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Techno-Economic Analysis of Heat Pump and Cogeneration Systems for a Typical Midrise Apartment in the Canadian Climate

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ABSTRACT

This paper presents an analysis of five energy efficient heating and cooling systems for a high performance mid-rise apartment in two Canadian regions: Calgary and Montreal. The analysis was performed using the TRNSYS simulation tool comparing the annual primary and secondary energy consumption, utility costs and greenhouse gas emissions of proposed technologies as well as the 20 year life cycle cost. The five systems selected for comparison include (1) a conventional mid-rise apartment heating and cooling system, (2) boiler/cooling tower water source heat pumps, (3) ground source heat pumps, (4) a cogeneration unit sized to meet the heating load of the building and (5) a cogeneration plus electric driven heat pump system. In Calgary, the cogeneration only system demonstrated the greatest primary energy savings, utility cost savings and greenhouse gas emission reductions of all systems evaluated primarily because of the utility rate structure and electricity generation in the region. The ground source heat pump system demonstrated the greatest secondary energy savings. In Montreal, the ground source heat pump system was predicted to have the greatest savings in all four categories. Evaluating the 20 year life cycle cost of the systems, the base case proved to be the most economical, demonstrating the challenges of implementing energy efficient systems in Canada due to low utility rates.

1. INTRODUCTION

With increased awareness on the importance and benefits of energy efficiency, building owners and designers are frequently confronted with the challenge of determining which mechanical system is most suitable to meet the building's energy needs now and in the future. The decision making process is often aided through the use of building simulation tools; however this type of analysis is often considered costly and time consuming in particular when various mechanical systems need to be assessed. Designers then often choose a mechanical system they are most familiar with, which may not always yield the best energy saving opportunity.

This paper presents an analysis performed on a variety of energy efficient mechanical systems for a mid-rise apartment in a heating dominated climate to aid decision makers in the early design process in selecting a suitable mechanical system to achieve the desired energy savings. Two Canadian regions (Calgary and Montreal) were selected for their cold winters and hot summers, different electricity production sources and ultimately different utility rates. The paper presents of variety of mechanical systems primarily focusing on heat pump and cogeneration technologies, comparing the primary and secondary energy consumption, greenhouse gas (GHG) emissions as well as annual utility costs. Heat pump systems were selected for analysis because of their benefit in upgrading and utilizing renewable energy sources and cogeneration systems were selected because of the conversion of natural gas to electricity and the combination of heat and electricity production by one system. A 20 year life cycle analysis on the incremental cost for each mechanical system selected is also presented.

2. METHODOLOGY

To perform the analysis, an energy model of a typical newly constructed mid-rise apartment was developed using the TRNSYS simulation tool. The newly constructed mid-rise apartment was designed to meet the National Energy Code for Buildings (NECB) 2011 (NRC 2011) and consists of four floors with 8 suites on each floor for a total of 32 suites. The apartment floor area is 3,135 m² with a footprint area of 784 m². The building has an annual heating load of 675 GJ, an annual DHW load of 300 GJ and an annual cooling load of 85 GJ in Calgary. Montreal has a similar load profile. Additional model details of the mid-rise apartment can be found in a paper entitled: Solar thermal trigeneration system in a Canadian climate multi-unit residential building (Kegel *et al*. 2013).

To perform an assessment on the heat pump and cogeneration technologies, the following systems were implemented into the mid-rise models and compared:

- Scenario 1: Central boiler and packaged terminal air conditioning (PTAC) units
- Scenario 2: Water loop heat pumps with central boiler and cooling tower
- Scenario 3: Ground source heat pump (GSHP)
- Scenario 4: Central cogeneration unit and PTAC units
- Scenario 5: Central cogeneration unit and GSHP system

2.1 Central Boiler and PTAC Units

Scenario 1 is considered the base case where each apartment suite is conditioned through a packaged terminal air conditioning (PTAC) unit with a hot water heating coil. This system is considered to be the baseline system, based on the US Department of Energy Benchmark energy models (Torcellini *et al*. 2008). Two central single stage natural gas fired mid efficiency boilers (83% thermal efficiency) meet the space heating requirements. Each boiler was sized for half the peak space heating load and the system is operated in a lead/lag mode such that the 2nd boiler fires when the first boiler reaches 90% of its maximum heating capacity. An outdoor air reset controller modulates the temperature set point maintaining 82.2°C at an outdoor air temperature below -16°C and 60°C at an outdoor air temperature above 0°C. Hot water through the apartment heating coils is modulated through a central thermostat in each apartment suite. The primary boilers pumps are continuous, constant flow and the secondary pump has variable flow and considered to ride its pump curve as per the NECB 2011 (NRC 2011). Cooling is accomplished by the apartment suite PTAC units turned on when there is a demand for cooling. The PTAC units rated coefficient of performance (COP) is 2.94 (Energy efficiency Ratio, EER = 10.0).

