TECHNICAL BRIEF

Sustainable Technologies
EVALUATION PROGRAM

Smart Grid

Residential Space Heating using Renewables and Battery Energy Storage

This study evaluated the performance of an integrated residential space heating system, in which a battery bank was used to perform load shifting on an air source heat pump (ASHP) with supplementary renewable energy generation. The project involved the development of monitoring and control software, whose goal was to power the ASHP using only renewable energy generation and a battery bank during mid- and on-peak time-of-use (TOU) periods. The controller would then allow the battery bank to recharge overnight, using relatively inexpensive off-peak electricity. This practice aims to reduce strain on the electricity grid during peak hours, and reduce electricity costs for the homeowner.

Experimental load shifting was performed during the heating season through the months of January to April 2016. Using the results of successful experimental trials, a financial analysis was performed showing estimated annual cost savings of 7%, and potential GHG savings of 60-65%. However, despite cost savings, residential battery prices remain too high for this practice to be financially viable. Note that this work only investigated one possible use of battery energy storage, and all potential advantages or drawbacks of residential energy storage were not examined. The proof-of-concept software developed for this experiment will be used for future smart grid studies involving battery energy storage.

Grid-scale energy storage has been used in the real-world for decades. Hydroelectric dams act as a form of energy storage – their output can be controlled to meet peak electrical demand when needed. Today, energy storage technologies such as batteries and flywheels are beginning to draw attention. Both are capable of providing off-grid support and complementing on-site renewable generation.

Residential space heating makes up a significant portion of energy end-use in Canada and is most commonly achieved with either natural gas or electricity. Natural gas had historically been more cost-effective in many areas but technological advancements are beginning to make electric space heating more cost-competitive. Electrically-powered heat pump technology has the potential to be greater than three times more efficient than conventional heating – with the added benefit that electricity is a low-carbon energy source in many Canadian jurisdictions.

INTRODUCTION

Space heating makes up 63% of Canada's residential energy consumption (NRCan, 2011). Depending on the availability of local resources and infrastructure, a building's space heating requirements can be met through a variety of energy sources including electricity, oil, natural gas, and wood. With developing concerns regarding the long-term effects of carbon emissions comes increasing interest in more efficient space heating technologies and practices. Burning oil or natural gas produces carbon emissions. Depending on the fuel mix of the electrical grid, space heating provided by electricity can have very low associated carbon emissions. In the Province of Ontario, initiatives such as the coal power phase-out have lead to cleaner electricity production – meaning that electrical heating systems can have significant environmental benefits compared to heating using fossil fuels.

Space heating with electricity is almost always achieved through electric resistance heating. Electric resistance heating is, at most, 100% efficient – all of the energy input as electricity is converted to heat. However, this type of electric heating is typically much more costly relative to natural gas heating.

Electrically-driven heat pumps are high-efficiency devices used for space or water heating. A heat pump extracts heat from a heat source, and rejects it to a heat sink, in the same manner as a common refrigerator extracts heat from its interior, and transfers that heat into the surrounding room. Air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs) use the outdoor air or ground, respectively, as heat sources in the heating season, and heat sinks in the cooling season. ASHPs and GSHPs can be up to 3 to 5 times more efficient than electric baseboard heating. Figure 1 shows an example of an ASHP.

Figure 1. The outdoor fan coil for the Mitzubishi Zuba ASHP used in this study.

Closely tied with the need for energy efficiency and conservation comes the need for cleaner energy or electricity generation at the source. This is clear from the increase in renewable energy generation capacity, both in large-scale projects and in smaller, distributed generation. At the residential level, renewable energy generation such as solar can be used to directly offset a consumer's electrical load on the grid. However, a major issue associated with renewable energy is the intermittency of their fuel sources.

Figure 2. The Archetype Sustainable House A (left) and House B (right) with roof-mounted solar PV and adjacent wind turbine.

Energy storage promises a means of addressing the variability inherent to renewable energy generation. Through some form of storage, commonly a battery, excess renewable energy generation can be stored and used at a later time. In the past, energy storage has primarily been applied in off-grid scenarios. However, with the increasing adoption of renewable generation, storage applications for grid-tied systems are beginning to be explored.

