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ORIGINAL RESEARCH

Heat pumps in Ontario

Effects of hourly temperature changes and electricity generation on greenhouse gas emissions

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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.

Keywords Energy · Heat pumps · Greenhouse gas emissions

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 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% efficiencies, 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

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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 to place large coils of piping under ground at a depth of approximately 1–2 m. 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 °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 [4]. Average temperatures in Reykjavik are a few degrees Celsius warmer than those in Windsor or Toronto, Ontario [4, 16]. ASHPs studied in Alaska were found to require backup heating only at very low temperatures and to have operating ranges extending to − 27 °C [56]. Such low temperatures make up a small portion of the heating season in Ontario's cities [16].

Why then are heat pumps in use in only 9.5% 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. 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.

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.

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 "Energy". Energy demand may also refer to a large number of homes as is the case in "Hourly energy consumption" and "Hourly net change in electricity demand".

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 [14], 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.

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 [2]. 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 [14]. 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 [12, 70, 71]. 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.

(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 "Hourly greenhouse gas emissions reductions", Fig. 16. 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.

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 seven 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 [6, 18]. 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, 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 proactively preparing to mitigate any consequences of increased heat pump use.

Assumptions

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

Weather data used are 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 [11]. This assumption may provide more conservative results than the future holds because warmer weather allows for a 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 are more readily available than independent experimentally obtained data sets. 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) 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 [9, 13, 21] are already set at their known quantities and cannot be changed. Furthermore, we have only average data (see "Climate") 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 "Climate"). We rely upon the accuracy of the building parameters used, and the building simulation software that has undergone validation against other building simulation software [5, 21, 31, 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.

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 1 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

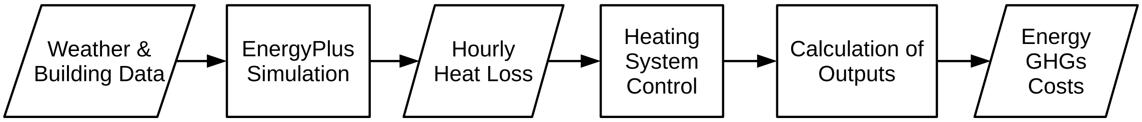

Fig. 1 Simplified flow diagram of the process followed in this study

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. 1) are detailed in the following sections.

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 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 "Dwellings and their construction, Walls, Attic and roof, Fenestration, Air infiltration, Heat loss estimation in EnergyPlus" sections.

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. [13]. As this seems impractical, we are proceeding with building energy simulations and relying upon the validation of Energyplus™ against other building energy simulation software [5, 21, 31, 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 "Heating system control".

Climate

Table 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 midafternoon, 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.

Dwellings and their construction

Heating demand is profoundly affected by building construction, and we therefore lay out in detail the average

Table 1 Usual number of HDDs (°C) per year, and normal daily average, minimum and maximum temperatures in January in the seven cities investigated [3, 16]

City	HDDs (°C days)	Daily normals in January (°C)		
		Min	Avg	Max
Kingston	3976	− 11.4	− 7.0	− 2.6
Ottawa	4441	− 14.8	− 10.3	− 5.8
Sudbury	5241	− 17.9	− 13.0	− 8.0
Thunder Bay	5594	− 18.9	− 13.4	− 7.9
Timmins	6017	− 23.0	− 16.8	− 10.6
Toronto	3533	− 6.7	− 3.7	− 0.7
Windsor	3444	− 7.3	− 3.8	− 0.3

Table 2 Properties of prototypical average SDD in Ontario [39, 40, 62]

Building properties	Value	Unit
Living area	173.0	m^2
Wall heights	2.4	m
Window (% living space wall area)	15.7	%
Wall insulation (RSI)	2.1	m^2K/W
Ceiling 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

Table 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]

Type of dwelling	Housing share (%)	Floor area (m^2)
Single detached	54.3	173
Single attached	17.9	131
Low-rise apartments	10.1	90
High-rise apartments	17.2	90

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 (see Table 4). 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 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) of dwellings in Ontario [42, 59]. SDDs are often built by similar methods, the details of which are discussed in the following sections.

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) was maintained for both. As a result, the footprint of the two-storey building was reduced. The four walls (Walls) of the structures are oriented to face the cardinal directions: north, south, east, and west. All features like windows and doors (see "Fenestration") are spread evenly across all the walls. The roof is a hip roof enclosing an attic space. Both are described in "Attic and roof". The effects of all weather conditions, including solar insolation, are calculated by Energyplus™ for each city using the appropriate TMY weather file (see "Estimation of hourly heating needs, Air infiltration, Heat loss estimation in EnergyPlus"). Both prototypical homes have a basement extending 1.5 m below grade that is not considered part of the conditioned living area.

Walls

Walls are a wood-frame wall common to North American home construction [1, 3, 36]. Wood studs are 39 mm wide by 90 mm deep and spaced on 400 mm centres (2 × 4 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°. The roof is covered with asphalt shingles on top of 19 mm wood sheathing. These are supported by 39 × 140 mm rafters. Details of the thermal modelling are shown in Table 4. Not shown in the table is attic ventilation. This was modelled as a leakage area of 5000 cm^2 for the single-storey detached home as per the work of Kneifel and Hendron et al. [22, 36] where 1 unit of ventilation is added for every 300 units of attic floor area. A two-storey home requires half of this leakage area because it has half the attic area due to the fact that the interior living 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 needs (inoperable windows have a slightly lower heat loss—$U = 2.24$ W/m^2K). Table 5 details the properties used to model fenestration. These properties are sourced from ASHRAE Fundamentals 2013, Chapter 17 [3].

