Increasing Renewable Energy Integration Using Residential Thermal Energy Storage

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Abstract

A simulation study was conducted to assess the potential of increasing the integration of renewable energy such as wind or solar using thermal energy storage. Several electrically charged residential thermal energy storage technologies being introduced in the Canadian market were simulated in TRNSYS considering space and domestic water heating loads. This included several different configurations of innovative sensible storage, using ceramic bricks, and latent storage, using phase change material (PCM). Additionally, three examples of electric heating systems without storage were modeled. These were an air source heat pump (ASHP), a cold climate air source heat pump (CCASHP), and baseboard heaters. The systems were simulated with four different home archetypes, which are representative of common classifications of homes in Canada, using weather data for Halifax, Nova Scotia, Canada. The energy storage systems increased the renewable usage factor, quite significantly in most cases. It was found that in scenarios with high-performance homes and sensible storage systems, the storage heat losses could lead to the homes overheating. Annual peak time-of-use energy consumption was also able to be reduced, but the specific performance of the thermal storage system type and size of the building load influenced which system performed best.

Keywords: thermal energy storage, solar, wind, renewable integration

1. Introduction

Energy use in Canadian housing, buildings, and communities accounts for about a quarter of Canada's energy consumption (NRCan, 2019) and 17% of GHG emissions (ECCC, 2022). In Canada, residential space heating (SH) consumed 885 PJ of energy in 2016, 47% of which was supplied by natural gas (26% by electricity) (NRCan, 2016). Domestic hot water (DHW) represented an annual load of 284 PJ of which 68% was supplied by natural gas. There is a national effort in Canada occurring to decarbonize the nation's energy loads through clean electrification in order to reduce greenhouse gas emissions (ECCC, 2022). Shifting building space and DHW heating loads to electrically powered systems represents a major increase in electrical energy consumption and would require massive upgrades to the power grid (ICF, 2019). Shifting building heating to clean electricity will require increasing renewable energy production. The temporal and capacity mismatches between the renewable generation and new electrified loads will be an issue that must be overcome. A new system's ability to aid in the management and balancing of the electric grid's power generation and loads is also important to this end (ICF, 2019).

A technology that could aid the clean electrification of the housing sector is the use of residential thermal energy storage (RTES). RTES has the capacity to reduce peak loads on the grid as well as the ability to increase the use of intermittent renewable energy (Gils, 2015). Storing energy allows for the energy to be gained within the system during periods of low demand and/or high renewable generation (i.e., during summer or at night with off-peak electricity). The stored energy is then used to provide heat during times of high demands and on-peak electricity and/or low renewable energy production rather than the energy provided by the electrical grid. The use of thermal energy storage, along with heat pumps (HP) will be a very important component of electrifying heating loads and establishing a clean electricity grid with low GHG emissions (MacCraken, 2020)

This study uses TRNSYS (Version 18) simulations of a variety of integrated storage heat pump residential space heating and DHW electro-technologies to determine the potential impact of these technologies on peak power, total energy consumption, and on the ability to use increased amounts of renewable energy resources (i.e., wind and solar PV) on a selection of different home archetypes. This is a first step in an overall ongoing larger study to model the community-wide application of these technologies in a real community in Eastern Canada.

2. Background

Thermal energy storage has several applications, but a critical one is its use in the building sector to help with the

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use and management of renewable energy. A detailed study of all TES technologies and their performance is outside the scope of this study, but a basic background will be provided to provide context to the current study. A recent review of this topic (Sarbu and Sebarchievici, 2018) discussed many examples of different storage technologies to increase the usability of renewable energy and highlighted the types of TES (Fig. 1).

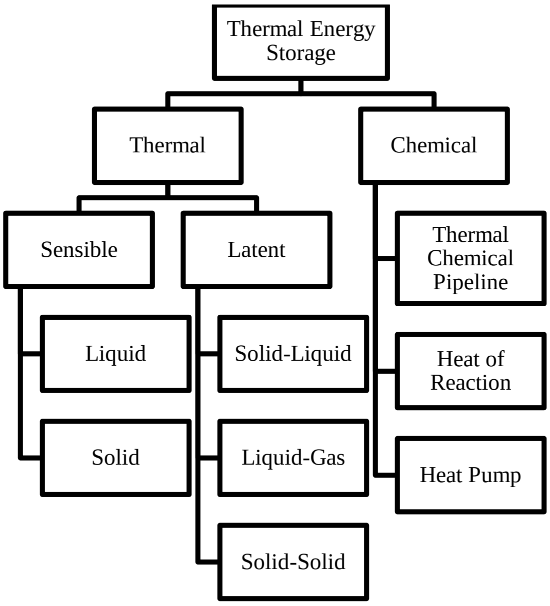

Fig. 1: Methods of thermal energy storage (Sarbu and Sebarchievici, 2018)

The use of thermal energy storage, via PCM storage, has been shown (Stropnik et al., 2019) to boost the performance of highly efficient homes and aid in the nearly net-zero energy operation as the loads in a building can be better distributed and controlled to match the timing of generation of on-site renewable energy. Onsite self-consumption of energy can be increased and stored when excess energy is available for later use. The PCM storage was also shown to help manage temperatures of heating systems to maintain them in temperature ranges which increased efficiency.

