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Offsetting Peak Residential Cooling Loads Using a Medium Temperature Chiller and Sensible Cold Thermal Storage

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ABSTRACT
Space cooling places a significant peak load on the electrical grid during hot, sunny afternoons. With the introduction of time-of-use billing, space cooling during these periods has become very expensive. To reduce utility costs and shift peak loads, the use of a medium temperature chiller coupled with a sensible cold thermal storage system was investigated. Optimal configurations were found for seven cities located within each of the seven ASHRAE climate zones and an analysis on the energy consumption and annual utility costs are presented. It was found that in all locations, peak loads from air-conditioning could be reduced or eliminated, and that when the cooling load was great enough, or the peak utility rate was sufficiently greater than the off-peak period, annual utility costs savings, approaching 30% in some areas, could be realized.

KEYWORDS
Cold Thermal Storage, Demand Side Management, Residential Air-Conditioning, Peak Loading, Time-of-Use Billing

INTRODUCTION
As global temperatures increase with global warming, the demand for space cooling has seen a significant increase. This coupled with the increase in residential floor space, has caused a spike in air conditioning use, and consequently the amount of energy consumed for space cooling. Both the United States and Canada have seen an increase in energy consumed for space cooling in excess of 50% in the last 25 years, while total residential consumption has only increased 2% and 5% in the United States and Canada respectively (NRCan-OEE, 2013; U.S. EIA, 2018).

This demand for space cooling is greatest during afternoon and early evening, when daily temperatures and solar radiation are at their peak. Since electrical grids are sized to the anticipated peak load, an increase in generation and transmission capacity is required to meet these increasing loads. In order to address the required increase in grid capacity (which is also extremely expensive), utility providers are implementing measures to control when electricity is being used and to shift consumption from peak to off-peak periods. Of these, the most common strategy is implementing time-of-use billing. Electricity rates during hours of the day, when electricity demand is at its greatest, is more expensive than electricity during low demand or off-peak periods.

One approach for a utility customer to reduce the higher cost associated with time-of-use billing is lowering the air conditioning set-point, or turning off the unit entirely. This can impact the desired comfort of the occupant and is not always possible, particularly for elderly occupants. An alternative solution is to couple an air conditioning unit with cold thermal storage, allowing the air conditioner to run during off peak periods, and storing the cooling potential for use during peak periods.

In a previous study, Baldwin and Cruickshank (2016) explored this possibility using a standard liquid-to-liquid heat pump coupled to a cold thermal storage system. This was studied for Ottawa, Canada and in this study, it was found that peak loads from air conditioning can be eliminated if adequate storage is installed in the system. That being said, a significant increase in off-peak power was observed. This was caused by the substantial drop in performance of the heat pump when storing cooling potential at low temperatures, as well as the relatively low total cooling load of a residential building located in Ottawa. As a result, an increase in the annual electricity cost was observed.

This paper builds on the previous study, and looks at using a medium temperature chiller coupled with a sensible, cold thermal storage system using a 50/50 (by volume) water/glycol solution as the sensible storage medium. Medium temperature chillers are designed to operate with evaporator temperatures between 0°C and -25°C. By utilizing a chiller designed for lower temperatures, it was hypothesized that chiller performance would not degrade as storage temperatures near or below freezing are utilized. Additionally, multiple locations throughout all of ASHRAE's major climate zones are utilized to determine the impact of load on the potential for offsetting peak electrical loads as a result of air conditioning.

METHODS

To determine the potential of shifting electrical consumption to off-peak periods, a city in each ASHRAE climate zone was selected. Cities were selected where the major electrical provider either used only time-of-use billing or provided it as an option for customers who wished to opt-in to the program. The selected cities and the utility rates are provided in Table 1. All utility rates are as of March 2017 and are shown in local currency.

