Proceedings of BS2015:
14th Conference of International Building Performance Simulation Association, Hyderabad, India, Dec. 7-9, 2015.

A PRELIMINARY STUDY OF UPGRADING AN EXISTING CANADIAN COMMUNITY TO SOURCE NET-ZERO USING BUILDING SIMULATION

Adam Wills[1], Ian Beausoleil-Morrison[1], V. Ismet Ugursal[2]
[1]Department of Mechanical & Aerospace Engineering, Carleton University, Ottawa, Canada
[2]Department of Mechanical Engineering, Dalhousie University, Halifax, Canada

ABSTRACT

This preliminary simulation study investigates the application of retrofitting roof-mounted solar photovoltaic (PV) modules to a community of 50 single-detached dwellings located in Toronto, Ontario, Canada. Natural gas was used to supply space heating and domestic hot water to 90% of the dwellings. Detailed simulations of both the dwellings and PV systems were carried out in the simulation tool ESP-r. Dwelling model parameters were sourced from the Canadian Single-Detached and Double/Row Database developed by Swan et al. (2009).

Annual energy performance was evaluated in terms of site and source net-zero definitions. Two different PV generation capacities were investigated: 2.5 kW and 9 kW per dwellings. Neither upgrade was able to achieve site or source net-zero. For the 9 kW case, the community southern-facing roof-area was saturated with PV, and capacity still needed to be increased by an additional 356% and 578% to achieve site and source net-zero, respectively.

INTRODUCTION

For 2012 in Canada, the residential sector accounted for 16.7% of secondary energy consumption, and 13.5% of greenhouse gas (GHG) emissions (NRCan, 2015). Compared to other sectors, the residential sector is an attractive target for energy consumption and GHG emission reduction initiatives since energy end-uses in dwellings have relatively low variability compared to other sectors. Consequently, successful strategies and technologies applied to a specific dwelling for energy and GHG emission reduction will likely have a similar effect on other dwellings in a geographically similar location.

Adoption of a net-zero energy building (net ZEB) target is one possible strategy to reduce energy consumption and GHG emissions in residential and commercial buildings. In a broad sense, a net ZEB may be considered as a “grid-connected building that generates as much energy as it uses over a year” (Salom et al., 2011). Both Torcellini et al. (2006) and Marszal and Heiselberg (2011) reviewed well documented definitions of net-zero, and illustrated that there are several definitions, or types, of net-zero. The most commonly used approach, referred to as “net-zero site energy”, is the balance of energy imported to the site from the electrical grid against the energy exported to the grid from on-site renewable generation. However, there is often ambiguity in the types of energy carriers, such as natural gas (NG), electricity, and propane, considered, and the building energy end-uses included in the balance.

Other proposed definitions of net-zero attempt to not only consider the balance of energy, but the interaction of the net ZEB with connected energy infrastructure and the impacts on the environment. One such definition is “source net-zero energy”, where energy imported to the site is penalized for the energy expended to extract, refine, convert, and transport the energy. The challenge of implementing this definition in practice is the determination of the penalty, or source energy, factors. Conversion and energy transportation efficiency vary both temporally and geographically. Deru and Torcellini (2007) developed a set of annual average source energy factors for electricity and common fossil fuels used in buildings. The electricity source factors include transmission and distribution losses, as well as the energy to extract, process, and transport fuel. Deru and Torcellini (2007) divided the electricity source factors geographically using the North American electrical grid interconnections. EPA (2013) provided annually averaged, national source factors for both Canada and the United States. Similar to the factors presented by Deru and Torcellini (2007), the source energy factors are divided by building energy type, such as electricity, wood, or NG. EPA (2013) stated that nationally-averaged values are used to not penalize or credit a specific building for the relative efficiency of its energy provider. Farhat and Ugursal (2010) generated annual transmission and distribution loss factors for each Canadian province using public records.

While net-zero energy targets are typically applied to single buildings, the physical boundary of the net-zero balance may also be considered for a cluster of buildings, if a synergy amongst between the buildings which are not necessarily net-zero by themselves (Sartori et al., 2012). A net-zero target at a community-scale may also be a more economically viable than single Net ZEBs (Finkelor et al., 2010; Managan 2012). Net-zero energy communities (net

ZECs) would benefit from economies of scale in technology procurement and deployment (Managan, 2012). Some community-scale renewable and low-energy projects have been realized in practice in Canada. The Drake Landing Solar Community in Okotoks, Alberta is a suburban community of 52 single-detached homes which achieved over 90% of its space heating and 50% of its domestic hot water needs from a solar thermal district heating system after five years of operation (McDowell and Thorton, 2008; Wamboldt, 2009). Community-scale retrofits to reduce energy consumption were applied to 100 dwellings in Windsor, Ontario (Now House, 2015). The project group stated that cost and knowledge barriers related to dwelling retrofits may be addressed using a community-scale model. Despite these benefits, there have been few net ZECs achieved in practice compared to net ZEBs (Finkelor et al., 2010).

