AN ANALYSIS OF DEEP ENERGY RETROFIT STRATEGIES IN THE EXISTING CANADIAN RESIDENTIAL MARKET

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ABSTRACT

This paper presents a techno-economic analysis of deep energy retrofit strategies aimed at improving a typical existing home to a Net Zero Ready (NZR) level. Three distinct pathways are selected to examine the impact of modifying the mechanical system and building envelope. Each pathway is analyzed in TRNSYS for both the Montreal and Vancouver regions using a validated housing model. A techno-economic analysis methodology then combines the calculated annual energy costs with the associated material and labour costs for each option. Results show that high performance heat pump systems are the preferred option in both cities, highlighting the potential of these technologies in reducing residential energy use in Canada.

INTRODUCTION

Canada is one of the highest per capita users of energy in the world, with the residential sector accounting for 16% of all secondary energy use (OEE, 2010a). Although the implementation of new building codes and standards has significantly improved the energy efficiency of new homes, 76% of the existing residential building stock was built prior to 1990 (OEE, 2010b). To achieve substantial reductions in residential energy use it is therefore important to focus on improving the energy efficiency of existing homes. One potential energy target for existing home retrofits is a Net Zero Ready (NZR) level, which is the point when it becomes cost effective to add on-site renewable energy generation as opposed to additional energy conservation measures (Parekh, 2010). Potential strategies for achieving this target include the implementation of a high performance heat pump system, or the adoption of a well insulated building envelope. Research has been performed on various pathways to net-zero for new homes (Carver and Ferguson, 2012). However, there is currently a lack of knowledge on how best to cost-effectively achieve these deep energy savings in *existing homes* in the cold Canadian climate.

This paper aims to identify the most cost-effective method of upgrading an existing home to a NZR level through a techno-economic analysis of three distinct pathways:

i. *Mechanical*: Installation of a high performance heat pump system
ii. *Envelope*: Large scale building envelope modifications
iii. *Mechanical + Envelope*: Conventional heat pump technology combined with smaller scale building envelope modifications

As part of a larger project, three Canadian regions (Montreal, Toronto, and Vancouver) have been examined to determine the impact of climate and market factors on the optimal solution. However, this paper focuses solely on the Montreal and Vancouver regions due to their significantly different climates.

A combination of simulation and techno-economic analysis techniques are applied to identify the preferred pathway. First, an energy model of the Canadian Centre for Housing Technology (CCHT) test home is developed and validated using TRNSYS. This model is then modified to represent a typical existing home in each climate region. Using this existing house model, each energy retrofit pathway is simulated in order to determine the annual operating energy cost. Techno-economic analysis techniques are then employed to identify the cost-optimal pathway based on a 20 year lifecycle.

DEVELOPMENT OF HOUSING ENERGY MODELS

Modelling and Validation of Housing Model

The Canadian Centre for Housing Technology (CCHT) twin test homes were selected as the basis for all housing models. These houses, located in Ottawa, Ontario, each have a floor area of 210 m^2 and are typical of a single family detached home in Canada. Detailed characteristics of the buildings can be found in a research report by Swinton et al. (2003). The CCHT homes have been selected for modelling purposes due to the availability of detailed construction information, and the ability to validate the developed model with measured data.

A model of the CCHT home was developed in TRNSYS v. 17 (Klein et al, 2010) using the multi-zone building component (Type 56a). The heating, cooling, and control systems were modelled using standard components from the TRNSYS library. The developed TRNSYS model was then validated with available recorded data from the 2003 CCHT data set, with results typically within 10% for temperature, energy consumption, and relative humidity. A more detailed explanation of the validation procedure can be found in Kegel et al. (2012).

Development of Typical Existing Home Model

Upon completion of the validation process, the developed energy model was modified to represent a typical existing home. A home built in the 1980s was selected as the baseline for each retrofit pathway, as 76% of all residences in Canada were constructed before 1990 (OEE, 2010b).

The Canadian Single-Detached and Double/Row Housing Database (CSDDRD) developed by Swan et al. (2009) was consulted to create a representative housing model for each region. The database was sorted by climate region and construction vintage in order to identify typical characteristics for the building envelope and mechanical system. The identified building characteristics, as provided in Table 1, were then implemented into the validated CCHT model and used as a starting point for analysis.

