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ORIGINAL RESEARCH

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

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Abstract
Home heating accounts for most of the 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 emission 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.

Keywords Energy efficiency · Residential heating · System dynamics · Life cycle assessment

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 g 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. 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 [14, 17, 26, 37]. Variation in performance occurs due to outside temperature, the need to defrost outdoor heat

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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 2–3 or more [17, 33, 37]. 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 temperatures of −15 °C [19, 30, 37]. 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 (see Fig. 3). 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 is 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 [5, 43, 44]. 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 "includ[e] 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 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 [3, 4, 25, 45, 46]. 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. Furthermore, the calculation of energy consumption and heating requirements are also modeled 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.

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 Fig. 1. In Fig. 2, this is shown as the number of adoptions calculated yearly (Adoptions in Fig. 2 and Ad in Eq. 1). The greater the number of households with a heat pump

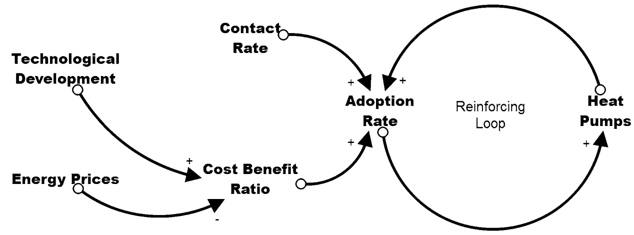

Fig. 1 Causal loop diagram of heat pump adoption

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 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 1 describes the calculation of the number of yearly adoptions (Ad) shown in Fig. 2.

$$\mathrm{Ad} = \mathrm{HH} \cdot \mathrm{CBR} \cdot \mathrm{CR} \cdot \frac{\mathrm{HP}}{\mathrm{HH} + \mathrm{HP}} \tag{1}$$

$$\mathrm{CBR} = \frac{\text{Incumbent Heating Cost}}{\text{Heat Pump Heating Cost}} \tag{2}$$

These two Eqs. (1, 2) form the main structure of the model; see Figs. 1 and 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, shows the stock and flow diagram of the main feedback loop shown above. This structure and the accompanying Eq. (1) are based upon an epidemiological model of infection rates in a population [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 Fig. 1.

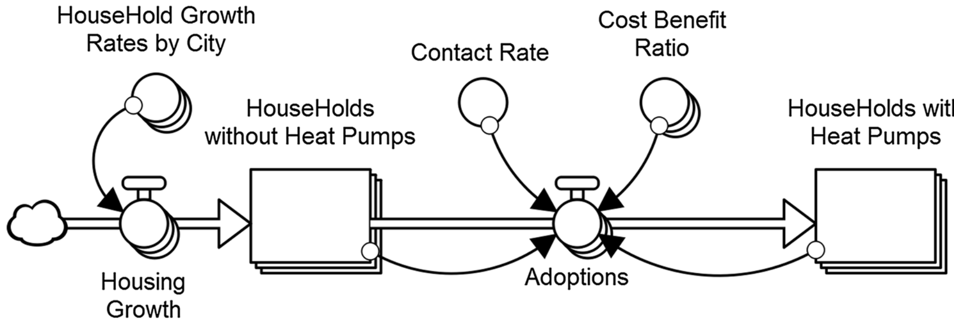

Fig. 2 Stock and flow diagram of adoption rate model.

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 Fig. 3, for the years 2005 through 2025.

The historical pricing for electricity and natural gas are gathered from Statistics Canada census and survey data [34, 35]. 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 Fig. 3 also includes the 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. 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 Fig. 3.

Similarly, historical furnace oil prices are compared to past oil prices and the difference between the two minimized to obtain a price forecast. Furnace oil prices are compared to a weighted average price 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 is 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

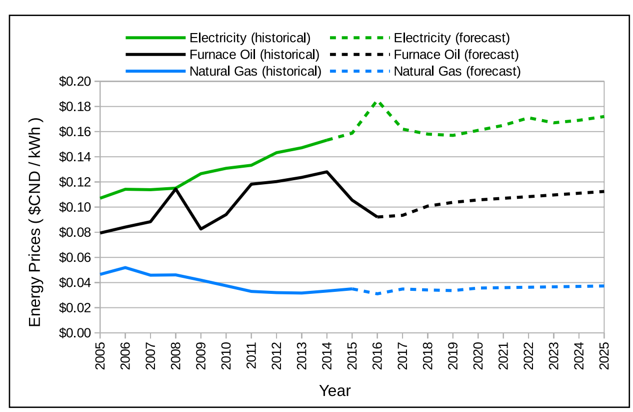

Fig. 3 Historical and forecast energy prices

equivalent (CO_2e) 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 federal minimum price is used in this study from 2020 onward, and it is calculated on a per kWh basis according to the global warming potential of each fuel as shown in Table 3.

