ecoENERGY Innovation Initiative

Research and Development Component

Public Final Report

Project: EEBE-024 Intelligent Net-Zero Energy Buildings

Table of contents

1 Project Snapshot

Project Title	**Intelligent Net-Zero Energy Buildings**
Project Identification Number	*EEBE-024*
Proponent	Concordia University
Number of Participating Partners	3 (directly) and about 20 indirectly (SNEBRN)
Total Project Cost ($000s)	1731
Total Contribution from Proponent and partners ($000s)	731
Total ecoEII Contribution ($000s)	1000
Total Government Contribution ($000s)	1000
Project Highlights	o A key scientific and engineering achievement from the work in IEA SHC Task 40 / EBC Annex 52 is the completion of the state-of-the-art advanced book "Modelling, Design, and Optimization of Net-Zero Energy Buildings". It was published by Wiley in February 2015 (374 pages) co-edited by Athienitis and O'Brien. The book includes fundamental sections on modeling and design as well as four detailed and well documented case studies, one of which is EcoTerra. About two thirds of the book were written by a group of 10 researchers and doctoral students associated with SNEBRN and participating in Subtask B of the above IEA task. o The design of geothermal bore fields relies on the determination of long-term thermal response factors (g-functions) which are typically obtained from numerical or analytical models. Using dimensional analysis to reduce testing time, a small-scale borehole was designed and fabricated to validate these models experimentally. The borehole was inserted in an existing sand tank with known properties. Test and simulation results constitute the first known experimental validation of g-functions. Dual U-tube prototypes were built and used to validate new numerical models; dual U-tube boreholes are particularly promising for geothermal systems. o New building-integrated photovoltaic/thermal system designs which eliminate the need for unglazed transpired collector and instead utilize distributed inlets have been developed and tested at Concordia's Solar Simulator. These systems have combined thermal and electrical efficiency of up to about 60% and enable optimized design configurations for NZEBs. o Novel integrated energy system configurations that combine liquid solar and PVT collectors with heat pumps were tested and modelled. o Novel predictive control algorithms for high performance buildings were developed and tested.
Date submitted to NRCan	August 31, 2016

2 Executive Summary

The objective of this project is to undertake complementary research to model development under the NSERC Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) research program at Concordia University and selected network university partners, with emphasis on applications, field trials and proof of concept of innovative systems that will advance the goal of optimising energy efficiency and integrating renewable technologies in buildings to drive them towards responsive, smart net-zero energy targets.

A key scientific and engineering achievement from the work in IEA SHC Task 40 / EBC Annex 52 is the completion of the state-of-the-art advanced book "Modelling, Design, and Optimization of Net-Zero Energy Buildings". It was published by Wiley in February 2015 co-edited by Athienitis and O'Brien. The book includes fundamental sections on modeling and design as well as four detailed and well documented case studies, one of which is EcoTerra. About two thirds of the book were written by a group of 10 researchers and doctoral students associated with SNEBRN and participating in Subtask B of the above IEA task.

The project studied selected promising technologies that will enable net-zero energy buildings, including building-integrated photovoltaic/thermal (BIPV/T) systems, solarium with active thermal storage, dual U-tube borehole storage for geothermal systems, solar source heat pump systems and predictive control strategies. New façade BIPV/T designs which eliminate the need for unglazed transpired collector and instead utilize distributed inlets have been developed and tested at Concordia's Solar Simulator, demonstrating a simplification in design that results in reduced cost and higher combined thermal-electrical efficiency.

The design of geothermal bore fields relies on the determination of long-term thermal response factors, known as g-functions, which are obtained from numerical or analytical models. Using dimensional analysis to reduce testing time, a small-scale borehole was built to validate these models experimentally. Test results from the small scale prototype constitute the first known experimental validation of g-functions. Dual U-tube prototypes were built and used to validate new numerical models; these boreholes are particularly promising for enhancing efficiency of geothermal systems.

Novel predictive control algorithms were developed and tested in a building with a hybrid ventilation system. Model predictive control algorithms were also developed to optimize solar energy utilization and reduce peak demand in NZEBs and high performance buildings in general.

3 Introduction

The project was conducted between *2011* and *2016* at the partner locations. It involved directly two partners in addition to the Proponent and indirectly much of SNEBRN. Natural Sciences and Engineering Research Council of Canada (NSERC) awarded the Proponent and 14 other partner universities a strategic research network grant of $5 million over 5 years (2011-2016). The network named NSERC Smart Net-zero Energy Buildings Strategic Research Network (SNEBRN) was funded after an international review and a site-visit. SNEBRN aims to perform the research that will facilitate widespread adoption in key regions of Canada, by 2030, of optimized net- zero energy buildings (NZEB) energy design and operation concepts suited to Canadian climatic conditions and construction practices, and to influence long-term national policy on the design of NZEB and communities in association with the Proponent's partners. Whereas the SNEBRN research program activities focus on the development of general modelling and methodologies, this Project encompasses tasks that are not funded by the NSERC funding and focuses on proof-of-concept, validation and pre-demonstration field trials of advanced building concepts studied under SNEBRN; that will advance the goal of optimising energy efficiency and integrating renewable technologies in buildings to drive them towards responsive, smart net-zero energy targets.

4 Background

The main SNEBRN goal is to investigate optimal pathways for achieving zero average annual energy consumption at both the building and neighborhood levels through combinations of passive systems and dynamic building envelope technologies that include building-integrated solar systems and high performance windows with active control of solar gains, short-term and seasonal thermal storage, heat pump systems, combined heat and power technologies and smart controls. In doing this, SNEBRN aims for simultaneous reduction and optimal shifting of peak loads through techniques such as predictive control both at the building and neighborhood scales. The design and operation of a smart NZEB needs to address a number of technological solutions. Thus, a multidisciplinary approach is required, and the five (5) research themes have emerged after considering the strategic priorities, the learning under the SBRN, the state-of-the-art, and the importance of load/generation profiles.

The Proponent plays a key leadership role in SNEBRN as a result of their expertise and leadership in building engineering in Canada. They have played a central role in the development of both SNEBRN and the preceding NSERC Solar Buildings Research Network (SBRN). The Principal Investigator and Scientific Director of SNEBRN is a professor in the Proponent's Department of Building Engineering, and the Proponent houses the SNEBRN network secretariat.

5 Objectives

This EcoEII Project managed by the Proponent on behalf of the SNEBRN advances the goal of optimising energy efficiency and integrating renewable technologies in buildings to drive them towards responsive, smart net-zero energy targets. It is composed of three phases that complement and expand on the research and development (R&D) projects currently being undertaken in SNEBRN. These activities and associated experiments were performed at the Proponent's Solar Simulator and Environmental Chamber (SSEC) Test Facility, the Queen's Solar Test and Educational Centre, and Solar Calorimetry Laboratory and at Polytechnique. Whereas the SNEBRN research program activities focus on the development of general modelling and methodologies, this Project encompasses tasks that are not funded by the NSERC funding and focuses on proof-of-concept, validation and pre-demonstration field trials of advanced building concepts studied under the SNEBRN initiative. This Project relates to four project objectives, and work was managed in three phases.

5.1 Objective 1 – Energy-plus envelope systems

This objective was to characterize the energy performance of novel envelope system designs including advanced glazing systems and building-integrated photovoltaic - thermal (BIPV/T) systems to move towards positive energy envelopes that are needed to achieve net-zero energy buildings. The

Proponent's solar simulator integrated with an environmental chamber (SSEC) was utilized to test active building envelope concepts under controlled and repeatable environmental conditions. This Project involved design and building of novel concepts for envelope systems such as:

(a) Facade systems that integrate photovoltaic/thermal (PV/T) systems with multiple inlets, eliminating the transpired collector plate, reducing installation time and cost, and improving quality through pre-engineering and prefabrication; and

(b) PV/T roof designs that improve overall efficiency through heat transfer enhancement options and manifold designs with reduced pressure drop.

Both designs were also applied to Northern housing concepts. Various parameters of each of these configurations were monitored to establish how each configuration measures up to the net-zero energy criteria for a building. The measurements of these parameters were used to establish appropriate performance indices of the envelope system tested, which will be used to validate models and generalize the findings. The models and guidelines developed assist designers to predict the energy performance of the above envelope systems at the schematic design stages.

This work built on previous world class work under the SBRN and two world leading demonstration projects led by SBRN – the EcoTerra house with its innovative BIPV/T roof system and its integrated energy system and the JMSB BIPV/T facade project at Concordia. It benefited from the establishment of the world class Solar Simulator and Environmental Chamber (SSEC) lab to develop, model and test new concepts for BIPV/T systems, including a new design that has multiple inlets in the PV frames.

