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Experimental EMS of an ASHP using Load Shifting based on Time-of-Use Pricing in Ontario, Canada

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Abstract

Energy management strategies for grid-friendly net-zero energy houses are investigated at the Archetype Sustainable Houses in Vaughan, Canada. These semi-detached houses are used as workspaces, as well as for the demonstration of various sustainable technologies in Canadian climates. The space and water heating needs of the house investigated are met by air source heat pumps. The facility features on-site renewable generation and energy storage, allowing for the implementation of smart grid control strategies. This project focuses on the development of energy management software to monitor the building's space heating needs, renewable generation, and storage capacity to influence the energy consumption of the ASHP. In particular, the project aims to reduce energy consumption from the grid during peak usage times through load shifting. *LabVIEW* software has been used to implement the controllers in the system. Experimental trials through the heating season investigated a system comprised of one ASHP used for space heating, wind and solar generation, and energy storage in a single battery bank. Load shifting results from winter trials are reported, and its effect on annual operation, both financially and in GHG emissions, is investigated.

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1. Introduction

The increasing world energy demand requires the active development of sustainable energy systems in all sectors. Of particular interest is the buildings sector's role in energy consumption. In 2012, residential buildings accounted for 22% of the United States' energy consumption [1], and 17% of Canada's energy

consumption [2]. Together, commercial and residential buildings contributed to 11% of Canada's total greenhouse gas emissions in 2012, while electricity consumption accounted for 12% of Canada's emissions in the same year [2]. International Energy Agency (IEA) scenarios project building energy demand is expected to rise by 15% from 2013-2030, the majority of which will be supplied by electricity [3]. Increased effort towards developing sustainable practices in the residential sector will therefore have a substantial impact on reducing world energy demand and greenhouse gas emissions. This includes the integration of on-site renewable generation, energy efficiency and conservation, and energy storage technologies.

1.1 Energy management systems

Effective energy management systems (EMS) will play a significant role in the development of the smart grid. Existing EMS will face difficulties adapting to changes to the grid, such as the increasing implementation of renewable resources or energy storage devices. Innovative EMS designs should be composed of plug-and-play components (hardware and software), allow for increased control functionality of components, and support services such as historical databases and user interfaces [4]. The objective of an effective EMS is often the minimization of a cost function. This makes the development of new EMS attractive to both consumers, by reducing utility cost, as well as the utility provider, through the development of more robust distribution systems. An optimized EMS is the key to the successful operation of a microgrid. There is no standard for the design of an EMS, and it is therefore an area of great interest for the development of the smart grid. They may use various tools and techniques to optimize energy management.

1.2 Demand response and load shifting

Demand response (DR) strategies will play an integral role in smart building energy management, and the evolution of the smart grid as a whole. They will aid in facilitating the effective addition of distributed energy resources to the electrical distribution grid [5]. Through DR strategies, the smart grid will have the capability to manage consumer energy consumption patterns based on incentives and disincentives [6].

DR utilizes time-of-use (TOU) electricity pricing information for decision making. An internet-scale distribution model has been shown to realize 12 – 32% electricity cost savings using optimized load shifting algorithms [7]. Load shifting is a form of DR that consists of moving elastic energy demand to off-peak times through price-based signalling.

2. Ontario electricity grid

2.1 Greenhouse gas emissions

In 2014, Ontario phased out its last coal-fired electric generation. Prior to the coal phase-out, the emission factor of the Ontario electricity grid was in the range of 189 – 221 gCO_2eq/kWh, in the years 2004 – 2006 [8]. Currently, the only remaining fossil fuel used for electricity generation in the province is natural gas, making for much cleaner electricity production; the life-cycle emission factor of natural gas is less than half of that of coal [9]. Fig. 1 shows the fuel mix of the Ontario electricity grid for the year 2015 based on total kWh generated by each generation type currently employed.

At any given time of day, the actual fuel mix of the Ontario grid varies, meaning that greenhouse gas (GHG) emissions associated with electricity use change hour-to-hour. Generation supply data for the year 2015 was provided by the Independent Electricity System Operator (IESO) in order to analyse the GHG emission changes on an hourly basis. Using hourly GHG emission factors, the effect of load shifting on associated GHG emissions could be determined.

