Designing an Optimal Urban Community Mix for an Aquifer Thermal Energy Storage System

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ABSTRACT

Aquifer thermal energy storage (ATES) is a technology that makes use of the thermal capacity of soil, bedrock, and groundwater as a storage medium. It can be used for inter-seasonal storage; to store summer heat for winter use, and vice versa for winter chill. It has been used extensively in Europe and is becoming more recognized throughout North America. ATES is promising because it can store and reuse normally wasted thermal energy. ATES usually supplies a significant portion of the heating and/or cooling base-load while combustable fuels, typically natural gas, are used to supply peak loads. To maximize ATES operation, peak demand must be decreased and a flatter energy demand profile must be created.

To reduce energy demand variation, an optimal building type mix should be found. Energy requirements vary significantly over time among different building types. The annual thermal energy demand profile for various building archetypes was modelled using the *Energy-10* and *EE4* building energy simulation programs. These profiles were combined into various community mixes, and then analyzed using Genetic Algorithm optimization techniques. An optimal community building-mix resulted from the flattest collective energy demand profile.

The resulting building-mix maximized large buildings and minimized small buildings. This mix reduces the need for natural gas auxiliary energy systems and their associated greenhouse gases (GHGs). It was found that applying the ATES technology to existing community mixes in the Toronto area would reduce their energy use and GHG emissions by approximately 30%; applying the mix optimization increased this number to 40%.

Introduction

In Canada, the residential and commercial sectors account for nearly one-third of all energy use. The combination of space and water heating accounts for 69% of the energy used by these sectors, and space cooling accounts for just under 5% (Office of Energy Efficiency 2006a - Table 2). Natural gas combustion, mainly used for space and water heating, in both residential and commercial buildings is responsible for nearly 40% of Toronto’s greenhouse gas emissions (ICF International 2007). These statistics illustrate the considerable burden that heating and cooling buildings places on society’s energy infrastructure and the resulting emissions it creates. There exists an opportunity for significant reductions in energy use and greenhouse gas (GHG) emissions if space conditioning of buildings can be reduced or met from renewable resources.

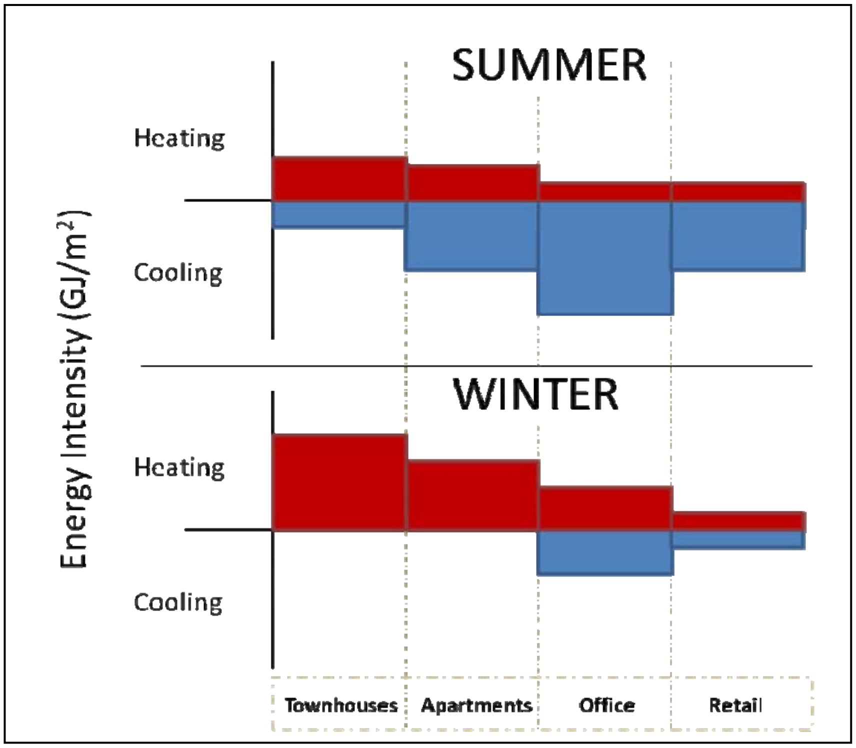
This paper will concentrate on two promising technologies which have significant potential for widespread adoption: *district energy*, and *aquifer thermal energy storage.* These technologies are not typically used in combination, however this paper will show that significant synergies are possible when these systems are combined with an optimized community energy profile based on building type selection.