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

Table 4 Properties of walls and their components [3, 8, 27]

Layer	Material	Thickness (mm)	RSI (m^2K/W)	U (W/m^2K)	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
Mainfloor exterior walls							
1	Gypsum wall board	12.7	0.075	13.4	0.17	800	1080
2	Wood-frame wall	90.0	1.3	0.78	0.07	119	766
	Wood studs 39 × 90 mm	90.0	0.82	1.2	0.11	420	1380
	Fibreglass insulation	60.5	1.6	0.42	0.038	28	835
3	Wood sheathing	19.0	0.35	2.9	0.055	290	1300
4	Felt/air gap	12.7	0.26	3.9	0.05	330	1360
5	Wood siding	12.7	0.14	7.4	0.094	640	1170
	Totals	155.8	2.1	0.477			
Basement exterior walls							
1	Concrete (heavy)	203.2	0.1	9.6	1.95	2240	900
2	Insulation board	39.0	1.3	0.77	0.03	43	1210
	Totals	242.2	1.4	0.71			
Basement floor							
1	Concrete (light)	101.6	0.19	5.2	0.53	1280	840
	Totals	101.6	0.19	5.2			
Upper ceiling/attic floor							
1	Gypsum Wall Board	12.7	0.075	13.4	0.17	800	1080
2	Wood-frame ceiling	140	2.5	0.40	0.036	126	971
	Wood studs 39 × 140 mm	140	1.27	0.79	0.11	420	1380
	Fibreglass insulation	140	3.68	0.27	0.038	28	835
3	Fibreglass batt insulation	77.0	2.03	0.49	0.038	28	835
	Totals	229.7	4.6	0.217			
Roof							
1	Wood rafters	140	0.32	3.15	0.44	105	345
	Wood studs 39 × 140 mm	140	1.27	0.79	0.11	420	1380
2	Wood sheathing	19.0	0.35	2.9	0.055	290	1300
3	Asphalt shingles	12.7	0.077	13.0	0.17	1100	1260
	Totals	171.7	0.747	1.34			

Table 5 Fenestration modelling properties

Property	Value
Glazing layers	2
Framing material	Wood/vinyl
U-factor	2.39 (W/m^2K)
Solar heat gain coefficient	0.52

(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 Eq. 2:

$$Q_r = \mathrm{ACH}^{50} \cdot V \cdot \frac{1\,\mathrm{h}}{3600\,\mathrm{s}}. \tag{1}$$

Q_r is the volume of exchanged air per second for the heated volume (V) in question, and it is calculated using Eq. 1 [3]:

$$\mathrm{ELA} = \frac{10000 \cdot Qr\sqrt{\rho/_{\Delta}P_r}}{C_D}. \tag{2}$$

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 Eqs. 2 and 3. The density of air in Eq. 2 is represented by ρ, and ΔP_r is the pressure differential of either 50 Pa or 4 Pa:

$$\mathrm{ELA}_{4Pa} = \mathrm{ELA}_{50Pa}\left(\frac{C_{D1}}{C_{D2}}\right)\left(\frac{\Delta P_{r2}}{\Delta P_{r1}}\right)^{n-0.5}. \tag{3}$$

The lower pressure of 4 Pa is used in Energyplus™ to model normal wind loading conditions, and the ELA_{4Pa} is determined using Eq. 3 also from ASHRAE Fundamentals [3]. As previously mentioned, $C_{D1} = C_{D2} = 1.0$ and n is a pressure exponent found empirically to be 0.65 [3].

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 Eq. 4). The coefficients C_{s} and C_{w} modify the stack effect and wind effects, respectively. The infiltration model described is based on the work of Sherman and Grimsrud [57] elaborated within chapter 16 of the ASHRAE handbook of fundamentals [3]. 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 on 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 one- and two-storey heights, respectively [3]:

$$\mathrm{Inf.} = \frac{\mathrm{ELA}_{4Pa}}{1000}\sqrt{C_{\mathrm{s}}(T_{\mathrm{in}} - T_{\mathrm{out}}) + C_{\mathrm{w}}(v_{\mathrm{wind}}^2)}. \tag{4}$$

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 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 [39, 44, 45, 47]. 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 6. 31,420 kWh/year is the estimate without subtracting July consumption. No heating system efficiencies were applied to the Statistics Canada data set, 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 can be weighted by secondary energy consumption [44]. The weighted efficiency is multiplied by the total energy used for heating to arrive at the approximately 25 MWh/year in Table 6. While these estimates are not 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 15–20% lower than the average, although there are relatively fewer SDDs and more apartments in Toronto than in other cities [59].

Table 6 Simulated annual heating needs in kWh for each city

City	Annual heating needs (kWh/year)
Kingston	23,873
Ottawa	23,588
Sudbury	27,171
Thunder Bay	29,331
Timmins	32,218
Toronto	19,935
Windsor	17,579
Ontario averages	
Statistics Canada (per household)	23,369
NRCan (per SDD)	24,966

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 [39, 44, 45, 47, 60]

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 2 shows the performance curve for the chosen single-stage heat pump—a Coleman TH4B36 heat pump [10, 49]. 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.

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”. 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 Fig. 3 [7, 49]. 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.

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.