Table 1 displays the emission factors used to determine the emissions associated with electricity. These emission factors are based on lifecycle analysis of each generation source, and should therefore represent accurate and conservative values.

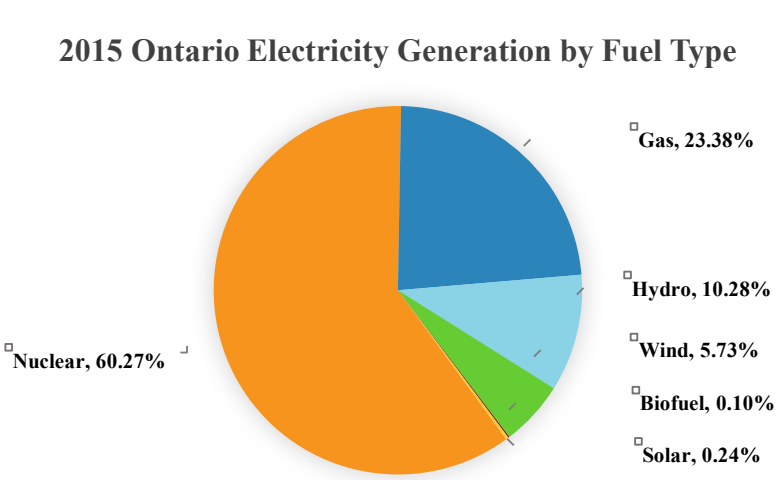


Fig. 1. Ontario Electricity Grid Generation by Fuel Type [10]

Table 1. Lifecycle emission factors of electricity generation sources [9]

Generation Source	Lifecycle GHG emission factors (g CO_2 eq./kWh)
Coal	1001
Natural Gas	469
Nuclear	16
Hydro	4
Wind	12
Biofuel	18
Solar	46

2.2 Time-of-use pricing

The Ontario electricity grid also charges customers based on a TOU pricing schedule. In addition to the base TOU electricity rates, the IESO applies three other sets of charges to a consumer's electricity bill: delivery charges, regulatory charges, and the Harmonized Sales Tax (HST). The former two charges are broken down into fixed monthly and variable (per kWh) charges. These two charges are applied to the total electricity cost, as calculated by the TOU rates. The HST is applied to the sum of the electricity, delivery, and regulatory charges.

Table 2 displays the TOU schedule as of May, 2016, with the total variable electricity cost per kWh. These prices do not include fixed monthly costs (totalling 23.75 $/month), or the HST (13% as of May, 2016), which can vary greatly depending on changing government policies. However, the fixed monthly costs and taxes were used for cost calculations.

The load shifting experiment performed was designed based on the TOU pricing scheme in Table 2, considering the seasonal variations and weekends, but ignoring holidays.

Table 2. Ontario TOU pricing rates as of May 1st, 2016 [11]

Hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Winter November 1 - April 30																								
Summer May 1 - October 31																								

Off-peak 13.4 ¢/kWh | Mid-peak 17.9 ¢/kWh | On-peak 22.7 ¢/kWh

3. Experimental Setup

3.1 Site Description

Experimental work took place at the Archetype Sustainable House (ASH) in Vaughan, Ontario, pictured in Fig. 2. This site is located approximately 30 km north of Lake Ontario, in the Greater Toronto Area (GTA). This facility is owned and operated by the Toronto and Region Conservation Authority (TRCA). It features two semi-detached model homes (termed House A and B) designed to test and showcase various residential sustainable technologies.



Fig. 2. The Archetype Sustainable House (centre-left) and Skystream wind turbine (right) at the Kortright Centre for Conservation in Vaughan, Ontario.

The Archetype house was designed to have an air tight building envelope in accordance with ASHRAE 90.1 [12]. Along with adjacent solar photovoltaic (PV) and wind turbine test fields, at the time of the study, the ASH had 3.4 kW of roof-mounted PV as well as a nearby 2.4 kW Skystream wind turbine.

The space heating needs of House A were considered for this study. The experiment took place between the months of January – March, 2016, at which point the thermostat set point temperature was maintained at 22˚C. Table 3 highlights some of the structural features of House A.

