Life Cycle Cost Comparison and Optimisation of Different Heat Pump Systems in the Canadian Climate

Martin Kegel, Roberto Sunye, Justin Tamasauskas
CanmetENERGY, Natural Resources Canada, Varennes, Qc

ABSTRACT

This paper presents a life cycle cost analysis of several combinations of heat pump systems with renewable sources in the Canadian climate. Using TRNSYS, the proposed systems were modeled for three housing types – a 1980's house, an energy efficient house and a future "Net Zero Ready" house in the Toronto region with a 210 m^2 heated floor area. Through optimisation and a 20 year life cycle analysis, it was found that a standard air source heat pump system is the most economically viable for a 1980's and energy efficient house. A ground source heat pump system is the most economically viable for a future "Net Zero Ready" house. The effect of natural gas pricing on system selection was also investigated.

1. INTRODUCTION

In Canada, the residential sector accounts for 16% of the secondary energy consumption, of which 83% can be attributed to space heating, space cooling and domestic hot water production (OEE, 2010a). Heat pumps are widely used to upgrade available heat from renewable sources in order to provide space heating and/or water heating as well as space cooling for houses. Capable of delivering more energy than they consume, heat pumps therefore provide a dramatic reduction in energy consumption, GHG emissions and ultimately household utility costs. Furthermore, if combined effectively with other energy systems, heat pumps can contribute to achieve net zero energy consumption in houses. However, the integration of heat pumps in households is very complex because of the interconnection between mechanical systems, housing envelope and with the indoor and outdoor climate. There are also no systematic analyses of the optimal integration of heat pump systems to specific buildings, regions and climates in Canada.

The objective of this paper is to address the lack of information on the optimal integration of heat pumps in Canadian households, by presenting a life cycle cost (LCC) comparison and optimisation of several combinations of heat pump systems with renewable sources for a 210 m^2 single detached house. The project considered three different Canadian regions representing 70% of the single detached housing market (OEE, 2010b) - Montreal, Toronto and Vancouver. For each city, three different housing constructions were considered - a house constructed in the 1980's, a current energy efficient house and a future "Net Zero Ready" house. This paper presents the analysis performed in the Toronto region since over 33% of the single detached houses in Canada are located in Ontario.

To perform the analysis a TRNSYS model of the 210 m^2 Canadian Centre of Housing Technology (CCHT) experimental test house located in Ottawa, Ontario was developed. The house features a fully automated system which operates the lighting, plumbing, appliances and occupancy loads of a typical Canadian family (Swinton et al., 2003). The test house is also fully monitored, enabling the validation of the housing energy model. Using this energy model, modifications to the HVAC system, building envelope, lighting and appliances were done to reflect the representative housing types. Four innovative commercially available heat pump and renewable energy combination systems were implemented into the developed reference housing models and the 20 year LCC was compared. The GenOpt optimisation software was also used to minimize the LCCs.

2. DEVELOPMENT OF THE VALIDATION HOUSE ENERGY MODEL

The Canadian Centre for Housing Technology (CCHT) constructed two twin research residential houses in 1998 to evaluate the effect of new technologies on the whole house performance (Swinton et al., 2001). Characteristics and features of these houses can be found in several research reports by Gusdorf et al. (2002) and Swinton et al. (2003). The houses have also been used as the housing archetype for research projects performing a techno-economic analysis on new HVAC concepts (Kegel et al. 2011). The CCHT house was modeled in TRNSYS v. 17 using the multizone building component (Type 56a). Heating, cooling and ventilation were controlled and modeled in the simulation studio using standard TRNSYS components. The energy model was validated with the CCHT 2003 data set containing the measured energy consumption, temperature and relative humidity profiles for January, March, August and October. The measured and modeled energy consumption is presented in Table 1 with the model results being generally within 10% of the measured data.

Table 1: Modeled and Measured Energy Consumption Comparison (2003 Data Set)

	Measured (*Modeled*)			
Electricity (kWh)	**January**	**March**	**August**	**October**
Lighting & Appliances	203 (*194*)	223 (*211*)	220 (*219*)	251 (*245*)
HRV, Furnace Fan	306 (*280*)	304 (*293*)	344 (*305*)	335 (*328*)
Cooling	0 (*0*)	0 (*0*)	407 (*379*)	39 (*31*)
Electricity Total	509 (*474*)	527 (*504*)	971 (*903*)	625 (*604*)
Natural Gas (m^3)	**January**	**March**	**August**	**October**
Domestic Hot Water	47 (*49*)	51 (*54*)	38 (*43*)	47 (*51*)
Heating	330 (*317*)	192 (*215*)	0 (*0*)	76 (*83*)
Natural Gas Total	377 (*366*)	243 (*269*)	38 (*43*)	123 (*134*)

3. DEFINITION OF THE BASE CASE HOUSING MODELS

Three housing construction types were considered for this project - a typical 1980’s house, a newly constructed house meeting the minimum energy efficiency design requirements as required by the Ontario Building Code (OBC) and a newly constructed house considered to be “Net Zero Ready” (NZR). To meet the minimum energy efficiency design requirements of the OBC, a newly constructed house will need to reach a minimum performance level of 80 on Natural Resources Canada’s “EnerGuide Rating Scale (ERS) for New Houses” (ERS-80) (Ontario Ministry of Municipal Affairs and Housing, 2010). A “NZR” house is defined as a home which has an infrastructure and building envelope in which the addition of renewables becomes cost effective to achieve Net Zero Energy (A house which produces as much energy as it consumes annually). For this analysis we have considered a “NZR” home as a house designed to meet ERS-86 (Parekh, 2010). The central heating and cooling system is sized according to the peak heating and cooling loads for a 21°C and 23°C heating and cooling set point temperature, respectively.