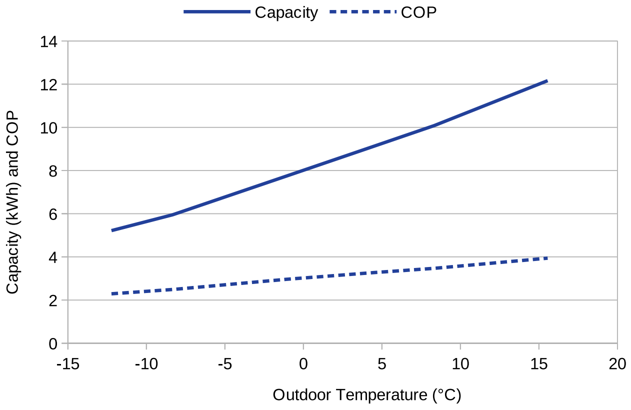

Fig. 2 Single-stage heat pump performance curves—SS [10, 49]

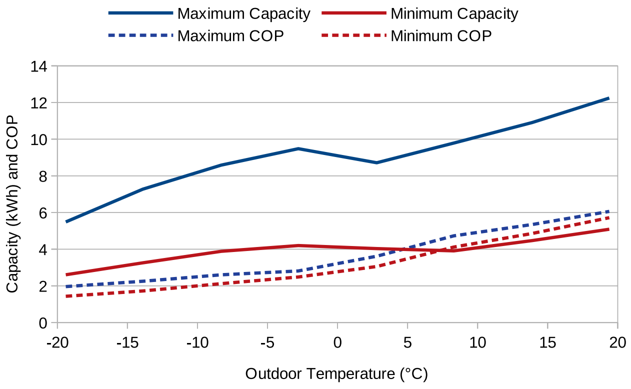

Fig. 3 Variable speed centrally ducted heat pump performance—VC [7, 49]

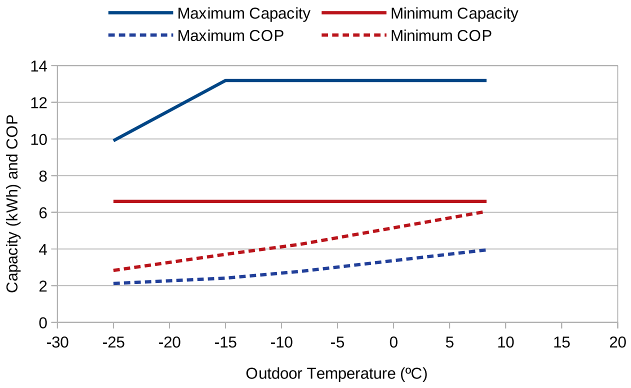

Fig. 4 Variable speed ductless heat pump performance—VD [37, 49]

The ductless heat pump is denoted by VD in all figures and results. Figure 4 shows the impressive performance of this heat pump system, with a minimum outdoor operating temperature of − 25 °C and full heating capacity maintained at − 15 °C [37, 49].

All three heat pump configurations are available in the NEEP data set [49], but data for Figs. 2,3, and 4 are generated from manufacturer performance data [7, 10, 37]. The single-stage heat pump is the least expensive. Units of this type can often be installed for approximately $5–6 k. The variable speed systems are more expensive, with costs varying between $8 and $15–20 k including installation. The third and best performing heat pump in Fig. 4 is likely to be priced in the $15–20 k range, especially when retrofitted, because each indoor unit will need to have piping and wiring fed through existing walls and ceilings.

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 data sets [44].

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 the 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 [37, 49, 61]. 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° 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 Fig. 5. Table 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 Fig. 6. We 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 that of the 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.

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].

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 7 pm–7 am. It is moderately priced between the hours of 11 am and 5 pm, and most costly from 7 to 11 am and 5 to 7 pm. 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

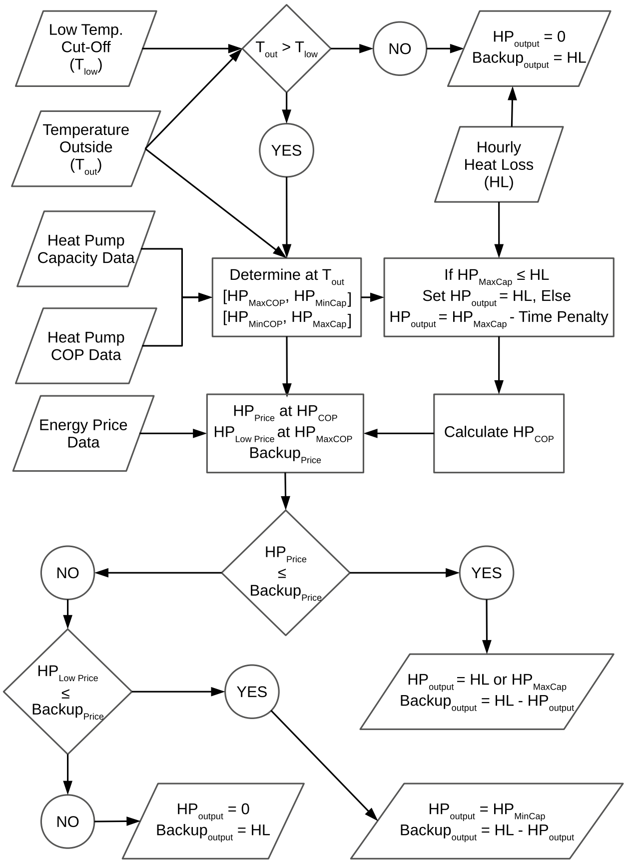

Fig. 5 Advanced heat pump control system flow diagram

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 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 9.