Table 1
Building Characteristics for Typical Existing Home

Characteristic	Montreal	Vancouver
Heating System	Electric Baseboard	Central Furnace 73.5% Eff.
Cooling System	Split System Rated COP = 3.36*	No Cooling
DHW	Electric	Natural Gas
Ventilation	None	None
Roof R-Value	4.80 m^2°C/W	4.28 m^2°C/W
Wall R-Value	2.79 m^2°C/W	2.17 m^2°C/W
Basement Wall	1.86 m^2°C/W	1.20 m^2°C/W
Basement Slab	Uninsulated	Uninsulated
Windows	2.92 W/m^2°C (incl. framing)	3.71 W/m^2°C (incl. framing)
Infiltration	5.9 ACH$_{50}$	8.77 ACH$_{50}$

*Rated: 26.7°C DB/19.4°C WB indoor, 35°C DB outdoor

Major appliances were assumed to consume a total of 14 kWh/day based on average 1990 EnerGuide values (OEE, 2011), and followed the same operating schedule as in the CCHT home. Receptacle loads were set at 3 kWh/day and followed the operating schedule defined in the EnerGuide Rating system (OEE, 2005). Lighting loads were set at 0.7 kWh/day based on the use of CFL fixtures, and followed the CCHT lighting schedule. The DHW draw was set to 233 L/day, while the building was maintained at 21°C in heating and 23°C in cooling.

NET ZERO READY ENERGY TARGET

Each retrofit strategy was developed to reduce energy use in an existing home to a NZR level. For this analysis, the NZR energy target was defined as a home operating at an EnerGuide Rating Scale (ERS) 86 level (Parekh, 2010), which represents a 30% reduction in energy use in comparison to an EnerGuide reference home (OEE, 2005).

It should be noted that the actual definition of total energy consumption in the ERS system only accounts for space heating, DHW and 24 kWh/day of miscellaneous electrical loads (lighting, appliances and receptacles). Furthermore, the EnerGuide rating scale only gives credit for improvements to the space heating and DHW systems. However, in this analysis the 30% energy reduction target from the EnerGuide reference home was assumed to also include improvements in space cooling and electrical base loads.

A two step methodology was employed to calculate the NZR energy target for each climate region:

i. First, each existing house model was implemented into the HOT2000 simulation program (NRCan, 2010).This program was used because it has the built-in capability to calculate the EnerGuide rating of a home. HOT2000 was used only to determine the percent energy savings needed to take an existing home to an ERS-86 level.

ii. The calculated percent savings was then applied to the annual energy use of each existing home (as determined in TRNSYS) to identify each regional NZR target. The resulting NZR targets are summarized in Table 2. Each NZR target was based on the use of all electric heating and DHW systems in order to allow future onsite electrical generation (i.e photovoltaics) to meet the full building loads.

Table 2
Development of NZR Energy Target

Characteristic	**Montreal**	**Vancouver**
Reference Energy Use	41,023 kWh	57,309 kWh eq.
Percent Energy Savings Reqd.	52.3%	70.6%
NZR Energy Target	**19,566 kWh**	**16, 825 kWh**

It should be noted that TRNSYS was selected for the overall analysis as opposed to HOT2000 due to its strength in modelling non-standard HVAC systems. One of the primary objectives of this study was to examine the potential use of high efficiency mechanical systems in meeting the NZR target. As such, the customizability and extensive component library of TRNSYS made it an ideal choice for this study.

PATHWAYS TO NET ZERO READY

Three distinct pathways were selected to achieve the NZR energy target. For each, an energy model was developed in TRNSYS v. 17 and simulated at a 15 minute time step using the appropriate TMY2 weather file. In addition to the modifications described in each pathway, the appliance energy use was set equal to the EnerGuide reference case (6 kWh/day). Electric DHW systems were also modelled for all pathways and climate regions to allow future onsite electricity generation to meet the full building energy load. All other receptacle, lighting, DHW and temperature set point information remained the same as described for the existing home.

Pathway 1: High Performance Heat Pump

The first pathway examined the implementation of a high performance heat pump system. In this case the envelope of the typical existing home was left intact, and all retrofit work focused solely on the mechanical system. Two heat pump alternatives were considered.

