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Assessing the Potential for Reduction in Peak Residential Electrical Loads Using a Heat Pump and Thermal Storage Systems

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ABSTRACT

Demand for space cooling in Canada has significantly increased in the past 20 years, and in conjunction with space heating loads in the winter are placing larger peak loads on the electrical grid. As a result, utilities must increase their generating and transmission capacity to meet the peak annual demand, with much of the capacity going unused for large portions of the year. Additionally, base loads are typically met using cleaner technologies including hydro and nuclear, while the variable peak loads are more commonly met using fossil fuel generation, increasing the greenhouse gas emissions per kilowatt-hour of electrical generation. To reduce this peak load, demand side management strategies are becoming more common, with one potential method for reducing the peak load produced by residential buildings is the pairing a heat pump with thermal storage. This paper outlines the first stage of a multi-stage research project to develop a comprehensive system and control strategy for a residential heat pump with sensible hot and cold thermal storage tanks. It outlines the steps that were taken to optimize the control strategy, with a focus on reducing consumption during peak periods while remaining cost and greenhouse gas emission neutral on an annual basis. It was found that using small scale sensible storage and a standard geothermal heat pump, a reduction in the percent of energy used during peak periods is realized, however the annual consumption, electrical costs, and greenhouse gas emissions increase. This was primarily the result of a significant decrease in heat pump performance as the result of lower source and higher load temperatures into the heat pump.

1. INTRODUCTION

As the demand in Canada for space cooling continues to increase, an ever growing peak load is being placed on the utility grid (Natural Resources Canada - Office of Energy Efficiency, 2013). As electrical utilities must size generating and transmission capacity to the peak load the grid experiences, a much greater emphasis is now being placed not only on reducing electrical consumption, but the time of day electricity is used (Ontario Ministry of Energy, 2013). A number of strategies are being employed by utility providers to reduce the peak load, including time of use billing which charges a premium for energy used during peak times and providing incentives to turn off high consuming devices (most notably air conditioners) during peak periods (Independent Electrical Service Operator, 2016). In addition to incentives and policy changes being implemented, the development of new systems and control strategies to shift energy consumption to off peak periods are being developed. One proposed method is using a liquid-to-liquid heat pump paired with thermal storage system(s). Before the wide scale implementation of heat pumps with thermal

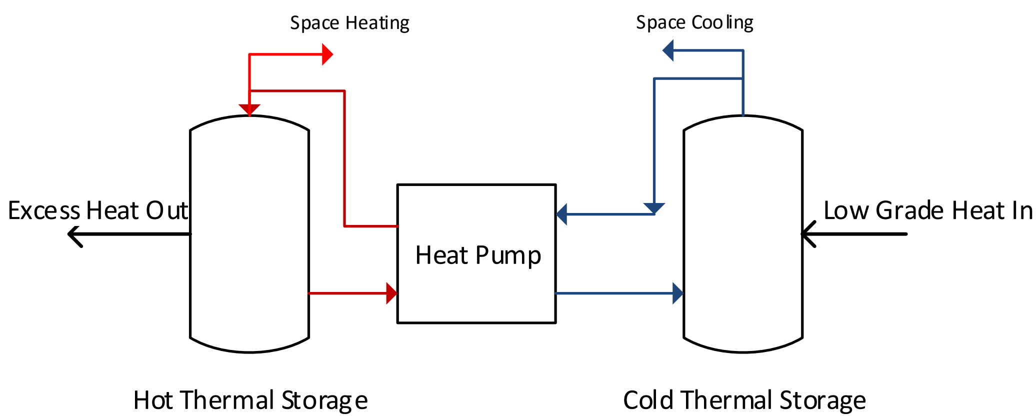

Figure 1: High level schematic of proposed system

storage systems is possible, extensive study must be conducted on their potential for reducing peak loading, utility cost savings and effect on overall energy consumption.

This paper examines the potential for peak load reduction using an integrated system consisting of a small, 6 $kW_{thermal}$ heat pump with a water tank based hot thermal storage and a cold thermal storage tank with a glycol/water mixture as the storage medium. A schematic of the proposed system is shown in Figure 1. A model of the heat pump and cold thermal storage tanks has been previously developed and calibrated to an experimental test system (Baldwin & Cruickshank, 2016). This previously validated heat pump model was then integrated into a house model developed in TRNSYS and , with the composite model used to determine the impact of different control strategies of the heat pump and thermal storage systems on total energy consumption, electrical consumption during peak periods, total electrical costs and total greenhouse gas emissions. This paper represent the first phase in a long term project, and examines whether a standard geothermal heat pump and sensible thermal storage will provide the necessary storage capacity and performance to efficiently offset a significant portion of peak energy consumption while reducing the annual costs and greenhouse gas emissions from space heating and cooling.