This type of system gives each apartment suite owner the ability to choose between heating and cooling, which cannot be accomplished in two pipe fan coil systems where the heating and cooling season is set by the building operator possibly leading to discomfort. To provide an equal comparison to the other systems in regards to space heating and cooling comfort, the central boiler and PTAC system was used as the base case in this system analysis.

2.2 Scenario 2: Water Loop Heat Pump System

Scenario 2 evaluates a water loop heat pump system connected to a central boiler and cooling tower. Each apartment suite is conditioned by a dedicated water to air heat pump connected to the water loop. This type of system has the benefit of transferring heat efficiently and effectively from one zone of the building to another. Typically these types of systems can be found in office buildings where heat rejected from the heat pump in the core zone is transferred to the perimeter zones for space heating where the heat is required. Similarly, the benefit in the mid-rise apartment would be that the heat rejected from the top floor for space cooling during the shoulder seasons is transferred to the mid and ground floors for space heating. The added benefit is that the water loop heat pumps upgrade the energy from the boiler and thus only one central boiler is required.

The boiler and cooling tower are installed in series, with the cooling tower controlled to maintain the circulating fluid below 30°C and the boiler fired to maintain a circulating fluid temperature above 20°C. The boiler is mid efficiency (83% thermal efficiency) and single stage, while the cooling tower is closed circuit and the cooling tower fan is controlled with a variable frequency drive. The water loop heat pumps were selected to meet the heating load of each apartment suite at a 20°C entering fluid temperature resulting in unit sizes rated between one and two tons of cooling (3.5 kW and 7.0 kW) in both regions. At the rated heating and cooling conditions the water loop heat pumps have a heating COP of 4.6 and cooling COP of 3.6 (EER 12.2).

Similar to the base case, the water loop heat pump system also gives the apartment owner a choice to heat or cool any time of the year. Energy efficiency wise, the water loop heat pump system transfers the heat efficiently from one zone to another, recovering the heat during the shoulder seasons and using it. One of the drawbacks is that there is no thermal storage for the rejected/absorbed energy. Thus, if there is no coincident demand for heating and cooling, the water loop heat pump is system is not as beneficial as in an office building for example.

2.3 Scenario 3: Ground Source Heat Pump System

Scenario 3 evaluates a GSHP, where ground acts as a source/sink for the heat pump loop used to meet the space heating and cooling load of the apartment. Similar to the water loop heat pump system, each apartment suite is conditioned by a water to air heat pump. The ground remains at a fairly stable temperature and if sized correctly provides a renewable energy source for space heating and cooling. The borefield was sized following the Kavanaugh and Rafferty equation (1997) taking into account the annual ground imbalance, peak monthly ground load and peak hourly ground load. For the mid-rise apartment building, 48 boreholes at 135 m length spaced 6.1 m apart were calculated to meet the heating loads in Calgary an ultimately apartment building cooling loads. A similar sizing was calculated for Montreal, with the same borefield configuration; however only 76 m in length. The design temperatures for space heating and cooling were set to 0°C and 35°C, respectively. The apartment suite GSHPs were sized to meet the space heating load resulting in unit sizes rated between 1.5 and 3 tons of cooling (5.3 kW and 10.6 kW) in both regions. The borefield was sized, such that neither a back up boiler was required to meet the space heating demand, nor a back-up cooling tower to meet the space cooling load. The borefield was also sized to ensure the borefield energy would not become depleted due to an imbalance in the heating and cooling ground loads.

The benefit of the GSHP system is that the system utilizes the renewable energy of the ground providing a uniform, constant source temperature for the heat pumps. At design conditions, the GSHPs have a heating COP of 4.6, essentially gaining 4.6 units of energy for every 1 unit of energy input into the system. The downfall, is the high associated cost with the borefield and furthermore the high cost of electricity compared to natural gas in some of the Canadian regions.

2.4 Scenario 4: Cogeneration System

Scenario 4 evaluates replacing the central heating boilers with a natural gas fired cogeneration system. The benefit of using a cogeneration system is the ability for onsite electricity production, which can be used to meet the buildings electrical load and sold back to the grid in the event there is excess electricity production. Through the production of electricity in a combustion engine, the heat recovered from the engine manifold and exhaust can be used to meet the space heating demand of the mid-rise apartment. Figure 1 presents a schematic of the proposed system.