Studies have also focused on the ability of energy storage to increase the penetration of renewables and reduce renewable energy curtailments. The increase in self-consumption and peak shaving with battery storage was researched by Luthander et al. (2016) who found that storage capacity had a strong influence on the amount of energy curtailed. This is an interesting note as this study used electrical battery storage and did not electrify heating loads. As fossil-fuel powered heating loads electrify, this presents a large potential for increasing self-consumption, but also requires a larger storage capacity, something that is difficult with electrical battery storage due to the high costs associated with storing electricity electrically.

Thermal storage is a potential method to get around these issues. Hughes (2010) predicted that by using distributed sensible thermal energy storage units, 95% of heating loads in a 500-home reference community could be met with intermittent wind energy (from a 5.15 MW windfarm) in eastern Canada vs. 65% without energy storage and using electric baseboard heaters. In a different study, the combination of heat pumps and thermal energy storage was found to have benefits in reducing GHG emissions and operating costs, mitigating the impacts of variable renewable energy generation, and managing utility peak and base loads (Vorushylo et al., 2018).

Seasonal thermal energy storage in Germany was studied and results indicated that increasing storage to enable higher penetrations of renewable energy also increased lifetime costs (costs including fuel and energy costs, operation and maintenance, and investment costs). A target value of 60-80% renewable energy was recommended to have the best tradeoffs between costs, emissions, and performance (McKenna et al., 2019). Luo et al., (2021) studied a microgrid in China utilizing a CHP power plant, wind power generation, and the implementation of TES systems. The storage was found to reduce operating costs by increasing the amount of wind energy that was able to be utilized. In a study (Agbonaye et al., 2022) of the power grid in Northern Ireland, a region with significant renewable generation from wind power, curtailments were shown to be a significant cost and barrier to adding additional renewable generation. A solution was proposed using an optimized system of distributed thermal energy storage to absorb excess wind generation. The potential was found to reduce constraints by 78% and curtailments by 100%, but optimization found that to manage cost savings for subscribers (i.e., rate payers) a scheme that reduced constraints by 67% and curtailments by 74% was ideal.

These studies all featured similar approaches, but the exact values found for the benefits and performance of the various systems all varied. This highlights the need for location-based study for this application as each region has different renewable generation potential, climates, housing constructions, occupant behavior, operating costs, structures, and other location specific techno economic parameters to be considered.

3. Methodology

This study used the simulation software tool TRNSYS (Klein et al., 2017) to develop detailed models of each of the energy storage systems, as well as the multi-zone home and DHW heating loads and renewable energy generation with a five-minute time step. A Canadian Weather year for Energy Calculation (CWEC) weather file for Halifax, Nova Scotia was used to provide ambient temperature, wind speed, and solar radiation data to the simulation. The time-of-use (TOU) schedule and pricing central to the data analysis and control of the systems are those used by Nova Scotia Power (NSPower, 2021).

3.1 Base Electric Systems with No Storage

Three base case systems without storage were simulated in addition to the storage systems. These were homes heated with an air-source heat pump (ASHP), a cold-climate ASHP (CCASHP), and electric resistance baseboard heaters. The heat pump systems were connected to a central air system, while the baseboard systems featured heaters in each zone of the home.

3.2 Storage Systems

Two different thermal energy storage methods, ceramic brick sensible energy storage and phase change material (PCM) energy storage were studied in a variety of configurations. The operation, capacity, and performance of the ceramic brick sensible storage systems were based on systems that are commercially available (Tab. 1). The PCM storage systems were based on near commercialized systems in consultation with the manufacturer. The ceramic brick storage RTES technology being considered for this study is currently being demonstrated and tested in different electrical jurisdictions across Canada, while the PCM RTES technology considered will be field tested shortly for the first time in Halifax, Nova Scotia. There were several configurations of the ceramic brick system modelled. Two storage capacities of central forced air systems, 240 kWh or 33 kWh, and a zonally distributed baseboard system. The large ceramic brick system was based on the largest residential unit available. This was done to test the maximum potential of the technology in absorbing renewables and shifting loads. It could be difficult to install this in a typical house as the unit would require significant upgrades to a home’s electrical systems, potentially including installing an additional 200 amp service to the home on top of existing electrical services. The zonal system features a baseboard-mounted storage system on each floor of the building (including the basement). The PCM RTES system is currently only available in one configuration and capacity (32 kWh), but it also has the additional function of pre-heating DHW. All storage systems modeled used electrical resistance elements to charge the storage.