2. BACKGROUND AND THE ONTARIO ENERGY LANDSCAPE

This study was conducted for a house located in Ottawa, Ontario, Canada, and as a result, the electrical landscape in Ontario is of vital importance to the work. Electricity in Canada is handled and managed at a provincial level, with each province having distinct electrical grid and generating capacity. Ontario's electrical generation is very diverse, with a significant portion of the annual electrical generation coming from 4 different sources (nuclear, hydro, wind and natural gas) (Independent Electrical Service Operator, 2016). Consequently, the hour by hour generating mix is unique each hour of the year, and as such, the greenhouse gas intensity per kilowatt-hour changes based on the province wide electrical demand and the availability of variable renewable sources (wind and solar). As the peak load is predominantly met using natural gas power plants, meaning that energy used during peak periods has a much higher greenhouse gas intensity on average compared to periods of low demand.

To promote the reduction in electrical consumption, Ontario introduced time of use billing, in which a premium is paid for electricity used during peak periods, while electricity used during off-peak periods is considerably cheaper. For the ease of the customer, peak, mid-peak and off-peak periods are pre-defined based on historical consumption patterns, allowing consumers to tailor their consumption to these time periods. During the summer months, which last from May 1st to October 31st, peak periods occur Monday to Friday, 11am to 5pm while mid-peak occur from 7am-11am and 5pm-7pm. During the winter months, from November 1st to April 30th, peak periods occur from 7am-11am and 5pm-7pm, while mid-peak occurs from 11am-5pm. In both the summer and winter periods, off-peak periods occur from 7pm to 7am, and 24hr on weekends. As of May 1st, 2016, peak rates in Ontario are 18 cents, mid-peak rates are 13.2 cents, and off-peak rates are 8.7 cents (Ontario Energy Board, 2015).

As Ontario has clearly defined peak and off-peak periods, for the remainder of this work, peak and off-peak periods will be as defined by the electrical providers in Ontario. Using data from the Independent Electrical Services Operator of Ontario, the amount of electricity generation from each sources on an hourly basis was calculated. From these values, and using the 50th percentile of greenhouse gas emissions by source as stated by the 2011 United Nations Intergovernmental Panel on Climate Change (Edenhofer, et al., 2011), the average greenhouse gas emissions per kilowatt-hour of electrical generation for peak, mid-peak and off-peak periods in both the summer and winter periods were calculated and are shown in Table 1.

Table 1: Greenhouse gas intensity in Ontario by usage period-2015

Period	Greenhouse Gas Intensity (g/kWh)		
	Off-Peak	Mid-Peak	Peak
Summer	54.9	70.5	76.0
Winter	51.8	59.9	60.2

The cost of electricity provides significant incentive to shift electrical consumption from peak to off-peak periods. For example, for each kilowatt-hour shifted, the consumer saves 9.3 cents (this represents a reduction greater than 50% in cost). In addition, each kilowatt-hour shifted provides a reduction in greenhouse gas emissions, that is, 21.1 g of CO_2 in the summer and 8.2 g of CO_2 in the winter. These reductions benefit both the consumers and utility provides.

3. HOUSE MODEL

Before the proposed system could be modelled to determine the annual performance, a house model had to be developed in TRNSYS (TRNSYS: A Transient Simulation Program, 2015) to provide building loads for the heating and cooling system. The house has modelled to represent a newly built house located in Ottawa, Ontario, Canada. The modelled house is a two-story, single detached house with a full basement. Each level has a floor area of 110 m^2 with a total volume of 835 m^3. The house was broken into 4 air zones, being the basement, main floor, 2nd floor and the attic, with air exchange between the basement, main and 2nd floor. The heating was an air based system, where 20% of distribution air goes to the basement, 35% to the main floor and 45% the 2nd floor, allowing the increased heating and cooling demand in the 2nd floor to be met as a result of the heat loss through the ceiling into the attic. A single thermostat has been placed in the main floor with a heating set-point of 20°C and a cooling set-point of 23°C. The remaining specifications for building insulation and windows are provided in Table 2.