The basic premise of district energy (DE) involves linking a number of energy users together on a common energy distribution system. This design can result in a more efficient energy system by, among other things, allowing centralized equipment to be better operated and maintained. Most DE systems use conventional fuel, typically natural gas. However, should a system be required to change fuel type (to biomass or biogas for example) the centralized design allows for any necessary retrofits to be significantly easier, another major benefit. DE networks are usually designed and built in a modular fashion, allowing for incremental expansion or reduction of the system to meet future requirements.

Aquifer thermal energy storage (ATES) systems must remain thermally balanced (Snijders 2008, Dickinson et al. 2009), meaning the energy injected must equal the energy withdrawn over a year. When coupled with the fact that most northern community's energy demands are dominated by heating rather than cooling, this design constraint puts a major restriction on the performance of the system. The result is a loss in system effectiveness by failing to meet a considerable portion of the heating demand loads. When multi-building developments are connected using a DE system, there exists more possibilities for energy balancing, profile levelling, and general manipulation and design of the thermal demand to more efficiently meet the thermal balancing constraint of ATES systems.

Buildings' thermal energy demand profiles, the amount of heating and cooling they require over time, vary with primary use and form. Figure 1 qualitatively illustrates the different thermal requirements of four different building types.

Figure 1. Thermal Energy Demand Profiles by Building Type



The goal of this research is to use the intrinsic building type variability in thermal energy demand profiles to optimize an urban community mix for use with an ATES system. By creating six different building type models, or archetypes, sample thermal energy demand profiles can be created for individual buildings types. These can then be combined and manipulated by a computer program to optimize the community mix to meet several constraints, including thermal balancing. The optimized community mix will result in reduced peak loads, thus allowing the ATES to satisfy a greater percentage of the community's thermal demand, reducing fossil fuel use and GHG emissions.

Aquifer Thermal Energy Storage

Energy for space heating and cooling is used to alter the temperature of air and water from their natural ambient temperatures to ones that are more acceptable to human comfort levels. The need for this energy is therefore due to the thermal disparity between ambient conditions and human comfort. During the winter, the ambient air is cold and natural gas is typically burned to increase the temperature of the air to a comfortable level. During the summer, ambient air is hot and electricity is typically used to run air conditioners to chill the air. The required winter resource, heat, is abundant in the summer. Similarly, the required summer resource, chill (or the absense of heat), is abundant in the winter. When viewed from this elementary perspective, it can be seen that the need for space heating and cooling is in fact a result of thermal *and temporal* disparity. To solve this mismatch, thermal energy should be stored in the season where it is abundant and utilized in the season where it is scarce. This process is known as *seasonal thermal energy storage.*

Thermal storage can be applied to solar thermal applications, greatly increasing their effectiveness. There are many examples of residential solar thermal systems without storage, or with small storage capacities, providing a large portion of the thermal load for domestic hot water or a swimming pool; however, "seasonal heat storage is necessary if solar heat is to provide any significant share of the annual space heating demand" (Nordell & Hellström 2000).

When storage occurs on the time scale of seasons, the storage medium volume must be very large. The earth itself turns out to be an extremely good storage medium, having high thermal capacity and relatively low cost (Dincer 2002).

ATES uses some saturated area of site geology, typically permeable sedimentary rock, as the storage medium. Water is accessed through a number of pumping wells. If the system is to be used for both heating and cooling purposes, separate hot and cold wells must be present. During the summer, cold water is extracted from the cold well and run through a heat exchanger. The water provides cooling to the building while acting as a thermal sink for waste heat. After leaving the heat exchanger it is pumped into the hot well, this process continues for the duration of the season. Some systems supplement heat to the water through solar collectors prior to returning it to the hot well, however, this is not required. During the winter, the flow is reversed. Hot water travels from the hot well into the heat exchanger where it provides heat while retaining chill. This cold water is then sent to the cold well for seasonal storage.

The use of an aquifer system relies on the geology of the site, and therefore can only be utilized in areas of specific geologic formations. The most common geology used for ATES is a sedimentary medium having high porosity and permeability – sandstone is a typical example. Igneous rock formations (bedrock) can also be used in areas with a significant degree of fractures. In cases where none of the above site conditions exist, an alternate technology known as borehole thermal energy storage (BTES) can be used. BTES systems work on the same principles as ATES systems, however pump hot (or cold) water through U-tube filled borehole fields to store thermal energy through convection. These systems are significantly more expensive due to the considerable drilling required (Wong, Snijders & McClung 2007).

