efficiency for oil furnaces in our model (2% higher than NRCan) [44]. This lack of efficiency results in the greatest energy needed to replenish the heat lost during the year of any of the heating systems analyzed. Figure 3.19 shows the high furnace oil energy needs alongside the much lower energy requirements of the six heat pump simulations. Because oil heating is often more expensive than using a heat pump, energy abatement remains economical. That is, energy consumption is always lower when heat pumps are modelled with advanced control partly because heat pumps can operate at lower temperatures than with a simple economic balance point,
but also because the control system can avoid times when heat pump performance is low and electricity prices are high. We can see an overall reduction of energy consumption of between 36% and 84% throughout the 7 cities and 6 scenarios in figure 3.19.

Figure 3.19: Energy consumption per home of heat pumps compared to furnace oil heating by city.

### 3.3.5 Greenhouse gas emissions

The natural consequences of significant reductions in energy consumption are reductions in GHG emissions. Figures 3.20, 3.21 and 3.22 below show GHG emissions in kilograms of carbon dioxide equivalent (kg CO$_2$e) using the 100 year global warming potential [30, 20]. They are calculated for both the emissions due to consumption of
electricity to operate the heat pumps, and also for each of the backup heating systems. Emissions are calculated hourly to reflect the changes in electricity production mix throughout the days and months.

![Figure 3.20: GHG emissions comparing electric heating and heat pumps with electric backup heating by city.](image)

With heat pump use, yearly emissions are reduced by between 0.2–0.7 tonnes for homes with electric heating, 1.5–4.5 tonnes for homes with natural gas heating, and 3–10 tonnes per home with oil heating. While it is certainly inaccurate to extrapolate these data to the whole of Ontario, we can make a simple estimate of the total potential for abatement. Knowing that most homes in Ontario have natural gas heating, and assuming it is possible to average 2 tonnes CO$_2$e of curtailment per year per household, we can expect approximately 5.5 MtCO$_2$e emissions reductions for all the SDDs in Ontario (54.3% of dwellings), if each of them had a heat pump in operation. A 5.5MtCO$_2$e represents approximately 25% of all GHG emissions from
3.3. RESULTS AND DISCUSSION

Figure 3.21: GHG emissions comparing natural gas heating and heat pumps with natural gas backup heating by city.

Figure 3.22: GHG emissions comparing oil heating and heat pumps with oil backup heating by city.
the residential sector in Ontario [41]. While we can be certain this will not come to pass any time soon, we can see there is potential for significant reduction of GHG emissions in the residential sector, especially since this calculation ignores all other types of dwelling (45.7% of dwellings).

### 3.3.6 Costs and savings

The cost of heating with conventional heating equipment is generally greater than the cost of heating with a heat pump. However, the typical method of control—balanced—often increases the cost of heat pump use. Advanced controls that are aware of the cost of electricity and the expected heat pump performance for the current weather conditions can make heat pump heating less costly.

![Figure 3.23: Cost of heating per year with electric heat and heat pumps with electric backup heat by city.](image-url)
3.3. RESULTS AND DISCUSSION

Electric heating

The cost of heating with electricity is one of the most expensive options available. Conventional furnaces or baseboard heaters show costs ranging from approximately $2,000 per year in Windsor, where both the weather is mild and the cost of electricity is low, to more than $3,600 per year in Timmins where electricity is more costly and the climate is much colder.

For homes using electric heat, even the single stage heat pump offers a considerable annual savings of approximately $600 to almost $1,000, using a balance point of \(-4^\circ\text{C}\). With advanced controls we can see that maximal savings occur in Kingston. The advanced control system provides a significant increase in economic performance for both the single stage (SS) and the variable speed centrally ducted (VC) heat pumps.

Variable speed heat pumps are even less expensive to operate. The variable speed
ductless (VD) heat pump system has a clear advantage regardless of the control system used. Savings often exceed $2,000 per year for the ductless system.

**Natural gas heating**

Natural gas heat is widely regarded as the least costly, but figures 3.25 and 3.26 show that heat pumps can provide lower cost heating in all climates. Unfortunately, it appears that only the variable ductless system can produce any significant savings. In fact, the variable centrally ducted heat pump tends to cost more to operate than conventional heating because it possesses the capacity for heating but not at high enough COPs to overcome the economic disadvantage imposed by very low natural gas prices.

Advanced control is able to ensure some savings, however marginal, in every jurisdiction with every heat pump, but as seen before this means that the heat pumps are often turned off in favour of conventional natural gas heat. Though cost efficient, natural gas furnaces are not as energy efficient as heat pumps, and energy consumption results in section 3.3.4 and Figure 3.18 confirm this.

The best of today’s technology—the variable speed ductless heat pump—is capable of providing heat for all or most of the heating season throughout Ontario, and it can also overcome the enormous price advantage of natural gas heat (see figure 3.26). However, it is unlikely that these yearly savings are sufficient to pay back the initial capital investment quickly enough for most homeowners.
3.3. RESULTS AND DISCUSSION

Figure 3.25: Cost of heating per year with natural gas heat and heat pumps with natural gas backup heat by city.

Figure 3.26: Savings per year with natural gas heat and heat pumps with natural gas backup heat by city.
Furnace oil heating

Oil heating is similar to electric heat in that it is costly. Oil furnaces are also less efficient than either natural gas or electric heat, and this further adds to their operating costs. There is therefore much opportunity to save on annual heating costs by adding a heat pump to an oil home heating system. Figures 3.27 and 3.28 show both the high cost of oil heating and the significant savings to be had when using a heat pump.

Figure 3.27: Cost of heating per year with oil heat and heat pumps with oil backup heat by city.
3.4 Conclusions

Energy consumption and GHG emissions can be significantly curtailed by adding a heat pump to any home heating system in Ontario. The least capable and costly heat pumps can provide significant energy and GHG emissions reductions, of at least 20% in most cases. It is conceivable that a reduction of 50% of all energy consumption and GHG emissions produced by heating SDDs in Ontario can be achieved in the coming decades. The inevitable reductions in the capital cost of today’s best available technologies will undoubtedly lead to an increase in the number of heat pumps installed.

The price of natural gas is currently so low that it inhibits heat pump adoption. We can see from this study that the cost savings with the chosen heat pumps are not
3.4. CONCLUSIONS

great enough except with the best possible technology (see figure 3.26, VD-A). Even in this case the initial capital investment required may be too great to be warranted. As carbon pricing increases the cost of natural gas heating, and as natural gas itself becomes more expensive, we may see a more favourable cost comparison between electrically powered heat pumps and natural gas heating.

From the results shown in figure 3.14 it is clear that TOU pricing can substantially affect the net electricity demand. With the price high enough at times of peak use, electric (and usually oil) heating will be displaced by heat pumps with capacity at the current outside temperature. This can be accomplished with existing wiring and new thermostats aware of the costs of energy sources, performance of the attached heat pump, and the time of day. These advanced control capable thermostats could easily be employed to provide other demand response services through programs administered by the IESO. Heat pump owners providing these services should be compensated duly, which in turn is a further incentive to purchase and operate a heat pump.

GHG emissions can be reduced significantly in part because electricity produced in Ontario uses very few fossil fuel inputs. It is also notable that, when unimpeded by economic factors, heat pumps can displace a large portion of the fossil fuel based emissions from home heating. Encouraging homeowners to switch away from furnace oil and natural gas produces the greatest reduction in GHG emissions. Adding heat pumps to electric and furnace oil systems provides the greatest economic benefit to the homeowner.

Acknowledgements The author acknowledges the support of the Natural Science and Engineering Research Council of Canada. Most importantly, the author would like to thank H.C. Hooker for advice, editing and encouragement.
Conflict of Interest The authors declare that they have no conflict of interest.
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Chapter 4

Energy price policy to electrify home heating in
Ontario, Canada

Prepared for Submission to the Journal of Energy Policy
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Abstract Climate conditions in Ontario, Canada are among the most challenging of any well-populated area. Winter temperatures reaching well below 0°C can require significant heat input to maintain comfortable indoor temperatures. Most homes in Ontario’s cities achieve this comfort with a central natural gas furnace that delivers heat via a system of ducts. Central air conditioning, present in 69% of Ontario’s homes, is provided through the very same ductwork. We investigate the possibility of replacing air conditioners in Ontario dwellings with low cost heat pumps. Paying back the added expense within 3-5 years has been feasible in many cities in the past, but varies greatly depending on the relative costs of natural gas and electricity. We suggest limiting the minimum price of natural gas to approximately 4 cents per kWh of heat energy, and selecting one of two time-of-use electricity rate plans. Annually, this
strategy reduces heating costs by $200-400, energy use by 9-12 MWh, and greenhouse gas emissions by 2.5-3.5 tonnes $CO_2e$ in single detached homes with a heat pump and natural gas forced-air furnace.

4.1 Introduction

Ontario, the most populous province in Canada, offers a range of climatic conditions requiring significant home heating in winter months. In cities, most homes have natural gas furnaces that deliver heat with a fan and duct system. Summer months can be uncomfortably warm and humid, but winters are much longer. Despite the relatively insignificant energy needs for cooling in summer months, many homes in Ontario have air conditioners installed in combination with their central heating system [21, 26, 1]. In fact, from 1990 to 2015, space cooling energy needs never reached 5% of the annual energy requirements in Ontario’s residential sector [23]. During 2014, a fairly typical year in terms of heating and cooling needs, space cooling accounted for 2.5% of energy use, while space heating accounted for 64.6% [23].

It is remarkable that homeowners are willing to incur the capital expense of an air conditioning system when it has comparatively limited utility. A 10–20% added expense would allow the replacement of an air conditioner with a heat pump capable of delivering both cooling in summer and heating in winter. Given the enormous need for home heating and potentially much greater utility of a heat pump, we investigate the costs and benefits of replacing the nearly ubiquitous home air conditioner with a heat pump.

We calculate the annual savings potential of heat pumps compared to conventional natural gas heating over a decade (2007–2017) of energy price data in 6 cities.
across Ontario. The same metrics are applied to potential future electricity rate plans currently under consideration. These are applied in all cities province-wide.

4.1.1 Background

Home heating in Ontario

The focus of this work will be on single detached dwellings (SDD). In this category of building there is usually one heating system servicing the entire building, and a surprisingly large number of SDDs have central air conditioning units attached to natural gas forced air furnaces (more than 1.4 million of 2.4 million SDDs in Ontario cities) [39, 1]. In 2014, the most recent year with heating and cooling needs that were approximately average, cooling needs were only slightly higher than average. Still, less than 3% of energy use in Ontario SDDs was for cooling, while 67% of energy was used for space heating (see figure 4.1). Space heating is by far the greatest single end use for energy in the home. Unfortunately, most homes use fossil fuels for this purpose [24]. Natural gas is the most likely fuel to be used in cities, because of availability and affordability.