The first heat pump system analyzed was a Cold Climate Air-Source Heat Pump (CCHP). The CCHP is a newer technology with the ability to deliver a higher heating capacity at cold ambient temperatures in comparison to a conventional air-source heat pump (ASHP). Conventional ASHP and CCHP performance is provided in Figure 1, using an entering indoor air temperature of 21.1°C. A higher efficiency ASHP (ASHP+) is also shown to illustrate the current state of the art of conventional ASHPs.

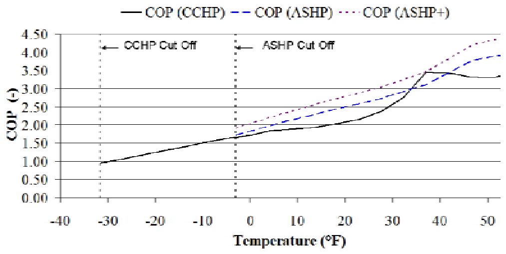

Figure 1: HP Performance Curves

Figure 2 shows the proposed integration of the CCHP into the Vancouver home. An outdoor unit serves an indoor component containing a fan and a refrigerant to air heat exchanger, with heating and cooling supplied using a ducted system. An electric duct heater is also used to supplement the heat pump during periods of extreme cold.

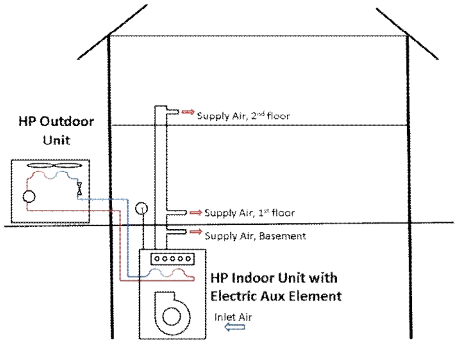

Figure 2: CCHP Integration in Vancouver

A similar integration was proposed for the Montreal home, with the exception that the ducted distribution system was replaced by a split system with two separate indoor units located on the first and second floors of the home. This modification was proposed as the typical existing Montreal home did not have a ducting system, with its installation being potentially cost and space prohibitive. The existing baseboard system operated as the auxiliary system in this proposed integration.

The second heat pump system examined was a Ground Source Heat Pump (GSHP). This type of system uses a water to air heat pump to draw thermal energy from the ground via a ground heat exchanger. During the cooling season the cycle is reversed, with the ground acting as the thermal sink for the system. Proper operations of the GSHP require appropriate sizing of the ground heat exchangers and circulation pumps. A two pipe borehole design was selected for this analysis, with the required heat exchanger lengths summarized in Table 3.

Table 3
Required Ground Heat Exchanger Lengths

	Montreal	**Vancouver**
Total Borehole Length (m)	180	156
No. of Heat Exchangers	2	2

The proposed integration of the GSHP into the Montreal home is shown in Figure 3. As with the CCHP layout, it was assumed that the Montreal system uses two unducted indoor units to supply heating and cooling to the home.

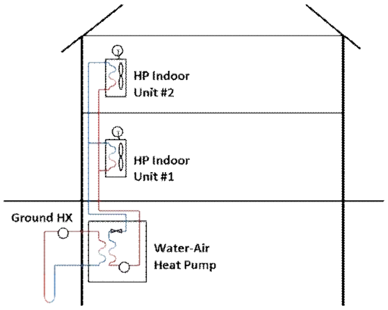

Figure 3: GSHP Integration in Montreal

Pathway 2: High Performance Building Envelope

The second proposed pathway focused on improving the building envelope while using a basic mechanical system. In Montreal the modelled heating and cooling systems were unchanged from the typical existing home. However, in Vancouver, the natural gas furnace was replaced with an all electric heating system to allow future onsite electricity generation to meet the full energy demands of the building. A central cooling system was also added to reduce overheating in the summer resulting from the improved insulation levels in the home. A Heat Recovery Ventilator (HRV) was implemented in both cities to meet the ventilation requirements of the improved, more air tight envelope.