Tab. 1: Specifications of storage systems.

System	Storage Capacity	Max. Storage Temperature	Storage Heater Capacity
Large Ceramic Brick	240 kWh	732 °C	38 kW
Small Ceramic Brick	33 kWh	732 °C	7.5 kW
Zonal Ceramic Brick	20 kWh	732 °C	7.5 kW
PCM	32 kWh	100 °C	5.4 kW

The ceramic brick TRNSYS storage models utilized a lumped capacitance methodology to predict the performance of the storage. This method was used as it was able to solve the performance calculations quickly and with good accuracy when validated against a more complicated finite difference mode. The PCM storage systems were TRNSYS modelled using a proprietary model based on the physical operation and thermodynamics of the PCM storage unit.

3.3 Storage Systems Control

The thermal storage systems featured auxiliary systems to provide an alternate source of heat. There were several different scenarios modelled to study the impact on the performance of the various thermal storage systems. Both the large and the small ceramic brick systems were each given three scenarios.

1. Electric Backup: The storage system was the primary source of heat. When there was a call for space

heating, heat was withdrawn from the storage until it was depleted or the call for heat ended. If the storage became depleted, a centralized electric resistance heater was activated to heat the homes.

2. ASHP Backup: The storage system was the primary source of heat. When there was a call for space heating, heat was withdrawn from the storage until it was depleted or the call for heat ended. If the storage became depleted, an ASHP was activated to heat the homes.
3. ASHP Primary: A smart controller was used to monitor the outdoor ambient temperature to determine the heat pump's expected COP and used the TOU electricity rates to determine if it was more economical for the residence to use low-cost, off-peak energy from storage, or to use the heat pump to provide heat. The ASHP would be used the majority of the time, and the storage would only be used when outdoor temperatures were low during on-peak rate periods.

The PCM storage system was not modelled with the electric backup option, as this is not available on the physical system the model was based on. The zonally distributed ceramic brick system was only modelled with the electric backup option as there is no available zonally distributed heat pump option for the physical unit the model was based on.

3.4 Home Space and DHW Loads

Four different building loads were investigated, each one representing an archetype found in Canada representing a range of construction dates and eras of building codes. Multi-zone TRNSYS home models were developed to characterize the yearly transient indoor temperature in the different main zones of the considered homes. Each archetype is described in Tab. 2 and the three-dimensional thermal model renderings are shown in Fig. 2. Cooling loads were not considered.

Tab. 2: Home archetype descriptions

Archetype	Living Space Floor Area	Type	Annual Heating Load
Pre-1980s (Fig. 2a)	91.2 m^2 (982 ft^2)	1-storey, detached	25762 kWh
1980-2000s (Fig. 2b)	146.2 m^2 (1574 ft^2)	2-storey, detached	24568 kWh
Post-2000s (Fig. 2c)	80.7 m^2 (869 ft^2)	1-storey, detached	15054 kWh
Net-Zero-Ready (Fig. 2d)	133.5 m^2 (1437 ft^2)	2-storey, mid-row, townhouse	2432 kWh

The homes were modelled with basements and full thermal interactions with the ground surrounding the basements. Each floor of the home (including the basement) was considered as a separate zone for the heating systems. The home's heating systems all used thermostats set to 21°C located on the first floor. The only exception was for the baseboard homes and the zonal ceramic brick homes, which had thermostats on the basement, first floor, and second floors (in archetypes with two stories). The central-air based systems each distributed air flows evenly between the basement, first floor, and second floors (in archetypes with two stories). The building models included unheated portions of the homes such as attics and garages, which were each modelled as zones separate from the living spaces.

Each system was assumed to have the same 170 L electric hot water tank and used the same morning-biased hot water draw profile with an average consumption volume (176 L/day) and an annual total energy draw of 4308 kWh (Edwards et al., 2015). Additionally, the systems using PCM storage were able to supply heat to the DHW as a preheat to water entering the DHW tank.