An important consideration when designing these systems is groundwater flow, since it can contribute to thermal losses. A numerical study on a porous medium with homogeneous hydraulic properties concluded that a protective hydraulic screen is required if groundwater flow exceeds 0.05 m per day (20 m/year) (Van Meurs & Hoogendoorn 1983); however, the majority of aquifers in urban areas have much slower rates and thus groundwater flow is usually not a critical design issue. If ATES systems are not thermally balanced, the long term result will be a considerable thermal change to the aquifer. This can result in geochemical and biological changes in the soil, rock, and microorganisms within, which can have detrimental effects on the functioning of the system over the long term.

ATES systems are especially popular in Northern Europe, with more than 750 major projects to date. Nearly one third of all new commercial buildings in the Netherlands have an ATES system installed (Snijders 2008).

Building Energy Demand Profile Simulations

In order to analyse and optimize the energy profile of a community, the energy profile of each building type within that community must first be simulated. All the results in this study must be viewed with the understanding that these models provide *estimates* of energy use. Actual building energy use will vary depending on occupancy behaviour and equipment operational schedules. These models aim to reproduce common schedules and occupancy behaviour to achieve the most accurate results possible, however real world situations always allows for further variation.

This research examined six different building archetypes; three residential and three commercial. The three residential building simulations used the energy simulation software *Energy-10*; while the commercial buildings used *EE4*. These software packages were both used to create an hourly thermal energy demand profile for each of the six building archetypes. A summary of these building archetypes is provided in Table 1.

Table 1. Building Archetypes Size and Modelling Software

Building Archetype		Simulation Software	Floor Area (m^2)	Storeys
Residential	Single Detached	Energy-10	223	2
	Double/Row House	Energy-10	135	2
	Apartment	Energy-10	12,513	13
Commercial	Small Office	EE4	4,012	3
	Large Office	EE4	22,187	18
	Retail (strip mall)	EE4	1,451	1

Each of the six simulation models were created using building characteristics representative of the Greater Toronto Area. The resulting annual energy use for each of the six archetypes was compared to validation sources. Numerous government databases were used to identify representative building characteristics and as energy use validaiton sources (Zizzo 2009).

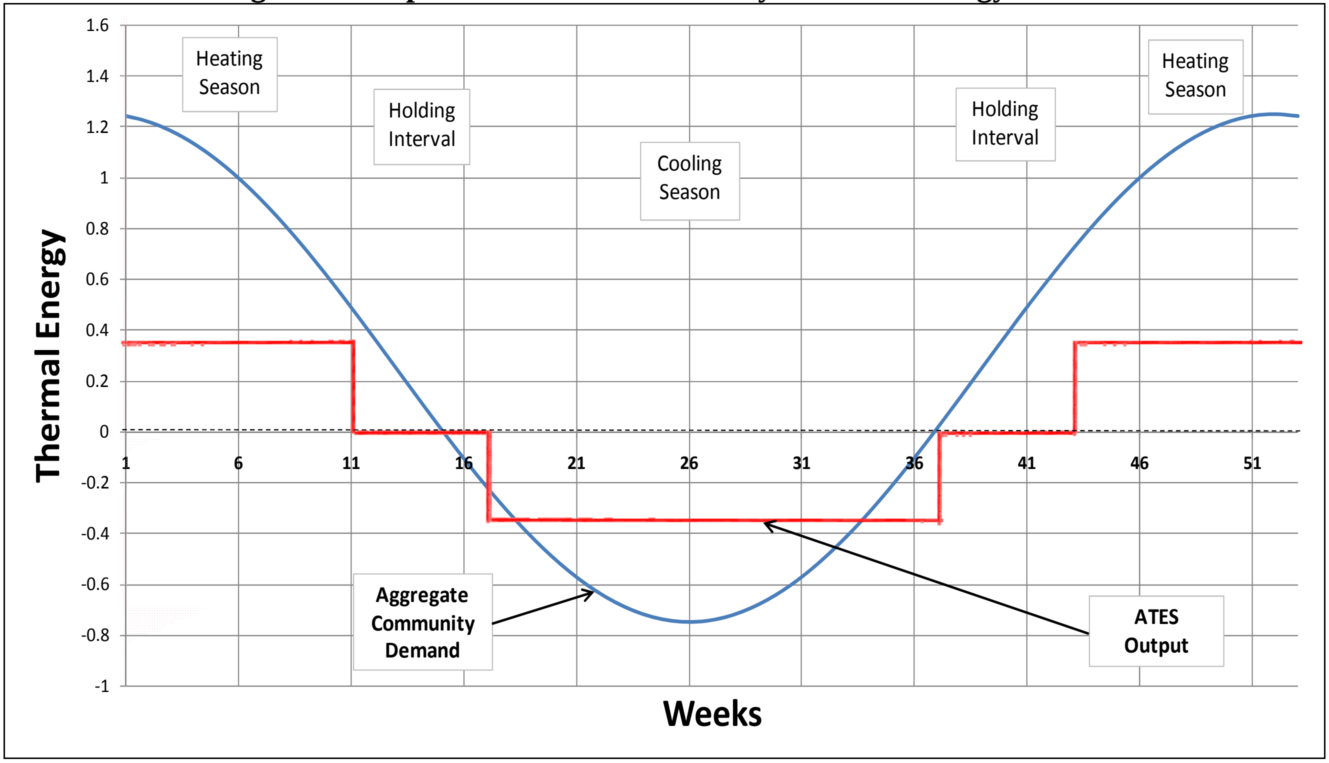
The residential simulations generally used less energy than the validation data set, however the variation was always within 20% of the validation data. The commercial simulations energy use was generally within the validation range, however the two values that fell outside the range were less than 20% away from the end of the range. As previously described, it is extremely difficult to achieve precise convergence between simulation and real world building energy use data due to the huge range possible in building and material properties, operational schedules, and user behaviour. Therefore, since the simulation results never exceeded the validation sets by more than 20%, the simulation values have been accepted for the purposes of this study.