A summary of the required envelope characteristics is provided in Table 4. In all cases, realistic constructions were specified within TRNSYS, with a focus on improving insulation levels while minimizing air infiltration into the home. The majority of the proposed modifications involved replacing existing batt insulation with spray applied polyurethane, adding rigid insulation to the walls, and replacing existing windows with triple glazed fenestration. For the Montreal case an additional 2" by 4" wood blocking was also added to create a larger insulation cavity. From a practical perspective, one of the main issues with this solution is the increased thickness of the walls: A wall thickness of 11.25" is needed for Montreal, and 9.75" in Vancouver (including a brick façade).

Table 4
Envelope Characteristics for NZR

	Montreal	**Vancouver**
Wall R-Value	5.41 $m^2°C/W$	4.44 $m^2°C/W$
Roof R-Value	8.93 $m^2°C/W$	8.93 $m^2°C/W$
Basement Wall R-Value	4.93 $m^2°C/W$	4.93 $m^2°C/W$
Window U-Value	1.35 $W/m^2°C$ (incl. framing)	1.35 $W/m^2°C$ (incl. framing)
Air Infiltration	0.75 ACH_{50}	1.0 ACH_{50}

Pathway 3: Combination of ASHP and Improved Envelope

The third pathway involved upgrading the mechanical system and building envelope. The existing heating and cooling systems in each home were first replaced with a conventional ASHP with COP of 3.78 (Rated at 21.1°C indoor air, and 8.3°C outdoor air dry bulb). The proposed system integration was similar to the CCHP layout (Figure 2), with the only difference being that a larger capacity electric duct heater was used to supplement the substantially reduced heating capacity of the ASHP at colder temperatures (For Montreal, the existing baseboard system was retained as an auxiliary). An HRV system was also added to supply additional fresh air to the home, as the upgraded building envelope was expected to significantly reduce natural air infiltration.

The remaining energy savings after integrating the ASHP were achieved through modifications to the building envelope. The required building envelope characteristics are summarized in Table 5.

Table 5
Envelope to Achieve NZR with ASHP

	Montreal	**Vancouver**
Wall R-Value	4.85 $m^2°C/W$	2.61 $m^2°C/W$
Roof R-Value	8.93 $m^2°C/W$	5.71 $m^2°C/W$
Basement Wall R-Value	4.93 $m^2°C/W$	1.21 $m^2°C/W$
Air Infiltration	1.5 ACH_{50}	1.5 ACH_{50}

Required RSI values were achieved primarily through the replacement of batt insulation with spray applied polyurethane and blown cellulose, and the addition of rigid polystyrene insulation on the walls. No window modifications were examined under this option due to the high capital costs associated with this type of renovation work.

TECHNO-ECONOMIC ANALYSIS

A systematic techno-economic analysis methodology was employed to determine the cost optimal pathway for each region. A 20 year lifecycle was used as the basis for analysis, with realistic utility and capital costs integrated into the calculation procedure. The total lifecycle cost for each pathway was defined as:

$$LCC = C_{Capital} + C_{Utility} \tag{1}$$

Maintenance costs were not included in this analysis.

Utility Costs

Current electricity and natural gas rates were used to obtain an accurate estimate of the operating costs associated with each pathway. The electricity rate structure is summarized for both climate regions in Table 6 (Hydro Quebec, 2013) (BC Hydro, 2013).

Table 6
Electrical Utility Rates

Montreal	
Tier	Price ($/kWh)
First Daily 30 kWh	$0.0532
Daily Beyond 30 kWh	$0.0751
Vancouver	
Tier	Price ($/kWh)
First 1350 kWh over 60 Days	$0.0680
After 1350 kWh over 60 Days	$0.1019

The cost of natural gas in Vancouver was set at $7.86/GJ (Fortis Gas, 2013).

Appropriate inflation and utility escalation rates were also included in the lifecycle analysis (CCBFC, 1997).

Capital Costs

Capital costs were obtained for each pathway, and included (i) the material and labour costs of installing new mechanical and envelope systems and (ii) the cost of demolition associated with the replacement of any existing material or equipment.

Mechanical System

All ASHP and CCHP costs were determined via a survey of local HVAC contractors, with adjustment factors (RS Means, 2013a) applied to account for potential differences between the Montreal and Vancouver markets. An additional incremental cost was also applied to each heat pump in the Montreal region to account for the proposed ductless supply system and the multiple indoor units required.