Energy storage can provide a benefit to both the consumer and the utility. From the consumer's point of view, storage can be used to improve energy reliability, reduce grid consumption during peak times, and allow users to harness greater potential of any on-site renewable generation. From the utility's perspective, energy storage can be used for demand response programs, and as dispatchable generation.

Together, all of these technologies give rise to synergistic opportunity for applications in buildings. This study investigated the performance of a renewable energy and storage-integrated space heating system. The space heating needs of a LEED™ Platinum house were monitored and offset through the use of onsite renewable energy production and local energy storage.

STUDY SITE

The Archetype Sustainable Houses (ASH) A and B are two semi-detached houses located at the Kortright Centre for Conservation in Vaughan, Ontario. Pictured in Figure 2, the ASH has been awarded LEED™ Platinum, EnergyStar, and GreenHouse certifications. Along with adjacent solar photovoltaic (PV) and wind turbine test fields, the ASH had 4 kW of roof-mounted PV as well as a nearby 2.1 kW Skystream wind turbine. This study investigated the operation of the space heating system in House A, which operates independently of House B. Table 1 highlights some of the key structural features of House A, along with its floor and zone sizes.

The ASH and adjacent testing facilities are equipped with an advanced LabVIEW-based monitoring system, measuring over 600 data points. Depending on the type of recording and ongoing experimentation, sensor data is logged every 1 – 5 seconds.

Table 1. Features of the Archetype House A.

Structural features	Value
Basement walls	A.O.Smith SHPT-50
Basement slab	190 L
Above grade walls	1.6 m
Windows	0.56 m
Roof (SIP)	2.78
Overall UA value	2.75
ACH @ 50 Pa	0.89
Floor areas – *m^2 (ft^2)*	
Basement	86.95 (936)
First floor	86.95 (936)
Second floor	86.95 (936)
Third floor	83.6 (900)
Total	344 (3708)
Zone volumes – *m^3 (ft^3)*	
Basement	234 (8264)
First floor	292 (10296)
Second floor	238 (7840)
Third floor	222 (7840)
Total	986 (34824)

Mechanical Systems

The design heating load of House A is 7.91 kW when outdoor and indoor temperatures are -22˚C and 22˚C respectively. House A is heated and cooled using a 10.5 kW (3 ton) high-efficiency variable capacity air source heat pump (pictured in Figure 1) manufactured by Mitsubishi™. It is coupled with a direct expansion (DX) coil housed in multi-speed air handling unit (AHU). This house uses a single zone AHU. The set point of the zone's thermostat was maintained at 22˚C for the duration of the experiment. House A also uses a heat recovery ventilator (HRV) in order to avoid wasting heat energy when ventilating the building. This device uses the stale exhaust air of a building to preheat the incoming fresh air. The space heating system can be coupled with the building's water heater to provide additional space heating, or supplemented with a natural gas mini-boiler. For this study, only the variable capacity ASHP was used for space heating.

Electrical Systems

The 4 kW of roof-mounted PV and 2.1 kW wind turbine were used as the renewable generation of the system. An Absolyte IIP Type 100A33 lead-acid battery bank (1600 Ah, 50 VDC) was used for energy storage. This is equivalent to approximately 75 kWh usable electricity storage if fully depleted. The battery bank was controlled by a Xantrex XW 6048 inverter/charger.

In order to maintain battery health, as well as reflect a more realistic real-world system, restrictions were placed on the battery bank's output. Within a 12-hour period a depth of discharge (DOD) limit equivalent to 25 kWh was maintained. Additionally, due to the size of the inverter, the peak output of the battery bank was limited to approximately 6 kW. A Conext ComBox was used to monitor battery parameters and issue control commands. Figure 3 shows the battery bank and inverter/charger.

OBJECTIVE & APPROACH

This project was conducted for SUMARAN Inc. The primary goal of this study was to design and implement an HVAC system with reduced reliance on the grid during peak time-of-use (TOU) hours. TOU hours and pricing in Ontario are displayed in Figure 4. The findings from this study were to be used for implementation in a real-world net-zero energy house (NZEH) in Guelph, Ontario.