The facility is equipped with an advanced monitoring system, comprised of National Instruments (NI)

data acquisition (DAQ) systems, and over 400 on-site sensors continuously recording at 1 – 5 second intervals. This existing monitoring system was used to monitor power consumption and renewable generation throughout the study [13].

Table 3. Structural Features of House A [12].

Structural features	
Basement walls	RSI 3.54 (R20)
Basement slab	RSI 1.76 (R10)
Above grade walls	RSI 5.64 (R32)
Windows	2.19 W/m^{2}K
Roof	RSI 7 (R40)
Overall UA value	160 W/K
ACH @ 50 Pa	1.204
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)

3.2 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 by a 10.5 kW (3 ton) high efficiency variable capacity air-to-air source heat pump, manufactured by Mitsubishi™. The ASHP operates at part load (2 – 3 kW) unless the temperature drops below -15˚C, at which point the compressor will draw its full 6 kW load. It is coupled with a direct expansion coil air handling unit (AHU) with a multispeed fan. This house uses a single zone AHU. House A also uses a heat recovery ventilator (HRV) in order to avoid wasting heat. This device uses the stale exhaust air of a building to preheat the fresh incoming air. The space heating system can be coupled with the building's water heater to provide additional space heating, however, these features were disabled for the duration of this study.

3.3 Electrical Systems

Along with the 3.4 kW PV and 2.4 kW wind turbine monitored, a newly installed means of energy storage was utilized for this experiment – an Absolyte IIP 1600 Ah (50 VDC) lead-acid battery. This battery bank was controlled by a Xantrex XW 6048 inverter/charger. In order to both maintain battery health and

reflect more realistic conditions, restrictions were placed on the battery bank's output. Within a 12-hour timescale, a depth of discharge (DOD) limit of 500 Ah was maintained. This is equivalent to approximately 25 kWh. Additionally, due to the size of the inverter, the peak output of the battery bank was limited to approximately 6 kW, matching the peak consumption of the ASHP. A Conext ComBox was used in order to monitor battery parameters and implement controls. Communication with the ComBox was enabled through Modbus.

Fig. 3 displays the experimental setup of the system. The solar PV is metered separately and feeds directly to the grid under a Renewable Energy Standard Offer Program (RESOP) contract, while the wind turbine is net metered. For the purposes of this study the solar PV was treated as if it were also net metered, such that its generated electricity would be used to power the ASHP in the house without exporting to the grid. Credits from net metering were ignored for the financial analysis to highlight only the effects of load shifting.

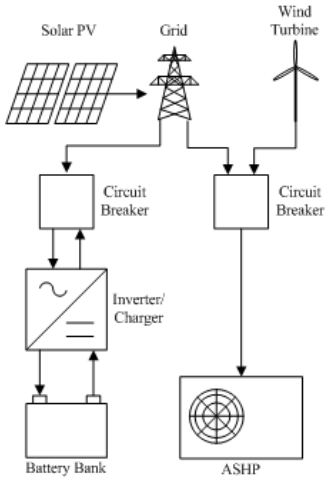


Fig. 3. Schematic of Experimental Setup

4. Methodology

The experiment consisted of two major goals. The first was to experimentally implement a load shifting procedure using all real-world devices. The second goal was to do so through the development of software with a general architecture such that it might be applied to future studies utilizing more advanced EMS. The software developed was modular, such that each component of the real world system had an associated segment of code that could be added or removed (e.g. renewable generation and/or loads were interchangeable). This work also aimed to promote the adoption of ASHPs in net-zero energy houses (NZEH).

4.1 Software development

All software for this experiment was developed and implemented using *LabVIEW*. The existing DAQ architecture was utilized to monitor the energy generation of the PV and wind turbine, along with the power consumption of the ASHP. In order to monitor and communicate with the battery bank, Modbus communication was integrated into the *LabVIEW* controller. This allowed specific battery parameters to be read by *LabVIEW*, as well as allowed certain control parameters to be written to the inverter/charger itself. These included modifying the settings to force charging or discharging, as well as the exact rate of discharge to the nearest 0.1 A. The charging rate was fixed at the maximum 6 kW capacity of the invertor/charger.