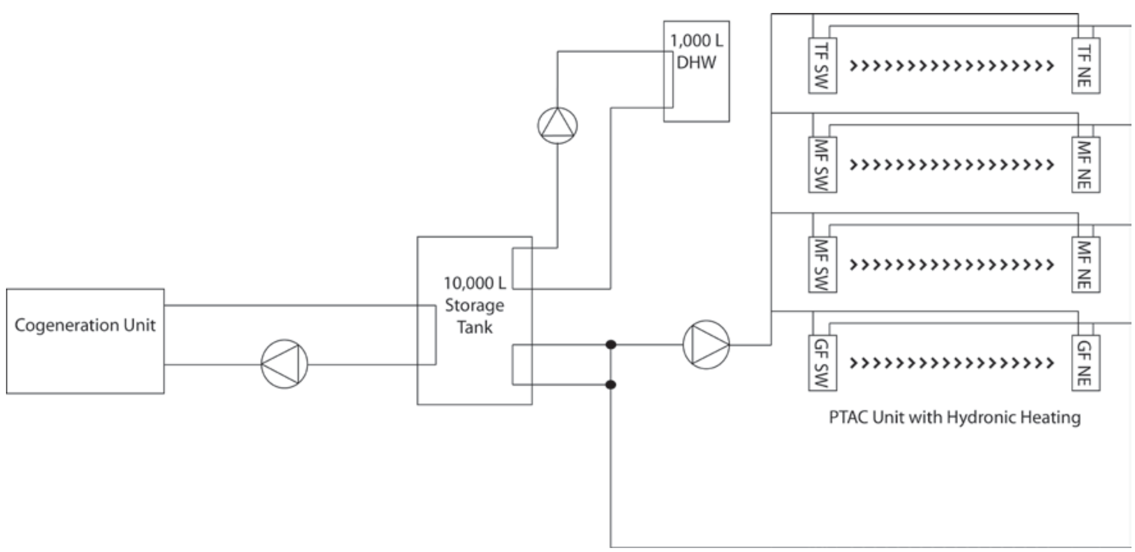


Figure 1: Schematic of the cogeneration system

The cogeneration system was sized to meet the heating load of the midrise apartment, with a total thermal capacity of approximately 185 kW and electric generation capacity of 96 kW in Calgary. In Montreal, the system was slightly smaller sized for a total thermal capacity of 175 kW and electric generation capacity of 90 kW. The performance data of the cogeneration unit was assumed to be similar to that of a unit tested for a residential project (Advanced Engine Technology, 2009). At full load conditions, the unit has a thermal efficiency of 47.9%, and an electrical efficiency of 26.7% for a total efficiency of 74.6%.

The cogeneration unit was modeled in TRNSYS using the Type 154 developed by the International Energy Agency (IEA) Annex 42 (Beausoleil-Morrison and Ferguson, 2007). The developed component relates the thermal and electrical efficiency of the cogeneration unit to the coolant mass flow rate, coolant temperature and electrical loading.

The cogeneration unit is operated to follow the thermal demand of the building. Energy from the cogeneration unit is stored in a 10,000 L storage tank to allow the cogeneration unit to operate for a length of time and then turn off. Energy from the storage tank is then injected into the building heating loop to maintain a desired setpoint temperature controlled by a similar outdoor air controller as that proposed in scenario 1. Similar to scenario 1, the apartment suites are heated and cooled through PTAC units with hydronic heating coils. To make use of the cogeneration unit during the summer, the cogeneration unit is also used to supplement domestic hot water production. Electricity produced by the cogeneration unit is used directly onsite, with excess electricity assumed to be sold back to the grid.

The benefit of the cogeneration system is the onsite electricity production and thus, high electricity rates can be offset through the conversion of natural gas into electricity. Cogeneration can be particularly interesting in several Canadian provinces, where natural gas rates can be often 5 times less per unit of energy than electricity and the marginal electricity production is through fossil fuel fired power plants. The downfall is the ultimate high secondary energy consumption to the building owner, since electricity is now being produced onsite instead of coming off the grid.

2.5 Scenario 5: Cogeneration with Ground Source Heat Pump System

Scenario 5 looks at the novel combination of cogeneration with a GSHP system to incorporate the renewable energy from the ground, while reducing the borefield size and heat pump electricity consumption through the use of a cogeneration unit. Figure 2 provides a schematic of the proposed system.