Table 2: House construction specifications

Type	Parameter	Units	Value
Thermal Resistance	Above Grade Walls	m^{2}K/W	4.5
	Attic	m^{2}K/W	11.5
	Below Grade Walls	m^{2}K/W	2.7
	Under Slab	m^{2}K/W	1.9
Windows	U-Value	W/m^{2}K	1.27
	Solar Heat Gain		0.624
House	Air Leakage	ACH	0.05
	Occupancy	Number of People	4

3.1 Baseline Energy Consumption

Once the house model was developed within TRNSYS, a baseline energy consumption for heating and cooling had to be determined. A fluid heater and fluid chiller, both with a coefficient of performance (COP) of 1 and with no losses where integrated into the model to represent an ideal heating system. The model was then run for 1 year (8760 hours), with the electrical consumption being recorded every 2 minutes. Based on these simulation results, the house being modelled was found to have an annual space heating load of 16,215 kWh and an annual cooling load of 4686 kWh. Of more importance than the total energy consumption, was the time at which the energy was used, the cost to the consumer and the total greenhouse gas emissions as a result of the space heating and cooling. The energy consumption was broken down by peak, mid-peak and off-peak as defined by Ontario's time of use billing, while the greenhouse gas emissions were calculated using the average for each time period for winter and summer periods. A summary of these results are presented in Table 3.

Table 3: Baseline energy consumption by time, heating costs and greenhouse gas emissions

Energy Type	Summer (kWh)			Winter (kWh)			Cost (CAD$)	Greenhouse Gas Emissions (kg)
	Peak	Mid-Peak	Off-Peak	Peak	Mid-Peak	Off-Peak		
Heating	17	87	2091	1975	752	11,293	1580	321
Cooling	2399	857	1430	0	0	0	664	871
Total	2416	944	3521	1975	752	11,293	2444	1192

Based on these results, a number of conclusions can be noted. The baseline energy consumption for space heating is predominantly off peak, with over 80% of the winter space heating load occurring during off-peak periods. This was expected, as during the overnight period, no solar gains are present to reduce the space heating load and the outdoor temperature is at its lowest. This results in the bulk of the heating required during the overnight, off-peak period. If a night-time temperature set-back was introduced, the energy consumption would shift towards a larger percentage during peak periods, particularly if the morning heating occurs at or after 7am. Although a large percentage of the heating load occurs during off peak periods, almost 2000 kWh of heating occurs during peak periods, accounting for almost 23% of the total space heating costs, of which most occurs early in the morning. This peak load could be easily shifted to off-peak periods through the use of thermal storage overnight.

When looking at the space cooling demand, a much larger percentage of the load occurs during peak periods, with 51% of the cooling load (and 65% of cost) occurring during peak periods, when peak periods only account for 18% of the summer period. As such, space cooling shows the greatest potential to see a meaningful benefit from shifting electricity consumption from peak to off-peak periods using heat pumps and thermal storage.

3.2 Baseline Energy Consumption Using a Heat Pump

The previous section indicated the total space heating and cooling loads, and the time of day they occurred using a generic auxiliary heater and chiller with a COP of 1. This provided useful data to recognize energy trends and a true baseline, however to make a true comparison of the proposed system that integrates both a heat pump and thermal storage systems, a baseline energy consumption using the same heat pump that will be integrated with the thermal storage had to be determined. Using the same house model and air distribution system, a 6 $kW_{thermal}$ heat pump was coupled with the heating and cooling coils. This work focused on the heat pump and thermal storage systems and not the potential heat source or sink for the system, and as such to remove any discrepancies or errors that could be introduced by these, a constant heat source was provided on the source side of 15°C and 450 L/hr during the heating season and a heat rejection of 25°C and 450 L/hr. The same thermostat set-points were used as for the baseline energy consumption and the electrical consumption for space heat and space cooling was independently reordered and is presented in Table 4.

Table 4: Baseline energy consumption using a heat pump for space heating and cooling

Energy Type	Summer (kWh)			Winter (kWh)			Cost (CAD$)	Greenhouse Gas Emissions (kg)
	Peak	Mid-Peak	Off-Peak	Peak	Mid-Peak	Off-Peak		
Heating	4	22	510	485	219	2282	351	190
Cooling	536	196	322	0	0	0	149	72
Total	540	218	832	485	219	2282	500	262

These results held the trends of the first baseline energy consumption, however, the introduction of the heat pump saw the energy consumption reduced by 78% for space heating and by 77% for space cooling. The values obtained from this base model incorporating the heat pump with no thermal storage will be used as the baseline for all future simulations incorporating thermal storage.