For simplicity, an open-loop controller was initially developed to control the battery output current. It

was determined that although typically not as accurate as its closed-loop alternative, it was acceptable for this application since the battery output current could be communicated directly to the inverter via the control software. The inverter ensured steady grid-voltage such that the power output could be easily determined. In later iterations of the control software, a closed loop PI-controller was implemented with similar accuracy to the open-loop controller.

The program monitored the instantaneous power draw of the ASHP, along with live solar and wind generation. Solar and wind power production were used to offset the load of the heat pump on the grid. Using the control software, the remaining ASHP load was matched with the output of the battery bank such that Equation (1) was satisfied.

$$P_{Battery} = P_{ASHP} - P_{Wind} - P_{Solar} \quad (1)$$

Where *P* indicates the power and the subscript indicates each component of the system. This equation was satisfied as long as the following three conditions were met:

1. The hour was between 7:00 and 19:00;
2. The output required by the battery was less than the output capacity of the inverter (6 kW); and,
3. The battery had not yet expended all of its useful energy (25 kWh) within its current discharge cycle.

4.2 ASHP Control

An initial goal of this study was to implement PID control on the ASHP as well, to minimize energy consumption while still maintaining thermal comfort. Throughout the course of this experiment however, it was determined that the ASHP model used did not allow for this control capability. Only ON/OFF control was possible programmatically over the ASHP. However, as mentioned in Section 3.2, the variable capacity ASHP continuously adjusted its output to meet the building load. Therefore, the ASHP was running part-load for most of the heating season, except during the extremely cold outdoor temperature of -15 ºC or below.

In order to try to reduce the power consumption of the ASHP further, thus reducing strain on the battery bank, a temperature setback was implemented during the second half of the experiment. This setback involved reducing the setpoint of House A to 18˚C between the hours of 10:00 – 17:00, assuming that homeowners would be away at work during these hours.

5. Results and Discussion

5.1 Controller Accuracy

Fig. 4 shows an example of one day of load and generation tracking during mid and on-peak hours. This specific day shows tracking with the initial open-loop controller. On this day, the average daytime outdoor temperature was -6.1˚C, and 93.5% of the ASHP load was met by the battery bank during mid and on-peak hours.

Table 4 highlights the accuracy of the controller over each experimental phase. It is shown that the controller had slightly more poor tracking when the ASHP was inhibited. This was determined to be due to the fact that while inhibited the inverter itself had difficulty outputting stable power to match the low standby power of the ASHP (>50 W). The final controller iteration improved upon steady-state errors, as well as the output at low levels. The remaining tracking error is associated with slow network speeds, and slow inverter communication/response time.

Table 5 shows the outcome of the temperature setback on the power consumption of the ASHP. While these results do show almost a 50% reduction in energy consumption, they cannot be taken at face-value since outdoor temperatures were warmer during the setback portion of the experiment.

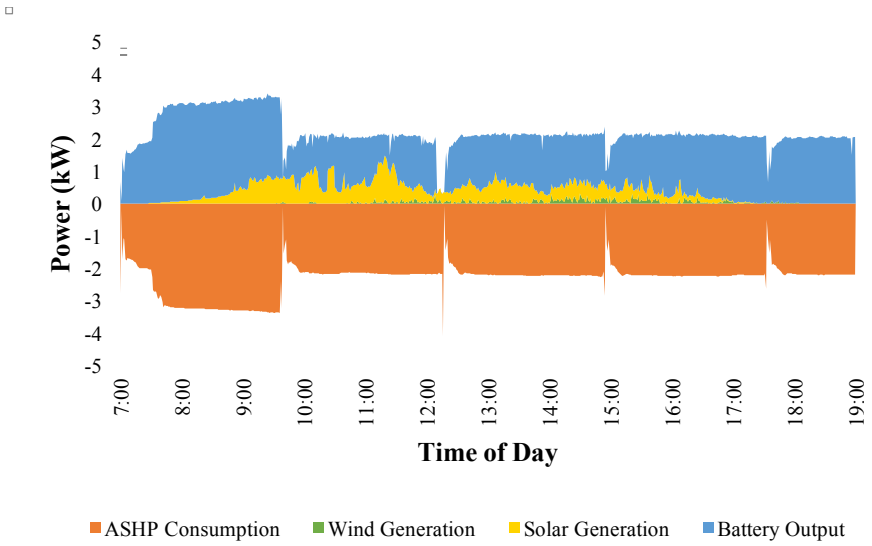


Fig. 4. Mid and on-peak hour consumption, generation, and battery output

Table 4. Percentage of load shifted and days of operation

Control	Percent of load met	Days of operation
Open-loop, normal ASHP operation	94.3%	6
Open-loop, setback operation	93.3%	11
Closed-loop, both modes of operation	98.0%	3 normal, 3 setback