5.2 Objective 2 - Retrofit of urban flat-roof buildings with integrated solaria/greenhouses and BIPV/T

This component was to study and develop optimal design concepts for retrofit of flat roofs with systems that integrate three functions – solarium, greenhouse, and solar heat and electricity production to facilitate reaching net-zero energy performance. This component was to examine through modeling, simulation and validation of the potential benefits of this concept as a technology that will facilitate reaching net-zero energy building status through electricity production and by utilizing the extra heat for the building heating needs.

A prototype of a novel fenestration system, including solar gain control (with motorized solar screens and hybrid ventilation) was built for testing and validation in the solar simulator – environmental chamber. System design also considered type and quantity of thermal storage, and BIPV/T area to balance heat and electricity production.

Meeting this objective results in a promising solution to retrofit of flat roofs of existing buildings that are often poorly insulated and turns them into net-energy generating surfaces that may contribute to converting existing buildings to net-zero energy systems.

5.3 Objective 3- Integrated solar and heating, ventilation and air conditioning (HVAC) systems

This component was to undertake laboratory experiments and pre-demonstration field trials in integrating solar technologies and HVAC systems with emphasis on proof-of-concept that is not covered under SNEBRN research program. Two concepts are considered.

Activity 1: Building integrated solar thermal, photovoltaic (PV) and combined PV/thermal concepts: Investigation of a dual-mode building integrated solar array for domestic hot water (DHW) and air heating and a tri-generation, building integrated solar array that sequentially, or alternatively, heats hot water, make-up air, and produces PV generated electricity – optimizing valuable roof and façade real-estate while maximizing energy production. Meeting this objective provides an integrated solution for generating DHW, solar electricity and heating fresh air through a small surface area on a roof.

Activity 2: Proof-of-concept laboratory experiments on small-scale double U-tube boreholes with two independent circuits: Borehole thermal energy storage systems offer the possibility of storing solar energy or waste heat over long periods. This activity was to undertake laboratory experiments on small-scale double U-tube boreholes with two independent circuits. These experiments were performed at École Polytechnique de Montréal using an existing facility consisting of a reservoir containing approximately 4 tons of laboratory-grade sand with known thermal properties.

The objective was met. Experiments were performed on two borehole prototypes. The first prototype was a single U-tube borehole while the second included two U-tubes fed by two independent circuits. The experiments led to the validation of numerical models of boreholes. These models are used to perform simulations on borehole thermal energy storage (BTES) systems. Thus, this work could potentially have an impact on BTES design improvements.

5.4 Objective 4 – Integrated design and control concepts of net-zero energy buildings

This objective focused on undertaking research in support of cost-effective approaches to design, build and operate net-zero energy buildings and of Canada's lead contribution to develop and publish the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 40/ Energy Conservation in Buildings and Community Systems (ECBCS) Annex 52 (T40A52) sourcebook on modelling, design process and tools (Vol. 2).

Activity 1: Integrated design and control concepts for NZEBs (houses and small commercial): Develop an optimal net-zero energy house model that combines a building-integrated solar system, passive solar design and a solar source heat pump plus thermal storage. The model will also integrate daylighting, natural/hybrid ventilation and predictive control.
Meeting this specific sub-objective will support adoption of NZEB design and operation concepts by the industry.

Activity 2: Predictive control strategies for small buildings: Develop robust predictive control strategies that optimize solar energy utilization from two sources, windows with controlled shading devices and a BIPV/T system. The key challenge is to manage the collected heat while avoiding indoor space overheating and to store thermal energy for later use, and reducing peak demand and optimizing electricity supplied to the grid.

Activity 3: The originally planned development of a prototype net-zero energy homeowner's toolkit for on-going commissioning of energy use and cost of a house was reoriented towards lab scale test-room and full scale office predictive control studies due to the fact that it was not possible to find a suitable case study house. A test-room in the SSEC lab and the Concordia EV building (hybrid ventilation, heuristic predictive cooling) were used in this activity.

The optimal operating strategies and predictive control strategies under activities 2 and 3 will allow management of actively and passively collected solar heat while minimizing indoor space overheating and to store thermal energy for later use. Through flexible cost function options, they allow maintaining or improving thermal comfort while minimizing the energy bill and/or reducing peak demand. The results of activities 2 and 3 will foster wider market acceptance of cost-effective approaches to operate net-zero energy and high performance buildings.

6 Results of Project

6.1 Project Achievements

6.1.1 Achievement 1: Novel energy positive envelope system prototypes and models (Concordia group)

To achieve net-zero energy buildings, their envelopes need to be energy positive and generate solar electricity, solar heat and optimize use of passive solar gains. Novel building-integrated photovoltaic/thermal (BIPV/T) prototypes were designed, built and tested in the Concordia SSEC lab including multiple inlets as opposed to one air inlet in previous studies and have been instrumented. A custom semitransparent BIPV/T façade for a greenhouse/solarium was also built in collaboration with partner Centennial Global Solar. Simulation models have been validated based on the prototype tests and the validated models are employed to develop improved designs. New façade BIPV/T designs which eliminate the unglazed thermal collectors (UTC) and instead utilize distributed inlets were developed and tested in the internationally unique SSEC Laboratory at Concordia (Fig. 1a). A typical test is shown in Figure 1 and key results in Figure 2, which show an improvement in thermal performance of 10% when two inlets are used (as opposed to 1) with transparent back sheet on the PV. Doctoral student Tingting Yang completed her doctoral thesis that documents the detailed experiments in the SSEC laboratory. The work was applied to northern housing by PhD student Ahmed Kayelo.

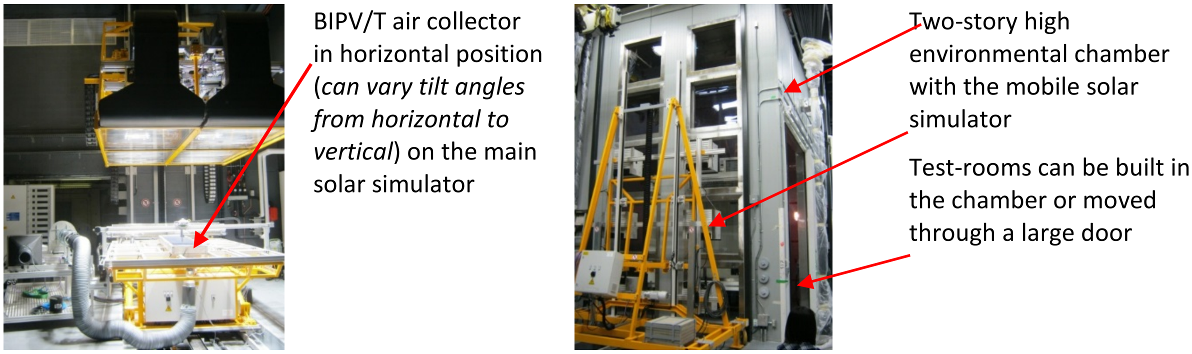


Figure 1a. Solar Simulator – Environmental Chamber facility (SSEC)

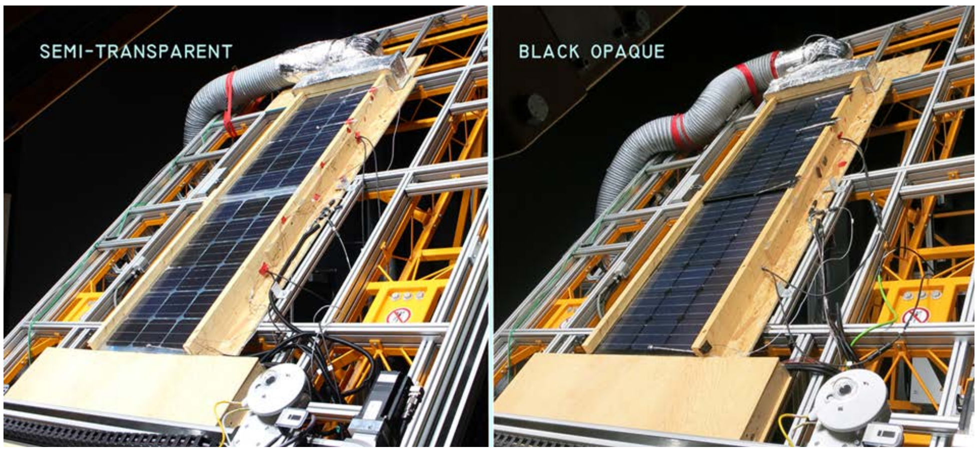


Figure 1b. BIPV/T tests with multiple inlets (2 in this case) tested in SSEC lab (left: with transparent back sheet; right: opaque back sheet).