4. INTEGRATING THERMAL STORAGE – TEMPERATURE BASED CONTROLS

After determining the baseline energy consumption for the modelled house with and without a heat pump, the complete systems including the heat pump, hot thermal storage and cold thermal storage was integrated with the house model. The specifications for each of the thermal storage systems are provided within Table 5.

Table 5: Baseline energy consumption using a heat pump for space heating and cooling (DOW Chemical Compnay)

Tank Property	Hot Storage	Cold Storage
Fluid	Water	Water/Glycol
Density (kg/m^3)	1000	1046.7
Thermal Conductivity (W/m·K)	0.594	0.378
Specific Heat (kJ/kg·K)	4.19	3.32
Viscosity (cP)	1	5
Thermal Expansion (1/K)	0.00026	0.000495
Capacity (L)	400	270

Once the thermal storage tanks were integrated into the model, a control strategy had to be developed to control the complete systems. The thermostat within the house model would still control when heating or cooling was provided to the house, however the control of heated water or chilled water/glycol solution to the air handler and the charging of the two thermal storages using the heat pump must be controlled independently. To accomplish this, four independent controllers were implemented.

The first controlled the flow of hot water through the air handling unit, providing space heat to the building. As the tank temperature at any given point is variable, the flow rate through the air handler must vary to produce a constant delivery temperature, and therefore, a variable speed pump, controlled using a PID controller to control the flow to meet a delivery output temperature of 30°C. A similar control strategy was implemented for space cooling, with a PID controller providing a control signal to a variable speed pump to meet the output temperature of 12°C. These set-points were used as the default values and the optimal value determined. A schematic of the air handler and heat pump control system is shown in Figure 2.

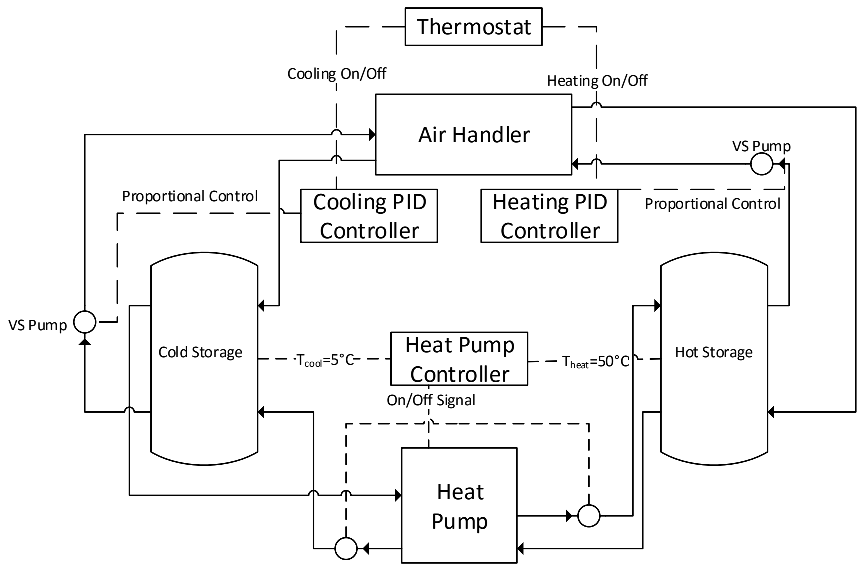

Figure 2: Control schematic for the integrated heat pump and thermal storage system

To control the heat pump, thermostats were placed within both tanks, with the thermostat in the hot tank placed at a height of 80% of the tank, while the thermostat is placed at a height of 20% of the tank. The hot tank was initially set to 55°C and the cold tank set to 5°C. For the heat pump to turn on, the hot tank must drop below the set-point, and be during the heating season or the cold tank must rise above the set-point and be during the cooling season. When the heat pump turns on, two single speed pumps (one on the load side, one on the source side) are simultaneously switched on at a default flow rate of 360 L/hr.

To ensure the hot tank does not overheat, or the cold tank temperature drops too low, a supplementary control system was implemented. This allowed the heat pump to draw heat from a supplementary source (e.g., from a ground loop) when the cold tank dropped below the set-point, or to reject heat when the hot tank was above the set-point (e.g., rejected outdoors). In these cases, when the cold tank is bypassed, a return temperature to the heat pump is set at 15°C and when the hot tank is bypassed, a constant return temperature of 20°C is set.