Defining the 1980’s House Model

To accurately define a typical 1980’s house, the *Canadian Single-Detached and Double/Row Housing Database* (CSDDRD) was consulted (Swan et al., 2009). This database contains detailed information of 17,000 houses representing the Canadian Housing Stock (CHS). The database was filtered for single detached housing constructed between 1980 and 1989, located in the Toronto region. These results were further filtered by the primary fuel for heating, natural gas being used in over 91% of the houses. Using these results, characteristics of the building envelope, HVAC and DHW heating were determined. Table 2 summarizes a representative 1980's house from the CHS. A single stage natural gas fired furnace was specified with the database weighted thermal efficiency.

Table 2: Key Characteristics of the 1980's House

Heating System	Central Air Furnace 78.0% steady state efficiency	Roof R-Value	4.96 $(m^2\cdot°C)/W$
Cooling System	Central Cooling Rated COP = 2.27	Wall R-Value	2.33 $(m^2\cdot°C)/W$
DHW	Natural Gas Fired Conventional Tank	Basement Wall	2.09 $(m^2\cdot°C)/W$
Ventilation	None	Basement Slab	Uninsulated
Infiltration	4.65 ACH @ 50Pa	Windows (COG)	2.86 $W/(m^2\cdot°C)$

The appliance energy consumption, lighting power and receptacle loads were not recorded in the CSDDRD database and thus several assumptions had to be made. The major appliances were assumed to consume the average annual energy consumption in 1990 published by the Office of Energy Efficiency (OEE, 2011). The same light fixture layout as in the CCHT house was assumed, however the 60 W and 40 W incandescent fixtures were assumed to be replaced by 15 W and 7 W CFL light bulbs, respectively. Receptacle (small appliance) loads were modeled at the energy consumption level used in the EnerGuide Rating calculations. Appliance and lighting schedules were kept the same as the CCHT schedules, while the receptacle schedules were modified to reflect the recommended energy consumption by the EnerGuide Rating Scale. The daily energy consumption of the appliance, lighting and receptacles are summarized in Table 3. The DHW draw schedule of 233 L per day from the CCHT house was maintained.

Table 3: 1980's House Modeled Appliance, Lighting and Receptacle Loads

Electrical Load	**Appliances**	**Int. Lighting**	**Receptacles**
Daily Consumption	14.0 kWh	0.7 kWh	3.0 kWh

Defining the ERS-80 House Model

HOT2000 is an energy simulation software developed and maintained by Natural Resources Canada that is primarily used to support energy efficiency improvements in Canadian low-rise housing (NRCan, 2010). Based on the housing floor area and primary fuel used for heating, the HOT2000 software calculates the minimum energy consumption required to meet the R-2000 energy target and ultimately the proposed design EnerGuide rating. Thus, to determine the building envelope and mechanical system requirements of a house meeting ERS-80, a HOT2000 energy model of a typical 1990 to 2003 house (determined from the CSDDRD Database) was defined. Using realistic building envelope constructions and heating system efficiencies, a 210 m^2 ERS-80 house was established, summarized in Table 4 and then implemented into the TRNSYS housing model because of the simulation tools ability to model non standard HVAC equipment. A commercially available single stage, natural gas fired, four position central air furnace was selected (the typical heating system specified in the database). The lighting and receptacle loads were maintained at the modeled 1980 levels, however being a new construction, it was assumed the appliances would meet the minimum

EnergyStar level and the daily appliance consumption was from 14.0 kWh/day to 6.6 kWh/day. Operating schedules were kept the same as the 1980's house.

Table 4: Key Characteristics of the ERS-80 House

Heating System	Central Air Furnace 81.2% steady state efficiency
Cooling System	Central Cooling Rated COP = 3.41
DHW	Natural Gas Fired Induced Draft
Ventilation	HRV, 0.84 effectiveness 31 L/s (65 cfm)
Infiltration	1.5 ACH @ 50Pa

Roof R-Value	6.76 (m^2·°C)/W
Wall R-Value	3.16 (m^2·°C)/W
Basement Wall	3.26 (m^2·°C)/W
Basement Slab	Uninsulated
Windows (COG)	1.70 W/(m^2·°C)

Defining the NZR House Model

Similar to the ERS-80 house, the HOT2000 energy simulation software was used to define the ERS-86 house. Using the HOT2000 CCHT ERS-80 energy model, the most suitable energy efficiency improvements were identified using a standard HVAC system to bring the house to NZR (ERS-86). Realistic building envelope insulation levels were specified following the suggestions of Parekh (Parekh, 2010). The characteristics of the house are summarized in Table 5. It was found that all market available single stage furnaces were significantly oversized for the required heating load. Thus, a multispeed, two stage furnace was selected since the 1st stage heat output was adequately sized to meet the heating demand. The same electrical and DHW loads and operating schedules as the ERS-80 house were used.