While heat pumps, specifically air-source heat pumps (ASHP), can provide heat at lower costs than conventional natural gas heating, it is still expensive to purchase an ASHP specifically for space heating. The conventional furnace will still be required as a backup heat source in the event that outside temperatures fall below the ASHP’s operating range. This requirement makes the ASHP an addition to the home heating system and not a replacement. The capital cost is therefore added to that of the existing home furnace.
Air conditioners in Ontario

In Ontario, 69% of all households, including rural areas and homes with oil, propane, or electric furnaces, have central air conditioning (AC) systems [1]. Amongst SDDs in cities with natural gas furnaces this percentage falls to approximately 58%, and ACs are more popular in southern cities than in northern cities [1]. AC units provide no energy savings and have rather limited use in terms of overall energy consumption (see figure 4.1), though they do provide a much-needed service when outside conditions are extremely hot or humid. For this service, homeowners must pay approximately $4-5k to install a basic AC for an average-sized home. Such a device has no utility for space heating, while a heat pump can provide both cooling in summer and heating
in winter.

**Heat pumps: A viable alternative**

Heat pumps rely upon the same principles of operation as AC, but possess a reversing valve allowing heat to be moved in the opposite direction when required. That is, AC allows heat from inside the home to be pumped outside; an ASHP can do this too, but it can also move heat from outside the home in. ASHPs, outwardly identical to AC systems, can extract heat from outside air as cold as -30°C\[20\]. However, the particular ASHP considered in this study is not operated below -12.2°C\[8\], which is its normal low temperature cut-off. It is a more affordable and therefore lower-performing heat pump.

For homes that already have AC, it is assumed that replacement will occur approximately every 15–20 years. When replacing the AC with a modern device, one could instead purchase a low-cost ASHP. The added cost would be approximately $1000. In this circumstance the homeowner would gain the ability to heat at a lower cost than natural gas heating at certain times of the day and year, and there is potential for a simple payback of the added cost in as little as 3–5 years in some cities at today’s energy prices.

Table 4.1: Cities, heating degree days (HDD) and winter design temperatures (WD).\[3, 12\]

<table>
<thead>
<tr>
<th>City in Ontario</th>
<th>HDD 18.3 (days °C)</th>
<th>99% WD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kingston</td>
<td>3976</td>
<td>-21.5</td>
</tr>
<tr>
<td>Ottawa</td>
<td>4441</td>
<td>-20.8</td>
</tr>
<tr>
<td>Sudbury</td>
<td>5241</td>
<td>-24.7</td>
</tr>
<tr>
<td>Thunder Bay</td>
<td>5594</td>
<td>-26.6</td>
</tr>
<tr>
<td>Toronto</td>
<td>3533</td>
<td>-13.7</td>
</tr>
<tr>
<td>Windsor</td>
<td>3444</td>
<td>-13.1</td>
</tr>
</tbody>
</table>
While ASHPs cannot yet satisfy heating needs for the entire winter in all of Ontario, they can provide for most of the heating needs in all of Ontario and even all of the heating needs in some of the warmer parts of the province. Table 4.1 has six cities listed with their corresponding 99th percentile winter design temperatures. Temperatures are typically lower than these winter design temperatures only 1% of the time. Many ASHPs available today can provide heat at temperatures of -25°C or lower, and many are able to maintain their full heating capacity at -15°C. However, low-cost ASHPs tend to stop operating at much warmer temperatures.

In terms of cooling performance, heat pumps and air conditioners of the same approximate value tend to have similar specified performance ratings for cooling. It is for this reason that we assume upgrading to a heat pump of comparable value will not significantly degrade cooling performance, if at all.

The clear advantage of using ASHPs is that despite their relatively low price premium compared to ACs they can provide heat at 200–400% efficacy throughout most of their operating range. Natural gas furnaces in contrast can achieve maximum efficiencies of only about 98%.

Consequently, energy consumption can be greatly reduced with increased ASHP use. GHG emissions can also be curtailed by reducing overall energy needs and also by switching from fossil fuel to electricity. Unfortunately, under current market conditions it can still be less costly to use natural gas. The result is a market failure to encourage energy conservation and resource efficiency. Furthermore, climate changing emissions will not be eliminated by continuing to use fossil fuel based home heating.

In contrast, heating cost savings in homes with electric or oil furnaces can be substantial if an ASHP is added. Replacement of an existing AC system in one of
these homes is always warranted, and payback times for the addition of a ASHP
where neither a heat pump or an AC was previously present can still be a financially
sound decision.

To reduce energy consumption and GHG emissions in Ontario, the electrification
of home heating with heat pumps is the best widely available technology to use.
Because electricity generation in Ontario relies upon so little fossil fuel, a switch to
electric heat means fewer GHG emissions.

**Electricity generation in Ontario**

Electricity generation in Ontario is dominated by nuclear power generation. Hydro-
electric power is next, and wind power has provided more power than natural gas
in the last two years. In figure 4.2 we see the proportion of electricity generated by
fuel from 2015 through 2018. The emissions for electricity generation are calculated
from the proportion generated by natural gas (some oil is also used). It is interesting
to note that although the total demand for electricity increased in 2018, natural gas
generation did not increase proportionately. Natural gas was displaced by the other
fuel types. If this trend should continue it will keep increases in GHG emissions due
to increased electricity demand lower than could otherwise be expected. The electrifi-
cation of transportation and hopefully home heating will cause increases in demand
in the coming years and decades.

Ontario enacted a feed-in-tariff (FIT) program in the 2009 Green Energy and
Green Economy Act [19]. By guaranteeing the price paid per kWh, the FIT encour-
aged the installation of renewable energy generating infrastructure. As of late 2018,
Ontario has more than 5.5 GW of wind power (4,486 MW transmission-connected)
4.1. INTRODUCTION

Dolter et al. [10] assert that the federal government implementation of a carbon tax and rebate system can reduce GHG emissions in the electricity sector by 20-21% from 2005 levels at $50/tonne CO$_2e$. An $80/tonne CO$_2e$ carbon price was found to eliminate coal fired generation in Canada, but natural gas plants remain viable even at $450/tonne CO$_2e$. This is due to the value of natural gas generators at times of peak demand, balancing when wind power is unavailable, and other grid level services. Dolter et al. [10] do not consider demand response using ASHPs or residential energy storage to potentially supplant natural gas generating capacity. [10]
4.1.1 Objectives

The main objective is to find viable policy alternatives to reduce energy consumption and greenhouse gas emissions due to home heating in the residential sector while ensuring little or no economic burden is borne by the homeowner. To this end, we study the replacement of existing AC systems with similarly valued ASHPs. Because the difference might only be $1000 to upgrade to an ASHP there is a possibility to pay back this initial expense in the form of savings on the cost of heating. This narrowed scope is necessary to provide a justification for heat pump use in homes with natural gas heating. The annual cost or savings due to heat pump use is calculated for average Ontario homes. Similarly, the annual reductions in energy consumption and GHG emissions are also estimated.

A secondary objective is to estimate the potential for annual reductions of energy, GHG, and home heating bills for wide-scale adoption of low-cost heat pump technology. We briefly examine the consequential change in electricity demand at this level of adoption.

A number of electricity rate plans already being examined are used to estimate savings across the province to gauge which rate plan might provide the greatest cost savings to homeowners while conserving energy and reducing GHG emissions.

4.1.3 Modelling home heating

Modelling residential sector heating and cooling has been performed at a global scale and over the very long term [17]. However, the methodology used does not allow for the hourly time resolution needed in this study. Hourly or better time resolutions in large-scale modelling have been achieved using satellite weather data and
4.1. INTRODUCTION

light detection and ranging (LIDAR) to bring spatial resolution down to the building level[6, 14, 18]. In Ontario, there is LIDAR data available for at least some cities, which could provide the shape of each building. However, whether the building type is detached, attached, a small apartment or even commercial cannot be linked back to this data because Statistics Canada source data used here is released at a spatial resolution where there are enough records to prevent the identification of individual buildings or persons. This prevents us from using the same methodology because we cannot determine which building is of a certain type, has a certain furnace, or central AC. Nor can we have any data on insulation, fenestration, or construction at that spatial resolution. We therefore use a representative average SDD in Ontario [41] and apply it to all the SDDs within areas (dissemination areas) divided up by population in the 2016 census.

Demand side management

While this study pursues pricing policy that allows heat pump use to be economical for the homeowner, there are other mechanisms for generating household revenue to be aware of. A number of researchers have explored the possibility of providing load balancing, frequency stabilizing, and peak shaving services at the grid level by coordinating the control of many home heating systems. It is possible to provide load-following or regulation services for wind power with thermostatically controlled electrical loads like heat pumps, although less seasonally variable water heaters are preferred according to Callaway et al. [7]. Using 14,000 ASHPs in residential buildings, Wang et al. demonstrate it is possible to provide regulation and spinning reserve
at higher efficiencies than with conventional generators. Optimization included maintaining comfort within the home, despite the main mechanism of control being small modifications of the indoor temperature set point [43]. Patteeuw et al. [37] present a number of demand side and supply side modelling strategies to best develop and examine demand response systems. Strbac et al. consider the potential for increasing efficiency of the electrical system using any time-flexible electrical load [40]. Glazanskas et al. investigate the use of demand response including a modelled home controller with optimization and neural network to improve performance. These control a mix of heat pumps and conventional heating systems [13].

Baeten et al. take demand response a step further combining heat pumps with thermal storage tanks, allowing the shifting of demand away from times of peak electrical use. In the Belgian context demand response is found to increase costs for homeowners but provide a significant reduction of peak loads [4]. Patteeuw et al. also found that heat pumps in a European context are able to provide peak shaving when coupled with an active demand response system [38]. Of course these heat pumps are air-to-water systems with underfloor heating and some of the modelled homes have thermal storage tanks. Homes with in-floor heating are able to time-shift heating for longer, especially if they are well insulated [38]. Bloess et al. review the area of power-to-heat research, finding that there is opportunity to “cost-effectively contribute to renewable energy integration” with heat pumps being a “particularly favourable option” [5]. Allison et al. designed and deployed a controller to allow load shifting and thermal storage with an air to water/hydraulic heating system [2].

A common finding in the literature is that heat pumps can provide services to the grid that mitigate the disadvantages associated with highly variable renewable energy
sources. This capability is an economic advantage at the grid level and a motivation for this work, and it also highlights the importance of finding a price policy regime that ensures heat pumps are financially viable for homeowners. Without an annual cost savings from heat pump use will anyone install them?