Pricing for the water-source heat pump used in the GSHP system was obtained from the RS Means

Mechanical Cost Handbook (2013b). The cost of borehole drilling was set at $60/m for both regions (Kummert and Bernier, 2008), and was assumed to include all necessary piping connections. The price of the circulation pumps used in the system was obtained from a pump manufacturer (Wilo, 2011), with labour costs estimated using RS Means (2013b).

The unit cost for the HRV was obtained from several online sources (Eccosupply.com, 2013; Ventingdirect.com, 2013), with the cost of installation estimated using RS Means (2013b). The total installed costs for all electric heaters, DHW tanks, and control systems were also obtained from RS Means (2013b).

Building Envelope

All building envelope modifications were priced using data from the RS Means Building Construction Handbook (2013a), and adjusted according to the region examined. Associated demolition costs, including the removal of plywood, insulation, and windows, were also included in the cost analysis. Table 7 provides a summary of the calculated capital costs for each region and pathway.

Table 7
Capital Costs for NZR

	Montreal	**Vancouver**
High Performance HP: CCHP	$14,214	$13,544
High Performance HP: GSHP	$25,671	$18,649
High Performance Building Env.	$56,630	$52,237
Combination ASHP + Building Env.	$50,511	$31,657

RESULTS

The techno-economic analysis methodology was applied to each pathway for both the Montreal and Vancouver regions. For each pathway, it was also assumed that existing appliances were replaced with new ones, with total appliance energy set equal to the EnerGuide reference (6 kWh/day). An additional case is also presented in which the existing heating and cooling systems are replaced with new equipment operating with the same efficiency. It should be stressed that these modifications do not meet the NZR target, and are supplied to show the cost impact of maintaining current performance.

Montreal

High Performance HP Systems

Table 8 shows the estimated annual energy consumption and lifecycle costs for each high performance heat pump integration in the Montreal region. While each system results in a significant reduction in energy consumption, only the GSHP is able to achieve the NZR energy target. This difference in system performance is largely due to the considerably higher heating season COP of the GSHP unit (COP 4.12) in comparison to the CCHP unit (COP 2.38). Since ground temperatures are relatively constant when using a properly sized ground heat exchanger, fluid temperatures into the GSHP system are often near the rated conditions for the unit. These higher source temperatures result in the heat pump being able to consistently meet the thermal loads of the building. However, source temperatures in to the air-source CCHP are far more variable. Although the CCHP is designed to have an improved heating capacity in comparison to a standard ASHP, the extreme cold temperatures in Montreal in January and February mandate the increased use of the auxiliary heating system, preventing the CCHP from achieving the desired NZR target. These colder temperatures also result in the reduced seasonal COP exhibited by the unit.

Table 8
High Performance HP in Montreal

	Case		
Annual Energy Use (kWh)	**Existing**	**CCHP**	**GSHP**
Primary Space Heating	27378	11159	7203
Auxiliary Space Heating	0	1478	12
Space Cooling	717	484	267
Fans + Pumps	187	253	470
Lighting, Appliances, Receptacles	7195	4476	4476
DHW	5545	4937	4928
Total	41023	22786	17357
Difference NZR	**21457**	**3220**	**-2209**
Lifecycle Operating Cost ($)	**$33,094**	**$17,256**	**$12,525**
Total Lifecycle Cost ($)	**$45,323**	**$31,470**	**$38,197**

Although the current CCHP technology is unable to meet the Montreal NZR target, this type of equipment remains appealing from an initial cost and installation point of view. As such, several additional simulations were performed within TRNSYS to identify the performance requirements of a CCHP meeting the NZR target, and to examine the potential for combining the system with other technologies.

Case 1 represented a theoretical CCHP operating with the seasonal heating COP required to achieve NZR. Case 2 combined the current CCHP with a solar DHW system, with flat plate solar collectors (area 5.97 m^2) used to meet a portion of the DHW load. Case 3 aimed to determine the required seasonal heating COP to achieve NZR assuming the installation of the above described solar DHW system. Results are summarized in Table 9.

Table 9
CCHP Performance to Meet NZR

Case	Energy Use (kWh)	Diff. NZR (kWh)	Seasonal COP (-)
CCHP	22786	3220	2.38
Case 1	19580	15	3.31
Case 2	21104	1538	2.38
Case 3	19624	58	2.73

An examination of the results indicates that a significant improvement in the seasonal COP of the CCHP would be required to achieve the NZR target.