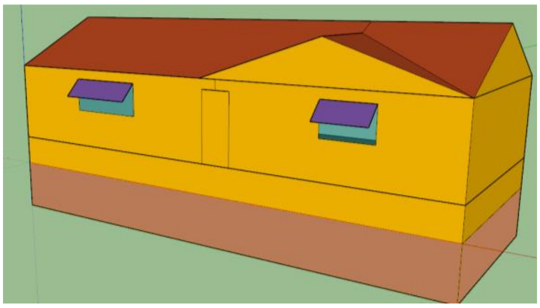

Fig. 2a: Pre-1980s home archetype

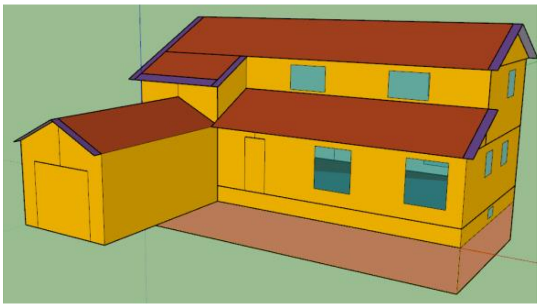

Fig. 2b: 1980-2000s home archetype

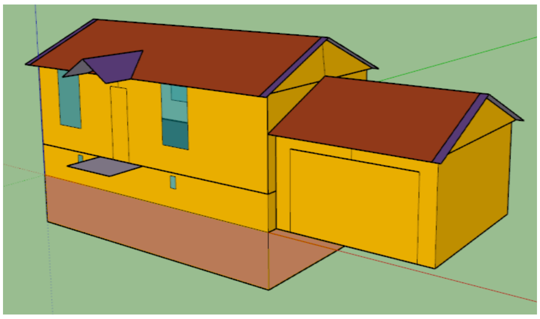

Fig. 2c: Post-2000s home archetype

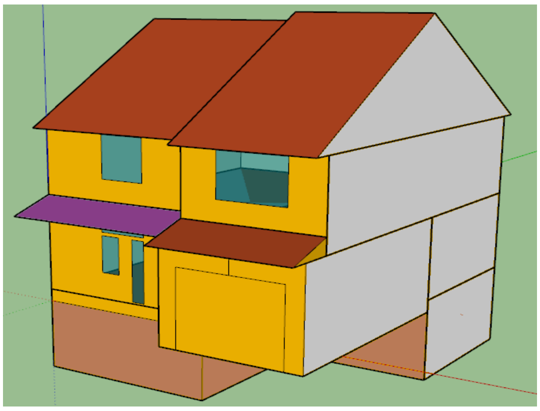

Fig. 2d: Net-zero-ready home archetype

3.5 Renewable Energy Generation

In order to determine the community-scale electrification implications of the considered RTES systems, a 3.3 MW wind turbine was simulated (Enercon GmbH, 2019), and a fraction of its output energy was made available to each of the modelled systems. Each simulated system was able to use up to 1/500th of the output power of the wind turbine (i.e., assuming the wind energy is evenly distributed in a community of roughly 500 homes). This creates a peak of 6.6 kW of available wind energy for one house.

Solar PV power was also modelled to give an identical peak capacity of 6.6 kW for the houses using the parameters from a typical PV panel (CanadianSolar, 2022). Due to the solar and wind conditions, the wind annual energy production was higher than the solar, but the peak power values of the systems were the same. This method of sizing both wind turbines and the solar PV array was used as a first step to assess the impacts of the different RTES technologies to be charged with coinciding onsite renewables and provide relief on peak loads and generation for the local utilities.

The renewable power generated at each time step was made available to the systems to be used to meet the heating loads. If there was excess renewable energy, the charge functions of the storage were activated. Typically, the storage systems can only charge during off-peak electricity TOU periods, but if renewable energy was available at any time, it could be used to charge the storage (until the storage was fully charged). This methodology was used to maximize the uptake of the renewable energy during times when otherwise the electricity grid would have to curtail the renewable power. The stored renewable energy could then be used to reduce peak loads during later time periods.

4. Results and Discussion

There are several key performance indicators (KPIs) that were considered in this study. They included: the amount of load shifting achieved (i.e., shifting from on-peak and mid-peak periods to off-peak); the renewable usage factor (defined as the annual renewable energy used by the space heating and DHW systems / the total available renewable energy); and total annual energy consumption. Other key simulation outputs were the indoor temperatures inside the various zones of the homes.

The example renewable usage factor results of the simulation for the pre-1980s home archetype, when considering electro technologies with and without storage integrated systems, are shown in Fig. 3 for both wind and solar PV-generated renewable electricity.