Space cooling needs are expected to increase across the globe and heating needs to decrease over the next century [17]. Since a hot and humid home is perceptibly uncomfortable, even unhealthy, people may be motivated to purchase an AC. In Ontario, it is safe to assume that heating will remain a significant energy demand; perhaps we should capitalize on this motivator and encourage the installation of ASHPs instead of ACs. Research has shown that some technologies are adopted because of a desire to fulfill needs dictated by values [36] such as a concern for the environment, or a preference for energy efficiency.

4.2 Methods

The overall methodology begins with the modelling of the average Ontario home. Data defining the average home are obtained from Swan, et al. [41]. The entire method is available in Szekeres, et al. [42].

This study proceeds in two phases. The first examines the historical performance of a particular heat pump in Ontario. The second examines the potential performance of the same heat pump under a variety of electricity pricing plans and a universal natural gas pricing plan.
4.2. METHODS

4.2.1 Cities and dwellings

In the first phase, six (6) cities are chosen. These are listed in table 4.1 along with two measures of heating needs. Much of the climate variation in Ontario is captured in these 6 cities. Windsor is one of the warmest cities in the province and Thunder Bay one of the coldest. Although some cities farther north have even colder conditions, populations there tend to be much smaller than in the south of the province. Toronto, in southern Ontario, is the most populous city.

In the second phase of investigation, all cities in Ontario with natural gas services are included. The number of dwellings in these cities are determined using geographic information systems (GIS) and 2016 census data divided up by dissemination area (DA). DAs within cities with natural gas services are included.

The study is restricted to single detached dwellings (SDD). These are both single and two-storey buildings. Approximately half of Ontario SDDs are of each height [41], and the heating needs of these one- and two-storey buildings are therefore averaged and used for all calculations.

From the households and the environment survey we are able to estimate the number of homes in 14 census metropolitan areas (CMA) that have natural gas forced-air heating and central air conditioning for cooling. These SDDs can easily have their AC systems replaced with ASHPs. Approximately, 1.4 million SDDs in Ontario cities have these properties [39, 1].

4.2.2 Heating Needs

Heating needs are dictated primarily by weather conditions. Weather data, including outside temperature, wind speed and direction, and solar radiation are provided by
4.2. METHODS

typical meteorological year (TMY) datasets. Environment Canada has provided these for 62 locations across Ontario in Canadian Weather for Energy Calculations (CWEC) format. Hourly need for heat in an average SDD is simulated for each of the 62 TMYs. Cities are divided among these 62 weather stations based upon proximity. Larger cities like Toronto can have weather data from several weather stations. SDDs are then assigned to the nearest weather station.

The average SDD is as described in table 4.2. Features like windows and doors are evenly distributed on all four sides of the basic structure. The homes have a square footprint, a hip roof with 6/12 pitch, and attic, wall and basement insulation. Modelled homes are put through a full year simulation using EnergyPlus building simulation software with 15 minute intervals and hourly output. The full details are available in Szekeres and Jeswiet, 2018 [42].

Table 4.2: Properties of prototypical average SDD in Ontario. [41, 21, 22]

<table>
<thead>
<tr>
<th>Building Properties</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living area</td>
<td>173.0</td>
<td>m$^2$</td>
</tr>
<tr>
<td>Wall heights</td>
<td>2.4</td>
<td>m</td>
</tr>
<tr>
<td>Window (% living space wall area)</td>
<td>15.7</td>
<td>%</td>
</tr>
</tbody>
</table>
| Wall insulation (RSI)                      | 2.1   | $m^2K/W$
| Attic insulation (RSI)                     | 4.6   | $m^2K/W$
| Basement wall insulation (RSI)             | 1.4   | $m^2K/W$
| Air changes per hour at 50Pa               | 6.5   | $ACH_{50}$
| Interior temperature (+/- 0.2°C)          | 21.0  | °C    |

4.2.3 Heat Pumps, Furnaces and Air Conditioners

The SDDs eligible for upgrading to a heat pump in this study have natural gas furnaces and central air conditioners. The furnaces are assumed to have a 96% efficiency.
4.2. METHODS

This is a high efficiency for a natural gas furnace; although furnaces of higher efficiency exist many furnaces in use today are of lower efficiency [25]. In 2015, more than 43% of natural gas furnaces in Ontario were still of medium efficiency (80%), according to Natural Resources Canada. High efficiency is defined as 90%. In using a higher efficiency we are ensuring a more conservative estimate of the potential for energy, GHG, and cost savings. Homes with lower efficiency furnaces may benefit even more from using a heat pump.

One model of ASHP is used in this study. It is a single-stage heat pump with relatively low performance specifications. The rated capacity is 36,000 Btu, or approximately 10.5 kW. Figure 4.3 shows the heating capacity in a solid line as a function of outdoor temperature. The rated heating capacity is available at approximately 8°C, but falls as the outside temperature gets colder. At -12.2°C, the minimum operating temperature, capacity falls to approximately 5 kWh/h. It should be noted that this heat pump can not supply enough heat for the modelled homes below 3°C. It therefore operates part of the time and requires added heat input from the backup heating system. There is a time penalty added by the control algorithm to prevent simultaneous operation of the ASHP and furnace, and to allow cooling of heat exchangers within the furnace assembly when switching occurs.

In a dashed line is the COP while delivering heat at the capacities shown. A COP of 2–4 is achievable during operation. At the minimum operating temperature (low temperature cut-off) the COP is just greater than 2, making this basic heat pump more than 2 times as efficient in terms of energy consumed per unit of heat delivered than a high-efficiency furnace, and nearly 4 times as energy efficient at warmer temperatures.
4.2. METHODS

Electricity and natural gas pricing are important in determining the cost benefit of heat pump use. Both types of energy have prices that can fluctuate as often as every three months. Pricing schemes include rates specified for the energy commodity, delivery and regulatory charges, and also monthly service fees. The latter are excluded in all calculations of cost. It is assumed that no one will terminate their energy service in favour of an alternative. For this reason only charges that vary with consumption are calculated. All charges varying with consumption are included in the cost of heating calculations.

Electricity and natural gas prices are regulated by the Ontario Energy Board (OEB). Current and historical energy prices are available through the OEB website.
4.2. METHODS

A Quarterly Rate Adjustment Mechanism (QRAM) is employed to change rates regularly as required. The changes are based upon current and future costs of providing energy, but can also include price corrections due to higher or lower than expected historical costs. Legislation passed by the Ontario government can also affect rate changes. By examining these QRAM reports a history of prices in 6 cities was constructed from 2007–2017 inclusive.

In the case of natural gas energy is purchased per cubic metre. This volume of gas provides 10.361 kWh of energy [28]. Using this conversion factor all energy prices are tabulated in kWh of energy thereby allowing for a direct comparison between natural gas and electricity—also priced in kWh. Ultimately, the only valid comparison is in terms of heat energy provided as this is the service or functional unit for home heating—$kW h_{heat}$.

A number of rate plans for electricity are being examined by the OEB [32, 31]. These plans are shown in figure 4.4. The first two, 2017 and 2018, are the actual time-of-use (TOU) rates charged to Ontarians in those years. The third, O4, is a rate plan identical to the 2018 rates, but with a 4¢ price over night from 7pm to 7am. TOU prices are not the full cost of electricity. Each kWh of electricity consumed ($E_{consumed}$) is multiplied by a total loss factor (TLF). In cities the TLF is approximately 4% or 1.04. There are also delivery and regulatory charges levied per kWh of electricity consumed. These have been combined into one value termed delivery and regulatory adder (DRA). The DRA is approximately 2.5¢/kWh consumed. The TLF and DRA vary from city to city. The tendency is for both to be higher in northern cities and lower in southern cities. The price calculation is shown in equation 4.1. Taxes on electricity ($E_{tax}$) are 5% and 13% for natural gas [30].
4.2. METHODS

\[ E_{\text{price}} = (E_{\text{consumed}} \cdot TLF + DRA) \cdot E_{\text{tax}} \]  

(4.1)

<table>
<thead>
<tr>
<th>Rate Plans</th>
<th>Hour of the Day</th>
<th>Season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2017</td>
<td>Jan-Apr</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>May-Jun</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>Jul-Oct</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>6.5</td>
</tr>
<tr>
<td>2018</td>
<td>Jan-Apr</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>6.5</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>6.5</td>
</tr>
<tr>
<td>O4</td>
<td>Jan-Apr</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>4.0</td>
</tr>
<tr>
<td>A</td>
<td>Jan-Apr</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>4.4</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>4.4</td>
</tr>
<tr>
<td>B</td>
<td>Jan-Apr</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>2.0</td>
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<tr>
<td></td>
<td>Nov-Dec</td>
<td>2.0</td>
</tr>
<tr>
<td>E2</td>
<td>Jan-Feb</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Mar-May</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Jun-Aug</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Sep-Nov</td>
<td>5.4</td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td>5.4</td>
</tr>
<tr>
<td>F</td>
<td>Jan-Apr</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>6.3</td>
</tr>
<tr>
<td>H</td>
<td>Jan-Apr</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>0.6</td>
</tr>
<tr>
<td>I</td>
<td>Jan-Apr</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>May-Oct</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td>Nov-Dec</td>
<td>4.9</td>
</tr>
<tr>
<td>L</td>
<td>Jan-Dec</td>
<td>9.8</td>
</tr>
</tbody>
</table>

Figure 4.4: Electricity rate plans investigated [32, 31]. Time-Of-Use prices of electricity shown in /kWh consumed. These do not include the total cost of electricity per kWh consumed. Total loss factor, delivery and regulatory costs, and taxes must be added to calculate the full cost of electricity.
4.2. METHODS

4.2.5 Annual heating simulation

Simulations of heating the average home are carried out for the 6 cities and a total of 62 weather stations around Ontario. Building simulation software, Energyplus, is used in combination with CWEC data to determine the hourly heat energy required. From this result the heat energy provided by heat pump and natural gas furnace is calculated.