The goal of the project was to use the battery bank during mid- and on-peak TOU hours to match the instantaneous net power draw of the ASHP, described in further detail below, recharging the battery overnight. This was achieved through the development of a *LabVIEW* controller that monitored power consumption and generation, and controlled the battery bank's output

Figure 3. The 1600 Ah lead acid battery bank with its protective plastic shielding is shown on the left. The Xantrax XW inverter and Combox are mounted to the right of the battery bank.

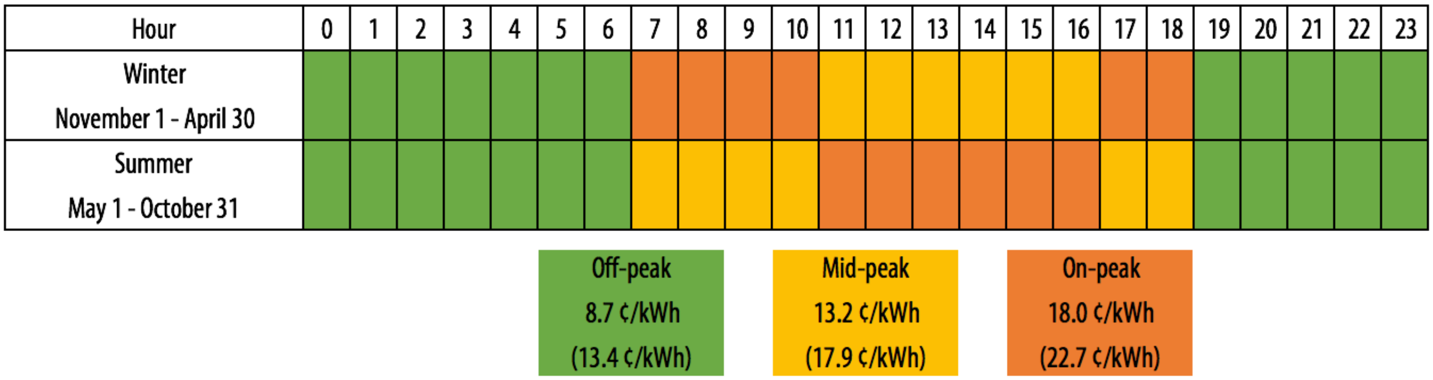

Figure 4. Ontario time-of-use electricity rates and schedule as of May, 2016. The total variable price of electricity is shown in brackets.

power such that it matched any net power consumption during peak hours. Table 2 summarizes the components of the systems used in this test, and Figure 5 displays their relative location.

Table 2. System components monitored and/or controlled in this study.

System Component	Type	Size
ASHP	Load	10.5 kW
Solar PV	Generator	4 kW
Wind turbine	Generator	2.1 kW
Battery bank	Storage	~75 kWh (25 kWh utilized)

During mid- or on-peak hours of the day (7:00 AM – 7:00 PM) the objective of the controller was to satisfy Equation 1. In Equation 1, P is the instantaneous power consumption of each component of the system. The minimum function means that if there is a generation surplus the battery bank does nothing. At off-peak times of day, the battery bank is allowed to recharge and the ASHP resumes normal operation, both using electricity supplied by the grid. This practice is called load shifting, and aims to reduce electricity costs for consumers, as well as reduce strain on the electrical grid.

$$P_{Battery} = \begin{cases} P_{ASHP} - (P_{Solar} + P_{Wind}), & P_{ASHP} > (P_{Solar} + P_{Wind}) \\ 0, & P_{ASHP} \leq (P_{Solar} + P_{Wind}) \end{cases} \quad (1)$$

Due to their physical distance from each other, the four system components were connected to the grid and metered separately. This means that energy generated by the PV panels could not directly flow into the battery bank, or be used to power the ASHP. Instead, each component of the system was monitored separately, and the instantaneous net energy consumed or produced was of interest. This type of system can be referred to as a "virtual microgrid" – a type of localized energy system in which the components are not all directly connected, but act as if they are.

The *LabVIEW* controller that was developed used very simple control techniques; first, a simple open-loop controller (one that does not consider the output of the control action) was deployed, followed by a slightly more complex closed-loop controller (one that considers the output of the control action). This software could easily integrate with the existing data acquisition architecture at the ASH. Communication with the Conext ComBox was possible using MODBUS communication protocol.