Analysis Procedure

As perviously explained, aquifers must remain thermally balanced, meaning the energy input has to equal the energy output over a year. Throughout the literature, this requirement has been interpreted such that the duration of loading periods (cooling and heating seasons) and flow rates (thermal energy extraction & injection rates) must be equal in opposite seasons. The question remains as to whether one period could have a slower flow rate over a longer timeframe than its opposing season. Thermodynamically, a thermal balance should be achievable through this configuration, although nowhere in the literature was this idea discussed and certainly no implemented examples were found. Since this non-symmetrical flow regime has not been adequately studied, the loading period durations and flow rates were set to be equal to each other, as was modeled by Lee and Jeong (2008).

The requirement of identical and symmetrical rates and durations was also assumed by Chevalier and Banton (1999). The idea of a *holding interval*, when the system is turned off due to moderate demand, is also a common characteristic of ATES systems (Lee & Jeong 2008). The two holding intervals must always be of equal duration, just as the two loading periods must be of equal duration; these regimes have been illustrated in Figure 2.

Figure 2. Simplified Annual Community Thermal Energy Profile



The hourly thermal energy use data for the six building archetypes were used as input for a genetic algorithm (GA) optimization. To measure the 'goodness' of a solution, the GA used an objective function, a simplified version of which is displayed as equation (1). This function measured the difference between the community energy demand, (C), and the ATES output, (A). In each generation of the GA, the input parameters are varied in an attempt to minimize the objective function. During the heating season this difference was measured between the ATES output and the natural gas hourly demand values, while in the cooling season it was measured against the cooling-electricity hourly demand values. During the holding intervals, when the ATES had no output, the absolute value of community cooling or heating, whichever was larger, was added to the sum. With each iteration of the GA code, the the optimization variables were explored using the principles of genetic algorithms (Goldberg 1989).

$$Objective\ Function = \sum_{w=0}^{51} \sum_{h=0}^{23} \left| C - A \right| \qquad (1)$$

The genetic algorithm attempts to minimize the objective function. Therefore if a community thermal energy profile were to take the same shape as the ATES output for the whole year (if the blue line and red line in Figure 2 overlap), the difference between them would be zero and this would be the ideal solution. This situation would never occur in reality, but is useful nonetheless to visualize as the ideal for an ATES system. The optimization code, therefore, attempts to find the community mix and ATES schedule that most closely brings these two lines into convergence. The GA will stop running and produce the final result when the objective function has been minimized. Note that the difference between the community thermal energy and the ATES output is more accurately called the absolute difference between them.