An advanced control scheme is used in these simulations. Typical home heating system controls call for heat when the interior temperature falls beneath a threshold. There is no regard in conventional controls for which equipment is used. Usually, the heat pump is called as the first stage of heating. If the heat pump is not able to deliver enough heat after some time, the second stage or backup heating system (natural gas forced air furnace in this case) is engaged. The advanced control system, in contrast, is aware of the outdoor temperature as well as the indoor temperature. This awareness allows for a decision to be made regarding the feasibility of heat pump use. If the heat pump can provide heat at a high enough COP to ensure money is saved at that time of day, it will be used. If the cost of electricity divided by the COP at that outdoor temperature is above the cost of natural gas heating, the natural gas furnace will be preferred. At times when the heat pump is economical to use, but incapable of providing for the full heating needs, the task of heating is shared between the heat pump and furnace. A time penalty is incurred, where both the heat pump and furnace cannot operate to allow for the transition to occur. A maximum of two transitions between heat pump and furnace can occur in each hour with a total of 6 minutes without heating. If this time penalty were to prevent heating needs from being fulfilled, the furnace is selected instead and the heat pump is not used for that
4.2. METHODS

4.2.6 Annual cost of heating

Under the advanced control system, the annual cost of heating will never be higher than the cost of heating entirely with natural gas. The heat pump will not be used if it cannot provide heat at the same cost or better than the natural gas furnace. Annual costs presented here are exclusive of service fees that are independent of consumption. All costs that vary with consumption of energy are included. Service fees incurred regardless of consumption tend to be about $250 per year per service.

4.2.7 Greenhouse Gas Emissions

GHG emission calculations are based upon consumption of energy at the home. There are no upstream emissions due to the extraction or transportation of natural gas. None of the life cycle emissions associated with electrical or natural gas energy are included, except for at the stage where the energy is used within the home to provide heat. Table 4.3 summarizes the GHG emissions for these two competing energy sources.

Emissions are calculated from the energy inputs. For natural gas this means that for each volume of natural gas containing 1 kWh of heat energy there is an emission of 215 \( g\text{CO}_2\text{e} \). The efficiency of the furnace is assumed to be 96% and the emissions per kWh of heat provided for the home are therefore greater.

Similarly, the emissions due to electricity consumption are calculated per kWh of electricity consumed. With an ASHP 1 kWh of electricity can provide 2-4 kWh of heat to the home, resulting in very low emissions per \( kWh_{\text{heat}} \). The GHG emissions
for electricity can be between 24 and 68 $gCO_2e$, depending on the time of day and month of the year due to the variation in generating technologies used to provide electricity. To calculate emissions we use an average day with hourly time resolution for each month of the year.

To generate the average days, hourly generation data by fuel type for all of 2016 are used. 2017 shows a significant reduction in emissions 2.5-1.8 times lower than 2016. Electricity demand fell 3.26% from 2016 to 2017. We continue to use the 2016 base year for GHG emissions calculations, since the proposed policies would result in increased demand and may result in greater use of NG generators, and therefore higher emissions when generating electricity. However, as noted in the introduction, 2018 saw an increase in demand beyond the levels of 2016, and yet emissions from natural gas generation did not reach 2016 levels.

Table 4.3: CO$_2$e emissions by fuel type (GWP$_{100}$) [11, 16, 34].

<table>
<thead>
<tr>
<th>Heating Energy Source</th>
<th>Carbon Emissions $(gCO_2e/kWh)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (varies by hour &amp; month)</td>
<td>24-68</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>215</td>
</tr>
</tbody>
</table>

4.3 Results

4.3.1 Six cities - historical pricing

Historical price data from 2007–2017 show that around 2008 when natural gas prices were higher than today and electricity prices lower, heat pumps were economically viable. Figure 4.5 shows that a basic heat pump can provide up to 70% of heating needs because natural gas tended to cost much more per $kWh_{heat}$ delivered than heat
4.3. RESULTS

delivered by heat pump.

Figure 4.5: Mean cost per kWh of heat energy in 6 Ontario cities from 2007 to 2017. Share of home heating provided via heat pump without incurring any added heating costs is shown for comparison.

In the years after the great recession of 2008 natural gas prices fell markedly and electricity prices in Ontario climbed steadily. The balance turned toward natural gas heating despite it being dramatically less efficient than heat pump heating. The trend begins to reverse again in 2017, but we cannot be certain it will continue. Price policies of the future, perhaps some of the alternatives investigated below, could ensure the trend continues.
4.3. RESULTS

Figure 4.6: Mean annual savings per average detached dwelling in 6 cities from 2007 to 2017.

Annual savings per dwelling

Savings on the cost of heating on a yearly basis is shown in figure 4.6. These are the annual savings due to ASHP use instead of natural gas heating for a single dwelling in the six cities investigated. Error bars indicate the variation across cities. When gas prices reach approximately 4.5¢/kWh_{heat} and electricity prices are relatively low, an enormous savings of $300–$400 annually per household is possible.

Unfortunately, in subsequent years energy prices reduced the potential savings per dwelling to approximately nothing. Potential savings again begin to grow positive under the pricing conditions of 2017 when electricity prices were reduced by about 25%.
4.3. RESULTS

Reduced energy consumption

Financial savings are delivered by reducing energy consumption. Because electricity prices per kWh consumed are always greater than the cost of natural gas per kWh consumed it is necessary for heat pumps to conserve significant amounts of energy to remain cost competitive. Consequently, figure 4.7 demonstrates a large energy savings in the years that have a potential for a cost savings. Approximately 5,000 kWh of energy per dwelling are conserved in 2017 when energy prices are only marginally favourable for heat pump heat delivery.

This potential for energy conservation begins as energy prices draw closer to one another per unit heat delivered. However, the effect of quickly transitioning to heat pump use is not possible without heating system controls that are aware of the weather and current energy prices. Homes will require newer internet connected thermostats with software coded to access energy prices, weather, and heating system performance data.

Greenhouse gas emission abatement

It should not be a surprise that energy conservation, as well as a transition to the use of electricity instead of fossil fuel, results in a reduction in GHG emissions. Figure 4.8 shows the potential for GHG abatement over the past decade. These reductions are achieved without adding any cost to the annual heating bill. Energy price policies that can ensure the cost of heat pump heating is low enough will allow for cost-effective GHG emission abatement. More than three tonnes of $CO_2e$ can be removed per qualified household in the six cities studied during the period of 2007–2008. Even in 2017 with barely feasible heat pump use we see more than one tonne $CO_2e$ abatement
Figure 4.7: Mean reduction of energy input required to supply heat to an average detached dwelling in 6 Ontario cities from 2007 to 2017.

per dwelling.

4.3.2 Six cities - rate plans

The rate plans studied by the OEB and shown in figure 4.4 are applied to the six cities whose historical prices were investigated. These rate plans are applied with the 2017 basic price data. That is to say that electricity prices use the TLF and DRA factors from the actual 2017 prices in each of the six cities. Similarly, natural gas prices are the same as those in 2017 in each of the six cities. The TOU prices are varied as per the rate plans and the results reported in figures 4.9-4.12.
4.3. RESULTS

As always, the savings per dwelling are estimated. Annual costs saved in the six cities are shown in figure 4.9 along with the share of heating by heat pump in figure 4.10. The highest heat pump heating share is induced by rate plan I, where the bulk of the weekday is charged 4.9 ¢ per kWh, and only four hours of the day have a high price of 28.0 ¢ per kWh (see figure 4.4). However, the greatest savings per dwelling occur for rate plan H. For this rate plan electricity is virtually free (0.6 ¢ per kWh) overnight between 7pm and 7am.

Annual savings are significantly different between cities for all rate plans. Ottawa, Toronto, and Windsor tend to have poor economic performance with a heat pump due to lower natural gas rates. The higher costs of natural gas in Kingston, Sudbury,
and Thunder Bay make heat pump heating more competitive despite fairly high electricity costs in these cities. More uniform energy pricing across the province might be considered more equitable even if the true cost of providing these services varies geographically.

Figure 4.9: Annual savings per dwelling in 6 cities under the various energy pricing regimes.

Energy conservation and GHG abatement

Energy conservation and GHG abatement in the following section are true measures in the physical world. These have consequences for energy production, the resultant pollution and climate change. Using an ASHP under almost any rate plan offers a significant potential for energy conservation and GHG abatement. The control system will prefer to use the heat pump if the price is the same as the price of using the natural gas furnace. Any time a heat pump can be used, energy is conserved.
4.3. RESULTS

The energy consumed will also be electricity instead of natural gas and emissions will be fewer. Rate plan I demonstrates the greatest potential for energy conservation and GHG abatement. Plan H follows closely behind. The results are quite uniform across all 6 cities for these two plans, which is an advantage if energy conservation and GHG abatement are the impetuses of policy decisions.

Figure 4.10: Average annual share of heating by heat pump and natural gas furnace per dwelling in 6 cities with various energy price regimes.
4.3. RESULTS

Figure 4.11: Annual energy conserved per dwelling in 6 cities under the various energy pricing regimes.

Figure 4.12: Annual greenhouse gas abatement per dwelling in 6 cities under the various energy pricing regimes.
4.3. RESULTS

4.3.3 Province-wide rate plans

The rate plans applied to the six cities in the previous section were also applied to all SDDs having natural gas home heating and AC in all cities across the province. However, energy prices were made uniform across the province—a significant change. Today prices tend to be higher in northern Ontario, while prices are lower in the more populous southern regions. The new prices shown in table 4.4 represent a rough average of the currently disparate pricing in the two regions. The baseline pricing of 2017 is no longer used for this portion of the study and the result will likely be that cities like Ottawa, Toronto and Windsor will perform better than in the previous section. This will be due to higher costs of energy, especially natural gas. Kingston and Sudbury will have a lower annual savings due to the new prices.

Table 4.4: Energy prices applied province-wide for electricity and natural gas.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Prices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>TLF (¢/kWh) DRA (¢/kWh) TOU</td>
</tr>
<tr>
<td></td>
<td>1.04 2.5 as per RPP</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>Commodity Delivery by Volume (¢/m³)</td>
</tr>
<tr>
<td></td>
<td>25 10 9.5 9.0</td>
</tr>
</tbody>
</table>

Economic performance

Annual savings in figure 4.13 are the result of weighting the savings per dwelling in each simulation by the number of SDDs in that region. In Toronto there are several weather stations with TMY data and the SDDs in Toronto are divided amongst them, but in most parts of Ontario a single weather data set applies to the SDDs in several
Table 4.5: Effective prices of energy applied province-wide for electricity and natural gas. Prices are in cents per kWh of heat delivered via heat pump for electricity, and via forced air furnace for natural gas.

<table>
<thead>
<tr>
<th>Energy Price Regime</th>
<th>Prices (\text{¢/kWh}_{\text{heat}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>3.33</td>
</tr>
<tr>
<td>2018</td>
<td>3.25</td>
</tr>
<tr>
<td>O4</td>
<td>2.42</td>
</tr>
<tr>
<td>A</td>
<td>2.50</td>
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<td>B</td>
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<td>I</td>
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<td>L</td>
<td>3.77</td>
</tr>
<tr>
<td>Natural Gas (all rate plans)</td>
<td>3.93</td>
</tr>
</tbody>
</table>

cities. Table 4.5 lists the effective cost of heat energy provided by heat pump versus the cost of natural gas heat, 3.93¢. The heat pump costs are calculated by dividing the cost of electricity by the COP of the heat pump during operation and averaging over the heating season. It is important to note that the heat pumps only operate when the resultant cost of heat pump heating is below the cost of natural gas heating. The share of heating provided by heat pump shown in figure 4.15 should therefore also be kept in mind.

