A TECHNO-ECONOMIC ANALYSIS OF HEAT PUMP SYSTEMS FOR COMMERCIAL BUILDINGS IN THE COLD CANADIAN CLIMATE

Justin, Tamasauskas, Research Officer, CanmetENERGY, Varennes, Quebec, Canada;
Martin, Kegel, Research Officer, CanmetENERGY, Varennes, Quebec, Canada
Roberto, Sunye, Program Manager, CanmetENERGY, Varennes, Quebec, Canada

Abstract: This paper applies a techno-economic analysis to identify promising heat pump integrations in an archetype large office building in Toronto, Canada. A detailed reference case energy model of a typical Canadian ten-story office is first developed using current national energy codes. This model then serves as a base for four market available heat pump systems, including conventional air-source, cold climate air-source, ground-source, and gas-fired absorption heat pumps. Energy performance and utility costs determined from annual system simulations are then analyzed within a techno-economic framework examining capital, maintenance, and operational costs. Results show that cold climate air-source heat pumps and ground-source heat pumps demonstrate the most potential, achieving up to 53% energy savings while reducing lifecycle cost by nearly 15% in comparison to the reference case.

Key Words: heat pumps, commercial buildings, energy modelling, techno-economic analysis

1 INTRODUCTION

Buildings have long been recognized as major consumers of energy, accounting for 30% of all global energy use (IEA 2013). In Canada, the commercial and institutional sector accounts for 14% of all secondary energy use (1205.9 PJ per year), with nearly 60% of this total directed towards space heating, space cooling, and domestic hot water (DHW) (OEE 2010). In order to reduce this energy use, a number of standards and targets for building energy performance have been presented. One of the most widely discussed concepts has been the Net Zero Energy Building (NZEB), which requires that a building balance its annual energy consumption with onsite renewable energy production (IEA HPC 2012). Proper design and operation of NZEBs require the optimal integration and management of renewable energy sources. Heat pumps play an important role in this process because of their ability to efficiently facilitate the integration of renewable energy and thermal storage technologies with the building mechanical system. However, the integration of heat pumps into the built environment is a complex process that involves examining the indoor and outdoor environments, building envelope, and mechanical systems. In order for heat pump systems to achieve a widespread market acceptance, it is important to understand the most effective integrations from an energy and economic perspective.

Previous studies have examined the viability of heat pump systems in Canadian households. Kegel et al (2012) demonstrated the potential of conventional and innovative heat pump systems in typical Canadian homes, while (Tamasauskas et al. 2012) showed that solar and thermal storage systems can achieve significant energy savings in the Canadian climate. However,

further economic and energy savings are possible when examining the economies of scale found in large commercial buildings.

CanmetENERGY has been examining the role of heat pumps in commercial buildings in order to provide consultants and design engineers with the appropriate knowledge and tools to effectively integrate these systems. The overall project objective is to determine optimal heat pump integrations by building type, region, and construction period. Detailed energy models of typical large office and multi-unit residential buildings have been developed. Each building type has been evaluated in five climatic regions across Canada, and according to current and former national building energy codes. These energy models serve as the reference for heat pump integrations involving both novel and market-available heat pump systems throughout Canada.

The objective of this paper is to demonstrate the potential of market-ready heat pump systems for a typical newly constructed large office building in Toronto, Canada. First, an energy model of a large office building is developed as a reference for system integration. This reference building then serves as a base for four heat pump systems encompassing a range of market-available solutions. The results obtained from these models are then integrated with a systematic techno-economic framework to determine the most promising solutions in the Canadian context.

2 DEVELOPMENT OF CANADIAN LARGE OFFICE MODEL

The commercial office archetype used in this study has been developed as part of a larger project, with the details and methodology used for archetype development outlined previously in the literature (Tamasauskas et al. 2013). For the large commercial office archetype, the physical geometry of the building was based on information from previous NRCan projects (Pope 2012) and is representative of typical newly built offices in major Canadian centres. A summary of the key physical parameters is provided in Table 1.