This project accomplished a secondary goal for STEP. It served as a platform to develop software that could be utilized in future smart grid-related projects. The proof-of-concept software developed for this project will act as the groundwork for future smart grid and energy storage-related projects, and is not dependent on the system described in this experiment.

Emissions Analysis

The carbon emissions impact of load shifting was also investigated. This analysis examined the effect of load shifting on emissions without the use of any renewable energy, such that the emission impacts of load shifting alone could be highlighted. In order to estimate potential reductions in emissions as a

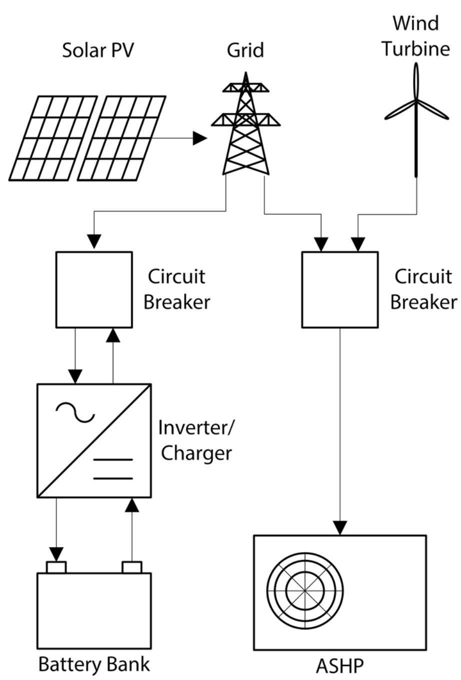

Figure 5. Schematic of system components.

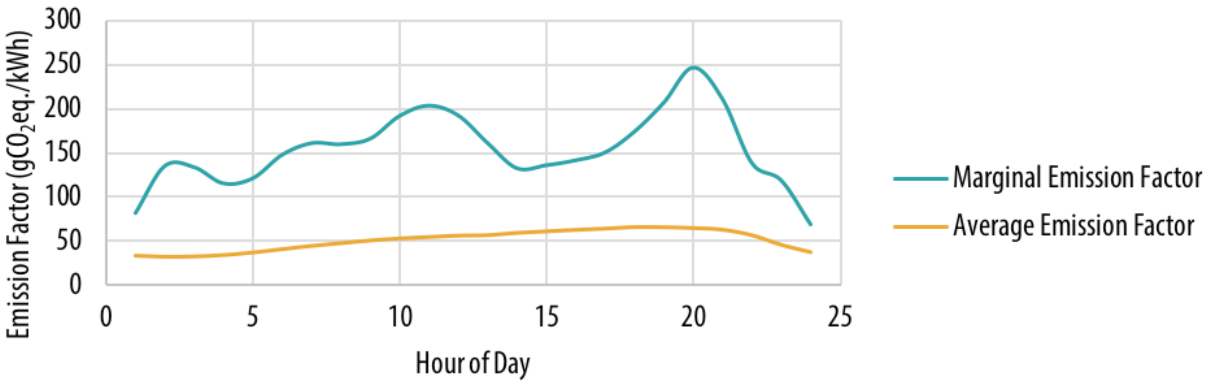

Figure 6. Ontario electricity grid average and marginal emission factors (TAF, 2017)

result of the load shifting intervention, marginal GHG emission factors were used.

The Atmospheric Fund (TAF) has developed guidelines for calculating associated emissions from the Ontario electricity grid, accounting for both hourly averaged emission factors and marginal emission factors (TAF, 2017). When estimating how a demand intervention would impact emissions, the marginal emission factor should be used. This is because if the electrical demand on the grid were to have changed, the entire fuel mix – nuclear, hydro, gas, wind, and solar – would not all shift with the demand in equal parts; only a fraction of the fuel mix supply would change as a result of changing demand. Generators whose output would be increased or decreased to follow changing demand are referred to as being "on the margin", and it is the emission factors associated with these generators that are relevant when calculating grid emissions for demand interventions. Load shifting is a prime example of this sort of intervention.