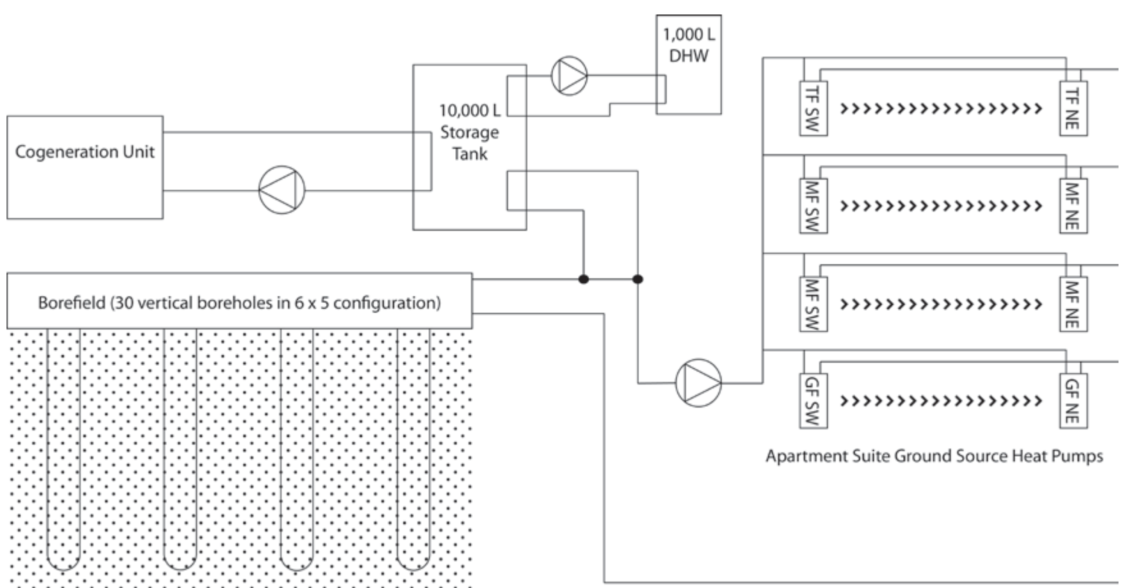


Figure 2: Schematic of the cogeneration and ground source heat pump system

As a preliminary analysis, the system was designed such that the borefield was sized to meet the space cooling demand (30 boreholes each 135 m deep) of the apartment building and the cogeneration unit would inject heat into the ground loop when the supply temperature falls below 0°C. The same borefield sizing and borehole length was used in both regions. Similar to the cogeneration only system, heat from the cogeneration unit is stored in a 10,000 L storage tank to prevent short cycling. The cogeneration unit was sized to have a 95 kW heating capacity and 48 kW electricity production capacity in both regions. To get use of the cogeneration unit during the summer, the DHW production is supplemented by the cogeneration unit as well.

While there are likely other control strategies, which could further optimize the equipment sizing of this scenario, the current iteration provides an analysis on the potential of cogeneration and GSHP systems.

2.6 Utility Rates, Equipment Costs and Life Cycle Cost Analysis

In order to perform the life cycle cost analysis of the systems, it is important to define the utility rates as well the incremental costs associated with each system.

For Calgary, electricity and natural gas rates were taken from ENMAX Corporation (2013a and 2013b). Each apartment unit was assumed to be individually metered and tenants paid the regulated rate estimated at slightly more than $0.12 CDN/kWh. Natural gas was assumed to be under the medium commercial rate (D300) and the monthly costs shared among all apartment units. A floating natural gas rate was assumed with the 2012 historical monthly rates used (ENMAX, 2013b). Natural gas cost was around $5.00 CDN/GJ. For the cogeneration systems, it was assumed electricity could be sold back to the grid at a feed-in tariff rate of $0.06 CDN/kWh (ENMAX, 2013a). In this set of utility rates, the natural gas is 6.7 times cheaper per unit of energy than electricity. Thus, it is anticipated that even with an efficient heat pump system, the low natural gas rates in this region are difficult to overcome.

As a comparison, the utility rates from Hydro Quebec (2013) and Gaz Metro (2013) for the Montreal region are the opposite, where the cost of electricity is only two times the rate/unit energy compared to natural gas. From Hydro Quebec, the electricity rates are approximately $0.075 CDN/kWh and from Gaz Metro, the natural gas rates are around $10.00 CDN/GJ.