4.1 Preliminary Results

The integrated system has a number of variables that are being simultaneously controlled for both the hot and cold settings. Values for each of the variables were chosen to determine preliminary results, which will provide a baseline for optimization of the system. These variables, and the initially selected values are shown in Table 6. In addition to the initial value, a high and low value are provided to show the range of interest for each variable that will be simulated to determine the impact of each variable on the overall system.

Table 6: Control variables within the integrated system

Variable	Units	Initial	High	Low
Hot Tank Set-Point	°C	50	60	40
Cold Tank Set-Point	°C	5	10	0
Hot Flow Rate	L/hr	360	480	240
Cold Flow Rate	L/hr	360	480	240
Cooling – Delivery Set-Point	°C	12	16	8
Heating – Delivery Set-Point	°C	30	35	25

As the heating and cooling systems are integrated, and the heat pump can simultaneously provide energy for space heating and space cooling, the electrical energy consumption cannot be differentiated between heating and cooling. As a result, the electrical consumption can only be reported as the total electrical energy required for space heating and cooling in the winter, summer and as an annual total. Using the initial values, the total electrical consumption, time of electrical consumption, total electricity costs and the greenhouse gas emissions are listed in Table 7.

Table 7: Results using the initial values for control variables

Variable	Summer	Winter	Annual
Electrical Consumption (kWh)	3265	4954	8219
Peak Consumption (kWh)	841	864	1705
Mid-Peak Consumption (kWh)	549	746	1295
Off-Peak Consumption (kWh)	1876	3344	5221
Electrical Costs ($CAD)	$379	$532	$911
Greenhouse Gas Emissions (kg)	206	270	476
Percent Consumption During Peak Periods (%)	25.7%	17.4%	20.7%

The initial results provided mixed results, with the amount of electricity being used for space heating and cooling seeing an electrical consumption increase of 105% in the summer, 66% in the winter and 80% over the whole year. As a result, greenhouse gas emissions and electrical costs have increased 82%. On the promising side however, the percentage of electrical consumption that occurs during the peak period in the summer period was reduced from 34% to 26%, however a large percentage of this energy was shifted to mid-peak as opposed to off-peak, as the percent of consumption during mid-peak almost doubled, from 9% in the base case to 16% with thermal storage.

From the baseline simulation with the complete system, an advantage can be seen in terms of shifting energy consumption, however significant optimization is required before the system out-performs the system without thermal storage. The first step is to determine which of the 6 control variable has the greatest impact on the annual performance of the system. To assess this, 12 additional simulations were conducted, changing one of the variables each time, first to the low value, followed by the high value, with the percent increase or decrease in total energy consumption, cost, greenhouse gas emissions and percent consumption during peak periods are shown in Figure 3.