Since the *absolute difference* is taken, the value will always increase with each time step, no matter if the community energy requirement for that step is less than or more than the ATES output. In this way, both an excessively large or an excessively small ATES system is discouraged; the system which minimizes the discrepancy between loads is ideal. Another important factor to note is that the difference between the community thermal energy demand and the ATES output is normalized with respect to the floor area of the community. If this was not done, the program would always select a community with the minimum number of buildings since fewer buildings would mean less of a discrepancy. Therefore, the difference is divided by the total floor area for each community development, and it is this normalized value that is minimized by the genetic algorithm.

An additional measure has been used throughout this analysis in conjunction with the objective function. This measure is the percentage of total community energy that is met by the ATES system (henceforth referred to as *ATES/COMM*), and is given as equation (2). The total community thermal energy is a measure of the entire community's heating and cooling needs, in kilowatt-hours, over a year. The useful ATES energy is the total thermal output of the ATES system, in kilowatt-hours, minus the excess ATES energy (when the ATES output is greater than the community requirement), and is shown as equation (3).

$$\frac{ATES}{COMM} = \frac{Useful\ ATES\ Energy}{Total\ Community\ Thermal\ Energy} \times 100\% \qquad (2)$$

$$Useful\ ATES\ Energy = Total\ ATES\ Energy - Excess\ ATES\ Energy \qquad (3)$$

One of the primary assumptions of this research was that minimizing the objective function would also simultaneously minimize the *ATES/COMM* parameter. However, it is useful to examine them both independently.

Neighbourhood Models

In a 2000 report by Wright, several two kilometer by two kilometer study areas were chosen within the Greater Toronto Area. The study quantified the land use, building, and roadway types in each study area. Four such study areas were selected for use in this research to represent typical neighbourhood design options. Integer multiplier values for each archetype was selected so that the floor area ratio between commercial and residential building types found by Wright was recreated. This excersie results in four example neighbourhoods, each having a different number of building archetypes based on actual Toronto neighbourhood design characteristics. The number of each building archetype as well as a neighbourhood form description are provided in Table 2.

Table 2. Sample Neighbourhood Characteristics and Resulting Archetype Multipliers

Neighbourhood		Don Valley	Milliken	Garrison	St. Lawrence
Description		Post-war suburban development, curvilinear streets, mixed densities and building types	Contemporary suburban, "fringe" development; "sprawl", low density residential	"Streetcar suburb" old style residential, streetcar network, high density	East of downtown, older neighbourhood, mix of planning types
Residential	Land area (km^2)	0.53	0.78	0.71	0.54
	Fraction of total (%)	11.8	16.4	15.9	13.9
Commercial	Land area (km^2)	0.07	0.05	0.09	0.11
	Fraction of total (%)	1.5	1.1	2.0	2.9
Community Archetype Building Multipliers	Large Office	1	0	1	1
	Small Office	9	6	11	14
	Retail	14	10	19	23
	Detached	1,187	1,747	1,591	1,210
	Double/Row	1,181	1,738	1,582	1,204
	Apartment	8	12	11	9

Optimization

The GA program creates various output parameters which are used to evaluate each scenario. Parameters of critical importance to the energy analysis include *coolExc*, *coolDef*, *heatExc*, and *heatDef*. The first part of the name represents the loading season; *cool* means the ATES is in cooling mode (during the summer), and vice versa for *heat*. The second part relates to the difference between the ATES output and the aggregate community energy profile. *Exc* (excess) means that the ATES output is providing more energy than is required at that given time by the community. *Def* (deficit) means that the ATES output is not meeting the full energy requirements of the community. Figure 3 provides a visual representation of these values.

The GA objective function calculates the difference between the ATES output and the community energy profile. The four parameters in Figure 3 are calculated on an hourly basis, and when summed over a year quantify this difference; therefore, the objective function can be thought of as the summation of these four parameters, and will be referred to as *DIFF* (difference between community energy profile and ATES output). The GA aims to minimize this objective function so that the ATES meets the community energy demand as closely as possible. After numerous iterations, it was determined that minimizing *DIFF* alone was not in itself adequate to create an optimized solution. Instead, a two part optimization was needed. First, the scheduling parameters of the ATES should be set to maximize *ATES/COMM* (earlier described in equation 2) to ensure the heating and cooling seasons were occurring at optimal times. Once the schedule is set, the ATES output and archetype multipliers can then be optimized by minimizing the *DIFF* value (the objective function).