Table 5: Key Characteristics of the ERS-86 House

Heating System	Two stage Air Furnace 82.4% steady state efficiency
Cooling System	Central Cooling Rated COP = 3.45
DHW	Natural Gas Fired Induced Draft (added insul.)
Ventilation	HRV, 0.84 effectiveness 31 L/s (65 cfm)
Infiltration	0.6 ACH @ 50Pa

Roof R-Value	8.93 (m^2·°C)/W
Wall R-Value	5.46 (m^2·°C)/W
Basement Wall	4.95 (m^2·°C)/W
Basement Slab	2.68 (m^2·°C)/W
Windows (COG)	0.97 W/(m^2·°C)

4. UTILITY COSTS

To perform the LCC analysis, the electricity and natural gas (NG) rates for the Toronto region were taken from Toronto Hydro (2011) (Table 6) and Enbridge Gas (2011) (Table 7). To assess the impact of utility pricing on the analysis, the highest NG rate listed by the Ontario Energy Board (2011) over the past five years is also considered (Table 7).

Table 6: Toronto Hydro (2011) Utility Rates

Time Period	Tier / 30 days	Rate, $/kWh
November 1st to April 30th	First 1000 kWh	0.10731
	Above 1000 kWh	0.11831
May 1st to October 31st	First 600 kWh	0.10731
	Above 600 kWh	0.11831

Table 7: Enbridge Gas (5 Year Low and High) Utility Rates

Tier	Low Rate, $/m^3 (*$/kWh eq.*)	High Rate, $/m^3 (*$/kWh eq.*)
First 30 m^3	0.2701 (*0.02573*)	0.5203 (*0.04955*)
Next 55 m^3	0.2654 (*0.02528*)	0.5155 (*0.04910*)
Next 85 m^3	0.2617 (*0.02493*)	0.5118 (*0.04874*)
Above 170 m^3	0.2589 (*0.02466*)	0.5091 (*0.04848*)

5. SIMULATED BASE CASE ENERGY CONSUMPTION RESULTS

The predicted energy consumption and utility costs of the three base cases evaluated are summarized in Table 8. The TRNSYS simulation was run with the Toronto TMY2 weather file and a simulation timestep of 5 minutes. It can be seen that the cooling load is higher in the ERS-86 house, which is expected since the internal loads have a greater impact.

Table 8: Toronto Base Case Predicted Energy Consumption and Utility Costs

Annual Energy Use	**1980**	**ERS-80**	**ERS-86**
Lighting, Appliances & Receptacles (kWh)	7,195	4,469	4,469
Heating, Cooling and HRV Fans (kWh)	2,800	2,269	2,269
Space Cooling (kWh)	1,190	828	925
DHW Electricity (kWh)	0	0	0
Space Heating Electricity (kWh)	0	0	0
Total Electricity Purchased (kWh)	**11,185**	**7,567**	**7,663**
DHW Gas (kWh eq.)	6,020	5,683	5,321
Space Heating Gas (kWh eq.)	32,111	16,265	6,104
Natural Gas Purchased (kWh eq.)	**38,131**	**21,948**	**11,426**
Total Energy Consumption (kWh)	**49,316**	**29,514**	**19,089**
Annual Electricity Cost	$1,462.30	$1,054.00	$1,110.50
Annual Gas Cost (Low)	$1,177.20	$777.70	$551.40
Annual Gas Cost (High)	$2,085.00	$1300.00	$856.20

6. DEFINITION OF HEAT PUMP CASES TO ASSESS

To determine the most cost-effective integration of heat pumps into each housing archetype, four different heat pump and renewable energy combination layouts were selected. Each heat pump was implemented into a central air distribution system:

1. Standard Air Source Heat Pump (air to air) (ASHP)
2. Cold Climate Air Source Heat Pump (air to air) (CC ASHP)
3. Ground Source Heat Pump (water to air) (GSHP)
4. Solar Assisted Air Source Heat Pump (air to air) (SAHP)