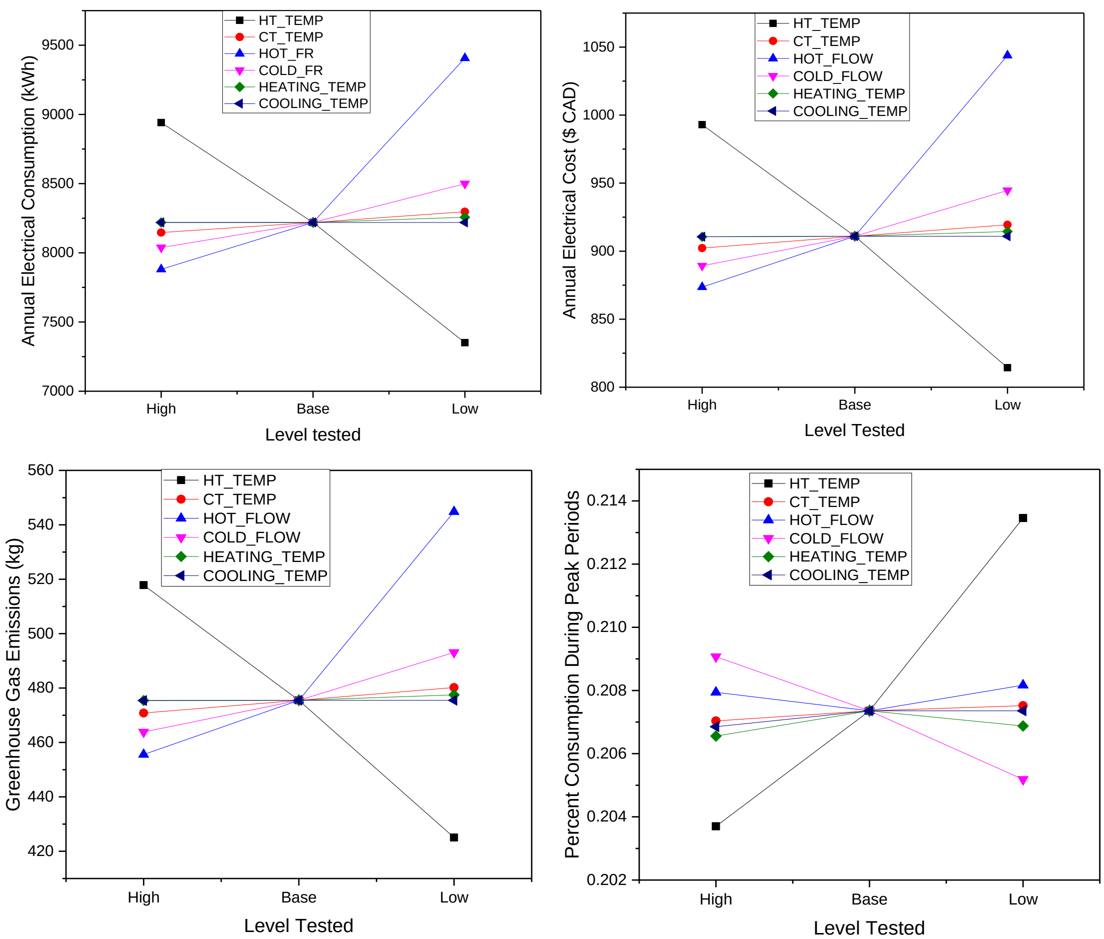

Figure 3: Comparison of high and low values of each of the 6 control variables

Based on the results of varying the 6 control variables, the parameter that provided the lowest annual energy consumption was selected (in every case this also provided the lowest cost and the least amount of greenhouse gas emissions). A hot tank temperature of 40°C, a cold tank temperature of 12°C, a hot side flow rate of 480 L/hr, a cold side flow rate of 480 L/hr, a heating distribution temperature of 30°C and a cooling distribution temperature of 8°C. The simulation was run using this control scheme and the results for all of the results of interest are shown in Table 8, and compared to the results using just the heat pump.

Table 8: Results using the optimal set-point for each control variable

Variable	Heat Pump with Thermal Storage	Heat Pump Only	Difference with Thermal Storage
Electrical Consumption (kWh)	6656	4576	+45%
Peak Consumption (kWh)	1411	1025	+38%
Mid-Peak Consumption (kWh)	871	437	+99%
Off-Peak Consumption (kWh)	4373	3114	+40%
Electrical Costs ($CAD)	$732	$500	+40%
Greenhouse Gas Emissions (kg)	382	262	+45%
Percent Consumption During Peak Periods (%)	21.2%	22.4%	-5%

These results showed that even when the optimal temperature based control strategy is implemented, a significant increase occurs in energy consumption on an annual basis and when each rate period is considered. Additionally, as a result of the increased consumption through each rate period, the annual electrical cost and the total greenhouse gas emissions also increased. This increase in consumption was primarily the result of decreased performance of the heat pump when charging the thermal storage systems as compared to directly heating and cooling the space. This was as result of the increased load temperatures returning from the hot thermal storage tank during the heating season and the much lower source temperatures returning from the cold thermal storage tank. Although the total electricity consumption during peak periods increased, the percentage of total consumption that occurred during peak periods decreased, showing that there is potential for this system in reducing peak loads, however further optimization of the control strategy is required.

5. TIME BASED CONTROLS

The results presented in the previous section clearly demonstrated that a simple temperature based control strategy significantly increased energy consumption and had a negligible impact on shifting energy consumption to off-peak periods. As such, a control strategy that takes into account the time of day is required when peak and off-peak periods exist. As such, a controller with a variable set-point for both the hot tank and cold tank was implemented, with the set-points for peak and off-peak periods for the two thermal storage systems indicated in Table 9.

Table 9: Thermal storage set-points for time based control

	Off-Peak Set-Point (°C)	Peak and Mid-Peak Set-Point (°C)
Hot Thermal Storage	50	30
Cold Thermal Storage	5	15

The simulation was run with this new control strategy, with the remaining control parameters left unchanged from the final simulation using a temperature based controlled strategy. Results utilizing the new control strategy on an annual basis are shown in Table 10, with a comparison to heating and cooling with the heat pump.