Various scheduling options were attempted; however, setting the cooling season start week to 16 always resulted in the maximum amount of energy being met by the ATES. Not a single scenario in this research resulted in the inclusion of a holding interval. This occurred because the heating load of the community is significantly larger than the cooling load.

The second part of the optimization deals with the number of each building archetype in a community, referred to as the multiplier, and the ATES output. Two scenarios were run for each neighbourhood, one with the community archtype building multipliers presented in Table 2, and a second with a variable building mix. In this second scenario, the code allowed the building multipliers to be varied by 50% from the fixed values. The results of these scenarios are presented in Table 3.

Figure 3. Excess and Deficit Energy Illustration

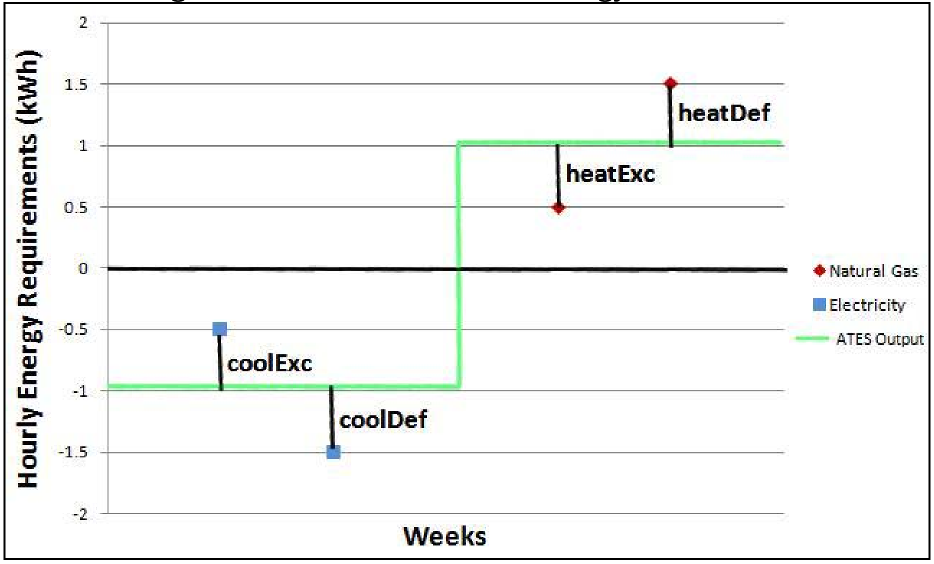


Table 3. Optimization Scenarios

	Don Valley		Milliken		Garrison		St. Lawrence	
	Fixed Mix	Variable Mix	Fixed Mix	Variable Mix	Fixed Mix	Variable Mix	Fixed Mix	Variable Mix
Large Offices	1	2	0	0	1	2	1	2
Small Offices	9	14	6	9	11	17	14	9
Retail	14	21	10	15	19	29	23	35
Detached	1,187	600	1,747	875	1,591	798	1,210	608
Double/Row	1,181	593	1,738	871	1,582	792	1,204	603
Apartments	8	12	12	18	11	17	9	14
Spring Holding Interval Start Week	16	16	16	16	16	16	16	16
ATES output (kW)	5,900	5,600	7,000	6,000	7,800	7,300	7,000	5,600
Total ATES Energy (MWh/yr)	51,542	48,922	61,152	52,416	68,141	63,773	61,152	48,922
Useful ATES Energy (MWh/yr)	32,283	31,825	37,949	34,040	42,507	41,370	38,374	31,871
Total COMM Energy (MWh/yr)	108,207	82,434	144,825	99,723	143,127	107,266	117,577	84,543
ATES/COMM%	**29.8**	**38.6**	**26.2**	**34.1**	**29.7**	**38.6**	**32.6**	**37.7**
ATES/COMM % unit increase from optimization	**8.8**		**7.9**		**8.9**		**5.1**	

It can be seen that the optimized (variable) mix always results in a greater percentage of the community energy requirement being met by the ATES (bolded). This shows that mix optimization results in the ATES more efficiently meeting the energy demands of the communities. The St. Lawrence neighbourhood results in the lowest energy savings because it has the highest percentage of commercial buildings in the current mix. The other three neighbourhoods had between 1-2% land area consumed by commercial buildings while the St. Lawrence neighbourhood had 3%. Therefore, existing developments with relatively high commercial densities can expect savings closer to the St. Lawrence scenario. It is most useful to examine the trends of the mix optimization. Table 4 displays the trends that were observed; an upwards triangle means the optimized mix increased the number of that archetype from the current mix, while a downwards triangle means the archetype number was decreased.