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.

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 [1, 2, 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 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 [1, 40, 41]. 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.

Weather

Heating needs can be estimated by 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 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 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.

$$Q = \frac{A \cdot U \cdot \mathrm{HDDs} \cdot 24 \cdot 0.75}{(18.3 - \mathrm{WD}) \cdot 1000} \quad (3)$$

Table 1 Cities, heating degree days (HDD), heat loss per unit area and time (U), and winter design temperature (WD).[2]

City in Ontario	HDD 18.3 (days, °C)	U (W/m^2h)	99% WD (°C)
Hamilton	3919	50.1	− 15.4
London	3954	50.1	− 15.4
North Bay	5192	60.9	− 24.6
Ottawa	4441	56.4	− 20.8
Sault Ste. Marie	4950	57.2	− 21.5
Sudbury	5241	61.0	− 24.7
Thunder Bay	5594	63.2	− 26.6
Timmins	6017	67.1	− 29.9
Toronto	3533	48.1	− 13.7
Windsor	3444	47.4	− 13.1

Table 2 Specifications of average home from Swan et al. [38]

Parameter	Value	Units
Living Area	144.7	m^2
Wall Area	141.7	m^2
Window Area	23.1	m^2
Indoor Ceiling Height	2.44	m
Ceiling Insulation	4.6	m^2 °C/W
Wall Insulation	2.1	m^2 °C/W
Basement Insulation	1.4	m^2 °C/W
Air Changes at 50Pa	6.5	ACH_{50}

Table 3 CO_2e emissions by fuel type (GWP_{100}) [8, 15, 28]

Heating energy source	Carbon emissions (gCO_2e / kWh heat)
Electricity	40
Natural gas	215
Furnace oil	351

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 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) 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^2h and are shown in Table 1. Equation 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.

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 Eq. 9). Energy requirements are then calculated by applying efficiencies of the heat pumps (see Sect. 2.7) and incumbent heating systems, and from these energy requirements, greenhouse gas emissions can be estimated.

Life-cycle assessment

This study does not constitue a full LCA. It is narrowly restricted to the use of energy to heat residences in the 10 cities chosen in Ontario (see Table 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 Sect. 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.

Greenhouse gas emissions

Greenhouse gas emissions are calculated first by determining the CO_2e emissions for natural gas, furnace oil, and electricity in Ontario. These carbon emissions are shown in Table 3. First the content of CO_2, CH_4, and N_2O 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_20. 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].

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 Eq. 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. Figure 9 shows the GHG emissions reductions as they were calculated for each year.

$$\mathrm{GHG}_{\mathrm{red.}} = \mathrm{GHG}_{\mathrm{disp.\ heating}} - \mathrm{GHG}_{\mathrm{HP\ elec.}} \tag{4}$$

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 energy is delivered for 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 current ASHP performance, and three scenarios used in the analysis of sensitivity to technological development (Sect. 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 (Sect. 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.

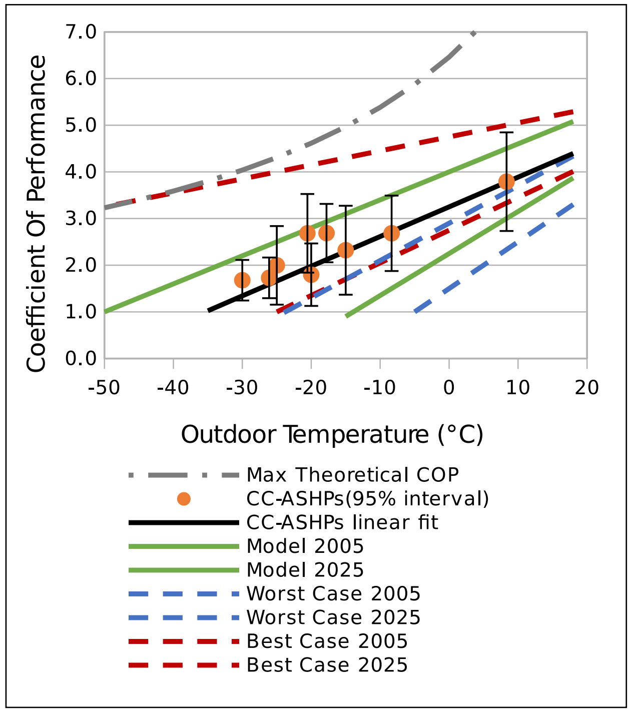

Fig. 4 Technological development of heat pump performance

Table 4 Standards for heat pump performance in Canada and the US [23, 42]

Effective dates	Split HSPF (COP)	Packaged HSPF (COP)
Natural Resources Canada		
After 2006	7.7 (2.25)	7.7 (2.25)
Before 2010	7.1 (2.08)	7.1 (2.08)
After 2010	7.4 (2.17)	7.4 (2.17)
U.S. Department of Energy		
1992–2006	6.8 (2.00)	6.6 (1.93)
2006–2015	7.7 (2.25)	7.7 (2.25)
After 1 Jan. 2015	8.2 (2.40)	8.0 (2.34)

Table 4 below shows the dates these standards were effective and the associated HSPF and average seasonal COP values [23, 42].