Table 10: Base results with a time based control strategy

Variable	Heat Pump with Thermal Storage	Heat Pump Only	Difference with Thermal Storage
Electrical Consumption (kWh)	6324	4576	+38%
Peak Consumption (kWh)	1112	1025	+8%
Mid-Peak Consumption (kWh)	506	437	+16%
Off-Peak Consumption (kWh)	4706	3114	+51%
Electrical Costs ($CAD)	$657	$500	+31%
Greenhouse Gas Emissions (kg)	356	262	+36%
Percent Consumption During Peak Periods (%)	17.6%	22.4%	-22%

From these results, it can be seen that switching to a time based control strategy shows significant benefit when compared to using a temperature based control strategy, however still uses more energy in each of the time periods when compared to space conditioning with just the heat pump. To ensure the selected temperature settings are optimal a range of values from 0°C to 10°C and 40°C to 60°C were simulated as the set points during the peak periods, with the results for total consumption and percent during peak periods shown in Figure 4.

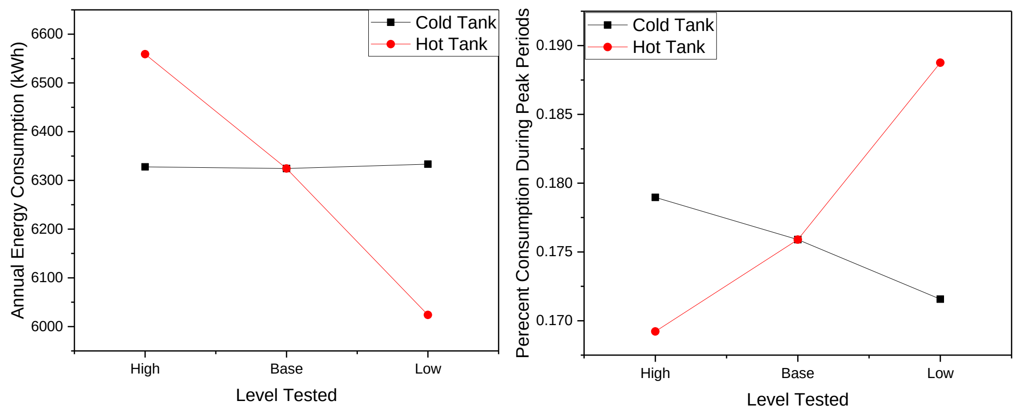

Figure 4: Comparison of high and low values for the set-point in the hot and cold tank

Based on these results, the set-point of the cold tank has minimal impact on the total energy consumption, with a less than a 0.25% change in the total consumption, however, the set-point did account for a 2.5% decrease in the percentage of energy consumption during peak periods. The temperature set-point on the hot tank had a much larger impact on the overall energy consumption, with decreasing the hot tank set-point to 40°C reducing total energy consumption by almost 5%, however the percent consumed during peak periods increased by almost 7%, while setting the hot tank to 60°C had the opposite effect, increasing the total energy consumption by 4%, while decreasing the percent consumption during peak periods by 4%. Although this looks beneficial in terms of reducing the percent consumed during peak periods, most of the change actually came from increasing the total consumption as opposed to actually reducing the consumption during the peak periods with the actual consumption during peak periods decreasing only 3 kWh from the base case. As such, the simulation was rerun using a hot tank set-point of 40°C and a cold tank set-point of 0°C and the results of this simulation are presented in Table 11, and compared to when only the heat pump was used for space conditioning.

Table 11: Results using the optimal control set-points for both the hot and cold thermal storage

Variable	Heat Pump and Thermal Storage using Time Based Controls	Heat Pump Only	Difference with Thermal Storage
Electrical Consumption (kWh)	6034	4576	+32%
Peak Consumption (kWh)	1112	1025	+8%
Mid-Peak Consumption (kWh)	511	437	+17%
Off-Peak Consumption (kWh)	4412	3114	+42%
Electrical Costs ($CAD)	$633.63	$500.45	+27%
Greenhouse Gas Emissions (kg)	341	262	+30%
Percent Consumption During Peak Periods (%)	18.4%	22.4%	-18%

From these results, it can be seen that a time based control not only reduces the overall annual consumption compared to temperature based controls, but considerably reduces the peak power consumption and the percentage of power used during peak periods. This shows that the control strategy has potential to reduce the peak load consumption, however the annual electrical consumption, costs and greenhouse gas emissions are still much greater than when using just a heat pump. It is important to note that the consumption during peak periods is now close in both scenarios and the percentage of total consumption during peak periods has decreased considerably.