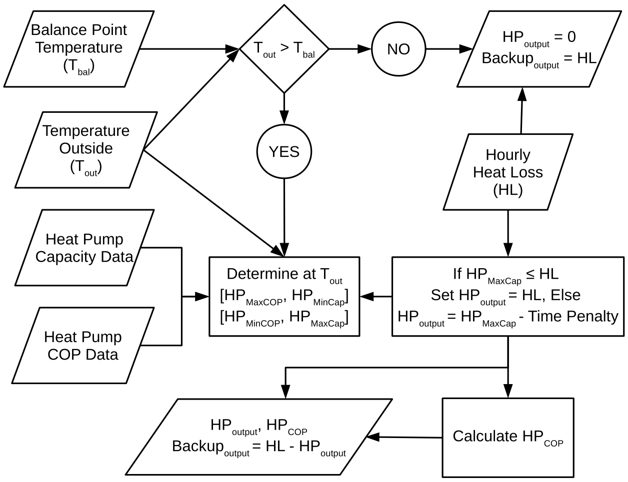

Fig. 6 Balanced heat pump control system flow diagram

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

Table 8 Added costs for electricity consumption

City	TLF (multiplier)	DRA ¢/kWh
Kingston	1.0393	2.620
Ottawa	1.0335	2.938
Sudbury	1.0540	1.940
Thunder Bay	1.0342	2.380
Timmins	1.0570	2.527
Toronto	1.0376	3.020
Windsor	1.0377	2.574

TLF is multiplied by consumption in kWh, and delivery and regulatory adders (DRA) are added per kWh consumed [17, 20, 23, 24, 35, 65, 67]

Table 7 Table of inputs and outputs for balanced and advanced control strategies. Control decisions are made hourly

Control strategy	Input	Output
Balanced and advanced	Building heat loss (kWh/h) Temperature outside (°C) Heat pump capacity (kWh/h)	Heat pump output (kWh) Backup heating system output (kWh)
Balanced only	Heat pump balance temperature (°C)	
Advanced only	Low-temperature cut-off (°C) Time of use (off–mid–peak) Energy prices ($/kWh) Heat pump COP	

Table 9 Energy prices in ¢/kWh [17, 20, 23, 24, 35, 65, 67]

City	Electricity (off — mid — peak)	Natural gas	Furnace oil
Kingston	9.80 — 13.1 — 17.2	4.5	11.3
Ottawa	10.1 — 13.4 — 17.4	3.5	11.3
Sudbury	9.20 — 12.6 — 16.6	3.8	11.3
Thunder Bay	9.60 — 12.8 — 16.8	3.8	12.5
Timmins	9.90 — 13.2 — 17.3	3.8	11.2
Toronto	10.3 — 13.5 — 17.6	3.5	12.1
Windsor	9.80 — 13.1 — 17.1	3.2	10.9

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 [17, 20, 23, 24, 35, 65, 67].

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/m^3 [48]. Delivery, transportation, storage and other consumption-related fees are shown in Table 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 9 [38].

GHG emission 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 [19]. Table 10 shows the GWP$_{100}$ GHG emissions due to consumption of one kWh$_{th}$ of either natural gas, furnace oil, or electricity [14, 26].

Table 10 CO$_2$e emissions by fuel type (GWP$_{100}$) [15, 30, 52]

Heating energy source	Carbon emissions (gCO$_2$e / kWh heat)
Electricity (varies by hour & month)	24–68
Natural gas	215
Furnace oil	351

Electricity GHG emissions

As shown in Table 10, GHG emissions due to the use of electricity vary 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]. An average day in January is shown in Fig. 14.

Emissions from all electricity generators in Ontario are available from Environment and Climate Change Canada [14]. 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 (560gCO$_2$e/kWh$_e$). The hourly generating mix for each month is averaged over the whole month to produce an average day.

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 "Electricity prices").

Results for these three metrics are shown for the average house in each of the seven cities studied for all six scenarios tested in "Energy", "Greenhouse gas emissions", and "Costs and savings".

Full adoption estimates

The results from the single home models are extrapolated to all the available SDDs in the seven 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 seven 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.

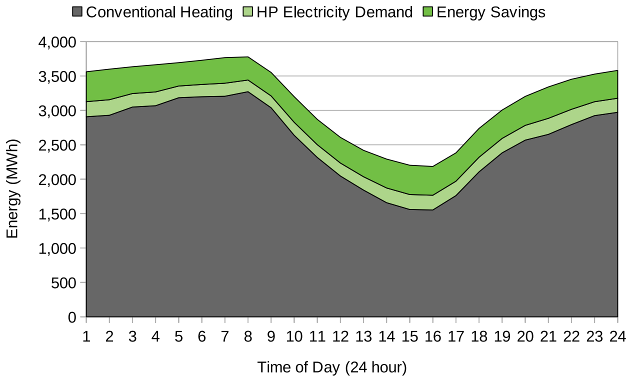

Fig. 7 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—SS-B

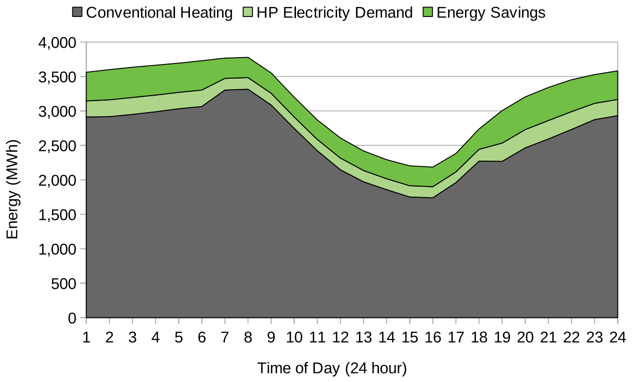

Fig. 8 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—SS-A

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 Fig. 13. 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 supplementary information). 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