Standard Air-Source Heat Pump System and Control

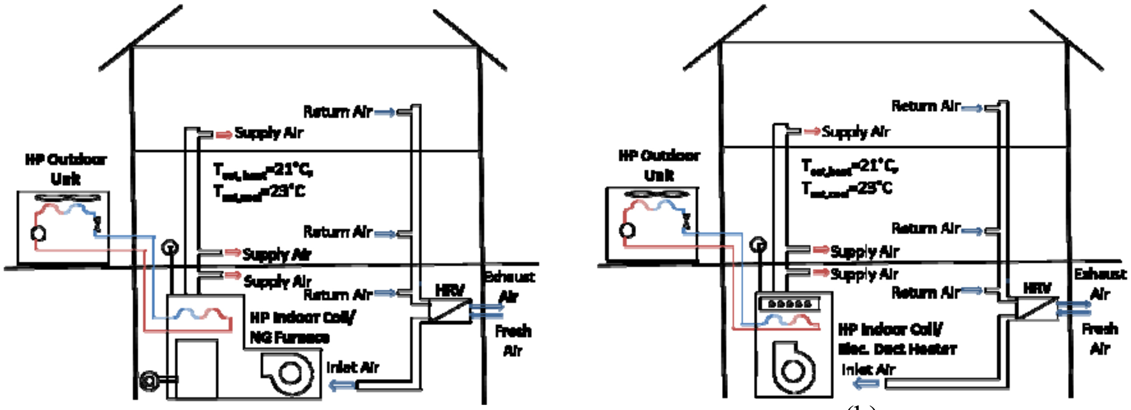
This combination evaluates a typical commercially available ASHP that is integrated into a central air distribution system. The system utilizes the renewable energy available in the outdoor air, upgrading low grade heat for heating, through an outdoor unit serving the refrigerant-air coil located inside the central indoor unit. At colder ambient temperatures (<5°C), the available heating capacity of the ASHP declines substantially and thus a natural gas furnace is used as the auxiliary heating system. A schematic of the proposed heat pump system is shown in Figure 1a for the ERS-80 and ERS-86 house.

A thermostat on the first floor of the home is used to control the HVAC system in order to maintain a temperature setpoint of 21°C in heating ($T_{set,heat}$), and 23°C in cooling ($T_{set,cool}$). Although the ASHP combination has a heating capacity that declines significantly as temperatures fall below 5°C, the coefficient of performance (COP) stays above 1.0. Thus, the natural gas furnace is controlled to operate when the heat pump system is unable to maintain the desired room temperature (room temperature falls below 17.7°C) or depending on the utility rate, at an ambient temperature, T_{cutoff}, where it is more cost beneficial to run the furnace. It should be noted that the control strategy prevents the heat pump and natural gas furnace from operating simultaneously.

Cold Climate Air Source Heat Pump System and Control

A cold climate air source heat pump (CC ASHP) implemented into the air distribution system is proposed in this combination. The CC ASHP is able to maintain a higher degree of performance and has an improved heating capacity at conditions where standard air source heat pumps become inefficient or unable to meet the heating load. A similar system is specified as in the first scenario, with the outdoor unit serving an indoor unit containing a fan and refrigerant-air heat exchanger. An electric duct heater is integrated to supplement heat pump operations during periods of extreme cold. A schematic of the proposed system for the ERS-80 and ERS-86 house is shown in Figure 1b.

System operations are controlled using a thermostat on the first floor, with $T_{set,heat}$=21°C and $T_{set,cool}$=23°C. Unlike the standard ASHP combination, the electric auxiliary system is designed to supplement heating operations, and is not sized for the full heating load. The duct heater is activated when the first floor temperature falls below 17.7°C, and operates in conjunction with the heat pump until the desired heat setpoint is reached.



(a) (b)

Figure 1: Heat Pump Layout Schematics (a) ASHP, b) CC ASHP

Ground Source Heat Pump System and Control

This combination evaluates a water to air GSHP system installed in the basement of the house (Figure 2a). In heating mode, the system functions on the principle that the ground is a source of renewable heat, upgrading the available energy stored in the ground. In cooling mode, the ground is used as a sink. As such, appropriate sizing of the ground heat exchanger is vital for proper system operations. The required ground heat exchanger lengths to meet the loads were calculated and summarized in Table 9. A two pipe borehole design is used for each housing archetype. An electric duct heater is also incorporated to supplement heat pump operations as necessary.

System operations are controlled using the thermostat on the first floor. As with the cold climate integration, the electric duct heater is used in conjunction with the heat pump when first floor temperature falls below 17.7°C.

Table 9: GSHP Borehole Length and Quantity

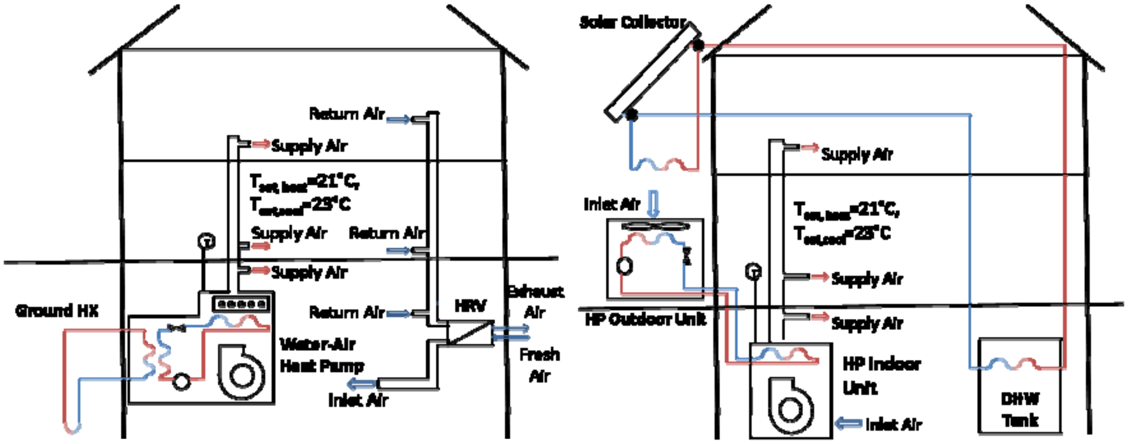
Archetype	1980	ERS-80	ERS-86
Total Borehole Length (m)	238	125	72
No. of Heat Exchangers	2	1	1