To perform the life cycle cost analysis, the majority of incremental equipment costs were estimated using the RSMeans mechanical costing data handbook (2013). For the cogeneration unit, storage tanks and borehole drilling, costs were estimated from online reports. For the cogeneration unit, an approximate cost of $1,950 per kW electric installed capacity was estimated from an article from IEA Energy Technology Systems Analysis Program (Lako *et al*., 2010). Storage tank costs were estimated from Hanson Tank (2014). Borehole costs are highly dependent on the region and soil type and can vary significantly. An $80/m borehole cost was assumed taken from the midpoint of the cost range reported by Kummert and Bernier (2008). Table 1 summarizes the system capital cost for each scenario which includes the anticipated labour costs as well. Calgary and Montreal have similar cost indexes (RSMeans, 2013).

Table 1: Estimated Equipment Capital Costs

Scenario	**Estimated Capital Cost ($ CDN)**	
	Calgary	**Montreal**
Base Case	$162,000	$156,500
Water Loop Heat Pump	$207,000	$207,000
Ground Source Heat Pump	$746,000	$496,500
Cogeneration	$404,000	$387,000
Cogeneration + Ground Source Heat Pump	$684,500	$660,500

It should be noted that the costs are approximate and can vary depending on the equipment used. A 10% contingency is also included in the incremental costs.

Maintenance costs for the base case system were estimated from ASHRAE HVAC Applications Handbook (2011). The water loop heat pump system was assumed to have the same maintenance costs of $5.06/m² floor area. For the cogeneration system, an additional maintenance cost of $200 per kW electric was assumed (Lako *et al*., 2010). For the GSHP an ASHRAE Transactions research report indicated that GSHP systems on average have lower maintenance costs of $2.49/m² of floor area (Cane *et al.*, 1998). Table 2 summarizes the anticipated maintenance costs for each of the systems considered. The same maintenance costs are assumed in both regions analyzed.

Table 2: Estimated Annual System Maintenance Costs

Scenario	**Estimated Annual Maintenance Costs ($ CDN)**
Base Case	$15,860
Water Loop Heat Pump	$15,860
Ground Source Heat Pump	$8,100
Cogeneration	$35,060
Cogeneration + Ground Source Heat Pump	$17,700

The 20 year life cycle cost is calculated summing the incremental capital cost to the present worth of the annual utility costs over 20 years and the annual maintenance costs.

$$LCC_{system} = C_{capital} + C_{annual\_utility} + C_{annual\_maintenance} \quad (1)$$

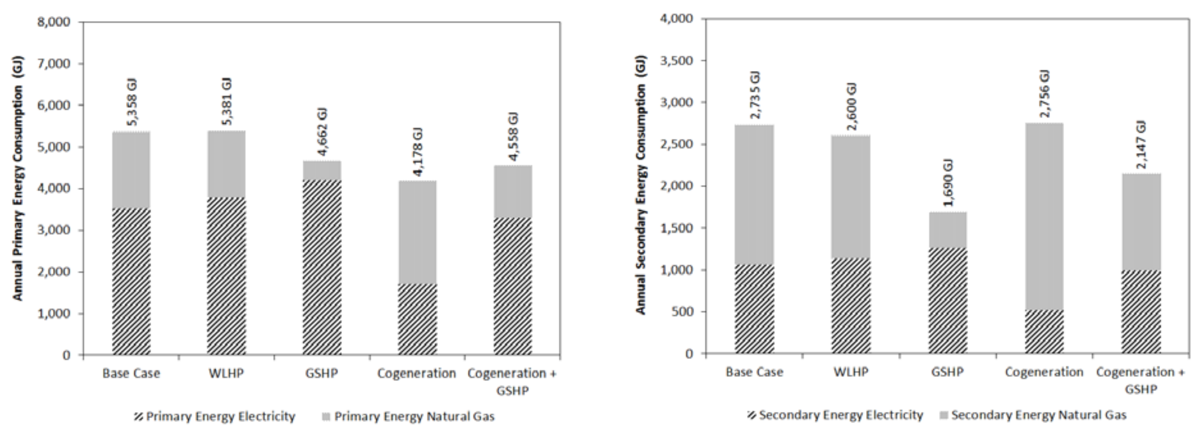
Where,

LCC_{system} = lifecycle cost of the system ($)
$C_{capital}$ = the capital cost ($)
$C_{annual\_utility}$ = sum of the annual utility costs in 2012 dollars ($)
$C_{annual\_maintenance}$ = sum of the annual maintenance costs in 2012 dollars ($)