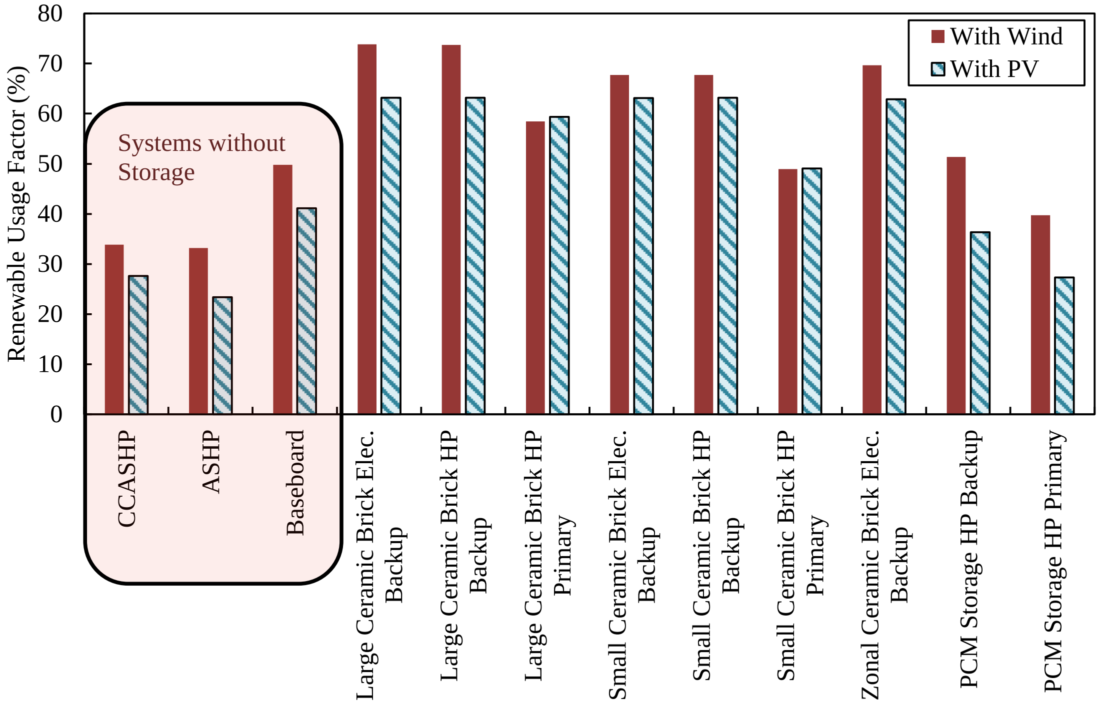

Fig. 3: Renewable usage factor for the various systems under study for a pre-1980s home archetype (The renewable usage factor is defined as the annual renewable energy used by the space heating and DHW systems / the total available renewable energy)

It was found that the use of the considered RTES technologies can increase the amount of renewable energy used. This is critical to the operators of the renewable energy plants as curtailments are a constant issue that limits the financial feasibility of the renewable energy generation stations. A method of storing unused renewable electricity which would otherwise be wasted or not generated through the deactivation of panels and turbines could reduce these curtailments. The differences in the temporal availability of the renewable resources between wind and solar played a key role in the higher renewable usage factor of wind over solar energy. Wind power is available day and night, and it is typically less variable than solar energy in the simulated eastern coast, ocean-adjacent climate. Solar energy is mostly available during periods when heating loads are smaller. Additionally, in the mornings, the storage systems are likely to be nearly fully charged, having access to off-peak electricity overnight, and they are less able to absorb the higher availability of solar energy at this time.

The larger ceramic brick storage systems were able to achieve the highest renewable usage factor, as they had excess storage capacity available to absorb additional renewable energy. They also had higher charging rates and were thus able to take on higher instantaneous power loads. When comparing the one PCM storage type of system, against the similar storage capacity of the small ceramic brick systems, the higher charge capacity of the sensible storage system was advantageous in being able to quickly absorb any renewable energy. The considered PCM system was designed to maintain low peaks to reduce the need for home upgrades and to slowly charge the storage overnight. The design goals were not to quickly charge, and thus in this particular comparison, they do not perform as well. The ceramic brick system's high charge rates require multiple circuits and potential upgrades to the homes due to the high current requirements.

The renewable energy usage factor is only part of the story of the energy storage systems, as different systems use greater annual amounts of energy (e.g., electric resistance heaters vs. heat pumps). This can inflate the renewable energy usage factor in ways that may not be desirable to other stakeholders. The total annual electricity consumption of the systems for the pre-1980s home archetype is shown in Tab. 3. Systems using heat pumps either as the sole heat source or as the primary heat source, with storage only being used when stored energy is cheaper than using peak energy with a heat pump, utilize less energy as expected. The PCM storage with the ASHP backup heat source used 26% more energy than the PCM storage with the ASHP acting as the primary heat source.