Solar Assisted Heat Pump System and Control

The fourth layout considered is a solar assisted air source heat pump system, which utilizes the renewable energy available from the air and sun. A typical split system air source heat pump as in the first combination is considered; however, solar collectors mounted on the south facing roof of the house serve a hot water coil used to preheat the ambient air to the outdoor unit of the ASHP. Similar to the ASHP combination, a natural gas furnace, sized to meet the full heating load, is used as the auxiliary heater. When the heat pump operates in cooling mode, preheating the air through the condenser is not required, so the solar collectors are used to preheat the DHW. The existing gas fired DHW tank is replaced with an indirect fired tank and a tankless electric hot water heater to boost the temperature. Figure 2b shows a schematic of the proposed system.

Heat pump operations are controlled by a thermostat on the first floor of the home. Operations of the auxiliary gas system are based on the same parameters defined in the standard air-source heat pump description.

Evacuated tube solar collectors are used for this application due to their improved efficiency at the higher inlet fluid temperatures anticipated during DHW operations. The solar array is sized based on the DHW demand of a family of four. The total collector area is 6.78 m^2, while the specific flow rate is set at 37.2 kg/(h·m^2), based on recommended manufacturer supplied data (Silicon Solar, 2011).



(a) (b)

Figure 2: Heat Pump Layout Schematics a) GSHP (b) SAHP

7. METHODOLOGY

To identify the most viable heat pump system for the Toronto region, a LCC analysis is performed. Each proposed system is analyzed over a 20 year period, with the objective of minimizing the final capital and annual operating costs and comparing the results to the lifecycle cost of the base case scenario. To perform this type of lifecycle optimisation analysis, an inflation rate of 3% is assumed, a discount rate of 6% and a natural gas and electricity escalation rate of 1.4% and 0.4%, respectively (Canadian Commission on Building and Fire Codes, 1997). Maintenance costs were not considered in the analysis. The capital cost, defined as the total cost to acquire and install the proposed system, is discussed below. Since the cost of future energy prices can greatly affect the results, the analysis also investigates the impact of high and low natural gas rates. For the 1980's housing archetype, it is assumed that the heating and cooling equipment has reached the end of its lifecycle and is due for replacement. The ERS-80 and ERS-86 housing archetypes are a new construction and thus new HVAC equipment must be purchased.

Capital Costs

The capital costs for the central air furnaces and air conditioners for the base case housing were estimated from the RS Means Construction Cost Handbook (2006). The costs are based on the size of the equipment installed and include the labour costs associated with the system installation.

For the standard ASHP and CC ASHP, the capital cost was based on a survey of local HVAC contractors and included all necessary piping, control thermostats and necessary modifications to the HVAC ducting. Pricing was obtained for a 1.5, 2 and 3 ton ASHP unit and coincided well with published values in RS Means (2006), which was between $700 to a $1,000 more than a central air conditioner.

Pricing for the water to air heat pumps used in the GSHP system were obtained from RS Means (2006). The cost of borehole drilling was estimated at $49.2/m ($15/ft) including all necessary piping connections (City of Toronto, 2010), while the cost of the circulation pumps was obtained from manufacturer supplied data (Wilo SE, 2010).

Pricing for the solar system was done on a component basis. The cost of the solar collectors and circulation pump (Silicon Solar, 2011), tankless hot water heater (E-Tankless, 2011), and DHW tank (e-ComfortUSA, 2011) were obtained from manufacturer representatives. The price of the standard air-source heat pump was obtained from the survey conducted among HVAC contactors.

Table 10 presents a summary of the capital costs for each archetype and system layout. The cost of the ASHP, CC ASHP and SAHP system include a replacement natural gas furnace and back-up electrical duct heaters, respectively. No back-up system is required for the GSHP system. The capital cost for the ASHP and SAHP is for a 1.5 ton system. Capital costs for the 2 and 3 ton system can be found in section 8.

Table 10: Summary of Capital Costs for the Proposed HVAC Systems

Archetype	Base Case	ASHP	CC ASHP	GSHP	SAHP
1980's	$5,377	$6,021	$10,000	$23,560	$12,304
ERS-80	$5,268	$5,912	$10,000	$9,815	$12,195
ERS-86	$5,055	$5,997	$10,000	$6,536	$12,281

System Optimization

Optimization techniques are applied to the standard ASHP and SAHP systems in order to determine the most economically viable configuration. The optimization problem can be subdivided into a series of design variables and constraints, an objective function, and an optimization algorithm.