Table 5. Effect of temperature setback on power consumption.

Mode of ASHP operation	Average ASHP peak-hour power consumption	Average daytime outdoor temperatures
Normal	19.7 kWh	-3.1˚C
Setback	8.9 kWh	1.1˚C

5.2 Financial Analysis

A financial analysis was performed on a load shifting system comprised of only the ASHP and the battery bank, neglecting any renewable generation. This was done to emphasize the cost savings associated only with load shifting.

Actual ASHP power consumption data was collected from May 2015 – April 2016. Additionally, the power consumption of the air handling unit (AHU) was collected over the same period as well. During this time period, the ASHP was solely responsible for space heating of the home. The accuracy of the controller (98%), along with the experimentally determined battery charging and discharging efficiency, was then used to calculate the cost savings associated with load shifting the annual operation of the ASHP and AHU. The same conditions listed in Section 4.1 were applied to these calculations. Table 6 shows the annual cost savings associated with load shifting both systems. These results show roughly a 7% reduction in annual electricity costs, associated with load shifting in the Ontario energy market. The costs shown account for all electricity charges, including a 13% tax, applicable as of May, 2016.

Table 6. Annual costs and savings associated with load shifting the ASHP and AHU at current Ontario TOU electricity prices.

	ASHP	ASHP and AHU
Normal operation cost	$ 1,355.46	$ 1,779.62
Load shifting cost	$ 1,261.58	$ 1,648.31
Annual savings	**$ 93.88**	**$ 131.31**

While this system does achieve annual cost savings, at current battery and inverter prices and TOU rates in Ontario, the system will never payback before the lifetime of the battery is reached. Currently, a residential battery bank of the size used in this experiment (25 kWh), would have a price ranging between $16,000 - $26,500 CAD [14-16].

Table 7 shows cost savings associated with increases in the ratio of both mid- and on-peak TOU prices to the current off-peak price of ¢13.4/kWh – fixed for this analysis. Note that prices along the diagonal represent a two-tiered TOU system, in which on-peak hours are from 7:00 – 19:00. Bolded prices indicate conditions in which a $16,000 battery model with a 10-year lifespan would payback (based on the Tesla Powerwall's claimed performance). Additional advances in residential battery technology are required to reduce system cost, as well as increase their lifetime in order to make load shifting by itself financially viable.

Table 7. Variation of annual savings of ASHP and AHU space heating system with change in TOU prices.

	On-peak ratio					
Mid-peak ratio	Current	3	4	5	7.5	10
Current	$131.31	$281.69	$443.12	$604.56	$1,008.15	$1,411.73
2	$189.20	$339.58	$501.02	$662.45	$1,066.04	$1,469.63
3	-	$459.45	$620.88	$782.32	$1,185.90	$1,589.49
4	-	-	$740.75	$902.18	$1,305.77	**$1,709.36**
5	-	-	-	$1,022.05	$1,425.63	**$1,829.22**
7.5	-	-	-	-	**$1,725.30**	**$2,128.88**
10	-	-	-	-	-	**$2,428.55**

5.3 Emission Analysis

Using generation data from the IESO for the Ontario electricity grid, the emission factor of the grid (gCO_2eq/kWh) could be determined using the values in Table 1. Hourly emission factor averages based on the 2015 dataset are presented in Fig. 5. The annual average emission factor for this year was 58.1 gCO_2eq/kWh.

The values in Fig. 5 were not used for calculation, rather they illustrate at which hours of the day have the highest associated emission factors.