Table 1: Key Physical Parameters of Large Office

Total Floors	10
Total Floor Area	13396 m^2
Aspect Ratio	1.00
Floor-Floor Height	3.96
Glazing Percentage	40 %

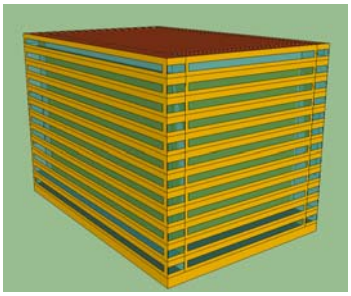
In order to represent new constructions, building envelope and mechanical system performance were based on information provided in the National Energy Code of Canada (NECB) 2011 for buildings (CCBFC 2011). Key building characteristics are summarized in Table 2. All building occupancy and operational schedules were also based on information in the NECB 2011.

Table 2: Building Envelope and Mechanical System Performance

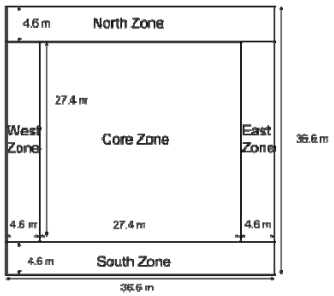
Walls	0.278 $W/m^2°C$
Slab	0.757 $W/m^2°C$ (for 1.2m)
Roof	0.183 $W/m^2°C$
Windows	2.2 $W/m^2°C$
Infiltration	0.25 $L/s/m^2$

Heating Central Plant	Boiler, 83% efficient
Cooling Central Plant	Water cooled electric chiller COP_{rated}=5.17
Ventilation	VAV system, 1 AHU per floor
DHW	Conventional gas boiler

A three dimensional model of the office was developed using the TRNSYS 17 energy simulation program (Klein et al. 2010) (Figure 1a). Each floor was divided into five zones in order to account for the diversity of loads due to differing levels of incident solar radiation (Figure 1b).



a)



b)

Figure 1: a) Three Dimensional Building Energy Model b) Thermal Zoning for Office Model

Annual energy use of the building was calculated to be 179 kWh/m^2, which corresponds well with available data for similarly sized new office buildings in Toronto ((Pope 2012) and (Caneta, 2012)).

3 SYSTEM INTEGRATIONS

The developed base case model served as a reference to examine a range of market-available heat pump systems, including:

Electrically Driven Heat Pumps

i. Air-source heat pump with gas boiler auxiliary (ASHP+Boiler)
ii. Cold climate air-source heat pump (CC ASHP)
iii. Ground-source heat pump (GSHP)

Thermally Driven Absorption Heat Pumps

iv. Air-source gas-fired absorption heat pump (GAHP)

3.1 Electrically Driven Heat Pumps

For all electrically driven heat pumps (ASHP, CC ASHP, GSHP), system integration was based on the use of a multi-split system. Each thermal zone was fitted with a dedicated outdoor unit connected via refrigerant piping to a series of smaller indoor units located throughout the zone. A separate constant volume ventilation system on each floor replaced the VAV base case system in order to provide sufficient fresh air to the building occupants.

3.1.1 Air-Source Heat Pump with Boiler

This concept integrates a conventional commercial air-source heat pump into the building, with the ambient air acting as a low grade thermal source or sink for the outdoor condensing unit. The examined heat pump had a rated heating COP of 4.5 and a rated cooling COP of 4.4 based on manufacturer data (Mitsubishi 2010), and was selected to be representative of a high efficiency conventional air-source unit. The heat pump system itself was sized for the peak cooling load, eliminating the need for a chilled water loop in the building. As conventional air-source heat pumps begin to lose significant heating capacity below 0°C, an auxiliary heating system was also implemented consisting of a natural gas boiler with hydronic baseboards sized for the peak heating load.

Control of the system was based on thermostats located in each thermal zone. In cooling mode the heat pump operated as necessary in order to maintain the desired space temperature. The control strategy was more complex in heating mode, as the conventional air-source heat pump has a diminished heating capacity at lower ambient air temperatures. In this case, auxiliary hydronic baseboards were used to supplement heat pump operations as necessary in order to maintain the desired room temperature.

3.1.2 Cold Climate Air-Source Heat Pump

This concept operates on the same principles as the conventional air-source heat pump, with the ambient air acting as a source of thermal energy for the heat pump. The main difference between the cold climate heat pump and the conventional air-source unit discussed above is the ability of the cold climate unit to retain a significant portion of its heating capacity below 0°C.

Figure 2 compares the normalized heating capacity of cold climate and conventional air-source heat pump units (Mitsubishi 2010). The cold climate heat pump is able to maintain within 25% of its rated capacity throughout the complete operating range of ambient temperatures, while the conventional air-source unit shows significant degradation of heating capacity below 0°C. Of additional importance is the extended operating range of the cold climate unit, which is particularly appealing in the cold climates of Canada.