Design Variables and Constraints

The current optimization procedure focuses on determining the ambient temperature at which there is no longer a cost benefit to use the ASHP or SAHP (T_{cutoff}) for 3 discrete heat pump sizes (1.5, 2 and 3 ton). The variable T_{cutoff} is treated as a continuous variable in the optimization procedure. The lower bound is set to -19.4°C based on the minimum operating temperature provided in the heat pump manufacturer performance data sheet, while the upper limit is set to the 21°C heating set point temperature. No system optimization was undertaken for the CC ASHP since it is capable of operating at low temperatures and comes in only one size. Similarly, no optimization for the ground source heat pump system was undertaken, since the ground heat exchangers were sized for a 2 ton system and no temperature switch point is required.

Objective Function

The objective of the optimization is to minimize the total cost of the system over a 20 year lifecycle. Mathematically, the objective function is defined as:

$$LCC_{system} = C_{capital} + C_{annual} \tag{1}$$

Where,

LCC_{system} = lifecycle cost of the system ($)
$C_{capital}$ = the capital cost ($)
C_{annual} = sum of the annual operating costs (excluding maintenance & fixed monthly charges), in 2011 dollars ($)

Optimization Algorithm

A Hooke-Jeeves search algorithm is selected for the optimization algorithm. This algorithm is selected due to its ability to deal with the discontinuous cost functions in building optimization problems (Wetter, 2009), while also requiring fewer simulations in comparison to more complex search algorithms (Wetter and Wright, 2004).

8. RESULTS AND DISCUSSION

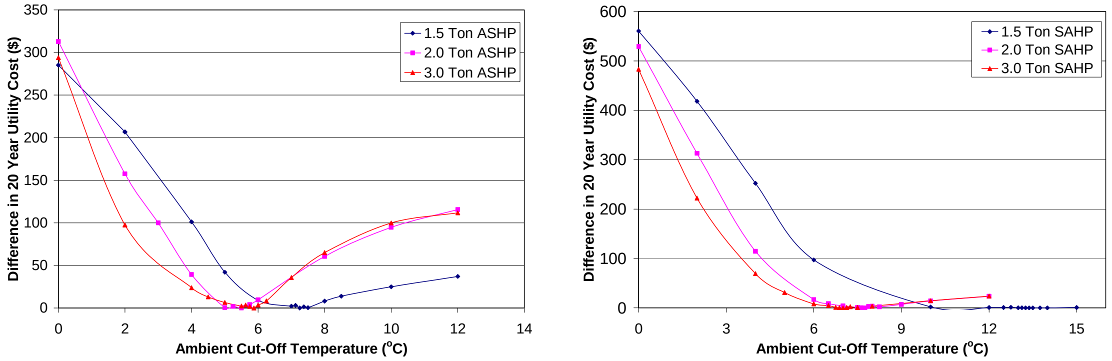
Table 11 summarizes the 20 year lifecycle cost for the base case scenarios predicted by the TRNSYS simulations.

Table 11: Economic Analysis of Base Case Homes

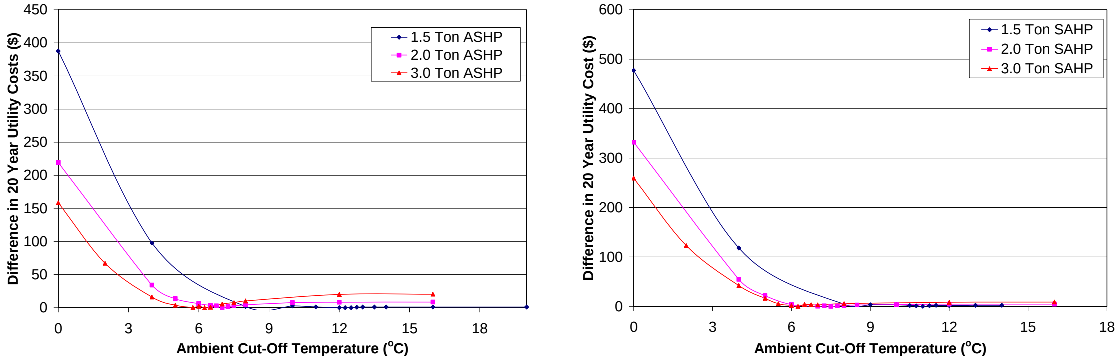
Archetype	Capital Cost	20 Year Utility Costs (Low & High NG)		20 Year Lifecycle Cost (Low & High NG)	
1980	$5,377	$27,132	$38,914	$32,509	$44,291
ERS-80	$5,268	$17,376	$24,514	$22,644	$29,782
ERS-86	$5,055	$15,102	$19,316	$20,158	$24,372