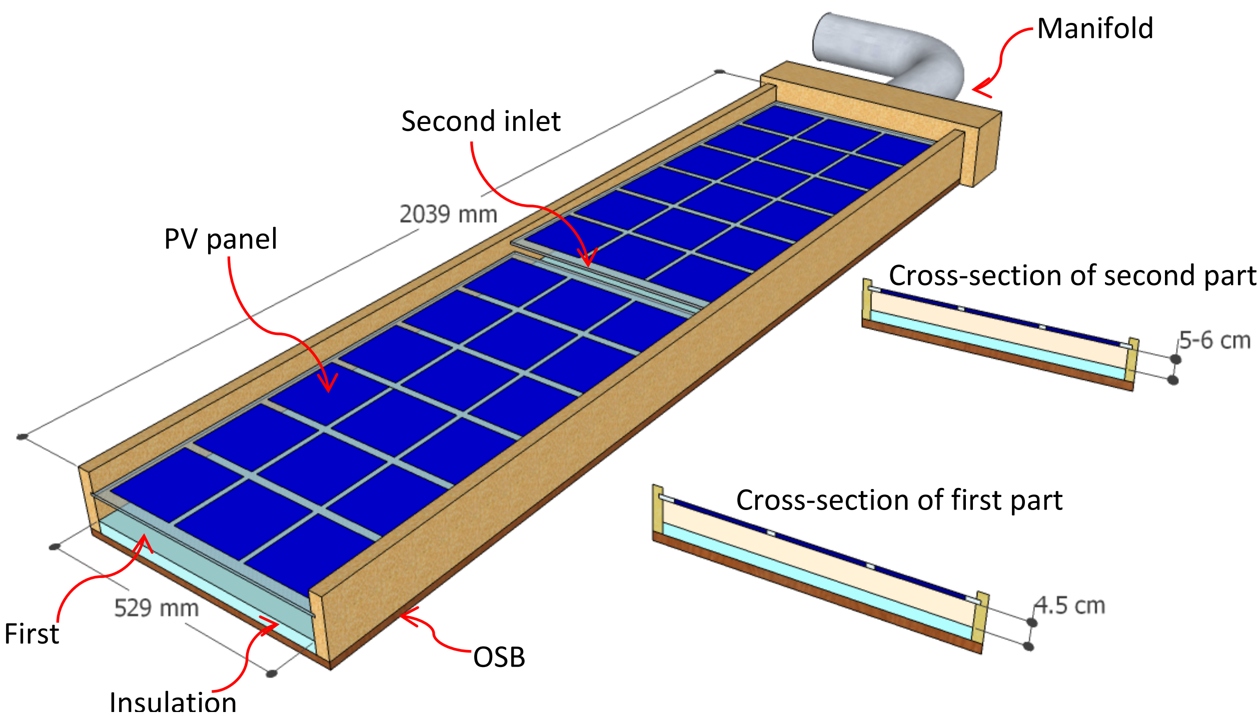


Figure 1c. Schematic of the semi-transparent BIPV/T system prototype with two inlets tested in SSEC

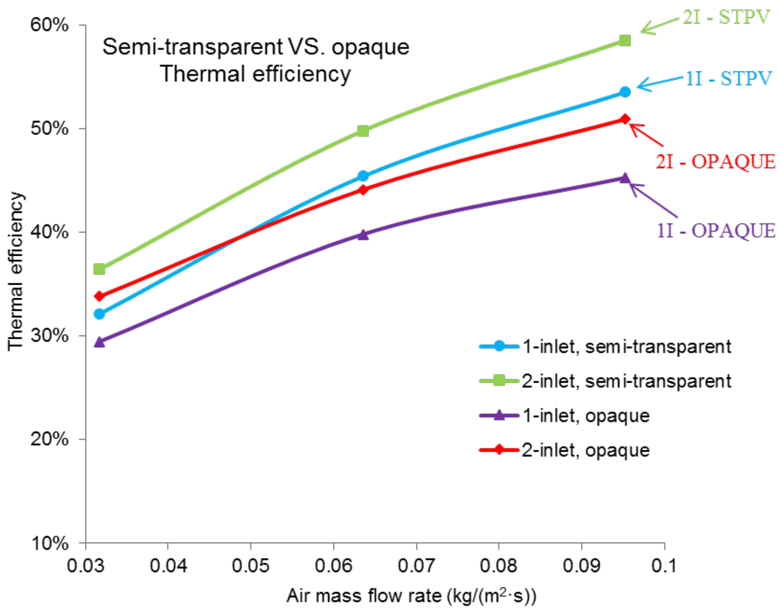


Figure 2. Comparative results of 2-inlet versus 1-inlet with STPV vs opaque PV

Key Outputs:

(a) SSEC facility development (a unique lab in the world) and novel BIPV/T porotypes

(b) *Journal papers:*

Yang, T. and A. Athienitis (2014). "A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets." Solar Energy 104: 82-92.

Yang, T. and Athienitis, A.K. (2015). "Experimental investigation of a two-inlet air-based building integrated photovoltaic/thermal (BIPV/T) system", Applied Energy, Vol. 159: 70-79.

(c) *Conference papers*

Vasan, N. and Stathopoulos, T., (2013). "The Effect of Wind Velocity Distribution on Unglazed Transpired Collectors", Building Simulation 2013 Conference, August, 25-28, Chambery, France.

Kayello, A., Athienitis, A., & Ge, H. (2016). Natural Ventilation of Attics Coupled with BIPV/T in Arctic Climates. eSim 2016 Conference, Hamilton, Ontario, May.

(d) Theses

Vasan, N. (2012). Experimental Study of Wind Effects on Unglazed Transpired Collectors MASc thesis, Concordia University.

Yang, T. (2015). A Numerical and Experimental Investigation of Enhanced Open-Loop Air-Based Building-integrated Photovoltaic/Thermal (BIPV/T) Systems. Ph.D. Thesis, Concordia University.

6.1.2 Achievement 2: Development of designs for integrated solaria/greenhouses and BIPV/T

At Concordia, a model for fenestration systems with two controllable layers for solaria/greenhouses has been developed (Diane Bastien; doctoral student in building engineering, supported by FQRNT scholarship). A test-room prototype has been built (Fig. 3), in part to validate Diane's solarium model and to develop and test near optimal control strategies to enhance solar energy utilization. It includes controlled motorized interior and exterior shades, controlled heating and phase-change materials (PCM) (Dupont Energain panels) as 5 layers in the back wall. The PCM was used as both passive and active storage (active with airflow through the wall). The prototype sunspace/solarium integrating a PCM wall with active charging and motorized blinds has been tested in the SSEC lab. Doctoral student Diane Bastien has completed her thesis and two journal papers focused on a design methodology for the facade system and thermal storage. A custom semitransparent BIPV/T façade for a greenhouse/solarium was also built in collaboration with partner Centennial. Simulation models have been validated based on the prototype tests and an eSim 2016 conference paper was written and presented by doctoral student James Bambara.

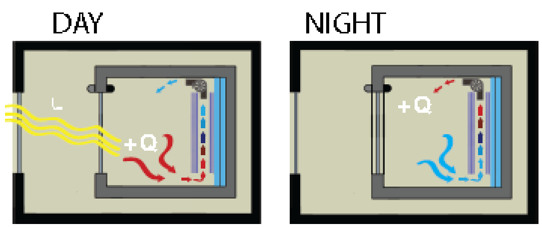


Figure 3. Test room in SSEC to test solarium concepts and active PCM thermal storage.

This test-room was also used for predictive control studies under a lab environment.

Key Outputs:

(a) Novel solarium concept with active PCM wall and controlled exterior plus interior shades

(b) *Journal papers:*

Bastien, D., Dermardiros, V. and Athienitis, A.K. (2015). "Development of a new control strategy for improving the operation of multiple shades in a solarium". Solar Energy, Vol. 122, 277-292. (partly supported)

Bastien, D. and Athienitis, A.K. (2015). "Methodology for selecting fenestration systems in heating dominated climates". Applied Energy, Vol. 154: 1004-1019.