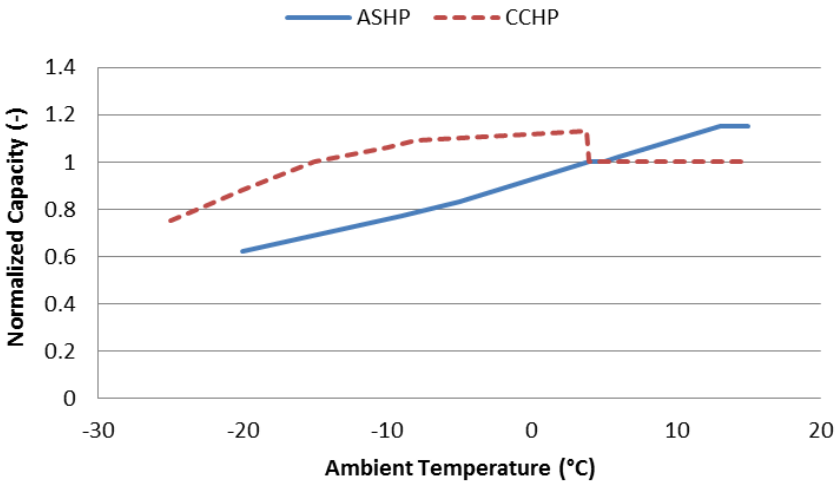


Figure 2: Comparison of ASHP and CCHP Performance

The cold climate unit used in the analysis had a rated heating COP of 3.8 and a rated cooling COP of 3.5 obtained from manufacturer data (Mitsubishi 2010). Each heat pump was sized for the peak load (heating or cooling) in each zone. Due to the extended operating range and improved capacity of the cold climate unit, no auxiliary heating or cooling equipment was required, with the heat pump units operating as necessary in heating or cooling to maintain the desired setpoint temperature.

3.1.3 Ground Source Heat Pump

This integration focuses on using the ground as a thermal source or sink for the heat pump system. Unlike the ambient air, deep ground temperatures remain relatively constant throughout the year, offering a stable source temperature for the heat pump. Proper sizing of the ground heat exchanger system is vital for optimal system operations. For this study, borehole sizing was performed based on the peak thermal load of the building using the spreadsheet by (Philippe et

al. 2010). A total of 64 boreholes were used in an 8 by 8 arrangement, with each borehole 125 m in length using a double U-Tube design.

Each ground-source heat pump unit used in the system had a rated heating COP of 6.1 and a rated cooling COP of 5.71 (Mitsubishi 2010). No auxiliary heating or cooling equipment was required since the borefield was sized to the meet the peak thermal loads of the building.

3.2 Air-Source Gas-Fired Absorption Heat Pump

The final system examines the potential of using a thermally driven heat pump. Similar to the air-source units discussed above, the absorption heat pump uses the air as a source of thermal energy for the unit. However, instead of using electricity to drive a vapour compression cycle, the unit relies on a natural gas burner to provide the necessary thermal input to an absorption cycle. The primary objective of this integration is to examine the potential operating cost savings resulting from the lower cost of natural gas versus electricity in the Toronto region.

Unlike the electrically driven heat pump systems, the gas fired heat pump operated in an air to water configuration and was designed to integrate with the base case VAV and baseboard system. The building was equipped with a heat pump array capable of meeting the peak heating loads of the building (approximately 915 kW). The gas fired heat pump had a rated gas use efficiency (capacity divided by gas input) of 1.26 in heating mode (Robur 2013). Since the gas-fired heat pump had a low COP in cooling mode in comparison to a standard electric chiller, the unit was operated in heating mode only in order to achieve the most energy efficient configuration. In this case all cooling was achieved using the same electric water cooled chiller as the base case.

4 TECHNO-ECONOMIC ANALYSIS

The objective of this study is to determine preferred heat pump integrations in Canadian commercial buildings. To properly assess the viability of each proposed system, it is important to examine not only the energy performance but also the economics of each design. As such, each heat pump integration was examined within a techno-economic framework over a lifecycle of 30 years. Economic factors focused on capital, maintenance, and operational costs. All lifecycle calculations were based on an inflation rate of 3%, a discount rate of 6%, and natural gas and electricity escalation rates of 1.4% and 0.4% respectively (CCBFC 1997).