Table 1: Selected cities and the associated utility rate

Location	ASHRAE Climate Zone	Peak Rate* ($/kWh)	Mid-Peak Rate* ($/kWh)	Off-Peak Rate* ($/kWh)
Miami, Florida	1	0.19165	N/A	0.0331
Phoenix, Arizona	2	0.1020-0.2226	N/A	0.0711-0.0741
Los Angeles, California	3	0.1456-0.2433	0.1456-.01641	0.1396-0.1492
Portland, Oregon	4	0.1998	0.1428	0.0421
Boston, Massachusetts	5	0.1973	N/A	0.0920
Toronto, Ontario	6	0.1564	0.1194	0.0894
Sudbury, Ontario	7	0.1504	0.1134	0.0834

* (FPL, 2018; SRP, 2018; LADWP, 2018; PGE, 2018; NG - ME, 2018; THC, 2018; GSU, 2018)

A model was developed in TRNSYS, and consisted of a two-storey house with a fully conditioned basement. The house had a total above grade floor area of 220 m^2 and a volume of 835 m^3. The house was also modelled to the current Ontario building code, with an above grade wall RSI value of 4.5 m^2K/W, and with windows on all 4 sides of the building, with an overall window to wall ration of 30%. A detailed description of the model is described in Baldwin and Cruickshank (2016).

For this study, baseline simulations to determine annual energy consumption using traditional heating and cooling methods were first run. In these models, space heating and cooling loads were met using a standard heat pump with a performance map developed by Baldwin and Cruickshank (2016). The domestic hot water demand was met using an instantaneous electric water heater. Baseline results and annual utility costs for space heating, cooling and domestic hot water were then determined for each location.

Once the baseline energy consumption was determined, the medium temperature chiller and cold thermal storage were integrated into the house model. A performance map for the medium temperature chiller was experimentally determined at steady-state. A total of 315 tests were performed. A number of simulations were then performed to determine the optimal storage volume and tank set-point for each location. Using these results, an analysis was conducted to determine the feasibility in each of the chosen locations. The results of these simulations are shown and discussed in the next sections.

BASELINE ENERGY RESULTS

Baseline energy consumption and the resulting annual energy costs were calculated for each of the seven locations. Annual energy consumption was calculated first by end use (i.e., hot water, space heating, space cooling), neglecting any appliance, plug or lighting loads. A second baseline analysis was conducted on the time of day the energy is used, breaking down the peak, mid-peak and off-peak periods as defined by the local utility, as well as the utility costs for each period of the day. The results of two analysis are shown in Figure 1.

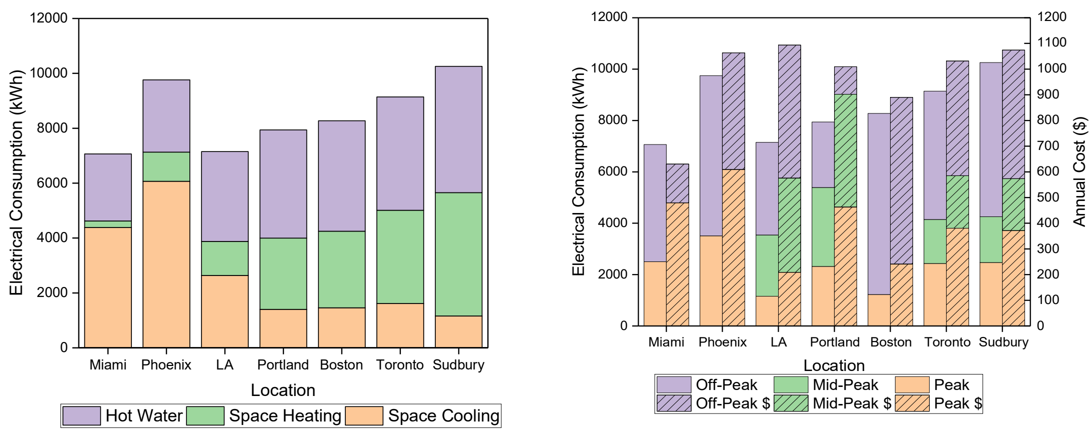
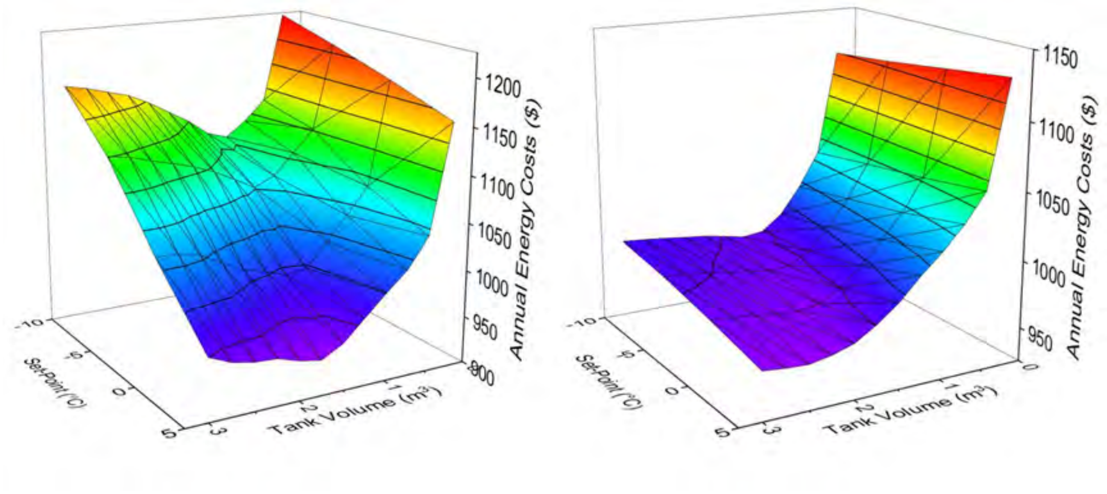