For example, if at a given hour of the day the fuel on the margin of the electricity grid is natural gas, then to increase or decrease the demand on the grid would result in natural gas generation increasing or decreasing. This is the fuel with the highest emission factor on the Ontario electricity grid. However, if at a different hour the fuel on the margin was hydro, then to increase or decrease the demand on the grid would have a much smaller impact on emissions. If some sort of intervention can reduce demand at times of day with emission-intensive fuels on the margin, then it can be said to produce carbon savings.

Figure 6 shows both grid's annual average emission factors and the marginal emission factors developed by TAF, and used in this analysis. In order to calculate the baseline emissions – with no load shifting intervention – the hourly load was multiplied by the average emission factor. To calculate the change in emissions that would have resulted if load shifting had occurred, the differences in hourly consumption, with and without load shifting, were multiplied by the marginal emission factor.

Figure 6 shows that if a battery takes 1 kWh of electricity consumption at 3:00 PM and shifts it to 8:00 PM, higher grid emissions would result even before considering round-trip battery efficiencies. It follows that it would be preferable to recharge a battery bank at certain hours of the night from a carbon perspective. This study quantified the emissions associated with recharging the battery bank at different times of night, in order to determine the ideal recharge hour.

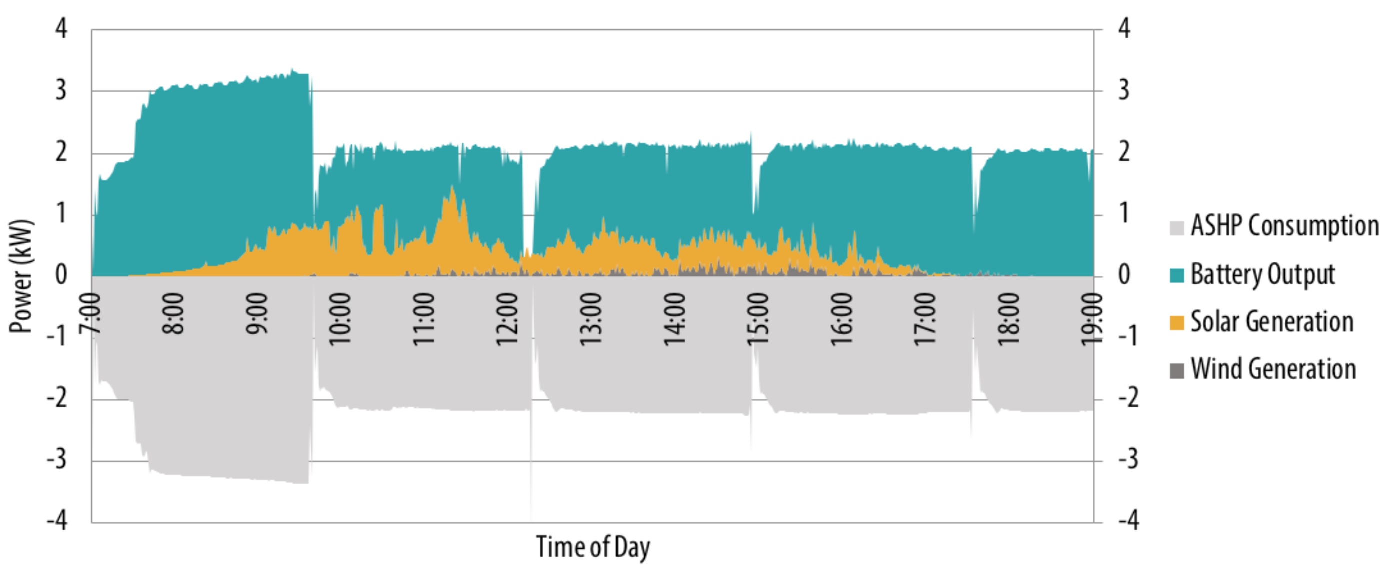

Figure 7. An example day of the open-loop controller's operation controlling the output of the battery bank to achieve instantaneous net-zero operation.

FINDINGS

The simplest available control strategy easily accomplished the goals of the study utilizing the available hardware. Control over the battery was implemented successfully utilizing a very simple open-loop controller. This type of controller assumes that the output command sent to the battery always achieves the desired control action, and does not consider any output feedback. This is the simplest type of controller that may be designed and implemented.