The best economic performance remains with rate plan H. There is a potential for an annual injection of $500 million into the domestic economy in the form of savings on home heating costs. Individual households would see more than $350 saved per year. Rate Plan I provides about 60% of the savings of plan H.
Figure 4.13: Average annual savings weighted by number of detached dwellings with a natural gas forced air furnace and central air conditioner in Ontario. Total province-wide savings on heating should all air conditioners be converted to low-cost, low-performance heat pumps is shown in green with the scale on the right.

**Energy conservation**

Energy conservation is high for all plans, and especially for rate plan I. Rate plan I could save each household more than 11,000 kWh per year and province-wide energy consumption could be reduced by more than 16 TWh. This quantity of energy is equivalent to more than 10% of all electricity generated annually in Ontario. However, this energy is conserved by shifting from natural gas to electricity and will result in an increase in electricity demand, if not mitigated by the adoption of heat pumps in enough homes heated with electricity.

Figure 4.15 shows how each rate plan can affect the share of heating performed...
4.3. RESULTS

Figure 4.14: Average annual energy conserved weighted by number of detached dwellings with a natural gas forced-air furnace and central air conditioner in cities across Ontario. The total province-wide energy conserved annually should all air conditioners be converted to low-cost, low-performance heat pumps is shown in green with the scale on the right.

with heat pumps. As always, rate plan I is most effective, encouraging more than 75% of heating to be performed with ASHPs across the province. Nearly all rate plans are able to encourage approximately 60% of heating to be done with ASHPs. This is probably due mostly to the uniform application of prices for natural gas and electricity price factors province-wide.

**Greenhouse gas abatement**

GHG abatement is also rendered more uniform across all rate plans due to egalitarian energy prices. Rate plan I, however, does show better performance allowing for nearly 3500 kg$CO_2e$ to be avoided per household and a provincial reduction of almost 5
4.3. RESULTS

Figure 4.15: Annual share (in percent) of heating by heat pump versus natural gas furnace, weighted by number of detached dwellings with a natural gas forced-air furnace and central air conditioner in cities across Ontario.

$MtCO_2e$ per year. This abatement is the equivalent of eliminating almost 23% of all GHG emissions from the residential sector in Ontario. Since this analysis only applies to SDDs it is fair to state that this level of abatement represents more than 32% of GHG emissions from SDDs in 2014, a year with average heating needs.

**New electricity demand**

There is an obvious cost to fuel switching for home heating. There will be an increase in the demand for electricity in the homes that reduce their use of natural gas. Figure 4.17 shows the increases in demand per dwelling. The results shown are weighted by the number of dwellings in each region, and so the figure represents a province-wide average that can be directly scaled by the number of affected dwellings to achieve a
4.3. RESULTS

Figure 4.16: Average annual greenhouse gas emissions avoided, weighted by number of detached dwellings with a natural gas forced air furnace and central air conditioner in cities across Ontario. Total province-wide greenhouse gas emissions abated annually should all air conditioners be converted to low-cost, low-performance heat pumps is shown in green with the scale on the right.

All months of the year are represented by average days. These are average weekdays only. Most rate plans have off-peak pricing for weekends and holidays and will show a more uniform need for electricity. Weekdays, however, are most important because of higher peak energy demands and more pronounced patterns of use.

The scale on the right has an upper limit of 1.7 kWh/h of new electricity demand due to heat pump use per dwelling. The central months of June, July and August show little heat pump activity because little heating is needed in the summer. No cooling needs estimates are made. They are assumed to be the same or similar
4.3. RESULTS

Figure 4.17: Average hourly electricity demand for the average household on a day in each month of the year. Each graphic represents one rate plan, and each vertical bar represents an average day in a month. The colour scale represents kilo-Watt-hours of electricity consumed in the hours shown.

to the prior situation where the home had only air conditioning available. Adding cooling energy needs here would double their contribution as the demand from air conditioning is already present in the underlying data.

December is the most favourable month for heat pump use. This propensity is demonstrated by bright yellow dominating the hours of the day when electricity prices allow for heat pump use. Rate plan I has less intensely bright colours in the afternoons on account of lower heating needs and greater heat pump efficiency when daytime temperatures rise.

Because December has the greatest demand increase, figure 4.18 was created to demonstrate the effect rate plan I has on electricity needs on the average December
day in 2017. There is a flattening effect on energy demands until 8pm where there is a definite spike in the need for electricity. This could be a problem for electricity generation, but only once many of the 1.4 million households having both natural gas and air conditioning have switched to using heat pumps. This increase will also only occur if few of the households using electricity to heat their homes today switch to heat pump use. Every electrically heated home that begins using a heat pump allows for approximately 2 homes to switch from fossil fuels to electric heat pump heating with potentially no increase in electricity demand, due to the fact that heat pumps have an approximate COP of 3.

Figure 4.18: Average hourly electricity demand on an average day in December. “Edemand I” denotes new electricity demand due to heat pump use under rate plan “I”. The December 2017 average generating mix is elaborated in colours for each type of generating station.
4.4. CONCLUSIONS

Ultimately, we may consider taking electricity price policy one step further to incorporate demand response pricing programs that are dynamic and capable of avoiding spikes in demand at any time of the day. It is even possible to provide load following with large numbers of heat pumps, simply by delaying or hastening the call for heat by seconds or minutes. Such a service is valuable to grid operations and should be remunerated accordingly. Homeowners might find this is another incentive to invest in heat pumps and advanced thermostatic controls.

4.4 Conclusions

There are physical realities. Heat pumps provide heat while using much less energy than natural gas furnaces. Simulations show this to be true all across the province of Ontario no matter the climate. The pricing of fuels having little or no basis in resource or energy efficiency appears to be the only barrier to heat pump use.

However, caution should be used when applying the province-wide savings per household since the prices of natural gas and the TLF and DRA values used are prescribed and not the actual prices levied across Ontario. These are, in effect, a price policy recommendation. The prescribed prices are lower than in northern Ontario and higher than in southern Ontario—a statement holding true for both electricity and natural gas prices. In southern Ontario prices per $kW h_{heat}$ of natural gas (at 96% efficiency) are approximately 0.5¢ lower than the prescribed value of 3.93¢/kW h_{heat}. This increase in the price of natural gas is equivalent to a $30/tonne price on CO$_2$ emissions. Before being repealed by the current provincial government, a cap and trade system in place in Ontario had reached a price of nearly $20/tonne. Now, the federal government promises to impose a tax and rebate system that will start with a
$20/tonne price on carbon in 2019 rising by $10 every year until it reaches $50 in 2022 \cite{9}. The $1000 premium paid to replace an air conditioner with a heat pump could be paid back in three years or less once carbon pricing reaches the $50/tonne level. These payback times could be achieved if electricity TOU pricing remains nearly constant. The effect could be magnified by choosing one of the proposed TOU rate plans.

Using less energy is not just cost effective. It is safer because it reduces GHG emissions. Of the energy used, emissions are further reduced by avoiding fossil fuel consumption and instead using Ontario’s low-carbon electricity. If natural gas that is not used for home heating in the residential sector does not find another use, we can also expect even greater reductions in energy consumption and emissions by avoiding the extraction of some natural gas. These upstream reductions in emissions are not included in the analysis, but are a potential benefit of implementing a policy based upon this work.

In any case, electricity is the alternative energy source to be used for home heating in the future. The question is, how soon can it be a financially sound decision for the people of Ontario? Financial gains can be had for homeowners. These gains can be guaranteed by employing one of the suggested rate plans for electricity. Rate plan H provides the greatest financial incentive while rate plan I performs best in terms of real results—energy conservation and GHG abatement.

Negative effects like increased electricity demand at the wrong times can be mitigated by simultaneously encouraging heat pump use in homes with electric heat. Until the recent change in provincial government there was a financial incentive of $4000 to install an ASHP in an electrically heated home \cite{35}. These homes will reduce their electrical demand by using heat pumps at all hours of the day. It is always cost
effective to use less electricity, something heat pumps facilitate in electrically heated homes.

Making adjustments to pricing plans can also prevent unwanted peak energy use at certain times. An even better solution is to create pricing plans or demand response programs tailored to residential heat pump use specifically and administered electronically over the internet with advanced thermostatic controls. Future work may consider designing and testing potential demand response programs for the Ontario residential sector.

Enormous reductions in energy consumption and GHG emissions are possible. The few policy tools used in this study can help achieve these goals while improving homeowner finances and causing little or no negative effects for energy providers in the short to medium terms.
References


[22] Natural Resources Canada. National Energy Use Database - Residential Sector, Ontario, Table 18: Floor Space by Building Type and Vintage, 2017. [dataset].


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[41] Lukas Swan, V. Ismet Ugursal, and Ian Beausoleil-Morrison. A database of house descriptions representative of the Canadian housing stock for coupling


Chapter 5

Conclusions

In chapters 3 and 4, we saw that low-cost low-performance heat pumps can reduce home heating energy consumption by 25% to 50% or even more under the right circumstances. High-performance ASHPs can achieve dramatic reductions of 75% of home heat energy needs. Similarly, a minimum of 20% of GHG emissions can be avoided in northern climates, and easily 50% or more can be abated in southern Ontario cities. We can remove 5 MtCO$_2$e from annual emissions once 1.4–2.4 million ASHPs are put into service. There is a substantial opportunity to reduce overall energy consumption and GHG production in the residential sector of Ontario, should we chose to encourage the adoption of heat pump technologies.

Technological development, itself, will not have a significant effect on the feasibility of heat pump use. ASHPs already have operating temperature ranges covering the bulk of heating needs in Ontario. Heat pumps are currently suitable as a primary cooling and heating device, provided there is auxiliary heating for extreme cold.

Specifically, temperatures rarely reach -30°C in southern Ontario. Windsor saw not even one hour at -30°C or below, from 1981–2010 inclusive [2]. Ottawa experienced an average of 3.1 hours per year at -30°C or below [2]. Colder cities like Sudbury
(21.2 hours), Thunder Bay (38.2 hours), and Timmins (106.6 hours) must contend with these temperatures more regularly but still for only 1.3% or less of the heating season [2]. For a complete heating system replacement it may be possible to design a system with a combination of thermal storage and/or electric backup to provide for the usually short durations of high heating need. Investigating the requirements of such a system in Ontario’s northern climates is a possible future addition to the body of knowledge. Backup heating needs from this work can provide a starting point.