Table 4. Mix Optimization Trends

	Don Valley	**Milliken**	**Garrison**	**St. Lawrence**
Large Office	▲	N/A	▲	▲
Small Office	▲	▲	▲	▽
Retail	▲	▲	▲	▲
Single Detached	▽	▽	▽	▽
Double / Row	▽	▽	▽	▽
MURB	▲	▲	▲	▲

It can be seen that both single-family residence archetypes (single detached and double/row) were decreased in every case. The other four archetypes (both office sizes, retail, and apartment) were increased in all but 2 of the 16 scenarios run. These two categories can most easily be separated by floor area; the buildings with small floor areas (single detached, double/row) were decreased, while the buildings with large floor areas (offices, retail, apartment) were increased. These findings are reasonable sense since larger buildings have a higher percentage of interior spaces which require more cooling than exterior spaces, and increasing the cooling load of communities makes the ATES more effective. Table 5 shows the considerable difference in floor area percentage of large vs small buildings in the neighbourhoods before and after optimization.

Table 5. Small and Large Building Floor Area Percentage Change

	Building Type	**% of Neighbourhood Floor Area**	
		Before Optimization	**After Optimization**
Don Valley	Large	30	57
	Small	70	43
Milliken	Large	23	48
	Small	77	52
Garrison	Large	29	56
	Small	71	44
St. Lawrence	Large	34	59
	Small	66	41

Prior to mix optimization, the small buildings accounted for roughly 70% of the community floor area, while after the optimization, they account for closer to 45% of the floor area. In some of the optimization runs, the number of optimized archetypes was at the upper or lower bound, characterized by a 50% change in the number of archetype multipliers currently found in the neighbourhoods. Therefore, it is likely that if the multiplier bounds were increased, the optimized mix would have a still greater percentage of large buildings.

An in-depth GHG savings calcuation using Ontario emissions factors was also performed as part of the research (Zizzo 2009). The results showed a nearly linear inverse relationship between increasing the amount of energy met by the ATES system (%) and the subsequent reduction in GHG emissions (in tonnes). Note that this relationship will change depending on the size of the community being optimized. Since any additional energy met by the ATES is in essense reused energy from the previous season that would otherwise be wasted, this result was expected.

Conclusion

This research has shown that there are real and significant energy and GHG savings that can be realized when communities are viewed as more than a sum of individual buildings. These savings should be realized in future developments by energy designs and plans that expand from the building level to consider interactions between buildings. There have been considerable movement in the past decade to reduce the energy requirements of individual buildings, however the next stage of engineering our cities must consider the interaction *between* buildings and begin designing our communities holistically by considering building energy interactions.

The use of an ATES system in the four sample Toronto neighbourhoods resulted in the systems providing between 26 – 33% of the total community space and water thermal energy required and reducing GHG emissions by a similar percent. This research has shown that further energy and GHG savings are possible through community optimization when using an ATES system. For the representative building and community characteristics chosen in this research, optimizing the mix results in a 5-9% increase in the amount of community energy being met by the ATES; GHG emissions are reduced by approximately the same percentage. Note that the 5% value was for the St. Lawrence neighbourhood, which had the highest relative amount of commercial buildings to begin with; in all other neighbourhoods, mix optimization resulted in a 9% decrease in GHG emissions. Therefore, optimizing the mix resulted in the ATES providing between 34 - 39% of the total community’s energy requirements, and reduced GHG emission by the same range.

This research found that optimization resulted in an increase in the percentage of large buildings (large office, small office, retail, and apartments), and a decrease in the percentage of small buildings (single detached, and double/row residential). Therefore it is the final recommendation of this research that communities where ATES systems are to be used should have their mix optimized by increasing the percentage of large buildings (larger than single-family and row-houses), and decreasing the percentage of small, single residential buildings. Although these findings are expected to be representative of a general trend, mix optimizations should be performed on a site-specific basis using the actual building and site properties.

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