High Performance Building Envelope

Table 10 summarizes the annual energy use and estimated lifecycle cost of upgrading the building envelope. The improved thermal performance and reduced air infiltration of the new envelope results in a significant decrease in the energy directed towards space heating. The increase in fan power consumption results from the installation of an HRV system in the home.

Although this pathway is able to meet the NZR energy target, the large capital costs associated with the envelope renovations are financially prohibitive.

Table 10
Montreal High Performance Envelope

	Case	
Annual Energy Use (kWh)	**Existing**	**Env.**
Primary Space Heating	27378	8169
Auxiliary Space Heating	0	0
Space Cooling	717	717
Fans + HRV	187	1199
Lighting, Appliances, Receptacles	7195	4476
DHW	5545	4919
Total	41023	19480
Difference NZR	**21457**	**-86**
Lifecycle Operating Cost ($)	**$33,094**	**$14,300**
Total Lifecycle Cost ($)	**$45,323**	**$70,931**

Combination of ASHP and Upgraded Envelope

Table 11 shows the annual energy use and lifecycle costs associated with the combination of an ASHP and an improved building envelope. Upgrading both the mechanical system and building envelope yields a large reduction in the primary space heating energy use. However, these savings are countered by the increased use of the auxiliary heating system, as the conventional ASHP is unable to provide sufficient heating capacity during the colder winter months in Montreal. The increased fan energy consumption is due to the installation of an HRV and the replacement of baseboard heating with indoor heat pump units.

Once again, the costs associated with modifications to the building envelope result in a financially prohibitive solution in the Montreal market.

Table 11
ASHP and Envelope in Montreal

	Case	
Annual Energy Use (kWh)	**Existing**	**ASHP + Envelope**
Primary Space Heating	27378	5696
Auxiliary Space Heating	0	2758
Space Cooling	717	441
Fans + HRV	187	1226
Lighting, Appliances, Receptacles	7195	4476
DHW	5545	4933
Total	41023	19531
Difference NZR	**21457**	**-35**
Lifecycle Operating Cost ($)	**$33,094**	**$14,350**
Total Lifecycle Cost ($)	**$45,323**	**$64,861**

Vancouver

High Performance HP Systems

A summary of the annual energy consumption and total lifecycle costs for each high performance heat pump integration in Vancouver is provided in Table 12. Due to the warmer climate, the CCHP was replaced with a high efficiency ASHP using a variable speed compressor. Performance of this unit is shown in Figure 1 (ASHP+). This new unit represented an extension on the ASHP modelled in the Montreal region, with a COP of 4.22 in heating mode (Rated at 21.1°C indoor air temperature, 8.3°C outdoor air dry bulb temperature).

Table 12
High Performance HP in Vancouver

	Case		
Annual Energy Use (kWh)	**Existing**	**ASHP+**	**GSHP**
Primary Space Heating	41875	6653	5308
Auxiliary Space Heating	0	94	1
Space Cooling	0	58	43
Fans + Pumps	2624	1305	3449
Lighting, Appliances, Receptacles	7195	4476	4476
DHW	5614	4509	4507
Total	57309	17094	17786
Difference NZR	**40484**	**270**	**961**
Lifecycle Operating Cost ($)	**$25,649**	**$17,465**	**$18,316**
Total Lifecycle Cost ($)	**$28,225**	**$27,801**	**$36,966**

While both integrations yielded substantial reductions in building energy use, only the high efficiency ASHP system met the NZR target. The low auxiliary energy use associated with the ASHP also confirmed the ability of the unit to meet the thermal demands of the home on its own.

High Performance Building Envelope

Table 13 shows the annual energy use and lifecycle costs of the high performance building envelope option in Vancouver.

Table 13
Vancouver High Performance Envelope

	Case	
Annual Energy Use (kWh)	**Existing**	**Env.**
Primary Space Heating	41875	6472
Auxiliary Space Heating	0	0
Space Cooling	0	495
Fans + Pumps	2624	1176
Lighting, Appliances, Receptacles	7195	4476
DHW	5614	4508
Total	57309	17126
Difference NZR	**40484**	**302**
Lifecycle Operating Cost ($)	**$25,649**	$17,492
Total Lifecycle Cost ($)	**$28,225**	**$74,316**

The increased insulation levels and reduced air infiltrations rates associated with the upgraded envelope resulted in an 85% reduction in space heating energy use. Fan energy use was also reduced, as the existing natural gas furnace was replaced with an all electric heating system and an HRV unit. The increased cooling energy use resulted from the integration of a central air conditioning system, which was added to prevent possible overheating resulting from the highly insulated envelope.