If improvements in operating ranges were to exceed all expected outdoor conditions (approximately -40°C), then heat pumps might serve to heat homes without backup heating. This would make ASHPs a direct replacement for conventional furnaces and dramatically change the calculus when choosing heating equipment. One could purchase a $5000 furnace and a $5000 AC, or purchase an ASHP worth up to $10000. The ASHP would provide both services, without the need to pay a natural gas bill or the associated service fees (approximately $250 per year), although it may still be prudent to have an electric backup in the event temperatures fall below statistically predicted minima. Homes with furnaces and no central AC would need to purchase an ASHP as an added expense of normally $5000 or more—an expense that may be difficult to justify. Dwellings already having an AC system have already justified a similar expense and could perhaps justify the marginally higher expense of an ASHP instead of an AC.

Because so many homes in Ontario have a central AC system attached to a forced air furnace, the possibility of encouraging their replacement with low-cost ASHPs was investigated in chapter 4. The results show that a low-cost ASHP can be a reasonable investment, even when natural gas is the competing heat source. In all cases ASHPs
5.1. POTENTIAL SIGNIFICANCE

Carrying out the price policy recommendations of chapter 4 could enable the replacement of AC with ASHPs in homes with natural gas, and further strengthen the heating cost savings potential for people using oil or electricity to heat their homes today. Chapter 3 demonstrates how all ASHPs are on the cusp of being cost effective in almost every circumstance, and in chapter 4 we see how recent changes in electricity prices as well as historical energy pricing has made the ASHP a viable solution for home heating in Ontario. Combined with carbon pricing and/or natural gas price
policies, we can realise a future where heat pump technologies can cut energy use for home heating in half, cut GHG emissions in the residential sector by 5 MtCO$_2$e (30%) or more, and all the while provide a modest savings on home heating bills. In chapter 4 the hypothetical case where 1.4 million SDDs in cities with natural gas furnaces have their central AC replaced with an ASHP, hundreds of millions of dollars in annual savings can be returned to those households—a potential boost to the domestic economy.

5.2 The future of homes, energy, and heating

As chapters 3 and 4 discuss, electrification of home heating is the future. Electricity is one of the only energy sources that promises a potential for low- or zero-emission of GHGs. ASHPs are currently the most affordable and effective choice for electric home heating. Other similar technologies, or entirely new technologies, will someday be developed, but today we can take action knowing that we have an adequate alternative to fossil-fuel-fired home heating in the ASHP. At the very least we can replace AC systems at end-of-life with ASHPs—the life cycle impacts are nearly the same, but an ASHP has the potential to cut energy use and GHG emissions drastically.

As homes become better insulated and better sealed, ASHPs will be able to provide for larger proportions of home heating needs. Better insulated homes require less heating at low temperatures than poorly insulated homes. The result is that, although an ASHP’s capacity falls with falling outdoor temperatures, the temperature at which the ASHP can no longer provide for a home’s full heating need will be lower and lower. The ASHP will provide heat for a greater proportion of the heating season. Unfortunately, the annual savings potential becomes smaller due to the reduced
overall need for heating. It is nevertheless imperative that we seek better building
envelope performance in parallel with the introduction of any heat pump-related in-
centives. How best to execute home retrofits to minimize life cycle cost and maximize
benefits is an area of potential future work.

5.3 Future work

Combining space heating with water heating is an excellent way to leverage the power
of heat pump technologies. However, the cost of installing such a system in Ontario
is currently much higher than the cost of basic ASHP systems. Perhaps the intro-
duction of relatively low-cost hydronic space heating and water heating systems is a
worthwhile consideration for future development.

Thermal storage of all kinds can increase the length of time during which an
ASHP can avoid operating to prevent incurring higher electricity costs. The extent
to which heat storage can be of benefit in Ontario is another related area for future
work. Paying ASHP users to defer heating for minutes or hours (even seconds) in
demand response programs could provide further incentive for using an ASHP. The
extent to which demand response can serve Ontario’s needs is another area that could
be further investigated. Inter-provincial cooperation could also form a part of future
efforts to avoid GHG emissions or increased electricity generating costs.

Because this thesis has concentrated on the SDD in Ontario, there is a need to
continue to investigate the use of ASHPs in apartments and attached dwellings. Often
these dwellings require less heating and will therefore require lower initial heating
equipment costs to help encourage ASHP adoption. Developing low-cost ASHPs
and/or enabling the sharing of one ASHP between two or more units could help
provide greater financial incentive.

5.4 Conclusion

Carbon pricing and/or increases to natural gas prices can greatly improve the economic argument for ASHPs. Without question, many \((\geq 16)\) TWh of energy per year can be conserved by employing heat pumps in Ontario homes. A third or more of all GHG emissions from the residential sector can be eliminated. ASHPs are a technology with an enormous potential to make home heating less damaging to our environment, and, with the right price policies, our home finances.
References


Appendix A

Appendix to Chapter 2
A.1 Introduction to System Dynamics

System Dynamics (SD) is similar to systems or engineering analysis in that it allows for the description of systems of nodes with connections describing their effects on each other. The causal loop diagram is a conceptual framework for developing an understanding of a system of nodes, or variables, that influence one another. Key to SD is the concept of feedback.

Take for example chickens and eggs (adapted from Business Dynamics by John Sterman, 2000). With more chickens, there will be more eggs, and with more eggs, there will be more chickens. This is a cycle that is reinforcing. The variables within this loop grow over time.

We might introduce a second loop that includes the predation of chickens by a population of foxes. As the population of chickens increases so too does the population of foxes due to the resulting abundance of food (chickens). More foxes will eat more chickens, thus reducing the population of chickens. This loop is therefore balancing. The two loops in combination should eventually find an equilibrium, but could be subjected to all sorts of perturbations over time as we include more detail about the functioning of this system. We can include the effects of fences, chicken coops, other food sources for foxes, other predators (like humans), availability of chicken feed, etc... The potential is almost limitless.

SD is also supported by software applications that allow for a visual construction of the model in terms of stocks, representing the population of chickens for example, and flows regulated by outside effects. The previously described system could be depicted with a stock for the chickens and a flow of new chickens being born at a rate regulated by a valve controlled by the number of eggs and in turn the number
of chickens laying eggs. The population of chickens would decline due to a flow of chickens out of the stock determined by the a valve regulated by the population of foxes who are in turn affected by the population of chickens. The model, once defined with data and relations, can be simulated and solved for the desired number of time steps, at a temporal resolution fitting the data sets used in its construction.

Delays can be incorporated to more accurately model the time it takes for eggs to hatch, for example. Multiple inputs can be included depending on where the modeller wishes to draw the boundary between the model and the rest of the complexity of world surrounding it. Equations and data must be used to describe the relations between elements of the model concretely, and model predictions are only useful if a reasonable historical data set can be used to ensure the model can follow those data. If the historical data exhibits many fluctuations, then more detail about the real system must be included to capture the causes of these phenomena to ensure the model can reproduce the observed data. Previously unseen influences can be added to allow prediction of changes to the system, but conclusions must be made with caution. Predicting the future is difficult.
A.2 Model Layout

This section displays the model layout in System Dynamics software application Stella Pro version 1.5. The model is hierarchical with a main module and one sub-module named "Tech Dev". The main module is shown first. The underlying code is available in the open format, XMILE.

![Diagram of Main Module – Adoption]

Figure A.1: Main Module – Adoption
Figure A.2: Technological Development Module – Adoption
Appendix B

Appendix to Chapter 3
B.1 Energy consumption and savings—SS-A

The following section contain charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July and August. Each chart represents a full adoption of a single-stage heat pump (SS-A) with an advanced energy price aware control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.8. The following are the other months of the heating season for the same scenario.

Figure B.1: January
B.1. ENERGY CONSUMPTION AND SAVINGS—SS-A

Figure B.2: February

Figure B.3: March
Figure B.4: April

Figure B.5: May
Figure B.6: September

Figure B.7: October
B.1. ENERGY CONSUMPTION AND SAVINGS—SS-A

Figure B.8: November

Figure B.9: December
B.2 Energy consumption and savings—SS-B

The following section contain charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July and August. Each chart represents a full adoption of a single-stage heat pump (SS-B) with an economic balance point control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.7. The following are the other months of the heating season for the same scenario.

![Figure B.10: January]
B.2. ENERGY CONSUMPTION AND SAVINGS—SS-B

Figure B.11: February

![February Energy Consumption Graph](image1)

Figure B.12: March

![March Energy Consumption Graph](image2)
Figure B.13: April

Figure B.14: May
Figure B.15: September

Figure B.16: October
B.2. ENERGY CONSUMPTION AND SAVINGS—SS-B

Figure B.17: November

Figure B.18: December
B.3 Energy consumption and savings—VC-A

The following section contains charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July, and August. Each chart represents a full adoption of a variable speed centrally ducted heat pump (VC-A) with an advanced energy price aware control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.10. The following are the other months of the heating season for the same scenario.

![Figure B.19: January](image-url)
Figure B.20: February

Figure B.21: March
B.3. ENERGY CONSUMPTION AND SAVINGS—VC-A

Figure B.22: April

Figure B.23: May
Figure B.24: September

Figure B.25: October
Figure B.26: November

Figure B.27: December
B.4 Energy consumption and savings—VC-B

The following section contain charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July and August. Each chart represents a full adoption of a variable speed centrally ducted heat pump (VC-B) with an economic balance point control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.9. The following are the other months of the heating season for the same scenario.

Figure B.28: January
Figure B.29: February

Figure B.30: March
Figure B.31: April

Figure B.32: May
**Figure B.33: September**

**Figure B.34: October**
Figure B.35: November

Figure B.36: December
B.5 Energy consumption and savings—VD-A

The following section contain charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July and August. Each chart represents a full adoption of a variable speed ductless heat pump (VD-A) with an advanced energy price aware control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.12. The following are the other months of the heating season for the same scenario.

Figure B.37: January
Figure B.38: February

Figure B.39: March
B.5. ENERGY CONSUMPTION AND SAVINGS—VD-A

Figure B.40: April

Figure B.41: May
Figure B.42: September

Figure B.43: October
Figure B.44: November

Figure B.45: December
B.6 Energy consumption and savings—VD-B

The following section contain charts of the energy consumption and savings by hour of day for an average day in each of the months of January through December, excluding the summer months of June, July and August. Each chart represents a full adoption of a variable speed ductless heat pump (VD-B) with an economic balance point control system in all the SDDS in the seven cities analysed in chapter 3. The month of January is already shown in the main body as figure 3.11. The following are the other months of the heating season for the same scenario.