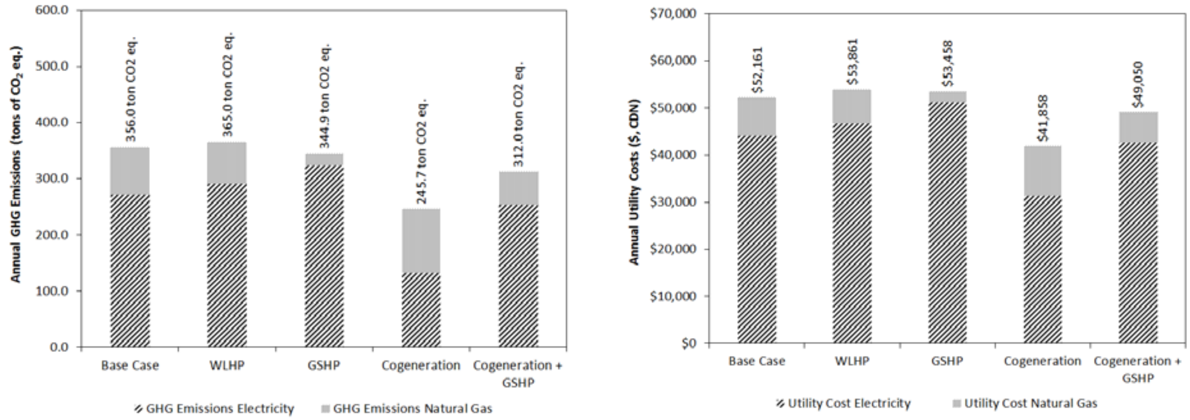
To calculate the present worth for the utility and maintenance costs, an inflation rate of 1% and a discount rate of 4% were assumed based on the current Canadian financial market. The residential electricity and natural gas escalation rates for Calgary and Montreal were obtained from the National Energy Board (2011) – 1.7% and 1.1% for Calgary, respectively and 0.8% and 0.7% for Montreal, respectively. The maintenance and fixed utility costs were assumed to follow the inflation rate.

3. RESULTS

The annual primary and secondary energy consumption, utility costs and GHG emissions for the systems evaluated in Calgary and Montreal are summarized in Figures 3 and 4, respectively.

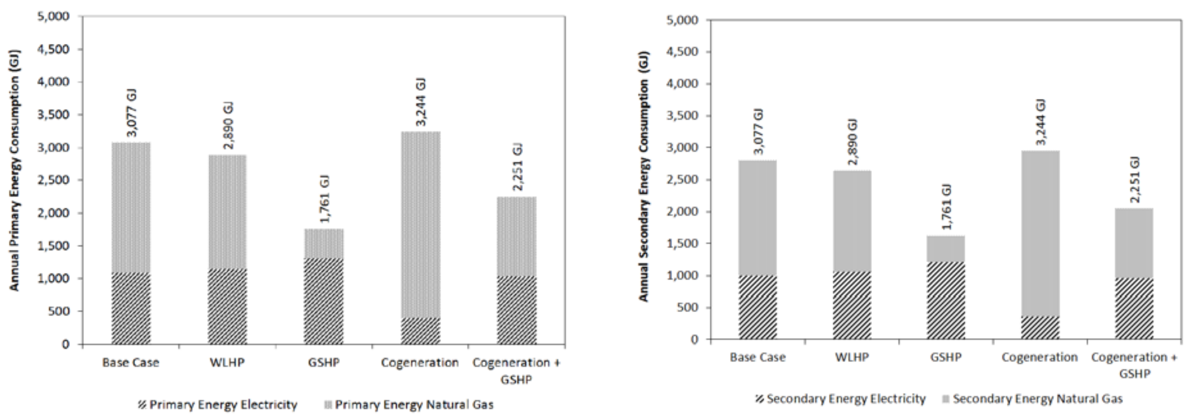


(a) (b)

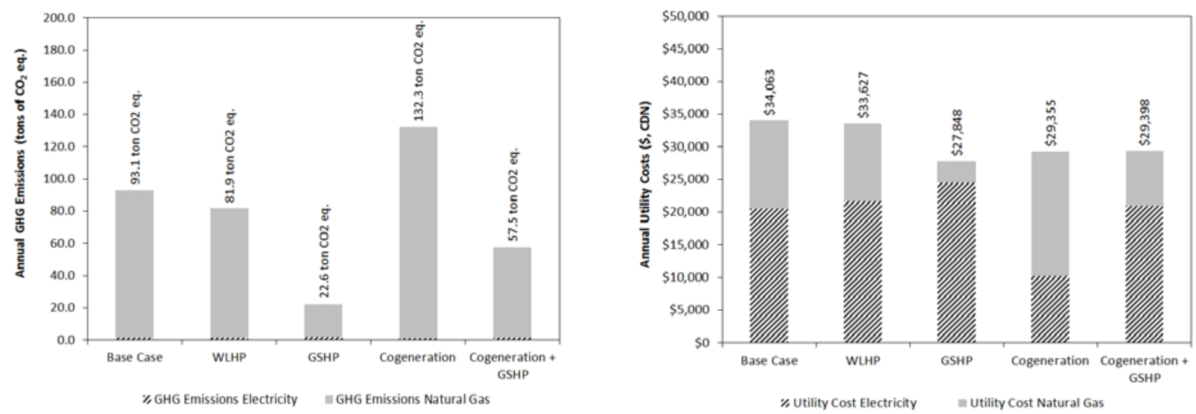


(c) (d)