(c) *Conference papers*

Bambara, J., & Athienitis, A. (2016). Comparison of Two Modeling Approaches for Semi-Transparent Photovoltaic Cladding in Greenhouses and Experimental Validation. eSim 2016 Conference, Hamilton, Ontario, May.

Bastien, D. and A. K. Athienitis (2012). A control algorithm for optimal energy performance of a solarium/greenhouse with combined interior and exterior motorized shading. International Conference on Solar Heating and Cooling for Buildings and Industry. San Francisco, U.S.A.

Bastien, D. and A. K. Athienitis (2013). Evaluation of the potential of attached solariums and rooftop greenhouses in Quebec. 3rd Climate Change Technology Conference. Montreal, Canada.

(d) Theses

Bastien, D. (2015). Methodology for Enhancing Solar Energy Utilization in Solaria and Greenhouses. Ph.D. Thesis, Building Engineering, Concordia University.

6.1.3 Achievement 3: Combined photovoltaic (PV) and solar thermal (ST) solar panels (i.e., liquid PVT) and Solar-boosted Heat Pumps. Preliminary evaluation of a Vented Roof-integrated PVT Array

PVT Evaluation (Queen's University)

Most commercial solar panels convert solar energy into electricity at fairly low efficiencies (e.g., less than 20%). Much of the solar energy that is absorbed by the panels is wasted as heat. Panels can reach temperatures in excess of 70°C on bright days, reducing output. In a PVT air system, PV modules are ventilated by natural or forced airflow to reduce panel temperatures and if desired, the heated air can be used for space and water heating, or to preheat ventilation air. Suitable liquid-based PVT collectors were not available in North America at the time of this project and thus separate liquid collectors and PV panels (ventilated) were employed. To investigate the benefits of PVT solar panels, an experimental test apparatus was constructed using two 235W solar panels. The panels were mounted at a slope of 22.5 in a column directly on a south facing, simulated roof section. Horizontal slots were cut through the upper and lower frame sections of the PV modules to allow air to circulate behind the PV panel by natural or forced convection. During testing, ambient air was drawn through the flow passage (i.e., air-channel) formed by the PV panel and the roof section. Three main cases were studied: 1) no air flow behind the PV panels (i.e., stagnation conditions); 2) buoyancy induced natural convection only through the air-channel; and forced convection (i.e., a fan was added to draw air through the air-channel).

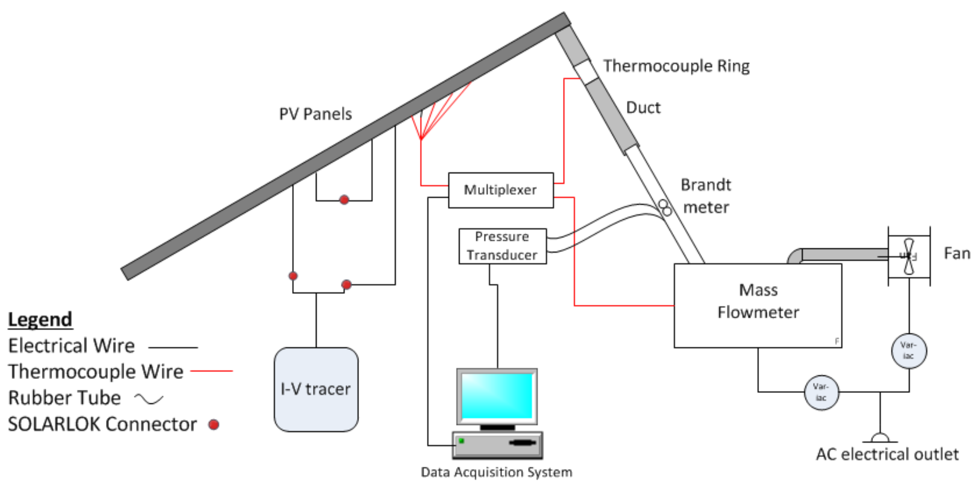


Figure 4. Schematic diagram of experimental set-up used to evaluate PVT Prototype.

The experimental rig is shown in Fig. 5 and a summary of the test results. The experimental results show a positive correlation between flow rate and thermal output (i.e., removed heat, Fig. 5 LH scale). Any level of airflow behind the panel, including natural convection, increased the electrical output when compared with closed vents (i.e., stagnation condition), however, gains in electrical output (Fig. 5 LH scale) were modest (or within the experimental error) for increased forced flow. An important finding is that electrical energy consumed by the fan (Fig. 5 RH scale) rapidly increase as air flow rates increase, significantly offsetting the gains in electrical output. This result shows that the careful analysis of both the electrical and thermal loads of a particular PVT installation, required to maximize the energy output of a PVT array. For example, above approximately 30 cfm, forced air circulation has a negative effect on net electrical output, as less additional electricity is produced than is consumed by the fan. In a related work Post-Doctoral researcher S. Hussain numerically studied natural convection in a backside venting channel of a PV/Thermal solar collector. The analysis was implemented with the ANSYS (Fluent) computational fluid dynamics (CFD) simulation software and considered both convective and radiative heat transfer; the temperatures and heat transfer rates (convective and radiative) of PV/absorber surfaces were evaluated for various flow channel geometries to investigate the effect of channel depth to length ratio and channel surface emissivities.

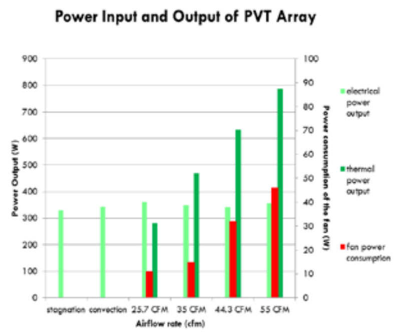


Figure 5. Photo of PVT collectors on simulated roof and summary of experimental results.

<u>Solar Heat Pumps (Queen's University)</u>. In general, the efficiency of silicon based PV increases at lower temperatures. When considering PVT collectors, however, higher collector temperatures (e.g., > 60°C) are needed to provide useful thermal energy for space and water heating in buildings. This apparent incompatibility can be addressed by the use of a heat pump to source heat at low temperature from the PVT panel, providing both high PV–electrical and thermal efficiency. The heat pump can deliver the heat, captured from the PVT array, at high temperature to a thermal load or a thermal storage. To practically achieve the full benefit of the heat pump, a liquid-based heat pump that directly cools the PV Array would appear to be the most promising configuration. Liquid-based PVT collectors are only produced by a small number of suppliers at this time, although their number is increasing. It is also important to identify a suitably sized heat pump that can operate at the desired temperature range with good performance.

In response to this need, development of an experimental test rig for evaluating the performance of Liquid-based CO_2 heat pumps was developed at Queen's University. Graduate student (Portia Murray) investigated the performance of various heat pumps for use in the solar boosted energy systems. She studied both a commercial heat pump with R410-A refrigerant and a prototype trans-critical CO_2 heat pump, Fig. 6. The R410-A heat pump operated well at low source temperatures but struggled to deliver heat at 60°C. The trans-critical CO_2 heat pump could deliver high temperatures (e.g., >90°C) but at the cost of increased complexity. Trans-critical CO_2 heat pumps are widely available in Asia and are currently being introduced to Europe,

Figure 6. Prototype trans-critical CO_2 heat pump under test at Queen's.

however, they are not available in North America at the time of this report (2016). North American manufacturers have indicated interest in developing trans-critical CO_2 heat pumps for residential applications, although, the limited availability of suitable compressors appears to be a significant barrier to their near term development.

Key Outputs:

(a) An experimental facility for measuring the electrical and thermal output of PVT modules;

(b) Experimental results from tests conducted on an air-based, edge ventilated PVT array;

(c) Development of an experimental test rig for evaluating the performance of Liquid-based CO_2 heat; pumps and capture of performance data recorded at various operational conditions.

(d) *Publications:*

Report:

Kevin Mulligan and Bailey Piggott (2014) "Optimizing the Electrical and Thermal Outputs of a PVT Air System", Internal report, Solar Calorimetry Laboratory, Queen's University, Kingston, ON.

Journal Paper:

S. Hussain, S. J. Harrison. (2015). "Experimental and Numerical Investigations of Passive Air Cooling of a Residential Flat-Plate Solar Collector Under Stagnation Conditions". Solar Energy. Vol. 122: 1023–1036.

Conference papers:

P. Murray, S. J. Harrison and B. Stinson. (2014) "Evaluation of Passive Anti-fouling Technology Applied CO2 Heat Pump Water Heaters". ASME 2014 International, Mechanical Engineering Congress and Exposition, 2014, Montreal, Canada.