6. DISCUSSION

Through the optimized control of the proposed system, mixed results were observed through this preliminary study of the potential for shifting peak consumption from off-peak to peak periods. The total electrical consumption of the system with the optimized control strategy has increased by 32% when compared to directly using the heat pump for space conditioning. The only parameter which decreased when going from the heat pump only to the heat pump and thermal storage was the percent of energy consumption during peak periods, which decreased by 18%, however this is somewhat misleading as it was as much the result of increasing the off-peak consumption as it was in reducing the peak consumption. These results indicate that there is potential for reducing peak consumption through thermal storage while remaining cost neutral, however other factors other than just the control strategy must be considered.

This study looked only at optimizing the control strategy with the stated components, and did not in any way look at optimizing the parameters of the components or the size and capacity of the system. It is anticipated that these factors could have a significant impact on the overall system performance. Of particular interest is the heat pump. Moving forward, the heat pump's thermal output should be increased as the current model just meets the heating demand in the winter, but must be on almost continuously during the coldest periods of the year. As a result, there is no time for the heat pump to charge the hot thermal storage overnight, and consequently almost no heating load is shifted from peak to off-peak periods when the heating loads are greatest.

The other factor that should be considered when selecting the heat pump is the performance at the load and source temperatures provided from the thermal storage systems. As this project focused on using a standard ground source heat pump, the source temperature from the cold storage is much lower than the design temperatures. This significantly decreases the performance of the system as a whole as the COP of the heat pump drops significantly. The same effect to a lesser extent is also observed with the hot thermal storage, however storage temperature are closer to the design temperatures for the load side of the heat pump. When using just the heat pump, the overall COP of the heat pump for space heating and cooling for the year is 4.5, while the overall COP when integrating thermal storage is 3.3. This amounted to a 25% reduction in heat pump performance. This phenomenon was discussed by (Dincer & Rosen, 2011), where they state that a decrease from 0°C to -10°C for a cold storage causes a reduction in COP of 70%, and a decrease in cooling capacity of 56%, which would account for the 25% annual reduction seen in this study. To achieve the goal of being cost and greenhouse gas emission neutral while shifting all or a substantial proportion of energy use to off peak periods, a heat pump that is designed to perform at lower temperatures must be employed.

In addition to changes required to the heat pump to improve performance of the system, the cold thermal storage is significantly undersized, and currently is unable to meet the cooling demand during peak and mid-peak periods during the day. As one of the objectives to this study was to determine whether small scale, sensible thermal storage systems can be utilized, it was determined that a thermal storage of this size is unable to provide the required load shifting, and alternative methods for cold storage needs to be explored, allowing for a greater thermal storage density. The most promising method for this is the future study of implementing ice storage into the system, capitalizing on the phase change from water to ice as the primary cold thermal storage mechanism. The introduction of ice storage would see a further decrease in the source temperature entering the heat pump, and as such, the implementation of ice storage would require a heat pump designed for low temperatures.

7. CONCLUSIONS

Based on the findings of this study, a number of conclusions can be drawn from the results. The use of a standard heat pump designed for a geothermal heating and small scale, sensible thermal storage, as tested in this study, increased energy consumption during each rate period on an annual basis, but did decrease the percentage of electrical consumption during peak periods. This proposed system, with the optimization of the control strategy implemented, did not achieve the primary goal of shifting a substantial amount of electrical consumption to off peak periods while staying cost and greenhouse gas neutral. Although this system was unable to reach the desired outcome, this study showed that there is potential for pairing of a heat pump and thermal storage systems. Once the complete design is optimized, including heat pump selection and thermal storage capacity, it is anticipated that the system can reduce peak loads within single detached housing, with a decrease in annual electrical costs and greenhouse gas emissions.

This was the first phase of a multi-phase project. Based on these results, further study will be conducted on determining the required performance from a heat pump to make the systems viable. Based on those results, a new heat pump will be specified and experimentally evaluated. Concurrently, work on increasing the storage density of the cold storage will be explored, with the end goal of developing a small scale, residential sized ice storage system that can provide adequate cooling potential to meet the maximum daily cooling load.

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