4.1 Capital and Maintenance Costs

Capital cost analysis was performed at the component level, and included all major equipment and controls. A summary of included equipment is provided in Table 3.

Table 3: Included Components in Capital Cost Analysis

Category	Included Equipment
Primary Heating/Cooling Equipment	Chiller, Boiler, Heat Pumps (condensing units), Cooling Tower,
Circulation	Pumps, Fans, Heat Recovery, Ventilation Units
Distribution	Water Piping, Refrigerant Piping, Air Ducts
Terminal Units	Heat Pump (Indoor Units), Baseboards, VAV boxes
Control	Thermostats, Valves, VFD Drives, Sensors/Receivers, OA Reset, Economizer
Borefield	Ground Heat Exchanger, Antifreeze

All component costs used in the analysis included both material and labour costs. All material heat pump costs were obtained from manufacturer supplied pricing lists ((Mitsubishi 2013), (Robur 2010)), while labour costs were estimated from (RS Means 2013). Ground heat exchanger costs were estimated to be $80/m (Kummert and Bernier 2008) and assumed to include all necessary ground loop piping and connections. All remaining material and labour costs were obtained from RS Means.

Annual maintenance costs were also determined for each system based on information derived from ASHRAE (Cane et al. 1998). Due to a relative lack of information, it was assumed that all electrically driven heat pump systems had similar maintenance costs. ASHP maintenance costs were higher since the auxiliary boiler system must also be maintained, while the GAHP was assumed to have the same maintenance costs as the base case because of its similar integration.

Table 4 summarizes the estimated capital and maintenance costs for each system.

Table 4: Summary of Capital and Maintenance Costs

System	Capital Costs (k$)	Annual Maintenance Cost (k$)
Base Case	$1,947	$49
ASHP + Boiler	$2,368	$48
CCASHP	$2,036	$16
GSHP	$2,276	$16
GAHP	$2,575	$49

4.2 Utility Costs

Annual natural gas and electricity costs were estimated based on current utility rates and structures for commercial clients in the Toronto area. Electricity rates were obtained from (Toronto Hydro 2013), while natural gas rates were obtained from (Enbridge Gas 2013). A summary of key monthly and usage charges is provided in Table 5 (electricity), and Table 6 (Natural Gas).

Table 5: Electrical Utility Rate and Structure

Charge	Tier/Category	Value
Use Charges	First 750 kWh	$0.0873/kWh
	Over 750 kWh	$0.1003/kWh
Monthly Charges	Customer and Supply	$687.39/month
Demand Charges	Network + Connection	4.1140 $/kW
	Distribution	4.4497 $/kVa

Table 6: Natural Gas Utility Rate and Structure

Charge	Tier/Category	Value
Monthly Charge	Customer Charge	\$70/month
Supply, Transport, Delivery	First 500 m^3	\$0.2854/m^3
	Next 1050 m^3	\$0.2686/m^3
	Next 4500 m^3	\$0.2568/m^3
	Next 7000 m^3	\$0.2492/m^3
	Next 15250 m^3	\$0.2459/m^3
	Above 28300 m^3	\$0.2450/m^3

5 RESULTS AND DISCUSSION

Each system integration was simulated in TRNSYS over a full year using a TMY2 weather file for the Toronto region. A time step of approximately 5 minutes was used in order to accurately represent the control logic of the heat pumps and other equipment.

5.1 Energy Performance

Table 7 summarizes the energy performance of each heat pump system. It is evident that integrating electrically driven heat pumps into the building results in a substantial decrease in total energy use, with the heat pump systems achieving total reductions between 45% and 53%. The lowest total energy use is achieved with the GSHP, primarily due to the higher COP of the water-source heat pump unit, and the stable source temperature provided to the heat pump from the ground heat exchanger.

An examination of results at the end use level identifies some important points. All electrically driven heat pumps demonstrate a clear reduction in the energy use for space heating, since the heat pump is displacing a boiler with a much lower overall efficiency. Of additional interest are the reductions in fan and pump energy use with the electrically driven heat pump systems. This is particularly pronounced in the CC ASHP and GSHP cases, as these systems are designed to act as the primary source of heating and cooling throughout the year. This eliminates the need for auxiliary hydronic heating and VAV air distribution systems, resulting in significant energy savings.