P. Murray, S. Harrison, G. Johnson, B. Stinson. (2014) Experimental Evaluation of a Water Source CO_2 Heat Pump Incorporating Novel Gas-Cooler Configuration, Proceedings of ASME 2014-8th International Conference on Energy Sustainability, Paper No. ES2014-6668, 10 pages, 2014, Boston, MA, USA.

(e) Theses

Murray, Portia J (2015). Performance Analysis of a Transcritical CO_2 Heat Pump Water Heater Incorporating a Brazed-Plate Gas-cooler, M.A.Sc. Thesis, Mechanical and Materials Engineering, Queen's University, Kingston, ON.

<u>Integrated Energy System for Team Ontario entry to 2013 US Solar Decathlon Competition:</u>

In 2011, "Team Ontario" (a consortium of Algonquin College, Carleton and Queen's Universities) was successful in its application to compete in the 2013 US DOE Solar Decathlon Competition. The Team was focused on developing a NZEB+ building based around a high performance energy system. The system was modelled using TRNSYS at Carleton and Queen's Universities. The results of this work identified the potential of coupling heat pumps with solar arrays to improve the performance of both the solar array and the heat pump. It was shown that an integrated approach to the design of an energy system for NZEBs could offer many advantages over a system consisting of discrete energy subsystems. The complete system was configured and assembled in the Queen's Solar Calorimetry lab and operated under simulated thermal inputs and loads (see Fig. 7).

The integrated energy system (IES) is an advanced energy system intended for high performance

NZEBs. Built around a small solar-boosted, liquid-to-liquid heat pump, it used a small (270L) cold storage as a source and delivered heat to a (450L) hot storage, Fig. 7. The system was capable of supplying hot water for DHW and space-heating requirements, as well as, cold water for air-conditioning and dehumidification. In this system, the solar thermal collectors supplied heat to the cold storage as required. The collectors operated at a high efficiency due to the heat pump, which reduced the temperature of the collector working fluid. The solar collectors also served to boost the temperature of the cold storage and as a result, the heat pump could operate at a higher coefficient of performance during times of the year. After testing was complete, the system was installed in the Team Ontario, Solar Decathlon Building at Algonquin College in Ottawa. The house was equipped with a (grid-connected) 7 kW photovoltaics array that was separate from the IES. Originally it was intended that the solar thermal and PV array should be integrated in to a single PVT array, however, due to a lack of a suitable PVT collector, the functions solar electricity and solar heat were provided from separate roof and wall mounted arrays. The complete house was subsequently, transported and assembled in Irvine California to compete in the 2013 Solar Decathlon Competition against 19 other entries in 10 categories Fig. 8a. ECHO finished with 1st places in Engineering, Energy Balance, and Hot Water, and 2nd place in affordability.

Key Outputs:

(a) Modelling and design of an high performance NetZERO+ home designed for Canadian Climate;
(b) Detailed modelling, specification and laboratory testing of an integrated energy system (IES);
(c) Construction of prototype home and evaluation at 2013 US DOE Solar Decathlon Competition.

Publications:

Journal Paper:

J. Chu, W. Choi, C. A. Cruickshank and S. J. Harrison. (2014). Modelling of an Indirect Solar-assisted Heat Pump System for a High Performance Residential House. Journal of Solar Energy Engineering. 136(4):041003-041011.

Conference paper:

J. Chu, C. Cruickshank, W. Choi, S.J. Harrison. (2013). "Modelling of an Indirect Solar-assisted Heat Pump System for a High Performance Residential House", ASME 7th International Conference on Energy Sustainability & 11th Fuel Cell Sci., Eng. and Tech. Conf., ES Fuel Cell 2013, Minneapolis, MN.

Theses:

Chu, J. (2014). "Evaluation of a Dual Tank Indirect Solar-Assisted Heat Pump System for a High Performance House", M.A.Sc. Thesis, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, ON, (Supervised by Prof. Cruickshank at Carleton).

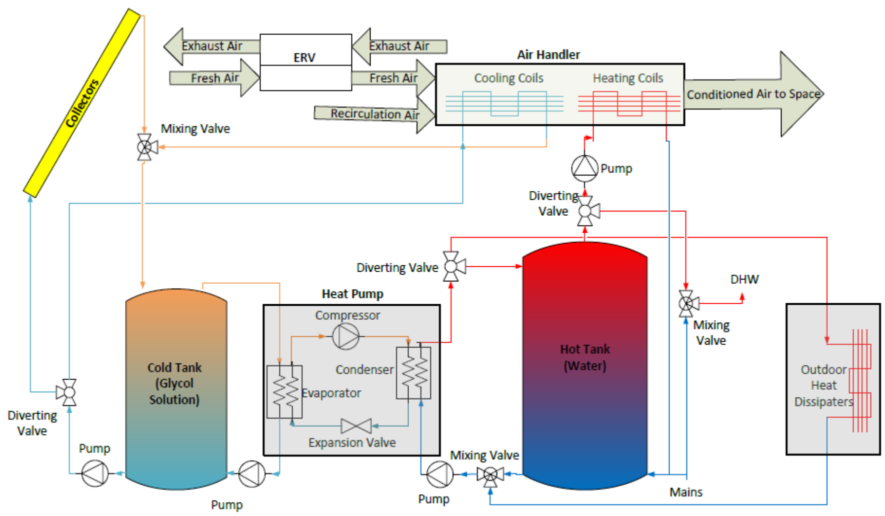


Figure 7. Schematic of Integrated Energy System (IES) for the 2013 US Solar Decathlon Entry (ECHO).

Figure 8a. ECHO in California during 2013 US Solar Decathlon competition.

Figure 8b. The QSDT demonstration house being moved to new location for monitoring Laboratory.

<u>Demonstration home</u>

The QSDT (Queen's Solar Design Team) demonstration home was moved to a permanent location to allow it to be fitted with an integrated energy system and stand-alone PV system, for demonstration and long term monitoring, Fig. 8b. The PV system and battery storage were installed and commissioned.

Key Outputs:

(a) establishment of an off-grid, energy-independent test/demonstration home;

(b) web-based monitoring of an off-grid solar boosted integrated energy system (IES).

Conference Papers:

Berger, J., and S. Harrison. (2016). "Modeling of Photovoltaic, Solar Thermal, and Photovoltaic/Thermal domestic Hot water Systems", eSIM 2016, Hamilton, Ontario, May 3-6, 2016.

Brendan A., B. McCormick, S. Harrison and J. Pharoah. (2016). "An Annual Model of a Solar-Hydrogen Energy Storage System". eSim 2016. Hamilton, ON. May 3-6.

6.1.4 Achievement 4: novel borehole prototypes designed, built, tested and models developed

Two small-scale borehole prototypes were built and tested under this project. These prototypes were inserted into an existing sand reservoir with known thermal properties. Calibration of the measuring instruments (flowmeter, temperature) was achieved as well as an overall commissioning of the facility.

The major achievement for the first prototype is the experimental validation, for the first time to the best of our knowledge, of thermal response factors for boreholes, also known as g-function. Figure 9 shows a schematic of the first prototype and the validation results. As can be seen from the figure on the right the theoretical g-function curve and the experimental results are in good agreement and are within the experimental uncertainty.