Figure 1: Energy consumption by: end use (left), time of day and annual utility costs (right)

From these results, it can be seen that as the ASHRAE climate zone number increases (going left to right on each graph), the proportion of heating to cooling of the building increases. It can also be noted that in all locations, the peak and mid-peak costs were disproportionately higher than the amount of energy used during the same period. Additionally, in general, the higher the percentage of the building load that is attributed to space cooling, the greater the percentage of utility costs as a result of energy used during peak periods.

OPTIMAL SET-POINT AND TANK VOLUME

Once the energy baseline was determined for each locale, a parametric study was undertaken to determine the optimal tank size and tank set-point for each location. The tank was controlled using the average tank temperature as the control variable and two set-points were implemented. The first was the tank set-point during peak and mid-peak periods, which was kept constant through all simulations at 15°C, and the second was the tank set-point during off-peak periods, which was varied through the simulations to determine the optimal value. During the study, the tank volume was varied from 0.25 m^3 to 3 m^3, in 0.25 m^3 increments, while the off-peak tank set-point was varied from -10°C to 5°C, in 5°C increments. As such, a total of 48 simulations were completed for each locale. The annual utility costs were then calculated for each simulation, and the results were plotted as a 3-dimensional surface plot, interpolating between the individual points, was developed for each city. The annual utility cost was the variable of interest, with the goal of minimizing the annual utility costs for the dwelling. Two examples for these plots for Phoenix and Portland are shown in Figure 2.



(a) Phoenix (b) Portland

Figure 2: Example simulation results for Phoenix and Portland varying the off-peak set-point and tank volume

From this series of graphs, it can be seen that the optimal configuration for any given locations is dependent on both the cooling loads of the building, the ratio between peak and off-peak utility costs, and the total energy consumption. In all cases, it was concluded that it is paramount to find the correct storage capacity, as if not enough storage is integrated into the system, the amount of peak energy that is off-set is minimal, increasing the annual energy costs. On the other hand, it is seen that a second spike in energy costs occur in most locations if too much storage is integrated into the system, as the chiller must constantly operate at lower temperatures, near the set-point of the storage tank, without realizing the stored cooling potential. This decrease in operating temperature resulted in a significant drop in chiller performance, and consequently an increase in electrical energy required. Additionally, a trend towards higher set-point temperatures seeing lower annual costs was observed, as again, the performance of the chiller decreases with the lower operating temperatures. In contrast however, the higher the set-point temperature, the larger the tank volume typically required, and as such, more space and a higher initial capital cost is required.

Taking the results from each location, the optimal tank size and tank set-point was determined for each of the seven locations. When results from multiple configurations provided the same, or very similar results, the configuration in which the tank size was smallest was selected to reduce the required volume within the system. The optimal configuration in which annual energy costs are minimized for each location, and a comparison of cost compared to baseline for each of the locations is shown in Table 2. Further, a comparison of when energy is used between baseline and optimized configurations is shown in Figure 3.