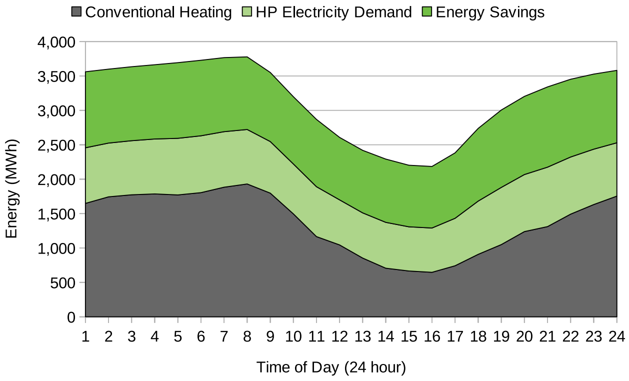

Fig. 9 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—VC-B

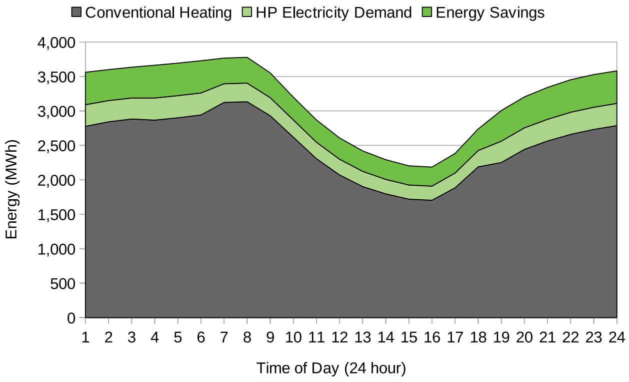

Fig. 10 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—VC-A

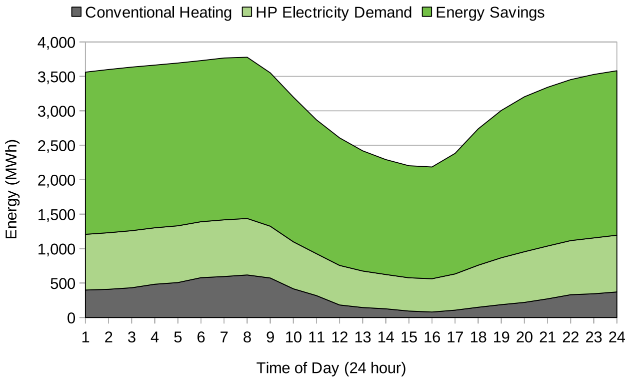

Fig. 11 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—VD-B

are investigated individually, the differences in climate and energy prices reveal some of their effects.

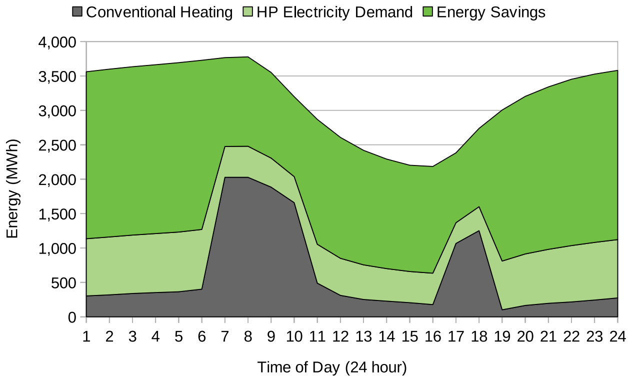

Fig. 12 Energy consumption and savings by hour of day in January for total number of SDDs in all seven cities—VD-A

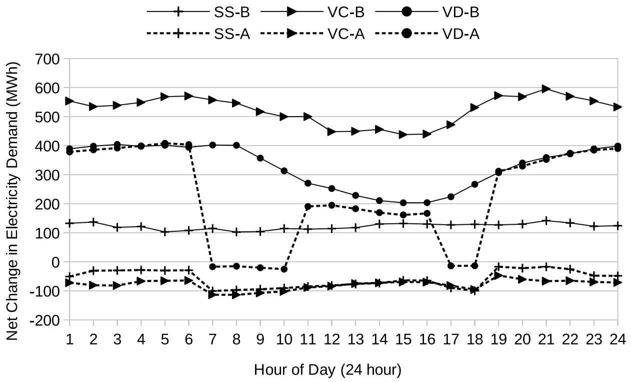

Fig. 13 Net change in hourly electricity demand during an average day in the month of January for all six scenarios

Hourly energy consumption

Figures 7, 8, 9, 10, 11, 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 are not very large. Consequently, we can conclude that the SS-B and SS-A scenarios (Figs. 7 and 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 9 confirms this for the variable speed centrally ducted heat 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 Figs. 3 and 4). The result is that we see energy savings (VC-A shown in Fig. 10) not much greater than that of a single-stage heat pump (Fig. 8) when advanced control is applied.

Performance is best with a ductless heat pump system. Figures 11 and 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 2000 MWh throughout the day. This is equivalent to an almost 60% energy saving during most of the day. The conventional heating needs become almost negligible during the warmest and sunniest hours of the day.