Tab 3: Annual total electricity consumption of the various space and DHW heating systems in a pre-1980s home archetype

CCASHP	17 MWh
Small Ceramic Brick HP Primary	20 MWh
PCM Storage HP Primary	20 MWh
ASHP	20 MWh
Large Ceramic Brick HP Primary	20 MWh
PCM Storage HP Backup	25 MWh
Small Ceramic Brick HP Backup	26 MWh
Zonal Ceramic Brick Elec. Backup	27 MWh
Small Ceramic Brick Elec. Backup	30 MWh
Baseboard	30 MWh
Large Ceramic Brick HP Backup	31 MWh
Large Ceramic Brick Elec. Backup	33 MWh

Another result from this study is shown in Fig. 3 and Fig. 4, which demonstrates the potential for shifting loads away from peak periods. Systems using HP back-ups are referenced back to a system using only a heat pump (Fig. 4a), and systems using electric resistance for backup are referenced to a system using electric baseboards (Fig. 4b).

Results indicate that the systems which used the HP as the primary heat source, and the storage only when most economical for the ratepayer had significantly less load shifting potential. The storage load shifting benefits are most apparent in systems that use the storage as much as possible, even though it may be more costly and consume more annual electricity. This is beneficial to the utilities/power generators, as the base loads are increased, and peak loads are decreased, which eases the difficult task of balancing the supply and demand requirements of electrical energy and increasing the use of base-load electricity production such as hydro or nuclear, vs carbon-emitting peaking power generators such as natural gas power plants. Other benefits are the balancing of peak loads, which reduces stress on the distribution grids and lowers the need for upgrading the grid as current non-electric building loads (e.g., propane, natural gas, or oil powered space heating systems) are electrified. This presents an interesting dilemma and a target area for future research. The community-wide implementation of such systems may provide enough benefit to the utility and grid that new pricing schemes can be used to not penalize the ratepayer for adding storage over using a heat pump alone.

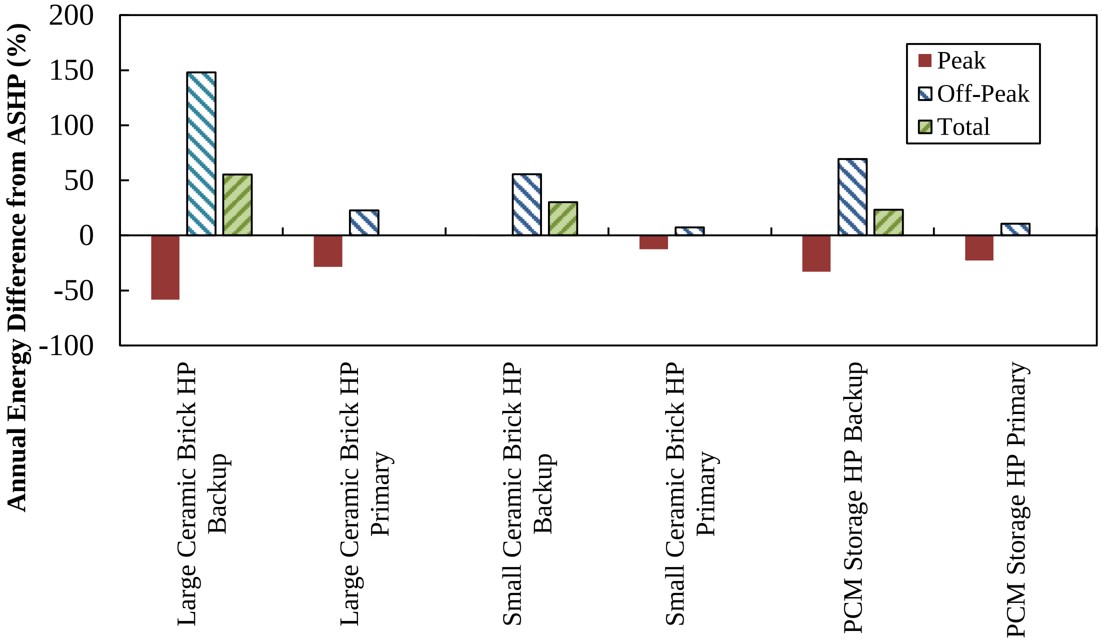

Fig. 4a: Difference between the total, peak, and off-peak ASHP annual system electricity consumption and the heat pump backup storage system's annual electric energy consumption