Table 2: Optimal configuration and electrical costs per location

Location	Optimal Tank Volume (m^3)	Optimal Set-Point (°C)	Annual Energy Cost ($)	Baseline Energy Cost ($)	Difference (%)
Miami	1.50	0	446.39	630.44	-29.19%
Phoenix	1.75	5	937.65	1063.40	-11.83%
Los Angeles	0.50	5	1083.40	1093.78	-0.95%
Portland	2.00	0	963.93	1009.48	-4.51%
Boston	1.50	5	954.81	890.11	7.27%
Toronto	1.25	0	1046.52	1031.52	1.45%
Sudbury	1.00	5	1175.67	1074.24	9.44%

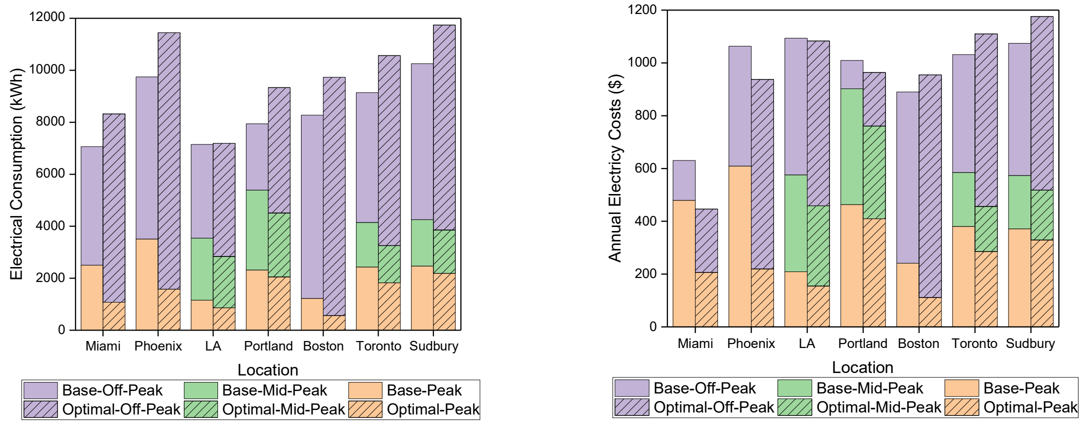


Figure 3: Comparison between baseline and optimal energy consumption and utility costs

DISCUSSION

Based on these results, a number of trends were observed. The first is the potential is greatest for offsetting significant peak loads in regions where building loads are dominated by cooling loads. In Northern climates a substantial reduction in peak loads can be obtained, however the economic benefits are not there when compared to southern climates. Even though climate appeared to be the most significant factor in determining the feasibility, the ratio between utility rates between peak and off-peak periods influenced the optimal configuration of the system. This can be seen in particular in the results for Los Angeles, where the small difference in peak to off-peak rates creates little economical benefits even though a high cooling load exists. When the ratio is high (peak to off-peak), it was beneficial to increase the storage capacity to offset as much of the peak load as possible, even if the increase in off-peak consumption is disproportionately large.

Although benefits were observed in most locations, additional benefits could be realized if heat recovery on the condenser side of the chiller was utilized, for one of, or both domestic hot water production or space heating. This could be in the form of a small hot water tank which is preheated using the waste heat from the chiller, or a direct heat exchanger between the condenser loop to the hot water inlet, warming up the water before it enters the on-demand heater.

In all locations, although the peak load is reduced, an increase in the overall annual energy consumption is also observed as a result of the decreased performance of the chiller in charging the thermal storage. Although the assumption is being made in the paper that it is always beneficial to switch consumption to off-peak periods, a more detailed analysis of each locations energy grid and specifically the generation methods used to produce power is required. If the location has a clean generation base using sources such as hydro or nuclear that can't be turned off, that there is benefit to switching, however, if a location's electricity is met using fossils fuels (e.g., coal, natural gas), the increased power consumption would significantly increase the greenhouse gases released to generate the required electricity.

Finally, although many locations have seen an annual economic benefit, the benefits in terms of actual costs are quite small, in some cases only a few dollars. If a detailed life cycle economic analysis was completed, the system under today's economic conditions would not be profitable over the life of the system. A significant increase in both the absolute cost of electricity, as well as the ratio between peak to off-peak periods would need to occur to improve the economics of the system.

CONCLUSIONS

This paper has shown that using a medium temperature chiller coupled with cold thermal storage has the potential to reduce, and in some cases, eliminate the electrical consumption required for air-conditioning during peak utility periods. It was found that in southern climates, and those with a large ratio between peak and off-peak utility rates, significant savings can be realized on an annual basis. This paper shows there is significant potential, however before these systems see widespread implementation, significant research is still required to improve performance and further optimize the control strategy and configuration.

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