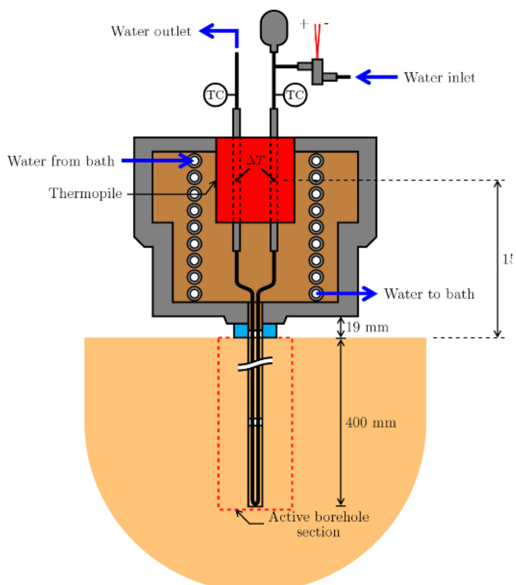
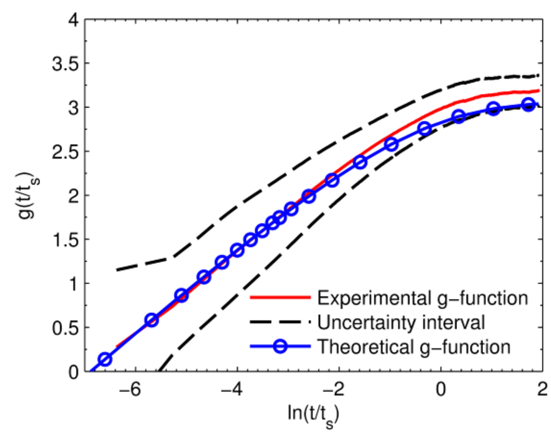


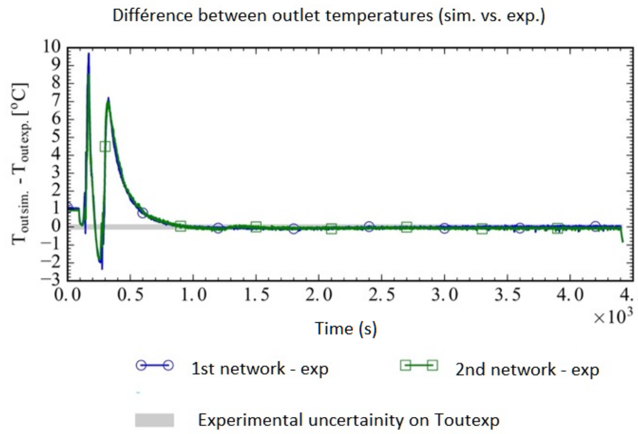
Figure 9. 1st Prototype borehole



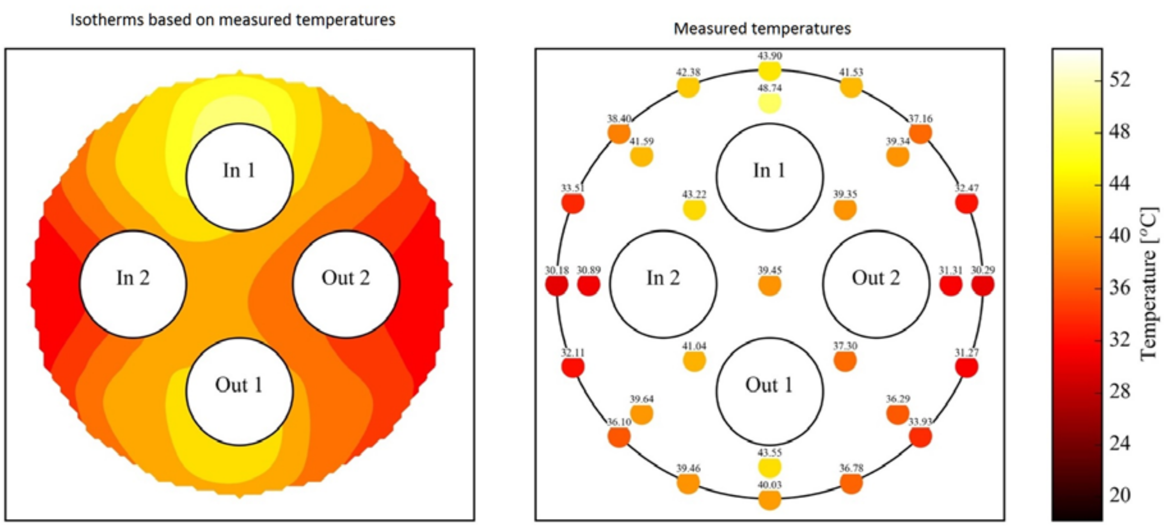
Comparison between g-functions curves obtained analytically and experimentally

For the second prototype, precise measurements where obtained on a four-pipe borehole (two U-tubes) with two independent circuits operating in transient conditions. The prototype is made out of ceramic so that holes could be drilled for precise placement of thermocouples. As shown below on Figure 10a, the second prototype is inserted into the sand reservoir. Figure 10b shows a comparison between the results obtained from a numerical model and the experimental results for both circuits (called réseau #1 and réseau #2 on the figure). After an initial period where there are some discrepancies, the numerical results agree with the experimental results within the experimental uncertainty. Finally, Figure 10c shows isotherms obtained from temperature measurements on a horizontal plane at mid-height. These last results are invaluable for model validation of four-pipe boreholes with two independent circuits.

a) 



b)



c)

a) Second borehole prototype inserted into the sand reservoir

b) Difference between the outlet temperature predicted by a numerical model and experimental results for both circuits (called réseau #1 and réseau #2)

c) Temperature measurements and corresponding isotherms on an horizontal plane at mid-height of the borehole

Figure 10. Dual U-tube borehole prototype

Key Outputs:

a) World-class facility for the study of transient behavior of geothermal boreholes

b) Journal Publication:

Cimmino, M. and M. Bernier. 2015. Experimental determination of the g-functions of a small-scale geothermal borehole. Geothermics, 56: 60-71.

c) Conference publications:

Gagné-Boisvert L. and M. Bernier. 2016. Accounting for borehole thermal capacity when designing vertical geothermal heat exchangers. ASHRAE summer conference, St-Louis, Missouri, June 2016. Paper ST-16-C027.

Godefroy, V., C. Lecomte, M. Bernier, M. Douglas, M. Armstrong. 2016. Experimental validation of a thermal resistance and capacity model for geothermal boreholes. ASHRAE winter conference, Orlando, Florida, January 2016. Paper OR-16-C047.

d) Theses

Marcotte, B. *Etude du transfert thermique transitoire dans les puits géothermiques à quatre tuyaux*. Mémoire de M.Sc.A., Département de génie mécanique, Polytechnique Montréal. 2016.

Cimmino, M. *Développement et validation expérimentale de facteurs de réponse thermique pour champs de puits géothermiques. Ph.D. thesis.* Département de génie mécanique, Polytechnique Montréal. 2014.

6.1.5 Achievement 5: Development of integrated design and control concepts of net-zero energy buildings

A key scientific and engineering achievement from the work in IEA SHC Task 40 / EBC Annex 52 is **the completion of the state-of-the-art advanced book "Modelling, Design, and Optimization of Net-Zero Energy Buildings"**. It was published by Wiley in February 2015 co-edited by Athienitis (Concordia) and O'Brien (a graduate of SNEBRN/Concordia and now an Associate Professor at Carleton). The book includes fundamental sections on modeling and design of NZEBs, as well as four detailed and well documented case studies, one of which is EcoTerra. About two thirds of the book were written by a group of 10 researchers and doctoral students associated with SNEBRN and participating in Subtask B of the above IEA task.

The above book represents an important design reference book for building designers and related advanced university courses. It has been well received by the international community. It advances the state of the art in NZEB design through Canadian leadership. It includes a key Canadian case study of near-net-zero energy house – the EcoTerra, including modelling considerations and optimization; the house includes a BIPV/T roof, a geothermal heat pump and an actively charged hollow core slab. The book also includes a chapter or grid interaction issues of NZEBs and predictive control to improve matching of loads and generation profiles. An optimization case study based on EcoTerra as an archetype produced guidelines on optimal design variable ranges (e.g. window area, PV system), published in an award-winning ASHRAE paper (Bucking, Athienitis & Zmeureanu, 2014).

Significant advances on predictive control for high performance buildings have been achieved through research at Concordia (Athienitis, Zmeureanu, Stathopoulos) and at Polytechnique (Kummert). Heuristic predictive control algorithms for zones with active building-integrated thermal storage have been developed and tested. At Concordia, motorized blinds were installed (in collaboration with Regulvar) in test sections of the Engineering building to test control strategies that take into account daylighting needs and control of solar gains. The predictive control strategies developed will be applicable (with appropriate modifications) to residential buildings and office zones. Some of the control strategies have been tested in a test-hut in the SSEC lab (Fig. 3).

An important case study on predictive control (heuristic) was the Engineering building at Concordia – a 17-storey high mass building with motorized inlet grilles on two opposing facades bringing air to the core of the building for ultimate exhaust though an atrium assisted by rooftop variable speed fans that were installed and specially instrumented and commissioned in 2016 (Fig. 11). Heuristic guidelines were developed for hybrid ventilation of the building, particularly precooling at night with cool outdoor air (Yuan et al. 2016).