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 temperatures (8.3, − 8.3, − 15 °C) for each heat pump in the dataset [26]. They are the three orange data points from the right shown in Fig. 4. Error bars indicate a 95% confidence interval at each of the three temperatures. From the

Table 5 Coefficients for calculating the heat pump performance during each year modelled

Scenario	Intercepts (I)		Slopes (S)	
	Initial (°C)	Delta (°C/year)	Initial (°C)	Delta (°C/year)
Model	2.25	0.875	0.09	− 0.0015
Worst	1.50	0.070	0.10	− 0.0010
Best	2.75	0.100	0.07	− 0.0020
Worst to best	1.50	0.163	0.10	− 0.0035

These are used in Eqs. 5 and 6. The resulting lines are shown in Fig. 4

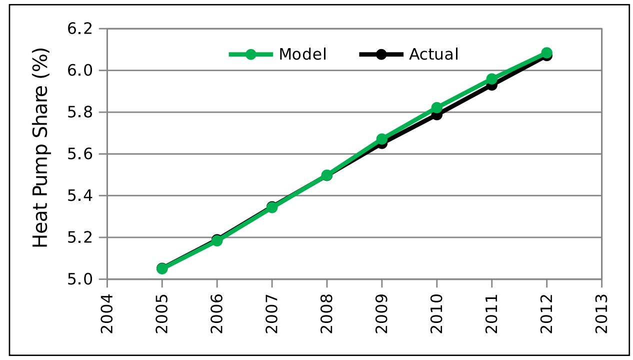

Fig. 5 Comparison of model and actual data 2008–2012

average performance at these three temperatures, a linear curve fit was applied. It is shown in Fig. 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.

$$I(yr) = I_{\text{initial}} + I_{\text{delta}} \cdot yr \tag{5}$$

$$S(yr) = S_{\text{initial}} + S_{\text{delta}} \cdot yr \tag{6}$$

$$COP(T) = S(yr) \cdot T + I(yr) \tag{7}$$

Figure 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 Fig. 4. The improvement in performance from year to year is linear. That is, the slope and intercept with the y axis (COP at 0°) of the COP line increases linearly every year as described in Eqs. 5 and 6. Coefficients for intercepts, *I*, and slopes, *S*, are shown in Table 5. Similarly, in dashed blue lines we see a "worst case" scenario for heat pump performance, and in dashed red lines we see a "best case" scenario. These scenarios are used for sensitivity testing, the results of which are shown in Sect. 3, Tables 6 and 7. In all scenarios—model, worst, best, and worst to best cases—both

Table 6 Sensitivity testing of the low temperature cut-off.

Scenario	Low temp. cut-off (L)			Heat pump share	
	Initial (°C)	Delta (°C/year)	Final (°C)	UEP (%)	REaCP (%)
Model	− 7.5	− 1.125	− 30	7.966	8.896
Worst	0	− 0.5	− 10	7.781	8.723
Best	− 15	− 1.5	− 45	8.006	8.904

Table 7 Sensitivity testing of heat pump performance

Scenario	Heat pump share	
	UEP (%)	REaCP (%)
Model	7.966	8.896
Worst	7.990	8.931
Best	7.974	8.286
Worst to best cases	8.862	10.323

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 7 shows the relationship between performance (COP) at outdoor temperature, *T*, using the yearly calculated intercepts (*I*) and slopes (*S*).

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 to 2010 inclusive are 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.

Results and discussion

This system dynamics model (see Figs. 1, 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 Fig. 5 is both the actual share of heat pumps as tabulated by Statistics Canada and the predicted share from 2005 to 2012.

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 Tables 6 and 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 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 6, Eq. 8 describes how the low temperature cut-off is calculated for each year. Equation 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 $HDD_{\mathrm{city}}(T)$ is the average number of heating degree days per year occurring at temperature T.