Figure 3: Annual Primary Energy Consumption (a), Secondary Energy Consumption (b), GHG Emissions (c) and Utility Costs (d) for Calgary



(a) (b)

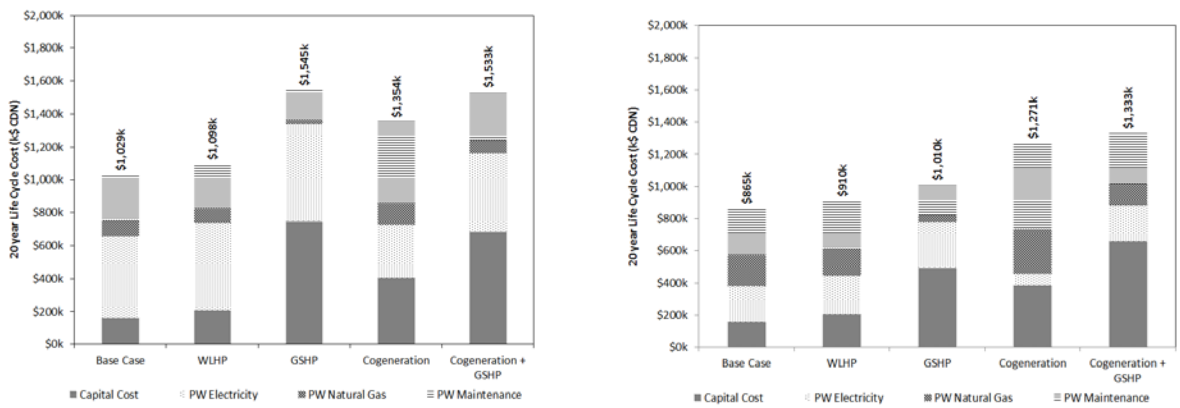


(c) (d)

Figure 4: Annual Primary Energy Consumption (a), Secondary Energy Consumption (b), GHG Emissions (c) and Utility Costs (d) for Montreal

In both cities, the GSHP is the most energy efficient system achieving 38% and 42% secondary energy savings in Calgary and Montreal, respectively. The similarities of the results for both cities stop at the secondary energy efficiency. In Calgary, due to the electricity fuel source and utility costs, the cogeneration system is the most suitable system achieving 22% primary energy savings, 20% utility cost savings and 31% GHG emission reductions. In Montreal, the GSHP system is the most suitable achieving 43% primary energy savings, 18% utility cost savings and 76% GHG emission reductions in comparison to the base case. In Calgary, the only system that was able to achieve savings in all four categories (primary energy, secondary energy, utility costs and GHG emissions) was the cogeneration + GSHP system. This system could be an interesting solution, as the cogeneration system could be operated during periods when natural gas rates are low and then shifted to the GSHP system if electricity rates become more favorable. The downfall is that two capital cost intensive systems must be installed. In Montreal, the benefit of cogeneration systems are non-existent as the predominant electricity production in the province is through hydro-electricity and electricity rates are only 2 times more than the natural gas rates per unit of energy in comparison to 7.5 times in Calgary. Also interestingly, the WLHP system did not demonstrate a significant benefit over the base case system. WLHP systems are only efficient when there are simultaneous heating and cooling loads as heat can be transferred from one zone to another. In the mid-rise apartment, coincident heating and cooling loads are not present and thus the WLHP system is not significantly efficient compared to the other cases evaluated. For the Montreal region, it would be interesting to evaluate the impact air source heat pumps can have in comparison to the systems evaluated.

The 20 year life cycle for each system is summarized in Figure 5 for Calgary and Montreal.



(a) (b)

Figure 5: Estimated 20 year life cycle cost for systems in Calgary (a) and Montreal (b)

The results highlight that the base case system offers the lowest 20 year life cycle cost of all systems evaluated in this study. This is not surprising as the systems evaluated addressed meeting the space heating and cooling loads more efficiently, which were already reduced through an improved building envelope. The 20 year life cycle cost of the WLHP systems for both regions were approximately 5% greater than the base case system attributed primarily due to the slightly higher capital cost of the system as the annual utility cost savings were minimal in both cases.