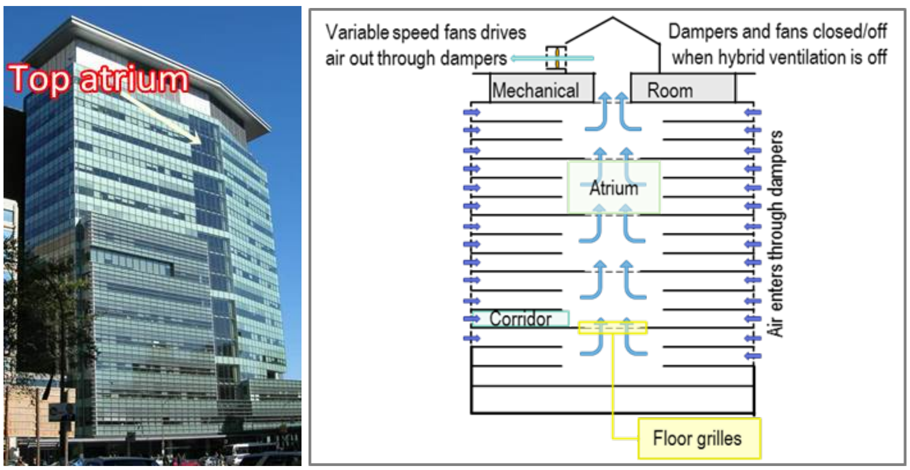


Figure 11. Schematic of hybrid ventilation system at Concordia EV building (Engineering).

A key achievement at Polytechnique was to demonstrate the use of Model-Predictive Control (MPC) strategies adapted to small residential and commercial buildings. Simplified state-space models were developed, these models were integrated in MPC strategies, and the control strategies were tested with simulation for real buildings.

The MPC strategies are a significant contribution towards a wider market acceptance of net-zero energy and high performance buildings because their flexible optimization criteria allow to satisfy the requirements of building owners but also grid operators by optimizing electricity imported from or exported to the grid. An example of this flexibility is illustrated in the Figure 12 for a typical residential building electrically heated (by resistance heating or heat pump). Instead of using a conventional optimization criterion (e.g. minimize operating cost and discomfort), the MPC strategy was used to minimize the power imported from the grid during on-peak periods (identified by yellow areas) while maintaining thermal comfort between acceptable boundaries (in this case maintaining the temperature of the living areas (magenta line) between limits (light blue dotted lines) defined for occupied and non-occupied periods. The resulting heating demand (and electrical power imported from the grid) is virtually zero during the on-peak period.

The developed MPC strategies address one of the key challenges of operating net-zero buildings with passive and active thermal and electrical solar collection: managing the collected heat while avoiding indoor space overheating, storing thermal energy for later use, and reducing peak demand and optimizing electricity supplied to the grid.

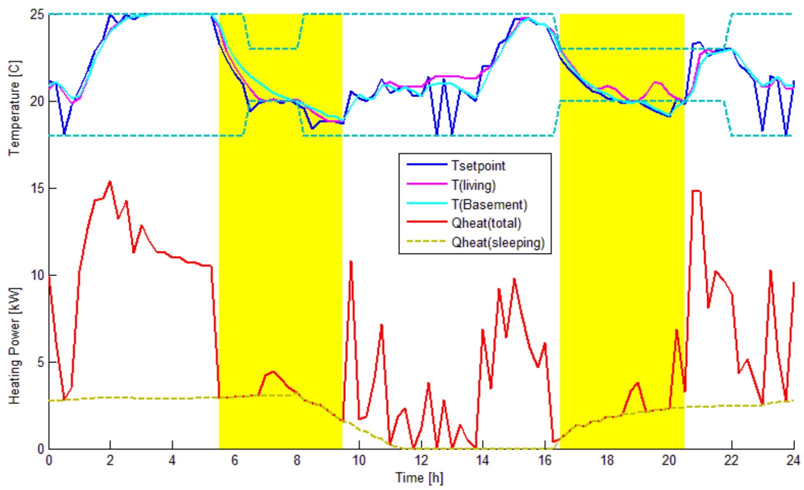


Figure 12. Example of MPC results to minimize the electricity imported from the grid during on-peak periods.

Key Outputs:

(a) *IEA Book published by Wiley*:

Athienitis, A. K., W. O'Brien, J. Ayoub, C. Kapsis, Y. Chen, V. Deslisle, S. Yip, J. Candanedo and S. Bucking et al. 2015. Modelling, Design and Optimization of Net-zero Energy Buildings, Ernst & Sohn – Wiley, Berlin, 396 pages (co-editors Athienitis and O'Brien).

(b) Journal papers:

Bucking, S., Athienitis, A., Zmeureanu, R. (2014). "Multi-objective optimal design of a near net-zero energy solar house". ASHRAE Transactions, Vol. 120 (1). **(Best paper award)**

(c) Conference papers

Yuan, S., Athienitis, A.K., Chen, Y., Rao, J. and Vallianos, C. (2016). An Experimental and Simulation Study of Night Cooling in a Building with Hybrid Ventilation. CLIMA 2016 & 12th REHVA World Congress, Aalborg, Denmark, May.

Zhang, K., Roofigari Esfahani, N., Quintana, H., & Kummert, M. (2014). Assessing simplified and detailed models for predictive control of space heating in homes. In Proceedings of SSB 2014: the 9th International Conference on System Simulation in Buildings, Dec.

Bucking, S., R. Zmeureanu and A. Athienitis (2013). An optimization methodology to evaluate the effect size of incentives on energy-cost optimal curves. 13th International Conference of the International Building Performance Simulation Association 2013. Chambéry, France.

(d) Theses

Bucking, S. (2012). Pathways to Net-Zero Energy Buildings: An Optimization Methodology Ph.D. thesis, Concordia University.

6.2 Benefits

6.2.1 Benefit 1: Enhanced energy efficiency and use of solar energy in buildings

Novel NZEB concepts, models, design techniques, and control strategies developed in this project will contribute to substantial reductions in energy consumption and peak demand for electricity. In Canada, commercial and institutional buildings alone represent 14% of end-use energy consumption while the residential sector accounted for 17% of secondary energy consumption. The improvement of building envelope performance towards energy positive systems will significantly improve the energy efficiency of these buildings and offset the greenhouse gas emission attributed to this sector.

6.2.2 Benefit 2: support of Canadian companies and technology development

The work provides a competitive edge to Canadian industry to develop sustainable building products and integrated energy systems both for Canada and for export, contributing to job creation and economic development. The project involved several Canadian companies directly (e.g. Regulvar, Centennial Global, Internat Consultants) or though SNEBRN (e.g. Hydro Quebec, Canadian Solar, Unicel) which acquired unique expertise through their collaboration in the project or by hiring graduate students who worked in the project.

6.2.3 Benefit 3: improved knowledge to support regulations ensuring technology uptake for NZEBs

The work has resulted in improved knowledge that will contribute to designing and operating cost-effective NZEBs. The new knowledge developed includes: detailed models for new technologies such as BIPV/T systems with multiple inlets that generate electricity and useful heat; integrated Energy Systems that use heat pumps, solar energy and heat recovery to increase energy efficiency; dual U-tube boreholes that enhance the effectiveness of geothermal systems; new storage systems and design concepts for solaria/greenhouses and predictive control strategies to optimize use of solar energy while reducing peak demand for electricity.

6.2.4 Benefit 4: Novel double U-tube boreholes – new designs and models

The validation work performed under this study increases the confidence that borehole designers have on borehole models. With the improved knowledge developed, engineers can design more efficient and cost effective bore fields. Also, the data obtained on four pipe boreholes with two independent circuits proves that the concept works and that it can be used in the next generation of borehole thermal energy storage systems.

6.2.5 Benefit 5: Enhanced operation and improved grid interaction

Net-zero energy buildings offer well-documented benefits in terms of energy efficiency and operating costs. They may also have negative impacts on the electricity grid if they are operated through simple, reactive, control strategies. Optimized predictive strategies that can be integrated within a communicating infrastructure (including smart meters and communicating thermostats) are necessary to increase market acceptance and adoption of net-zero building design concepts and configurations. They also open the door to even better environmental performance through real-time optimization taking into account the time-varying environmental impact (e.g. CO2 emissions) of electricity generation and distribution. The achievements of this project have demonstrated that such strategies can be successfully developed and implemented.