An analysis of the gas assisted heat pump also identifies potential energy savings. As with the electrically driven systems, the GAHP is able to achieve a substantial reduction in heating energy in comparison to the base case design, primarily due to the superior COP of the absorption heat pump ($COP_{GAHP,Heat}$=1.26, COP_{Boiler}=0.83). This results in a 37% reduction in heating energy and an overall energy use reduction of 18% from the base case, demonstrating the potential benefits of the system from an energy perspective.

It is important to note that heating energy use for both the GAHP and base cases represents primary energy consumption, while for the electrically driven heat pumps the heating and cooling energy represents secondary energy use. As such, while energy use reductions for the GAHP appear modest compared to the electrically driven units, the electricity generation profile of the region may lead to more substantial reductions from a primary energy perspective.

Table 7: System Energy Performance

	Case				
	Base Case	ASHP+Boiler	CC ASHP	GSHP	GAHP
Heating (MWh)	1,137	271	150	58	717
Cooling (MWh)	104	77	140	104	104
Fans and Pumps (MWh)	256	48	47	67	256
DHW (MWh)	144	144	144	144	144
Lighting & Appliances (MWh)	751	751	751	751	751
Annual Natural Gas Use (MWh)	1,281	382	144	144	861
Annual Electricity Use (MWh)	1,111	909	1,089	980	1,111
Total (MWh)	2,392	1,292	1,233	1,124	1,972
Normalized Energy Use (kWh/m^2)	179	96	92	84	147

5.2 Techno-Economic Performance

Table 8 summarizes the lifecycle economic performance of each system. The results show that total cost savings can be obtained with any of the three electrically driven heat pump systems proposed. In particular, the CC ASHP and GSHP systems are able to obtain a nearly 15% reduction in lifecycle costs in comparison to the base case. In addition to their superior energy performance, these systems also offer the building owner significantly reduced maintenance costs through the elimination of more complex mechanical equipment.

While all the electrically driven heat pumps had lower lifecycle costs than the base system, these cost savings were not as substantial as the calculated energy reductions. An examination of the utility costs shows that strong energy savings do not necessarily translate into significant economic benefits. Although electrically driven heat pumps were able to achieve between 45% to 53% energy savings, total utility costs savings do no exceed 23%, primarily due to the current lower price of natural gas in comparison to electricity in Toronto.

The primary objective of the GAHP analysis was to make use of the lower natural gas prices available in Toronto. However, while this system was able to achieve substantial utility cost savings, this was outweighed by the significant capital costs associated with this integration, resulting in a system with the highest total lifecycle costs.

Table 8: Techno-Economic Analysis

	Case				
	Base Case	ASHP+Boiler	CC ASHP	GSHP	GAHP
Capital Cost (k$)	$1,947	$2,368	$2,036	$2,276	$2,575
Lifecycle Utility Cost (k$)	$2,740	$2,052	$2,341	$2,122	$2,605
Lifecycle Maintenance Cost (k$)	$688	$675	$221	$221	$688
Lifecycle Cost (k$)	$5,376	$5,095	$4,599	$4,619	$5,868

5.3 Discussion

From both an energy and economic perspective, it is clear that heat pumps can play a significant role in meeting the heating and cooling loads of a typical office building. In general, the preferred design should be able to serve as the primary source of heating and cooling throughout the year. This minimizes both capital and maintenance costs, resulting in substantial benefits for the building owner. Selection of the CC ASHP or GSHP systems can be largely dependent on the building designer's tolerance to initial capital costs, with the GSHP having a higher initial cost but offering superior energy performance.

It is important to remember that all results are presented within the context of the climate and utility rate structure of the Toronto region. While the GAHP system does not appear to be most beneficial option in the current study, a region with higher heating loads and larger discrepancies between gas and electricity prices (e.g. Alberta) could show significant promise. Likewise, in regions where natural gas prices and electricity are more closely matched (e.g. Quebec), the cost savings of electrically driven heat pump integrations could be more on-par with the calculated total energy savings (i.e. Larger cost savings would be seen). These possibilities will be addressed as part of a larger project, along with the impact of different building types and construction periods, and the potential of novel systems integrating heat pump technologies with solar energy and thermal storage.