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 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.

$$L(yr) = L_{\mathrm{initial}} + L_{\mathrm{delta}} \cdot yr \tag{8}$$

$$HDD_{\mathrm{HP}}(yr) = \sum_{T=L(yr)}^{T=18.3} HDD_{\mathrm{city}}(T) \tag{9}$$

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 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 Fig. 5. Figure 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 7 and Fig. 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 Fig. 2). Conceptually,

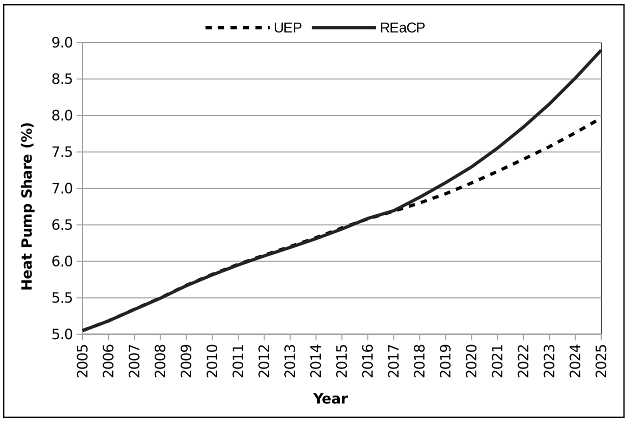

Fig. 6 Effect of electricity price reductions and carbon pricing on the share of households with heat pumps

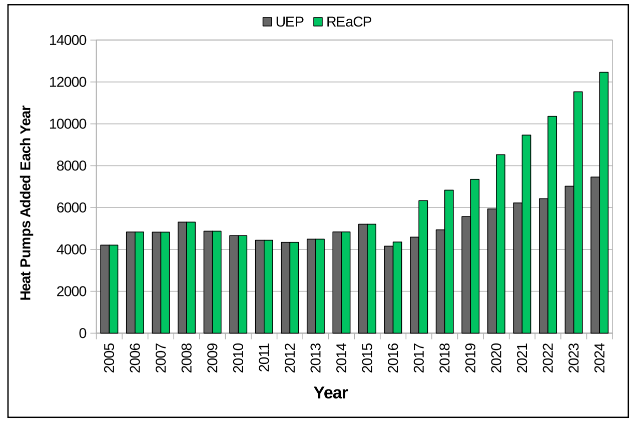

Fig. 7 Number of heat pumps installed each year

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.

Predicted heat pump share

The model behaviour follows trends in pricing of fuels and the performance of the technology. Shown in Fig. 6 is the predicted share of residences with heat pumps. A dashed line represents the predicted heat pump share with unchanged energy prices 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 Fig. 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 Fig. 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 Fig. 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 Fig. 4. It is still a contributing factor because even with unchanged prices (UEP), the number of heat pumps added each year increases from 2016 onwards.

Energy savings and greenhouse gas emissions

The reduction of electricity prices by 25% and the introduction of carbon pricing have 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 7 demonstrates a pattern of heat pump

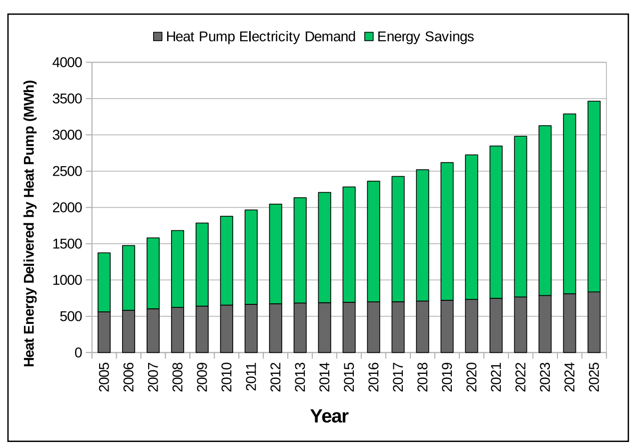

Fig. 8 Heating energy provided and energy savings by year

adoption greatly increased by the new energy price policies and aided by improved heat pump performance.

Figure 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 (Fig. 9) show exactly 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 Fig. 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 Fig. 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 3% of the total residential GHG emissions due to home heating in 2013 (15 $MtCO_2e$) [21].

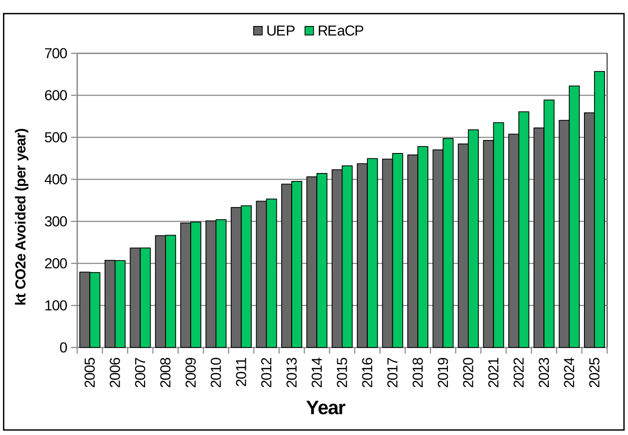

Fig. 9 Greenhouse gas emission reductions by year

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 [17, 29, 30]. 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 Sect. 3.1.2) 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.

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