Although this option is able to meet the NZR target (1.8% difference), the associated costs of improving the building envelope remain a significant hurdle for widespread acceptance in the marketplace.

Combination of ASHP and Upgraded Envelope

A summary of the annual energy use and lifecycle costs associated with the combination pathway in Vancouver is provided in Table 14. It should be noted that the ASHP used in this analysis is a readily available unit with a reduced efficiency in comparison to the variable speed unit discussed above (Rated heating COP of 3.78 vs. 4.22).

The combination of an improved building envelope and an ASHP resulted in a substantial reduction in the energy used for space heating and air circulation. Although the addition of the ASHP resulted in increased energy being directed towards space cooling, this also allows the homeowner to make full use of the installed system while maintaining a higher degree of thermal comfort in the home.

The main drawback with this pathway appears to be capital costs. While the initial investment required under this pathway is reduced in comparison to the super insulated option, a significant financial commitment is still required to reach NZR.

Table 14
ASHP and Envelope in Vancouver

	Case	
Annual Energy Use (kWh)	**Existing**	**ASHP + Envelope**
Primary Space Heating	41875	5643
Auxiliary Space Heating	0	1
Space Cooling	0	88
Fans + Pumps	2624	2269
Lighting, Appliances, Receptacles	7195	4476
DHW	5614	4507
Total	57309	16985
Difference NZR	**40484**	**160**
Lifecycle Operating Cost ($)	**$25,649**	$17,337
Total Lifecycle Cost ($)	**$28,225**	**$48,993**

Summary

Table 15 summarizes the total lifecycle costs for each city and pathway. The high performance heat pump option was clearly preferred for both climate regions, even when examining the case where the status quo for equipment performance was maintained. In general, upgrading the energy performance of the home via the mechanical system required less equipment and fewer labour hours in comparison to the other pathways. Modifications to the building envelope were found to be extremely costly due to the large surface areas involved. In addition, the potential inconvenience and loss of floor space associated with the envelope modifications mean that these options are likely to achieve far smaller market penetrations. Overall, the results indicate that heat pumps should play an important role in reducing energy use in existing Canadian homes.

Table 15
Lifecycle Cost Summary

	Montreal	**Vancouver**
Maintain Existing Performance Levels	$45,323	$28,225
High Performance HP: GSHP	**$38,197**	$36,966
High Performance HP: CCHP/ASHP	$31,470*	**$27,801**
High Performance Building Env.	$70,931	$74,316
Combination ASHP/ Env.	$64,861	$48,993

*CCHP in MTL did not meet NZR target

CONCLUSION

A techno-economic analysis was performed to determine the most cost effective method of retrofitting an existing home to a NZR level in Montreal and Vancouver. Three distinct pathways were examined: A high performance heat pump system, a high performance building envelope, and a combination of an ASHP with smaller envelope modifications. For each climate region, the CSDDRD database was used to identify the building characteristics of a typical existing home. This home then served as a base for energy models developed to analyze each retrofit pathway. A techno-economic analysis was then performed on each option taking into account capital and operational costs.

The results highlighted the strong potential for using high performance heat pump systems to retrofit existing homes. For Montreal, the GSHP system was found to have the lowest lifecycle costs, primarily due to the high performance of the system during the harsh winter months. For Vancouver, a high efficiency ASHP unit was the most cost-effective option for achieving the desired energy savings. Retrofit options involving the building envelope were found to be extremely costly in both markets.

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NOMENCLATURE

ACH_{50} = Air changes per hour @ 50 Pa
ASHP = Air source heat pump
CCHP = Cold climate heat pump
COP = Coefficient of performance
$C_{Capital}$ = Capital costs
$C_{Utility}$ = Utility costs
DHW = Domestic hot water
GSHP = Ground source heat pump
HP = Heat pump
LCC = Total lifecycle cost
NZR = Net zero ready

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