Figure 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 Figs. 8 and 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 lower performance heat pumps, as well.

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 Fig. 13). 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 Fig. 14. 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 13 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 Fig. 14). 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

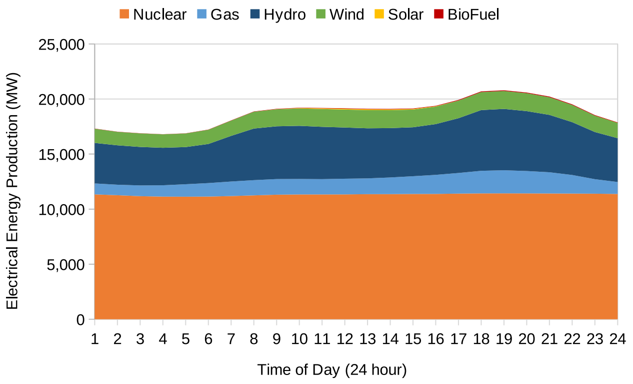

Fig. 14 Electricity generation by fuel type for each hour of the average day in January 2016

demand late at night may even be beneficial, since demand is typically lower at these times.

It seems likely that in the next 5–10 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 [25, 26, 64]. Policy makers might 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.

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, as shown in Fig. 14. 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 Fig. 14), 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 Fig. 15. 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_2e 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 seven cities chosen. This represents almost 1/6th of the total number of SDDs in Ontario, and about 1/10th (9.3%) of the total number of dwellings of all types in Ontario in 2016 [59].

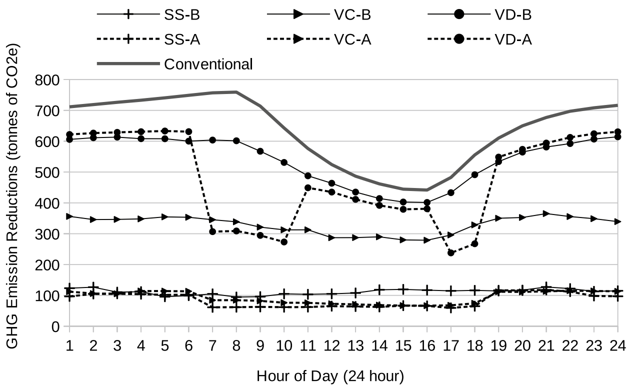

Fig. 15 GHG emission reductions for each hour of the average day in January in all six scenarios

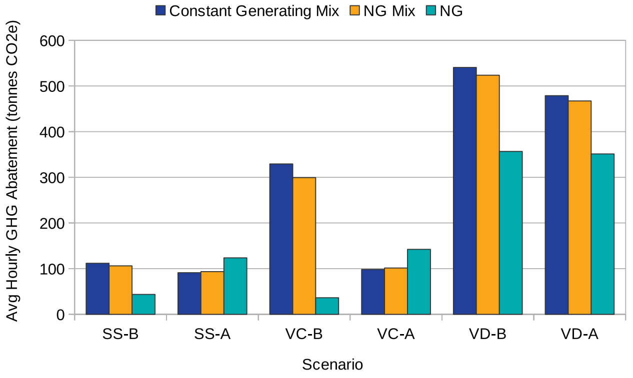

Fig. 16 Average hourly GHG emission abatements for six scenarios under three GHG emission attribution schemes: generating mix remains constant (constant generating mix), natural gas generators meet net demand but overall mix attributed (NG mix), and natural gas generators meet net demand (NG)

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 1 day in advance, and 1 h 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 Fig. 16, we consider the implications of a worst-case scenario: all new demand is met by natural gas generators. Natural gas generators produce, on average, $560 kgCO_2e$ emissions per MWh of electricity consumed in Ontario [14]. Figure 16 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 Fig. 16.

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 Fig. 13). 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.

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 Fig. 17 are therefore equivalent to the heating needs of our prototypical average home in each city (shown in the left).

We see, in Fig. 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 systems are powered with electricity and any time that 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.