6.3 Technology/Knowledge Development Objectives

Advanced NZEB design and optimization concepts

The work produced advanced NZEB concepts with examples such as the EcoTerra house – one of the four case studies presented in much detail in the IEA T40A52 book mentioned above. The work of the Concordia group was also applied to the design of the Varennes Library, Canada's first institutional NZEB (with energy produced by the building) with a roof-integrated solar system. The two projects point the way forward to widespread adoption of NZEB concepts in new Canadian buildings based on use of BIPV/BIPV/T systems, passive solar design with optimized daylighting systems, heat pumps (air source or geothermal) and building integrated thermal storage. The new knowledge is being disseminated nationally through the SNEBRN Network and eSim conferences, and internationally through IEA Tasks, the APEC NZEB experts group (in which Athienitis is one of the key leaders), participation in ASHRAE conferences and technical committees, solar energy conferences and IBPSA international conferences.

Novel BIPV/T systems

The development of novel BIPV/T systems with multiple inlets eliminates the need for unglazed transpired with collector while allowing for good thermal efficiency. Demonstration projects on public/institutional buildings are being considered. In addition, more R&D is needed to integrate framed and frameless PV panels into curtain walls and also on roofs with the option of heat recovery but also natural venting when the heat is not needed.

Borehole models and new designs

This project has contributed to the advancement of scientific knowledge on geothermal boreholes. First, it was demonstrated that the thermal response of boreholes (also known as g-function) which is usually obtained numerically or analytically, can be reproduced experimentally. To the best of our knowledge, no other research group had performed such a validation of g-functions. Secondly, the validation work on four-pipe boreholes generated a data base of measurements on the transient behavior of geothermal boreholes that could be used by other research groups in Canada and abroad and the industry through ASHRAE design handbooks and other publications.

Predictive and Model Predictive Control (MPC) algorithms

The developed Model-Predictive Control (MPC) strategies and the simulation test beds (Concordia, Polytechnique) represent a valuable advancement of knowledge. The flexible optimization criteria allow to show the value of MPC to different types of stakeholders, from building operators to control companies and utilities. They will allow follow-up projects to refine the technology and transfer it to the industry, helping to improve the market acceptability of net-zero buildings.

7 Conclusion and Follow-up

Key outcomes of the project include:

1. A key scientific and engineering achievement from the work in IEA SHC Task 40 / EBC Annex 52 is the completion of the state-of-the-art advanced book "Modelling, Design, and Optimization of Net-Zero Energy Buildings". The book includes fundamental sections on NZEB modeling and design as well as four detailed and well documented case studies, one of which is EcoTerra. A longer term outcome is the training of about six PhD students that have developed extensive and in-depth expertise in the area; they are now Professors in Canadian universities or researchers.
2. New building-integrated photovoltaic/thermal system designs which eliminate the need for unglazed transpired collector and instead utilize distributed inlets have been developed and tested at Concordia's Solar Simulator. These systems have combined thermal and electrical efficiency of up to about 60% and enable optimized design configurations for NZEBs.
3. The design of geothermal bore fields relies on the determination of long-term thermal response factors, also known as g-functions which are typically obtained from numerical or analytical models. The first known experimental validation of g-functions for boreholes was performed. Dual U-tube prototypes were built and used to validate new numerical models. These models enable more accurate design and sizing of geothermal systems.
4. New designs and optimal operating strategies of solarium/greenhouse with automated exterior and interior shades and PCM thermal storage were developed.
5. Novel integrated energy system configurations that combine liquid PVT collectors with heat pump operating between a hot and cold tank were modelled. A simple configuration was implemented in the Solar Decathlon competition.
6. Novel predictive control algorithms were developed and tested in a building with a hybrid ventilation system. Model predictive control algorithms were also developed to optimize solar energy utilization and reduce peak demand in NZEBs and high performance buildings.

7.1 Next Steps

Integrated concepts and models for NZEBs and their optimal operation (Concordia)

1. **R&D:** The next step in this area includes design and construction of **a small modular test house** (at Concordia's Loyola Campus) to replace the test house from the 2005 Solar Decathlon competition. The house with have reconfigurable facade and flexibility in using different energy systems (BIPV/T – roof, BIPV/T facade, semitransparent PV windows, different heat pump configurations) to validate, test and develop NZEB configurations. In parallel there is a Concordia – McGill team (Team Montreal) that is participating in the Solar Decathlon China 2017 competition and will test some of its concepts, including integration of EV/PHEV and load/generation profile studies.
2. **Innovative NZEB demonstration projects/case studies**: based on the experiences from EcoTerra house and more recently the Varennes Library – Canada's first NZEB (with the energy generated by the building) institutional building, several new projects are being discussed as possible case studies/innovative demos linked to a new Network that will follow SNEBRN. In addition net-zero smart community projects are being considered.

BIPV/T systems and positive energy envelope configurations (Concordia)

Lab scale prototypes of air-based BIPV/T envelopes with multiple inlets (and no UTC) have been developed and modelled in the SSEC lab at Concordia. Next, full scale prototypes will be tested in the planned test house and in an existing outdoor test-room. Next steps include testing the BIPV/T prototypes with frameless and framed PV panels for facades and for curtain walls, and also connected to air-water heat pumps where the heated air from the BIPV/T provides the heat source. Discussions have started with a curtain wall manufacturer and a modular house firm to commercialize the technology and its various options. A declaration of invention was done at Concordia for the specific configuration with inlets in the PV frames.

The Varennes Library has attracted a lot of interest and provides a real living laboratory to test and demonstrate a realistic NZEB concept and to educate the public and the building industry. At the same time it served as technology transfer venue for much of the SNEBRN knowledge on NZEB modelling and design. Some of its aspects could be improved in a future NZEB demo such as an improved BIPV/T roof with multiply inlet that could generate additional energy to heat surrounding buildings (for example the Varennes Library could possibly use heat from the BIPV/T to heat and adjacent municipal swimming pool).

BIPV technologies[1] are forecasted to be one of the fastest-growing segments of the solar industry with up to 4.6 GW of installations forecasted through 2017. RnR Market Research predicts that this market will surge to $9 Billion in 2019, and $26 Billion by 2022, as more integrated BIPV products emerge that are fully integrated and multifunctional, including STPV and BIPV/T.

A group of Waterloo MBET (Masters of Business in Engineering Technologies) – named Erbium Consulting worked with Concordia to look into commercialization pathways and options for BIPV/T technologies and their integration into NZEBs, including IP issues, demos and field trials. More detail on their conclusions is available.

Integrated Energy System at QSDT demonstration Home (Queen's U)

A portion of the existing PV array could be replaced by a full PVT (liquid) array and coupled to the Integrated Energy System. Suitable liquid-based were not available in North America at the time of this project (but are available in Europe). Future work will include encouraging a Canadian manufacturer of PV panels to offer PVT panels.

Borehole designs and models (Polytechnique)

R&D: The next step is to fully utilise the two prototypes to generate more data for different operating conditions in order to further our understanding of the thermal behavior of geothermal boreholes. A number of scientific publications are also planned to disseminate the knowledge acquired during this project. First, a publication describing the unique design of the second prototype will be written. Secondly, the validation of models representing four pipe boreholes with two independent circuits will form the basis of a second publication.

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[1] RnR Market Research (2015, August 18). BIPV Market Worth $26 Billion by 2022 Says a New Research Report on BIPV Technologies and Markets for 2015-2022. Retrieved from PR Newswire: http://www.prnewswire.com/news-releases/bipv-market-worth-26-billion-by-2022-says-a-new-research-report-on-bipv-technologies-and-markets-for-2015-2022-522139451.html

Double U tubes (with one circuit) are routinely used in Europe. The Harvey center in Fredericton uses a double U tube system with two independent circuits (one charging and the other discharging) like the one investigated in the project. With the current work and the planned continuation, designers in North America will have more confidence for using them. They would be particularly valuable for BTES systems like the one in Drake Landing.

Implementation of predictive control strategies in real residential buildings and in NZEBs such as the Varennes Library will take place. The results of this research will be used in field trials to demonstrate their usefulness to stakeholders (building owners, control companies, utilities) and the algorithms will be further developed to include electrical storage management.

How the Federal government can help

1. Through adoption of NZEB technologies and demonstration projects in government buildings, linked to long term monitoring and research. A strong dissemination program for builders and the design community is also required.

2. Through incentive measures to adopt and further develop transformative technologies such as BIPV/T linked to heat pumps and advanced geothermal systems.

3. Funding programs for continued research in NZEBs and enabling technologies, with a strong training component such as the NSERC SNEBRN Network; a key requirement in transforming the building and energy industries is the training of highly qualified personnel (HQP). SNEBRN has trained more than 120 HQP that have joined universities as professors (at least 10), industry and government organizations/labs such as CanmetENERGY and CMHC.