Standard ASHP and SAHP

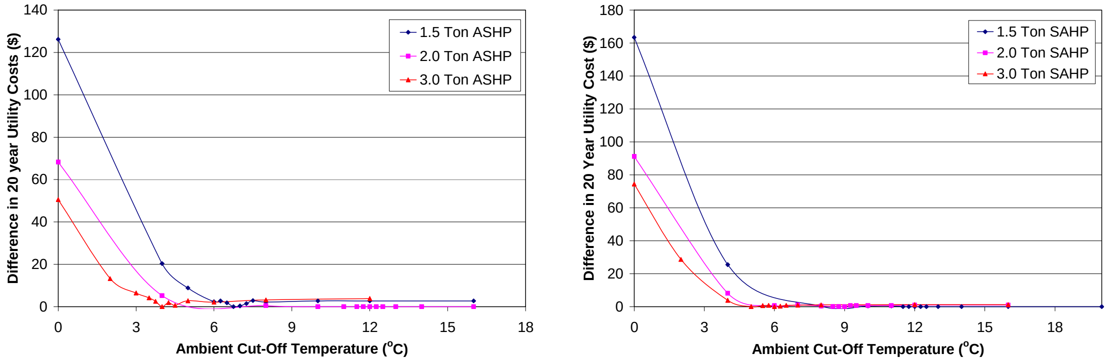
Prior to assessing the ASHP and SAHP systems, the ambient temperature at which the ASHP and SAHP are no longer cost beneficial to operate was determined. Using GenOpt, TRNSYS simulations of the proposed systems were run with the objective of minimizing the utility cost over the 20 year period. For each housing type and discrete ASHP size, the 20 year lifecycle costs at various ambient cut-off temperatures were recorded. The difference between the recorded lifecycle cost and the minimum calculated lifecycle cost are plotted in Figure 3 at the low NG rate. At the high NG rate, it was cost beneficial to operate the heat pump up to its minimum operating temperature in most cases.



(a) ASHP 1980 (d) SAHP 1980



(b) ASHP ERS-80 (e) SAHP ERS-80



(c) ASHP ERS-86 (f) SAHP ERS-86

Figure 3: Difference between the 20 Year Minimum Utility Cost and Utility Cost at Various Ambient Cut-off Temperatures
ASHP: a) 1980, b) ERS-80, c) ERS-86
SAHP: d) 1980, e) ERS-80, f) ERS-86

As expected, the cut-off temperature is much lower at the higher natural gas rates because of the utility pricing. It is encouraging however, that at the low NG rate the cut-off temperature is below 21°C, thus indicating there is a benefit to installing a standard air source heat pump system over a conventional air conditioner. In most housing archetypes and heat pump sizes, the 20 year lifecycle cost tends to rapidly increase as the cut-off temperature goes below 4°C – the point at which the standard ASHP heating capacity begins to decline.

The benefit of using a solar collector to preheat the ambient air through the condenser did not show any benefit when compared to the standard ASHP cut-off temperatures. In most cases, the cut-off temperature was actually higher. This is likely caused due to the additional electricity usage of the DHW and pumping from the solar collector, causing more electricity usage at the 2nd tier pricing level. As a result, the heat pump should not be used as often, thereby resulting in a higher cut-off temperature. The 20 year lifecycle costs are summarized in Table 12 and Table 13 using the optimum cut-off temperature.

Table 12: Economic Analysis of ASHP Integration

Archetype	HP Size (Ton)	Capital Cost	20 Year Utility Costs (Low & High NG)		20 Year Lifecycle Cost (Low & High NG)	
1980	1.5	$6,021	$25,591	$31,311	**$31,612**	$37,331
	2.0	$6,319	$26,070	$31,000	$32,389	**$37,319**
	3.0	$6,916	$27,199	$32,168	$34,115	$39,085
ERS-80	1.5	$5,912	$17,294	$21,320	**$23,205**	**$27,231**
	2.0	$6,210	$17,263	$21,025	$23,473	$27,236
	3.0	$6,807	$17,194	$21,022	$24,001	$27,829
ERS-86	1.5	$5,997	$14,703	$17,710	**$20,700**	**$23,707**
	2.0	$6,296	$14,655	$17,483	$20,951	$23,779
	3.0	$6,893	$14,605	$17,366	$21,498	$24,259

Table 13: Economic Analysis of SAHP Integration

Archetype	HP Size (Ton)	Capital Cost	20 Year Utility Costs (Low & High NG)		20 Year Lifecycle Cost (Low & High NG)	
1980	1.5	$12,304	$27,810	$32,077	**$40,114**	$44,381
	2.0	$12,602	$28,371	$31,762	$40,973	**$44,364**
	3.0	$13,199	$29,548	$32,931	$42,748	$46,131
ERS-80	1.5	$12,195	$19,440	$22,035	**$31,635**	$34,230
	2.0	$12,493	$19,406	$21,713	$31,899	**$34,206**
	3.0	$13,090	$19,331	$21,683	$32,422	$34,774
ERS-86	1.5	$12,281	$16,611	$18,124	**$28,892**	**$30,405**
	2.0	$12,579	$16,556	$17,871	$29,135	$30,450
	3.0	$13,176	$16,499	$17,744	$29,675	$30,920

As anticipated from the cut-off temperature analysis, the ASHP presents lower 20 year utility costs and lifecycle costs than the SAHP. Thus, it can be concluded that using solar energy to preheat the air through the outdoor unit is not a cost-beneficial option under this control strategy.