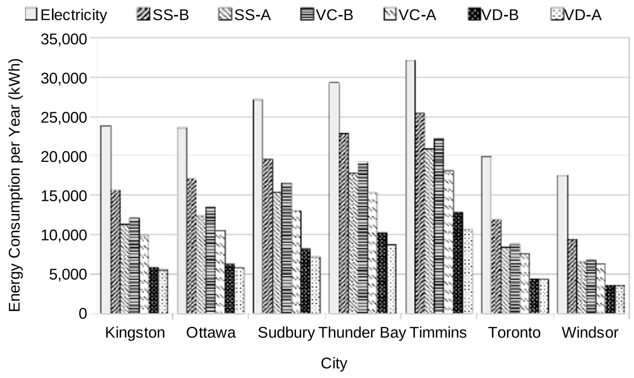

Fig. 17 Energy consumption of heat pumps compared to electric heating by city

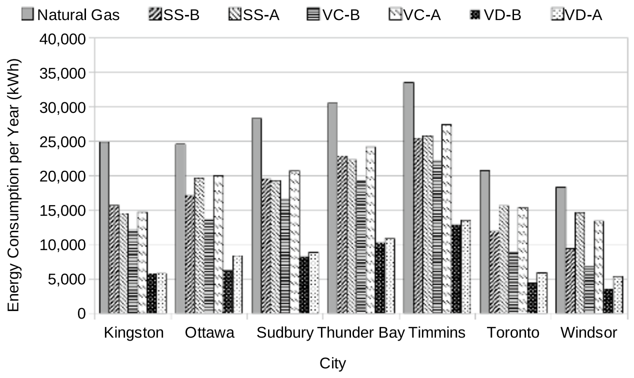

Fig. 18 Energy consumption of heat pumps compared to natural gas heating by city

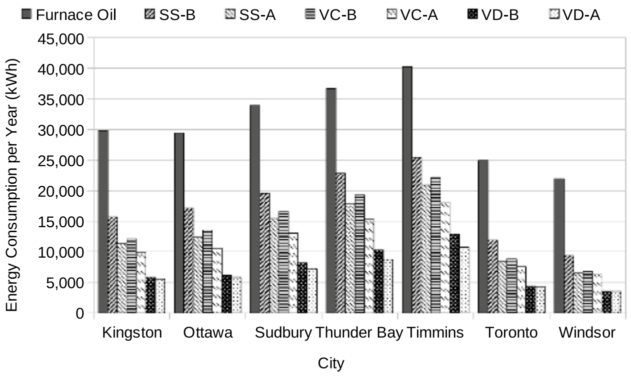

Fig. 19 Energy consumption of heat pumps compared to furnace oil heating by city

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 Fig. 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.

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 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.

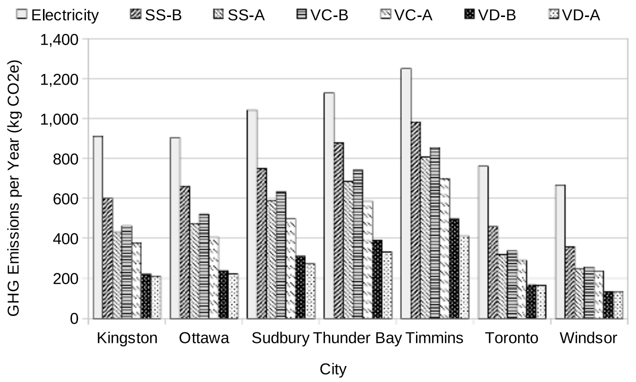

Fig. 20 GHG emissions comparing electric heating and heat pumps with electric backup heating by city

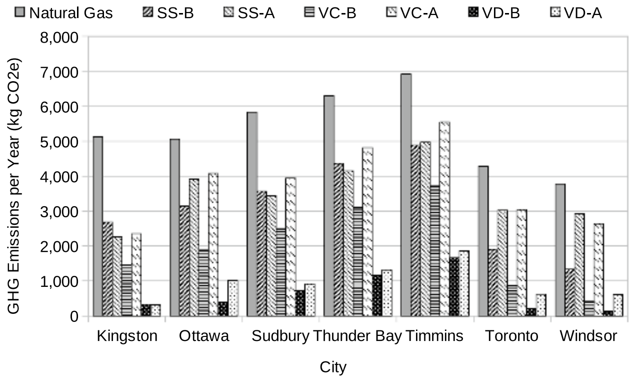

Fig. 21 GHG emissions comparing natural gas heating and heat pumps with natural gas backup heating by city

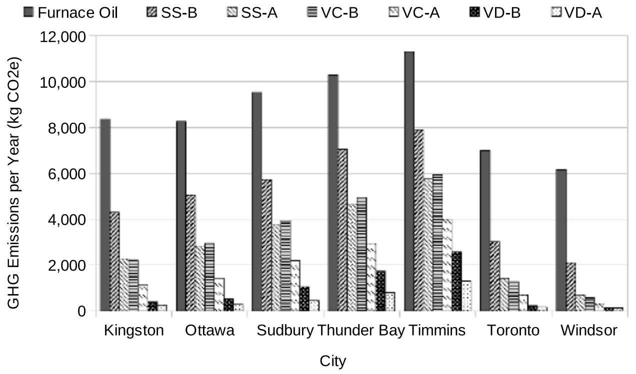

Fig. 22 GHG emissions comparing oil heating and heat pumps with oil backup heating by city

We can see an overall reduction of energy consumption of between 36% and 84% throughout the seven cities and six scenarios in Fig. 19.

Greenhouse gas emissions

The natural consequences of significant reductions in energy consumption are reductions in GHG emissions. Figures 20, 21, and 22 show GHG emissions in kilograms of carbon dioxide equivalent (kg CO_2e) using the 100 year global warming potential [19, 30]. 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.

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 that it is possible to average 2 tonnes CO_2e of curtailment per year per household, we can expect approximately 5.5 MtCO_2e emissions reductions for all the SDDs in Ontario (54.3% of dwellings), if each of them had a heat pump in operation. 5.5 MtCO_2e represents approximately 25% of all GHG emissions from 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).

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. However, controls–advanced—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.

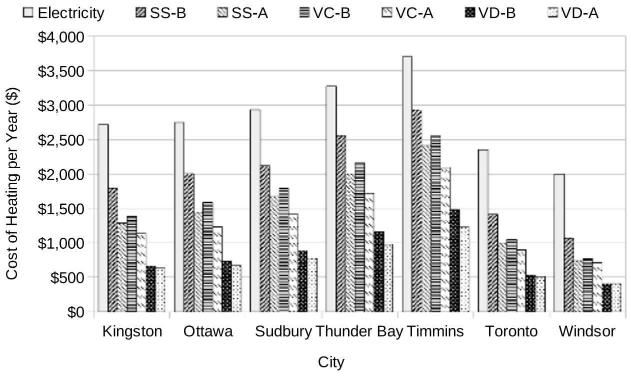

Fig. 23 Cost of heating per year with electric heat and heat pumps with electric backup heat by city

Electric heating

The cost of heating with electricity is one of the most expensive options available (Fig. 23). Conventional furnaces or baseboard heaters show costs ranging from approximately $2000 per year in Windsor, where both the weather is mild and the cost of electricity is low, to more than $3600 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 $1000, using a balance point of – 4 °C (Fig. 24). 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.