Figure B.46: January
Figure B.47: February

Figure B.48: March
Figure B.49: April

Figure B.50: May
Figure B.51: September

Figure B.52: October
Figure B.53: November

Figure B.54: December
This section contains 9 charts for the months of January through December excluding June, July and August. Each chart represents an average day in that month. The net change in the demand of electricity for each hour of the day is shown for all six scenarios of full adoption of ASHPs in the seven cities analysed in chapter 3. These charts include a second copy of figure 3.14 and together make up the complete results for one heating season.

Figure B.55: January
B.7. NET CHANGE IN ELECTRICITY DEMAND

Figure B.56: February

Figure B.57: March
B.7. NET CHANGE IN ELECTRICITY DEMAND

Figure B.58: April

Figure B.59: May
### B.7. NET CHANGE IN ELECTRICITY DEMAND

#### Figure B.60: September

![Graph showing net change in electricity demand for September.](image)

#### Figure B.61: October

![Graph showing net change in electricity demand for October.](image)
B.8 Net reduction of GHG emissions

This section contains 9 charts for the months of January through December excluding June, July and August. Each chart represents an average day in that month. The net change in the emission of GHGs for each hour of the day is shown for all six scenarios of full adoption of ASHPs in the seven cities analysed in chapter 3. These charts include a second copy of figure 3.16 and together make up the complete results for one heating season. The black line labelled "conventional" represents the baseline or status quo scenario, where the current heating system mix is in operation. All scenarios show a reduction in GHG emissions for all months of the year, with some months seeing a near 100% reduction in GHG emissions due to heating for some scenarios.

Figure B.64: January
B.8. NET REDUCTION OF GHG EMISSIONS

Figure B.65: February

Figure B.66: March
B.8. NET REDUCTION OF GHG EMISSIONS

Figure B.67: April

Figure B.68: May
B.8. NET REDUCTION OF GHG EMISSIONS

Figure B.69: September

Figure B.70: October
Figure B.71: November

Figure B.72: December
B.9 Model Layout

This section displays the model layout in System Dynamics software application Stella Pro version 1.5. The model is hierarchical with a main module and two sub-modules named "HP Perf" and "GHG Emissions". The main module is shown first. The underlying code is available in the open format, XMILE.

Figure B.73: Main Module – Hourly Effects
Figure B.74: Heat Pump Performance Module – Hourly Effects
Figure B.75: GHG Emissions Module – Hourly Effects
Appendix C

Appendix to Chapter 4
Figure C.1: Geographic Information System Map – Ontario
C.1 Model code (python)

```python
#!/usr/bin/env ipython

""
Code Layout:

Read globally required input data from CSVs

Setup global variables

Define functions for repetitive work
- Calculate HP/Heating: hourly per location, output to CSV per location
  - Advanced Control Function
  - Calculate GHGs: hourly per month and hour of day
""

import matplotlib
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np
from scipy.optimize import curve_fit
import csv
import time

begin = time.time()

# Set Flag for writing CSV output.
CSVoutput = True
CSVedemand = True
CSVdfout = False
prefix = "ZEdemand0C-" # Set prefix for CSV Output

""" Cities/Weather Stations """
C.1. MODEL CODE (PYTHON)

```python
# Read in Data from CSVs

# Read All Weather Stations (Cities) into DataFrame
weather_station_data = pd.read_csv('input-weather_station_names.csv', names=['WS']).WS.tolist()
cities = weather_station_data

heat_pumps = ['TH4B36']
dwelling_types = ['sdd', 'sad', 'apt']

# Set years/scenarios for simulation
baseyear = 2017

# hours at which to check energy prices
monthly_check = (1, 745, 1417, 2161, 2881, 3625, 4345, 5089, 5833, 6553, 7297, 8017)

# Global Constants
HighTemp = 19
GST = 1.05
HST = 1.13
kWh_per_m3 = 10.361
NGefficiency = 0.96
NGghg = 214.74  # gCO2e/kWh