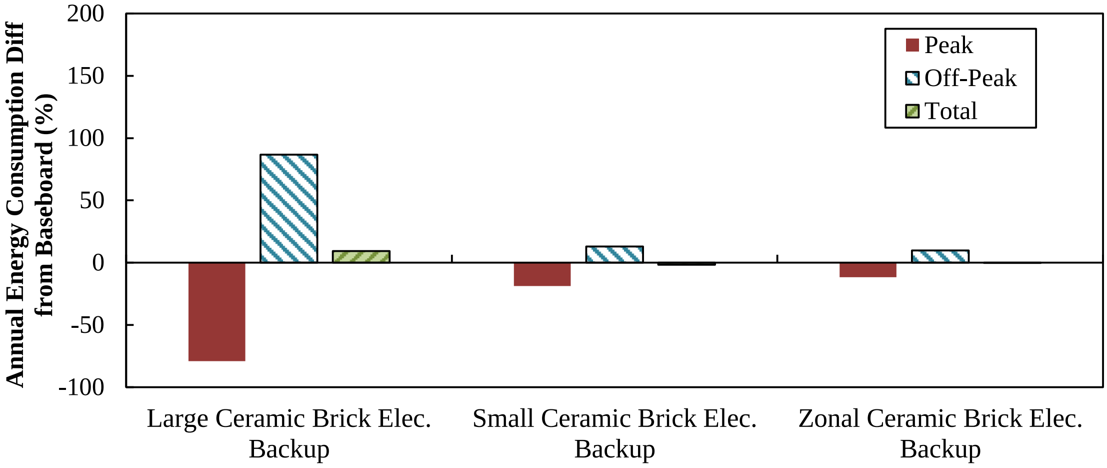

Fig. 4b: Difference between the total, peak, and off-peak baseboard annual system electricity consumption and the electric resistance backup storage system's annual electric energy consumption

When comparing the various system's load-shifting performances between the various considered four home archetypes, the results followed similar trends. An example of the results is shown in Fig. 5a where the large ceramic brick storage system with electric resistance backup is compared to the baseboard electric resistance heated system. The annual total heating loads of the pre-1980s and the 1980s-2000s home archetypes are quite similar (approximately 25 MWh vs 26 MWh respectively). The pre-1980s home archetype is a 91 m^2 single-story home with two occupants, while the 1980s-2000s archetype is a 146 m^2 two-story home with 4 occupants (282.5 kWh/m^2 vs. 168.0 kWh/m^2 respectively). The timing of the loads throughout the year was slightly different, with the pre-1980s home resulting in better load shifting potential. The post-2000s and the net-zero-ready home archetypes have smaller energy loads (19400 kWh and 6800 kWh respectively). The annual DHW loads (4600 kWh) play a much larger role in these loads as well, and thus the percentage capacity of peak load reductions was reduced as these are not impacted by the thermal storage systems in this case.

The same scenario, but with the PCM storage system (which has a smaller storage capacity, reduced heat losses, and can shift a small portion the of DHW loads energy to off-peak) is shown in Fig 5b. The peak load reduction and total energy consumption in the homes with lower demands was improved when compared to the ceramic storage in the same archetypes. Due to the lower overall thermal storage capacity of the considered PCM RTES system, the homes with larger loads had reduced load shifting (i.e., peak load reduction) potential.

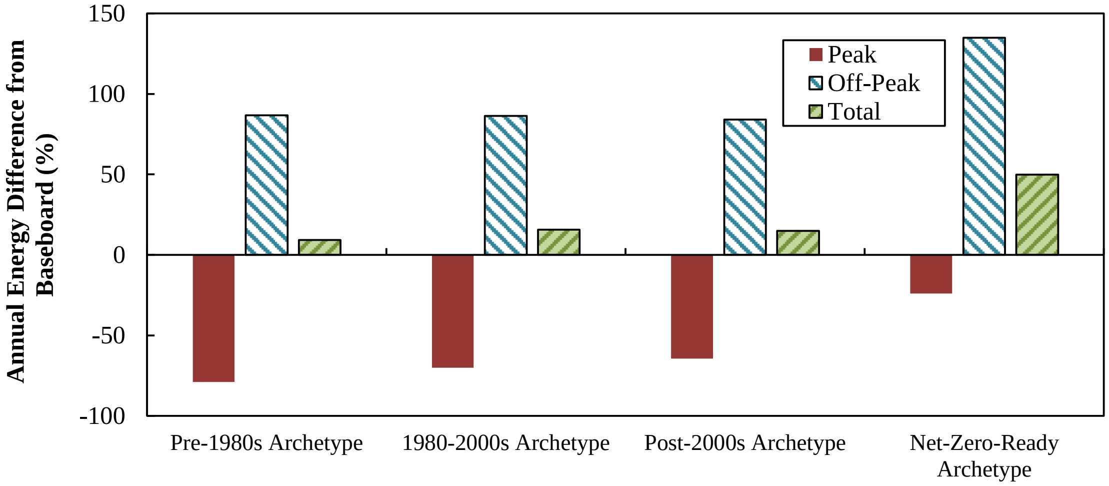

Fig. 5a: Large ceramic brick with electric backup load shifting performance in different house archetypes