The general trend of the standard ASHP is that the 1.5 ton unit minimizes the 20 year lifecycle cost for the three housing archetypes. Even with the low NG rate, the standard ASHP shows a 20 year utility cost saving compared to the base case with a minimal incremental cost. A slightly higher 20 year lifecycle cost was only predicted in the ERS-86 housing archetypes where the capital cost of the equipment can not overcome the 20 year utility cost savings. With the high NG rates, the results are even more promising, in which 20 year lifecycle cost savings close to $7,000 are predicted for the 1980's housing archetype. A similar trend for the ERS-80 and ERS-86 housing archetypes are seen; however with less lifecycle costs savings ($4,500, $650 respectively). The addition of the air source heat pump allows greater flexibility in meeting the thermal demands of the home, mitigating the impact of steep increases in NG rates.

CC ASHP

The economic performance of the CC ASHP is summarized in Table 14. The system has a higher capital cost than the standard ASHP system. However, it has an improved heating capacity and coefficient of performance at low ambient temperatures and thus the back-up heating system size is reduced.

Table 14: Economic Analysis of Cold Climate ASHP Integration

Archetype	Capital Cost	20 Year Utility Costs (Low & High NG)		20 Year Lifecycle Cost (Low & High NG)	
1980	$10,000	$27,095	$28,977	$37,095	$38,977
ERS-80	$10,000	$17,992	$19,769	$27,992	$29,768
ERS-86	$10,000	$14,014	$15,789	$24,014	$25,789

At the low NG rates, the CC ASHP showed savings only with the ERS-86 housing archetype compared to the base case and standard ASHP systems. Savings of $1,000 and $700 over the 20 year period were predicted. With the higher capital cost, the CC ASHP did not show any cost-benefit for any of the housing archetypes at the low NG rate. At the high NG rate, 20 year utility cost savings ranging from $10,000 to $2,000 were predicted for all housing archetypes. Similar to the results under low NG rate, the standard ASHP demonstrated a larger cost benefit compared to the base case.

GSHP

The GSHP system 20 year lifecycle cost is presented in Table 15. Similar to the CC ASHP, a GSHP system has a higher capital cost than a standard ASHP, but it has improved performance characteristics at lower ambient temperatures.

Table 15: Economic Analysis of GSHP Integration

Archetype	Capital Cost	20 Year Utility Costs (Low & High NG)		20 Year Lifecycle Cost (Low & High NG)	
1980	$23,560	$20,606	$22,488	$44,166	$46,048
ERS-80	$9,815	$14,036	$15,813	$23,851	$25,628
ERS-86	$6,536	$12,147	$13,921	$18,683	$20,457

From the results, it can be seen that the GSHP system has the lowest annual utility cost of all the systems considered in this paper regardless of which NG rate is used. Comparing the GSHP system to the base for the low NG rates, savings ranging from $6,500 to $3,000 were predicted, while 20 year utility savings between $16,500 and $5,400 were predicted at the high NG rates. Similar to the CC ASHP system, the 20 year utility cost savings were not able to overcome the higher capital cost associated with the system. Only for the ERS-86 house was the GSHP system the most cost-beneficial system under both NG rates considered. The ERS-80 showed a cost-benefit at the high NG rate.

Summary

A summary of the economic analyses results are presented in Table 16. Based on the 20 year lifecycle cost, the standard ASHP system tends to be the best selection for houses that are less efficient on size having a higher heating load. As the heating load reduces, the GSHP system becomes a better option as the ground heat exchanger sizes are reduced. The proposed SAHP system did not show any 20 year utility cost benefits for any of the housing archetypes. Alternate strategies and combinations of solar and heat pump combinations will be investigated in the future. The CC ASHP typically showed 20 year utility cost savings compared to the base case for most housing archetypes at both NG rates considered. The savings were not able to overcome the higher capital cost.

Table 16: Summary of the Optimum 20 Year Lifecycle Costs for each System

		Lifecycle Cost				
NG Rate	**Archetype**	**Base Case**	**ASHP**	**SAHP**	**CC ASHP**	**GSHP**
Low	1980	$32,875	**$31,612**	$40,114	$37,095	$44,166
	ERS-80	$23,010	**$23,205**	$31,635	$27,992	$23,851
	ERS-86	$20,523	$20,700	$28,892	$24,014	**$18,683**
High	1980	$44,657	**$37,319**	$44,364	$38,977	$46,048
	ERS-80	$30,148	$27,231	$34,206	$29,768	**$25,628**
	ERS-86	$24,737	$23,707	$30,405	$25,789	**$20,457**

9. CONCLUSIONS

A LCC analysis of four renewable energy and heat pump combinations has been undertaken for three different housing types located in the Toronto region. The systems analysed include a standard air source heat pump, a cold climate air source heat pump, a ground source heat pump and a solar assisted air source heat pump system. Using the CSDDRD database, a TRNSYS model of a typical 1980's house in the Canadian Housing Stock was developed. With the aid of HOT2000, a TRNSYS model of a current energy efficient house and a future NZR house was developed. Using GenOpt, the air source heat pump systems were optimized for sizing and switch point temperatures. Through a 20 year lifecycle analysis, it was found that the standard air source heat pump systems had the lowest 20 year lifecycle cost for less efficient houses with a higher heating load. Ground source heat pump systems were found to be the most economically viable for the NZR house.

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