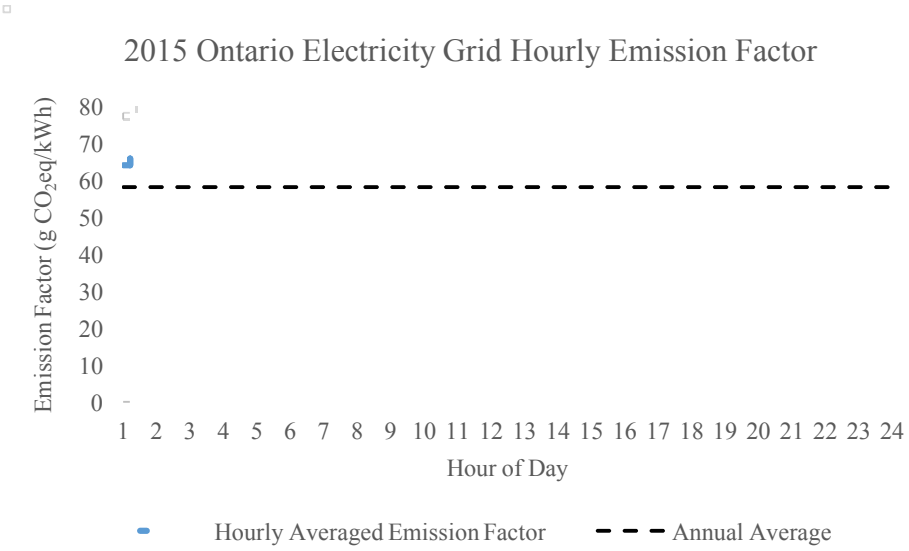


Fig. 5. Hourly averaged emission factors based on 2015 IESO generation data

To determine the GHG emissions associated with load shifting of the ASHP and AHU system, actual generation data from each hour was used for calculations, along with the same power consumption data spanning May 2015 – April 2016 used for the financial analysis. Although off-peak pricing begins at 19:00, Fig. 5 clearly shows that this time of day has the highest grid emission factor of any hour. Therefore, in order to claim reductions in emissions, the time of night at which the battery begins recharging is crucial. Charging times between 19:00 and 2:00 were investigated, since the battery could take a maximum of just under five hours to charge, and recharging should end before 7:00. Table 8 shows that midnight is the optimal time to begin recharging the battery bank based on the current Ontario electricity fuel mix.

Table 8. GHG emissions associated with load shifting.

Battery recharge start time	Normal operating emissions ($kgCO_2eq$)	Load shifted emissions (gCO_2eq/kWh)	Percent Change (%)
7:00 PM	433	481	11.0
8:00 PM		460	6.2
9:00 PM		432	-0.3
10:00 PM		408	-5.8
11:00 PM		395	-8.9
12:00 AM		390	-10.0
1:00 AM		391	-9.7
2:00 AM		397	-8.5

It is worth noting that this analysis assumes that the grid does not change its operation in response to the operation of this battery bank. While this assumption is reasonable for a single residential unit in a province with an estimated 4.9 million dwellings [17], the grid's operation would likely change as a result of widespread battery charging at night.

Currently, Ontario generates a surplus of electricity on an annual basis. This surplus is in large part due to the amount of nuclear energy being generated, which cannot easily be curtailed. When there is a generation surplus, other jurisdictions, such as the United States, are paid to take the excess electricity, or charged a very low price. The adoption of energy storage technologies could provide benefits to both consumers and the utility grid, as energy storage infrastructure (electric vehicles, residential- and grid-scale batteries, etc.) could potentially act as an energy sink for Ontario's surplus generation.

6. Conclusion

This project investigated the operation of an ASHP coupled with a renewable energy/battery storage system, to support the application of ASHPs in residential applications. It has been shown that through the implementation of a basic open-loop battery controller and temperature setbacks, nearly the entirety of the ASHP load can be supplemented by renewables or shifted off-peak. This practice showed some financial savings, however, these savings are not sufficient to make the system as a whole financially viable with current electricity prices. Load shifting also shows the potential to reduce GHG emissions associated with the variable generation fuel mix of the Ontario electricity grid. This work will act as the foundation for further research towards more intelligent energy management systems.

Acknowledgements

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