In analysing the results, although the GSHP is the most energy efficient system and has the lowest maintenance costs, the high capital cost of the system cannot overcome the annual utility cost savings. Furthermore, by using electricity as the primary heating source, the significantly cheaper natural gas rates are not used to meet the space heating demand, ultimately hindering the benefit of the system. Although the cogeneration system demonstrated the greatest annual utility cost savings, the 20 year life cycle cost highlights the challenges of high capital and high maintenance costs faced by cogeneration systems. Taking the annual maintenance costs into account, the cogeneration system results in having the highest annual costs of all systems evaluated. If annual maintenance costs for the cogeneration system were the same as the base case system, the 20 year life cycle is still more than the base case system (~10% greater). The cogeneration + GSHP system was the only system where primary energy, secondary energy, utility cost and GHG emission savings were achieved. The high capital cost of the GSHP borefield and cogeneration system, result in this type of system having a similar 20 year life cycle cost as a GSHP system sized to meet the full building load.

In Montreal, the GSHP system is much more cost competitive; however it still has a higher 20 year life cycle cost compared to the base case. Systems with cogeneration were less cost competitive as the efficient use of electrical heat was either replaced or supplemented through expensive natural gas. Although the GSHP system had significant primary energy, secondary energy, utility costs and GHG emission savings compared to the base case, these savings could not overcome the high capital cost of the system. The 20 year life cycle cost of the system would be equal to the base case if the borefield drilling costs are around $35/m. With an already improved building envelope, the savings achieved through an efficient heating system are minimized. Future work will look into comparing these systems in an existing building to determine the benefit and address some of the industries question in regards to which type of system is most suitable in a retrofit application.

4. CONCLUSIONS

An analysis was conducted on several standard and high efficiency systems for a mid-rise apartment located in Calgary and Montreal. The primary energy consumption, secondary energy consumption, utility costs and GHG emissions were compared for a typical mid-rise apartment heating and cooling system to a boiler-cooling tower water loop heat pump system, a GSHP system, a cogeneration system and a cogeneration combined with a GSHP system. The capital costs of each system were estimated along with the annual maintenance costs and the 20 year life cycle cost was calculated.

In Calgary, the cogeneration system was predicted to have the greatest primary energy savings, lowest annual utility costs and greatest reduction in GHG emissions. These savings are attributed to the high electricity rates compared to the low natural gas rates as well as the primary electricity production, which is predominantly through thermal power plants. Although the GSHP system had the greatest secondary energy savings (~38%), the efficient use of electricity for space heating was not able to overcome the low cost of natural gas to meet the space heating loads. Of all systems evaluated, only the cogeneration + GSHP system had savings in primary energy, secondary energy, utility costs and GHG emissions. This system presents an interesting combination, as the mid-rise apartment can benefit from the current low natural gas rates and the energy efficiency from a GSHP system. Thus, in the event natural gas rates significantly increase in the future, the midrise apartment is already equipped with an energy efficient system. Unfortunately, with the high initial cost of two types of systems, the 20 year life cycle cost was not attractive compared to other scenarios, costing almost 50% more than the base case system over 20 years.

In Montreal, the GSHP system was predicted to have the greatest primary energy, secondary energy, lowest annual utility costs and largest GHG emission reductions of all systems evaluated. This was to be expected, since the electricity production in this region of Canada is primarily through hydro, which has significantly less GHG emissions than thermal power plants. Furthermore, the electricity rates are comparable to the regions natural gas rates and thus the efficient use of electricity to meet the space heating demand is beneficial. The cogeneration systems evaluated did not have interesting results as there is limited benefit in onsite electricity production in this region due to the utility rate structure and electricity generation. In evaluating the 20 year life cycle costs of the systems, none of the proposed systems were able to overcome the higher capital cost in comparison to the low electricity rates. The GSHP system had a 20% greater life cycle cost in comparison to the typical base case system. Future work will investigate the potential of standard and cold climate air source heat pumps in this region.

The results from both regions highlight the challenges faced in Canada’s current utility rate structure to achieve wide spread energy savings. The low utility rates in both regions make it difficult to economically justify energy efficient systems. As such, NRCan is currently conducting research on two fronts to address the challenges heat pumps face in the Canadian market. Extensive research is being conducted with using CO_2 as refrigerant for GSHPs to reduce the borehole size. Research is also being conducted on implementing ejector technology in air source heat pumps to make them more efficient at low ambient temperatures a key requirement for the Canadian sector.

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