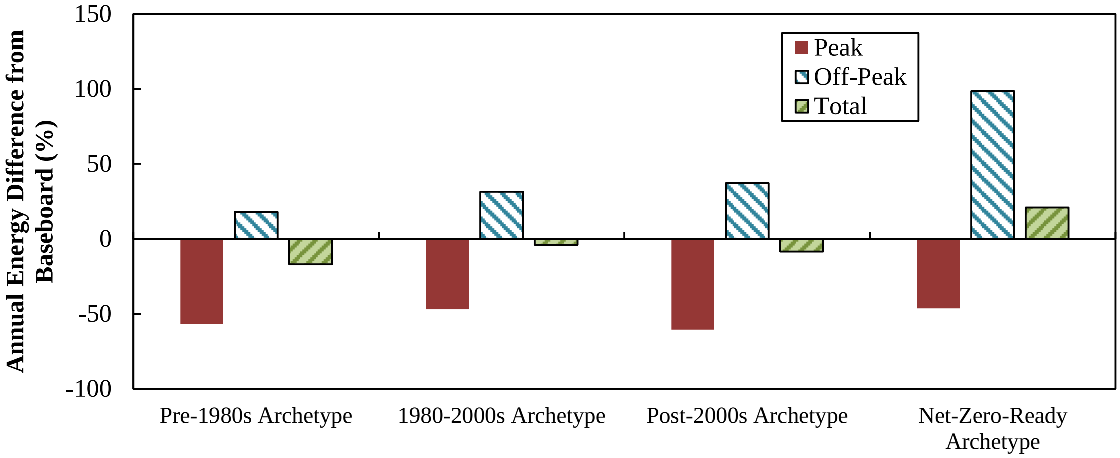

Fig. 5b: PCM storage load shifting performance in different house archetypes

For the case of the more efficient homes, results show that the energy storage was less beneficial. The total energy consumed percentage does increase more with these, as the additional energy requirements to heat the storage are larger when compared to the smaller base loads. Additionally, there is a greater ratio of heat loss from the storage to the space heating load. The heat losses from the storage tank were simulated as heat gains in the basement zones of the building models. This caused some of the home archetypes to overheat. This was especially apparent for the ceramic brick energy storage systems in the net-zero-ready home archetype (Tab. 4). The sensible storage operates at temperatures over 700°C and thus has significant heat losses. An outdoor air reset controller was simulated to reduce the storage set point temperature when the outdoor conditions were milder, but there was still significant overheating in some scenarios.

Tab. 4: Average winter temperature inside the two primary zones of the net-zero-ready home archetype

	First Floor	**Basement**
Baseboard	21.9 °C	18.3 °C
Large Ceramic Brick Elec. Backup	24.9 °C	28.0 °C
Small Ceramic Brick Elec. Backup	23.4 °C	24.0 °C
Zonal Ceramic Brick Elec. Backup	29.1 °C	26.4 °C
PCM Storage Elec. Backup	22.0 °C	19.4 °C

The DHW systems and resultant energy consumptions were modeled along with the space heating loads and the energy consumption was included in the total energy values discussed in this paper. The only storage systems that interfaced with the DHW system were the PCM storage units, as this was an extra feature of the systems on which the performance was based. The PCM system pre-heated any fresh mains water drawn into the house as makeup for hot water drawn inside the house. The water heaters and the PCM storage used electric resistance heating, thus, whether the water was heated by the DHW tank or the PCM storage, the energy consumption was the same. The PCM storage did not heat the water to the set point temperature of the DHW tank (55 °C), thus the thermostats in the DHW tank would still trigger the elements to heat the water, but the duration of the heating cycle was shorter. Overall, the impact of this on the total electricity consumption, and the load shifting of the energy demand was minimal. Further optimizations and methods to use the storage are required to improve the impact of this feature.

5. Conclusions

Several residential thermal energy storage systems being introduced into the Canadian market were simulated for use in Halifax, Nova Scotia, Canada. Four different home archetypes and several key performance indicators were studied and showed the potential benefits and drawbacks of the various systems. Additional renewable energy was able to be used and peak loads were shown to be reduced through the use of energy storage. The high heat losses of the ceramic brick storage systems were identified as a drawback in some cases as they could overheat homes when thermal energy storage systems with higher heat losses were used in a home with very small heating demands. In these cases, the PCM systems, with the reduced thermal losses and ability to load shift some energy from the DHW loads, were better suited and could increase the annual peak load energy consumption. The ceramic brick storage systems were more appropriately used in homes with larger heating loads, as the increased storage capacity, and larger heater charge capacities were better utilized and able to shift more energy from peak periods and have a higher renewable energy utilization rate. The results of this study highlight how the specific nature of the loads including timing and scale of demand have a significant impact on the overall system performance, and thus the careful matching of the storage technology and the loads should be conducted, and a one size fits all application may cause over heating the basement issues that need to be addressed.

6. Acknowledgments

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