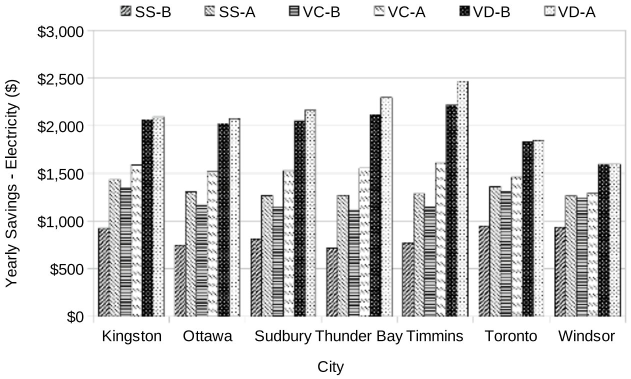

Fig. 24 Savings per year with electric heat and heat pumps with electric backup heat by city

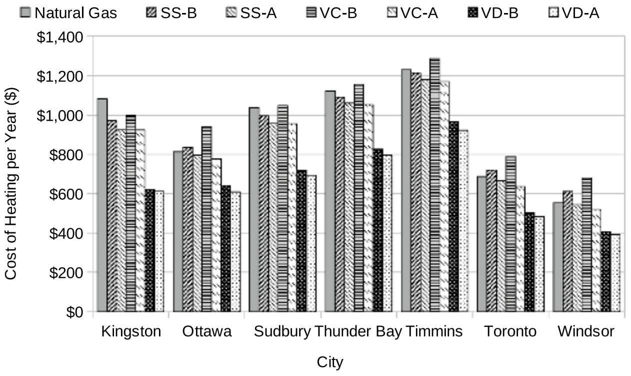

Fig. 25 Cost of heating per year with natural gas heat and heat pumps with natural gas backup heat by city

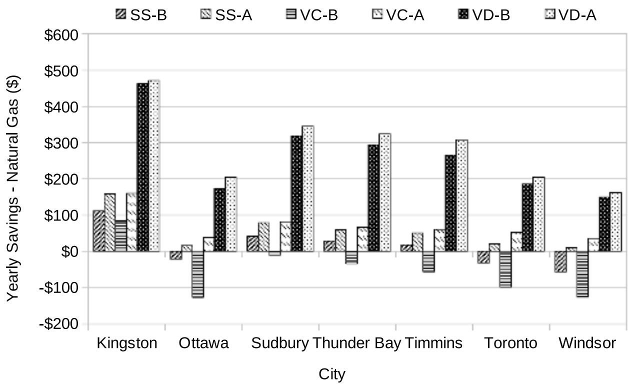

Fig. 26 Savings per year with natural gas heat and heat pumps with natural gas backup heat by city

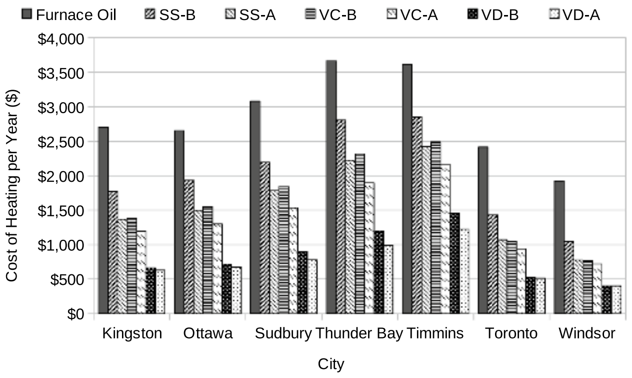

Fig. 27 Cost of heating per year with oil heat and heat pumps with oil backup heat by city

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 $2000 per year for the ductless system.

Natural gas heating

Natural gas heat is widely regarded as the least costly, but Fig. 25 and 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 "Natural gas backup heat" and Fig. 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 Fig. 26). However, it is unlikely that these yearly savings are sufficient to pay back the initial capital investment quickly enough for most homeowners.

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 27, 28 show both the high cost of oil heating and the significant savings to be had when using a heat pump.

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 emission 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 great

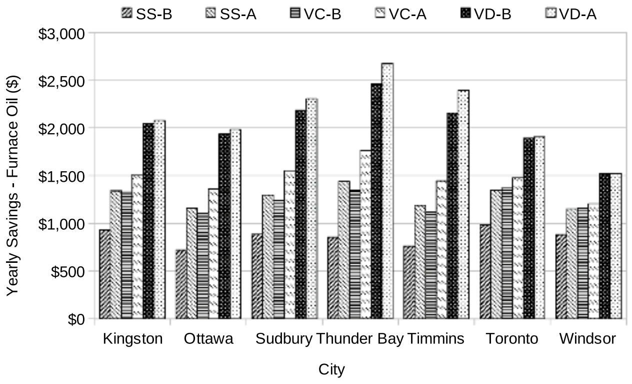

Fig. 28 Savings per year with oil heat and heat pumps with oil backup heat by city

enough except with the best possible technology (see Fig. 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 Fig. 13, 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.

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Compliance with ethical standards

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

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