# Read in Data from CSVs

# Used for all iterations: Dates and Hours of Day and TOU codes
```

---

Cities = pd.read_csv('input-weather_station_names.csv', names=['WS']).WS.tolist()

heaters = ['TH4B36']
dwelling_type = ['sdd', 'sad', 'apt']

# Set years/scenarios for simulation
baseyear = 2017

# hours at which to check energy prices
monthly_check = (1, 745, 1417, 2161, 2881, 3625, 4345, 5089, 5833, 6553, 7297, 8017)

# Global Constants
HighTemp = 19
GST = 1.05
HST = 1.13
kWh_per_m3 = 10.361
NGefficiency = 0.96
NGghg = 214.74  # gCO2e/kWh

# Read in Data from CSVs

# All Weather Stations (Cities) into DataFrame
weather_station_data = pd.read_csv('input-weather_station_T_HL.csv', index_col='hour')

# Used for all iterations: Dates and Hours of Day and TOU codes
DateTimeTOU = pd.read_csv('input-DateTimeTOU.csv', index_col='hour')
#TOUcode = DateTimeTOU.loc[:, 'TOUcode']

# Load TOUprices.csv 2006–2018 data
TOUpricedata = pd.read_csv('input-TOUprices.csv', index_col='yr-hr')

# GHG Data
GHGs = pd.read_csv('input-2016GHGsbyMonth.csv', index_col='hour_of_day')
# GHGs[hour_of_day, month] -> gCO2e/kWh

""" DataFrames for output """

savings = pd.DataFrame(index=cities, columns=years) # annual savings estimates
ghgs = pd.DataFrame(index=cities, columns=years) # ghg reduction estimates
hp_heating_share = pd.DataFrame(index=cities, columns=years) # heat pump heating share
energy_savings = pd.DataFrame(index=cities, columns=years) # reduction in energy consumption
effective_price_HP = pd.DataFrame(index=cities, columns=years) # $/kWh heat HP
effective_price_NG = pd.DataFrame(index=cities, columns=years) # $/kWh heat NG

def HP_performance(hp_name):
    # read TH4B36 HP performance curves Temperature as index
    hp = pd.read_csv('input-TH4B36-HP-perf.csv', index_col=0)
LowTemp = hp.iloc[0, 2]  # load low temperature cut-off
BalTemp = hp.iloc[0, 3]  # load balance temperature cut-off

hp = hp.iloc[:, 2]  # trim dataframe to relevant columns

# create index (temperature) for full range of TH4B36 use
hpindex = np.arange(LowTemp, HighTemp, 1)

# create column headings
hpcolumns = ['Capacity', 'COP']

# create dataframe with index and column headings
hpint = pd.DataFrame(index=hpindex, columns=hpcolumns)

# merge performance data into empty dataframe
hpmerged = hpint.combine_first(hp)

# fill NaNs with cubic spline interpolation
hpinterpolated = hpmerged.interpolate(method='cubic')

# fill remaining NaNs with extrapolation

---------------------------------------------------------------------------------------------

def exfunc(x, a, b, c, d):
    return a * (x ** 3) + b * (x ** 2) + c * x + d

guess = (0.5, 0.5, 0.5, 0.5)

hp_perf = hpinterpolated
hp_fit = hp

col_params = {}

for col in hp_fit.columns:
    x = hp_fit.index.astype(float).values
y = hp_fit[col].values

params = curve_fit(exfunc, x, y, guess)
col_params[col] = params[0]

for col in hp_fit.columns:
    x = hp_perf[pd.isnull(hp_perf[col])].index.astype(float).values
    hp_perf[col][x] = exfunc(x, *col_params[col])

return (hp_perf, LowTemp)

def loadGasPrices(city_name, gasCompany):
    gasPriceData = pd.read_csv('input-' + gasCompany + '.csv', index_col='yr-hr')

    if gasCompany in ['Union-NW101', 'Union-NE301', 'Union-NE601']:
        gasVolumes = (0, 100, 300, 500, 1000)
    elif gasCompany == 'Union-SM1':
        gasVolumes = (0, 100, 250)
    elif gasCompany == 'Enbridge':
        gasVolumes = (0, 30, 85, 170)
    elif gasCompany == 'EPCOR-NRG':
        gasVolumes = (0, 1000)

    return(gasPriceData, gasVolumes)

# NGdelivery(m3, gasVolumePricing):
for gas in gasVolumePricing.index:
    if m3 >= gas:
        gasDeliveryPrice = gasVolumePricing.loc[gas, :]

return(float(gasDeliveryPrice))

def GHGcalc(electricity_demand, backup_heat_output, heat_loss, hour_of_day, month):
\[ \text{HP\_GHGs} = \text{electricity\_demand} \times \text{GHGs\_loc[\ hour\_of\_day,\ month]} + \text{backup\_heat\_output} / \text{NG\_efficiency} \times \text{NGghg} \]

\[ \text{Incumbent\_GHGs} = \text{heat\_loss} / \text{NG\_efficiency} \times \text{NGghg} \]

\[ \text{return} (\ \text{HP\_GHGs}, \text{Incumbent\_GHGs}) \]

---

'\text{Data Structure for Output}'

Use 1 DataFrame per city dwelling type and heat pump combination.

\[ \text{City\_DwellingType\_HPName[\ Hour,\ Toutside,\ Heat\_Loss,\ Month, Weekday/Weekend/Holiday,} \]
\[ \text{Hour\_of\_Day, TOU\_code, Electricity\_cost, NG\_cost, HP\_output, Backup\_Heat\_Output,} \]
\[ \text{Electricity\_Demand, HP\_GHGs, Incumbent\_GHGs} ] \]

---

\[ \text{def simulate\_year(\ city, hp\_perf, LowTemp, dwelling, year):} \]
\[ \quad \text{# Create DataFrame for output} \]
\[ \quad \text{output\_fields} = [\ 'Month', 'Weekday', 'Holiday', 'Hour\_of\_Day', 'Toutside', 'Heat\_Loss', 'TOU\_code', 'HP\_output', 'backup\_heat\_output', 'Electricity\_Demand','} \]
\[ \quad 'Electricity\_Cost', 'NG\_Cost', 'IncNG\_Cost', 'HP\_GHGs', 'Incumbent\_GHGs', 'NGprice', 'Eprice', 'hp\_COP' ] \]

\[ \text{dfout = pd.DataFrame( index = range(1, 8761), columns = output\_fields )} \]

\[ \quad \text{# zero some constants} \]
\[ \quad (\ \text{TotalHP\_cost, TotalIncNG\_cost, Savings, TotalHP\_ghgs, TotalInc\_GHGs} ) = ( 0, 0, 0, 0, 0 ) \]
\[ \quad (\ \text{HP\_m3, NG\_m3} ) = ( 0, 0 ) \]

\[ \quad \text{# Set Prices Province-Wide} \]
\[ \quad \text{NGprice\_per\_m3} = 0.25 + \text{carbon\_price} * \text{NGghg} * \text{kWh\_per\_m3} \# /m^3 \]
\[ \quad \text{gasVolumes} = ( 0, 100, 250 ) \# from Union-SMI NG delivery volume pricing \]
\[ \quad \text{gasVolumePrices} = ( 0.100, 0.095, 0.090 ) \# NG delivery volume pricing \]
\[ \quad \text{gasVolumePricing = pd.DataFrame( index=gasVolumes, columns=['Delivery'])} \]
\[ \quad \text{gasVolumePricing.\_loc[::, 'Delivery'] = gasVolumePrices} \]
# Electricity Total Loss Factor (TLF) and Delivery and Regulatory Adders (DRA)
( TLF, DRA ) = ( 1.04, .025 )

# determine capacity and COP at every hour in TMY
#

for hour in city.index:
    Toutside = city.loc[hour, 'Toutside']
    Tout = round( Toutside, 0 )

# check energy prices at certain hours in the year
if hour in monthly_check:
    ( HPm3, NGm3 ) = ( 0, 0 ) # clear monthly gas volume count
    pricetime = str(year) + '-' + str(hour)
    if pricetime in TOUpricedata.index:
        TOUpricetime = pricetime

    HPgasDeliveryPrice = NGdelivery( HPm3, gasVolumePricing )
    NGgasDeliveryPrice = NGdelivery( NGm3, gasVolumePricing )

# Price of NG in $/kWh of heat
    NGprice = ( NGprice_per_m3 + HPgasDeliveryPrice ) * HST / ( kWh_per_m3 * NGefficiency )

# *** Advanced Control Scheme - Begin
if DateTimeTOU.loc[hour, 'holiday'] == 1 or DateTimeTOU.loc[hour, 'weekday'] in ['Saturday', 'Sunday']:
    if 'B' in str(year):
        TOUprice_now = TOUpricedata.loc[ 'B-weekend', str( DateTimeTOU.loc[hour, 'hour_of_day']) ]
    else:
        TOUprice_now = TOUpricedata.loc[ TOUpricetime, '23' ]
else:
    TOUprice_now = TOUpricedata.loc[ TOUpricetime, str( DateTimeTOU.loc[hour, 'hour_of_day']) ]
# Price of electricity this hour in $/kWh
hour_of_day = DateTimeTOU.loc[ hour, 'hour_of_day' ]
month = DateTimeTOU.loc[ hour, 'month' ]
Eprice = ( TOUprice_now * TLF + DRA + carbon_price * GHGs.loc[
    hour_of_day, month ] ) * GST

if Tout > (LowTemp−1) and Tout < HighTemp:
    hp_COP = hp_perf.loc[ Tout, 'COP' ]
    hp_output = hp_perf.loc[ Tout, 'Capacity' ]
else:
    hp_COP = 0.1

heat_loss = city.loc[ hour, dwelling ]

if NGprice > ( Eprice / hp_COP) and Tout > (LowTemp−1) and Tout <
    HighTemp:
    if hp_output > heat_loss:
        hp_output = heat_loss
        backup_heat_output = 0
    elif hp_output < heat_loss:
        hp_output = hp_output * ( 0.95 - ( heat_loss +
            hp_output / 20 + 18 / 20 - hp_output ) / ( 18 -
            hp_output ) )
        backup_heat_output = heat_loss - hp_output
    elif hp_output == heat_loss:
        backup_heat_output = 0
else:
    hp_output = 0
    backup_heat_output = heat_loss

# *** Advanced Control Scheme – End

HPm3 = backup_heat_output / ( kWh_per_m3 * NGefficiency ) + HPm3
NGm3 = heat_loss / ( kWh_per_m3 * NGefficiency ) + NGm3

# Cost of Energy
electricity_demand = hp_output / hp_COP
electricity_cost = Eprice * electricity_demand

NG_cost = NGprice * backup_heat_output

incNGcost = heat_loss * (NGprice_per_m3 + NGgasDeliveryPrice) * HST / (kWh_per_m3 * NGefficiency)

# Calculate GHGs; hour_of_day and month assigned before Eprice
(HP_GHGs, Incumbent_GHGs) = GHGcalc(electricity_demand, backup_heat_output, heat_loss, hour_of_day, month)

dfout.loc[hour] = [month, DateTimeTOU.loc[hour, 'weekday'],
DateTimeTOU.loc[hour, 'holiday'], hour_of_day, Toutside, heat_loss, DateTimeTOU.loc[hour, 'TOUcode'],
hp_output, backup_heat_output, electricity_demand, electricity_cost, NG_cost, incNGcost, HP_GHGs, Incumbent_GHGs, NGprice, Eprice, hp_COP]

TotalHPcost = dfout.loc[:, 'Electricity_Cost'].sum() + dfout.loc[:, 'NG_Cost'].sum()

TotalIncNGcost = dfout.loc[:, 'IncNG_Cost'].sum()

TotalHPghgs = dfout.loc[:, 'HP_GHGs'].sum() / 1000

TotalIncGHGs = dfout.loc[:, 'Incumbent_GHGs'].sum() / 1000

Savings = TotalIncNGcost - TotalHPcost

Totals = (TotalHPcost, TotalIncNGcost, Savings, TotalHPghgs, TotalIncGHGs)

return(Totals, dfout)

#

def elec_demand(dfout):

months = ['Jan', 'Feb', 'Mar', 'Apr', 'May', 'Jun', 'Jul', 'Aug', 'Sep', 'Oct', 'Nov', 'Dec']
hrs = range(1, 25)

E_demand = pd.DataFrame(index=months, columns=hrs)
E_demand.index.name = year
for mon in months:
    df = dfout.loc[ dfout['Month'] == mon ]
# Electricity Demand for Weekdays; Holidays Omitted
    df = df.loc[ df[['Holiday']] == 0 ]
    df = df.loc[ df[['Weekday']].isin(['Monday', 'Tuesday', 'Wednesday', 'Thursday', 'Friday']) ]
for hr in hrs:
    E_demand.loc[ mon, hr ] = df.loc[ df['Hour_of_Day'] == hr, 'Electricity_Demand'].mean()
return( E_demand )

def dfout2csv( city_name, hp_name, dwelling, year, dfout ):
    CSVoutput_filename = 'output−' + city_name + '−' + hp_name + '−' + dwelling + '−' + str(year) + '.csv'
    dfout.to_csv( CSVoutput_filename )

def print_outputs( city_name, hp_name, dwelling, year, Totals ):
    print( ' ' )
    print( city_name + '−' + hp_name + '−' + dwelling + '−' + str(year) )
    print( '---------------------------------------------' )
    print( 'Total Heat Pump Costs ${:2f}'.format( Totals[0] ) )
    print( 'Total Natural Gas Costs ${:2f}'.format( Totals[1] ) )
    print( 'Savings ${:2f}'.format( Totals[2] ) )
    print( 'Total Heat Loss $0.0f kWh/year'.format( dfout.loc[:, 'Heat Loss'].sum() ) )
    print( 'NG Effective price $0.0f/kWh'.format( effective_price_NG.loc[ city_name, year ] ) )
    print( 'HP Effective price $0.0f/kWh'.format( effective_price_HP.loc[ city_name, year ] ) )
    print( 'HP Heating Share %'.format( dfout.loc[:, 'HPoutput'].sum() / dfout.loc[:, 'Heat Loss'].sum() * 100 ) )
    print( '---------------------------------------------' )
# Main Loop

city = pd.DataFrame(index=range(1,8761), columns=['Toutside','sdd'])
city.index.name = 'hour'

for city_name in cities:
    run_start = time.time()
    city.iloc[:, 'Toutside'] = weather_station_data.loc[:, city_name + 'Temperature']
    city.iloc[:, 'sdd'] = weather_station_data.loc[:, city_name + 'HeatLoss']

for hp_name in heat_pumps:

    (hp_perf,LowTemp) = HP_performance(hp_name)

    for dwelling in dwelling_types:

        for year in years:

            (Totals,dfout) = simulate_year(city, hp_perf,
                                          LowTemp, dwelling, year)

            savings.loc[city_name,year] = (dfout.iloc[:, 'IncNG_Cost'].sum() - (dfout.iloc[:, 'Electricity_Cost'].sum() + dfout.iloc[:, 'NG_Cost'].sum()))

            ghgs.loc[city_name,year] = ((dfout.iloc[:, 'Incumbent_GHGs'].sum() - dfout.iloc[:, 'HP_GHGs'].sum()) / 1000)

            hp_heating_share.loc[city_name,year] = (dfout.iloc[:, 'HPoutput'].sum() / dfout.iloc[:, 'Heat_Loss'].sum())

            energy_savings.loc[city_name,year] = (dfout.iloc[:, 'Heat_Loss'].sum() / NGefficiency - dfout.iloc[:, 'backup_heat_output'].sum() / NGefficiency - dfout.iloc[:, 'Electricity_Demand'].sum())

            effective_price_NG.loc[city_name,year] = (dfout.iloc[:, 'IncNG_Cost'].sum() / dfout.iloc[:, 'Heat_Loss'].sum())
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effective_price_HP.loc[city_name,year] = dfout.loc[:,
 'Electricity_Cost'].sum() / dfout.loc[:, 'HPoutput']
 .sum()

if CSVdemand:
    Edemand = elec_demand(dfout)
    Edemand.to_csv( prefix+'Edemand-'+city_name
 +'-'+str(year)+'.csv' )

print_outputs(city_name, hp_name, dwelling, year,
 Totals )
if CSVdfout: dfout2csv(city_name, hp_name, dwelling,
 year, dfout )

print('City_processed_in_{:.1f}_seconds'.format(time.time() - run_start ) )

# Capitalized City Names

city_names = cities
j = 0
for city_name in city_names:
    city_names[j] = city_name.title()
    j = j + 1

# Switch index column to Capitalized city names
savings.index = city_names
ghgs.index = city_names
hp_heating_share.index = city_names
energy_savings.index = city_names'''

# Write CSV output files
savings.to_csv( prefix+'savings.csv' )
ghgs.to_csv( prefix+'ghgs.csv' )
hp_heating_share.to_csv( prefix+'hp_heating_share.csv' )
energy_savings.to_csv( prefix+'energy_savings.csv' )
effective_price_HP.to_csv( prefix+'effective_price_HP.csv' )
effective_price_NG.to_csv( prefix+'effective_price_NG.csv' )
print('Total Processing Time: {:.1f} sec'.format(time.time() - begin))