Figure 7 shows the battery bank's output (regulated by the open-loop controller) and its response to changing electrical load and generation. The controller begins to match any deficit power requirement of the ASHP at 7:00 AM, and ends discharging at 7:00 PM to recharge the battery. This resulted in an instantaneous net-zero system over the 12-hour mid- and on-peak time scale.

Over the course of this study, total renewable generation only made up 7% of the energy consumed by the ASHP, leaving the majority of the mid- and on-peak hour load to be matched by the battery bank. This is due to the fact that the PV array was not originally sized to accomplish this task, and testing primarily occurred over the winter months when solar energy production is at a minimum.

Implementing the load shifting procedure showed up to a 98% reduction in grid-consumption during mid- and on-peak hours. The controller was not perfect – some of the instantaneous power requirements of the ASHP were not always matched for a few reasons.

To improve accuracy, the control algorithm was modified and refined over the course of this study. Initial trials showed an average load matching of 94.3%. It was identified that with the initial open-loop control algorithm, the inverter was not accurately outputting low amounts power (>50 W), levels typical of the ASHP's standby power consumption. The initial control algorithm was then refined to attempt to achieve more accurate load tracking.

The final iteration of the controller used closed-loop proportional-integral (PI) control, and achieved an average tracking accuracy of 98%. This means that the ASHP only drew 2% of it's daily power consumption from the grid, and the remainder was made up by renewable energy generation and battery bank output. Table 3 displays the load tracking results between the two different control methods.

Table 3. Experimental controller load shifting accuracy.

Control type	Average daily percent of load met
Open-loop controller	94.3%
Closed-loop controller	98.0%

The open-loop nature of the initial controller was a major factor in the inaccuracy of the system – this type of controller does not change its control action in response to system feedback. Additionally, occasional network loss and inverter faults caused some of the ASHP load to go unmatched. Nevertheless, even the simplest control algorithm deployed showed more than satisfactory performance with respect to matching instantaneous on-site demand.

At this time, residential-scale battery prices are too high to make this practice financially beneficial for homeowners. A high-level financial analysis was performed on the battery bank–ASHP system to investigate the potential savings of the load shifting practice. This analysis excluded the use of any renewable generation in the system, such that the financial effects of only load shifting could be investigated, neglecting any benefit from on-site energy generation that may be free or sold for a profit.

The energy consumption of both the ASHP and AHU were monitored over the period of May 2015 – April 2016. Throughout this period, the ASHP alone was responsible for the heating and cooling of House A. In order to estimate financial savings, the effect of the battery control software was simulated over the course of the real-world 2015 – 2016 data set. The load shifting simulation was run on two different systems: (i) the ASHP alone, and (ii) the "system as installed" – comprised of the ASHP and the AHU distribution system.

Estimated reductions in annual electricity bills are the result of shifting the electrical loads to off-peak time while considering battery charging and discharging efficiencies, as well as the battery output limit of 25 kWh per day. Table 5 shows the electricity costs and savings associated with the system based on Ontario electricity prices. These calculations took into account all costs included in a homeowner's electricity bill, according to Toronto Hydro pricing (IESO, 2016). This includes electricity prices, deliv-

Table 4. Residential-scale battery sizes, costs, and lifetimes, based on a 25 kWh battery bank. All specifications and costs are based on values obtained in May 2016.

	GNB Absolyte IIP 100A33 (GNB, 2006)	**Rolls AGM S2-1275** (Rolls Battery Engineering, 2011)	**Enphase AC Battery** (Enphase, 2016)	**Tesla Powerwall I** (Tesla, 2016)	**Panasonic LJ-SK84A** (Panasonic, 2015)
Battery type	Lead Acid	Lead Acid	Lithium Ion	Lithium Ion	Lithium Ion
Maximum DOD	80%	50%	>95%	100%	99%
Equivalent System Cost	$10,064 (USD)	$15,600 (CAD)	$21,570 (USD)	$12,000 (USD)	Unlisted
Lifetime	1200 cycles	1280 cycles	7300 cycles	5000 cycles	3650 cycles
Lifetime with daily cycling	3.3 years	3.5 years	20 years	13.7 years	10 years

Table 5. Annual electricity costs and savings associated with load shifting the ASHP and distribution system of House A.