6 CONCLUSION

This study has examined the potential of heat pumps in a typical large office in Toronto, Canada. A reference case model was first created with the TRNSYS energy simulation program using current energy codes and standards. The model then served as a base for the examination of four market-available heat pump systems, including a conventional air-source heat pump (ASHP), a cold climate air-source heat pump (CC ASHP), a ground-source heat pump (GSHP), and a natural gas driven absorption heat pump (GAHP). Each system was analyzed from an energy and lifecycle cost perspective to identify preferred solutions. In general, all electrically driven heat pump systems demonstrated significant energy and economic savings, with the CC ASHP and GSHP systems showing the most potential. Overall, the CC ASHP and GSHP systems were able to achieve the highest energy and cost savings, with an up to 53% reduction in total energy use and a 15% reduction in lifecycle costs. While these results are case specific, they demonstrate the high potential of heat pump systems in Canada. Further work as part of a larger project will expand the analysis to other building types, climate regions, and construction periods in Canada.

7 ACKNOWLEDGEMENTS

This project has been funded by the Natural Resources Canada Program of Energy Research and Development (PERD) Built Environment Heat Pump program. The authors also wish to thank Mr. Stephen Pope for his valuable insights into archetype development.

8 REFERENCES

Canadian Commission on Building and Fire Codes (CCBFC) 2011. “National Energy Code of Canada for Buildings (NECB) 2011,” National Research Council of Canada, Ottawa.

Canadian Commission on Building and Fire Codes (CCBFC) 1997. “Model National Energy Code of Canada for Buildings (MNECB) 1997,” National Research Council of Canada, Ottawa.

Cane D., A. Morrison, and C. Ireland 1998. “Maintenance and Service Costs of Commercial Ground-Source Heat Pump Systems,” *ASHRAE Transactions*, Vol. 104, No. 2, pp. 699-706.

Caneta 2012. “ASHRAE 90.1 2012 and NECB 2011 Cross Canada Comparison,” Caneta Research, Toronto.

Enbridge 2013. “Gas Rates,” Enbridge Gas Distribution. Available at: www.enbridgegas.com/businesses [Accessed January 2013]

International Energy Agency (IEA) 2013. “Energy efficiency,” Available at: www.iea.org [Accessed January 2013]

IEA Heat Pump Centre (IEA HPC) 2012. “The role of heat pumps in net zero energy buildings,” *IEA Heat Pump Centre Newsletter*, Vol. 30, Iss. 3, pp. 3.

Kegel M., Sunye R., Tamasauskas J. 2012. “Life cycle cost comparison and optimization of different heat pump systems in the Canadian climate,” *Proceedings of eSim 2012*, IBPSA-Canada, Halifax.

Klein S. A., et al., 2010. “TRNSYS 17 – A TRaNsient SYstem Simulation program, user manual,” University of Wisconsin-Madison, Solar Energy Laboratory, Madison.

Kummert, M. and M. Bernier 2008. “Sub-hourly simulation of residential ground coupled heat pump systems,” *Building Service Engineering Research and Technology*, Vol. 29, No 1, pp. 27-44.

Mitsubishi 2010. “City Multi Data Book,” Mitsubishi Electric, Japan.

Mitsubishi 2012. “City Multi Product Pricing Guide,” Mitsubishi Electric Cooling and Heating, Suwanee, USA.

Office of Energy Efficiency (OEE) 2010. “Energy efficiency trends in Canada 1990 to 2007,” NRCan, Ottawa.

Pope S. 2013. Personal email communications, January 2013.

Philippe M., M. Bernier, and D. Marchio 2010. “Vertical Geothermal Boreholes: Sizing Calculation Spreadsheet,” *ASHRAE Journal*, July 2010, pp. 20-28.

Robur 2010. “Price list: High efficiency integrated heating and cooling systems,” Robur S.p.A., Verdillino, Italy.

Robur 2013. “GAHP Line AR Series,” Robur S.p.A., Verdillino, Italy.

RS Means 2013. “RS Means Mechanical Cost Data 2013,” Reed Construction Data, Norwell, USA.

Tamasauskas J., Poirier M., Zmeureanu R., Sunye R. 2012. “Modeling and optimization of a solar assisted heat pump using ice slurry as a latent storage material,” *Solar Energy*, Vol. 86, Iss. 11, pp. 3316-3325.

Tamasauskas J, Kegel M, Sunye R. 2013. “Development of Canadian Building Archetypes in TRNSYS for NZEB Analysis,” *Proceeeds of EIC Clinate Change Technology Conference 2013,* Engineering Institute of Canada, Montreal.

Toronto Hydro 2013. “Electricity Rates-Business Rates,” Toronto Hydro-Electric Systems. Available at: www.torontohydro.com [Accessed January 2013]