	Standalone ASHP	System as installed
Normal operation cost	$ 1,355.46	$ 1,779.62
Load shifting cost	$ 1,261.58	$ 1,648.31
Savings	**$ 93.88**	**$ 131.31**

ery and regulatory fees, and taxes. This analysis shows estimated annual savings of 7% in both cases.

These savings, presented in Table 5, cannot make up for the high prices of residential batteries on or close to market. Table 6 displays some general residential-sized battery information, including the cost of an equivalent 25 kWh battery bank system.

Due to both short lifetimes and high costs, a battery-load shifting system cannot result in financial payback. Improvements in battery technology are still required in order to decrease cost and increase system lifetime in order to make this use-case financially viable for homeowners. At this time, it is best to consider load shifting to be a secondary use-case, after battery backup systems. However, as the technology advances and system costs decrease, it is expected that this practice could eventually provide economic benefit to homeowners, particularly if local electricity rate structures provide incentives.

It should be noted that this study only investigated load shifting as a use-case, and many benefits of home battery storage have not been quantified, including increased reliability during blackouts, and the benefit of storing excess renewable generation.

Depending on the time of night that the battery bank is recharged, load shifting has the potential to produce notable GHG emission savings. This analysis investigated the annual emissions associated with load shifting if overnight recharging were to occur at each hour between 7:00 PM and 1:00 AM. Each hour within this range is during the off-peak TOU period, so the associated cost would be unchanged, yet the marginal emission factors vary drastically over this period.

Tables 6 and 7 show the baseline annual emissions and saved emissions as a result of shifting loads to different hours of the night. Negative values indicate an *increase* in emissions, while positive values are saved emissions. As would be expected based on Figure 5, shifting the load to near 8:00 PM results in an annual increase in associated emissions. The analysis was performed on measured energy consumption of both the standalone ASHP and the system as installed, and both cases show that the optimal time to recharge the battery bank lies near 11:00 PM.

It should be noted that this analysis is only an estimation of what would have been as a result of a load shifting intervention. In reality, the way the grid would react to changing demand could be different than this analysis assumed. The analysis is contingent upon the demand intervention action being sufficient to elicit a response from the grid (i.e. a generator actually being throttled back), but at the same time not so drastic as to cause a significant change in the IESO's demand matching algorithms. Nevertheless, this type of analysis can help give insight as to what practices would be helpful, in general, to reducing emissions.

Table 6. GHG emissions associated with the electrical operation of the ASHP and the impact of load shifting at different times of night.

Battery recharge start time	Associated emissions (kg CO_2 eq.) Baseline	Saved	Percent of emissions saved
7:00 PM		-238.91	-81.3%
8:00 PM		-92.75	-31.6%
9:00 PM		68.11	23.2%
10:00 PM	293.89	135.57	46.1%
11:00 PM		**191.80**	**65.3%**
12:00 AM		123.09	41.9%
1:00 AM		36.55	12.4%

Table 7. GHG emissions associated with the electrical operation of the system as installed and the impact of load shifting at different times of night.

Battery recharge start time	Associated emissions (kg CO_2 eq.) Baseline	Saved	Percent of emissions saved
7:00 PM		-307.06	-73.9%
8:00 PM		-101.57	-24.4%
9:00 PM		114.57	27.6%
10:00 PM	415.74	199.86	48.1%
11:00 PM		**251.97**	**60.6%**
12:00 AM		158.43	38.1%
1:00 AM		56.35	13.6%

CONCLUSION

This technical brief analyzed a real-world integrated residential space heating system utilizing renewable energy and energy storage. The system involved using a battery bank to offset the net load of an ASHP and on-site renewable energy generation. A monitoring and control software application was developed, designed to perform load shifting aiming to achieve instantaneous net-zero operation during peak hours of the day. Based on successful experimental trials, annual analyses have shown that load shifting in Ontario can produce operational cost savings of approximately 7%, and GHG savings up to 65%, however, upfront system costs are still very high. This study only investigated one possible application of residential batteries. Additional use-cases for residential batteries, including increasing renewable energy utilization, system reliability, off-grid applications, or the ability to participate in demand response programs with the local utility will be considered in future work to fully evaluate the financial, environmental, and social impacts of residential battery storage.

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