This paper presents a preliminary simulation study on converting an existing Canadian community to net-zero. In order to have a meaningful impact on energy consumption and GHG emissions in the immediate future, the existing housing stock needs to be considered. A Canadian community comprised of 50 single-detached homes is modelled using the full building simulation tool ESP-r (ESRU, 2015). The performance of roof-mounted solar photovoltaic (PV) arrays are simulated for the community, as well as the energy performance of the individual dwellings and community as a whole is evaluated in terms of net-zero site and source energy.

METHODOLGY

Dwelling modelling

Swan et al. (2009) created the Canadian Single-Detached and Double/Row Database (CSDDRD) as a representative set of the entire residential housing stock in Canada. The database is composed of 17,000 detailed records of Canadian dwellings that were collected by professionals conducting on-site audits. Each record contains information on dwelling geometry, envelope construction, air-tightness, and heating, ventilation, and air conditioning systems. The Canadian Hybrid Residential Energy End-use and Emissions Model (CHREM) (Swan, 2010; Swan et al., 2013) utilizes the CSDDRD to generate, simulate, and post-process detailed dwelling models in ESP-r.

The physics models in ESP-r were used to simulate dwelling space heating and cooling. Other dwelling energy end-uses such as appliance and lighting (AL) electrical loads require additional information on occupant behaviour. The CHREM uses an artificial neural network approach developed by Aydinalp et al. (2002) to estimate the annual AL load for a specific dwelling. To translate the annual estimates to sub-hourly load profiles to be used in ESP-r simulations, Swan (2010) used the 5-minute synthetic Canadian AL profiles developed by Armstrong et al. (2009). The AL loads were disaggregated into clothes dryer, cook stove, and other AL loads. Each type of AL load had three levels of annual energy consumption: high, medium, and low. The CHREM selects the most appropriate sub-hourly profile based on the annual energy consumption estimate, and applies a linear multiplier to the profiles to match the annual estimate of the artificial neural network.

PV and inverter modelling

PV array energy output was simulated using the ESP-r PV model implemented by Mottillo et al. (2006). This model is based on the equivalent one-diode circuit WATSUN-PV model created by Thevenard et al. (1992). The equivalent circuit is characterized using readily available manufacturer's data, such as open circuit voltage and closed circuit current (Thevenard, 2005). The model also accounts for variations in the PV module current-voltage curve due to temperature variation using manufacturer reported temperature coefficients. It was assumed that the PV modules were operating at their maximum power point, and had unobstructed views of the sky.

Power losses from array DC-AC inverters were also explicitly modelled using the power conditioning unit (PCU) model created by Ulleberg (1998). Originally implemented as a model in the energy system simulation tool TRNSYS by Ulleberg (1998), the model had been ported to ESP-r. The relationship between the power input of the PCU, $\dot{Q}_{in}$, and power output, $\dot{Q}_{out}$, is given by Ulleberg (1998) as:

$$\frac{\dot{Q}_{in}}{\dot{Q}_{nom}} = \frac{\dot{Q}_0}{\dot{Q}_{nom}} + \left(1 + \frac{U_s}{U_{out}}\right)\frac{\dot{Q}_{out}}{\dot{Q}_{nom}} + R_i\left(\frac{\dot{Q}_{in}}{\dot{Q}_{nom}}\right)^2 \quad (1)$$

where $\dot{Q}_{nom}$ is the nominal power rating of the PCU, $\dot{Q}_0$ is the power loss when there is a voltage across the PCU, U_s is the setpoint voltage, U_{out} is the output voltage, and R_i is the internal resistance of the PCU. The PCU idling constant, C_{idle}, is defined as :

$$C_{idle} = \frac{\dot{Q}_0}{\dot{Q}_{nom}} \quad (2)$$

For this preliminary study, the grid was assumed to be an infinite sink and source. All power generated by the roof-mounted PV system of a specific dwelling is first used to meet the electrical loads of the dwelling. Excess PV production is assumed to be exported to the local distribution system, where other dwellings in the community with a net-demand could consume it. Net-surplus of PV generation for the entire community was determined and used in the annual net-zero balance.

Calculation of energy balance

The CHREM outputs annual secondary energy consumption for each dwelling sorted by both end-use and type of energy carrier, such as electricity or NG. Residential end-uses considered by the CHREM are space heating and cooling, DHW production, and AL loads, which are also the energy end-uses considered in the annual net-zero balance for this study.

The annual net-zero balance, N_{ZE}, may be expressed as:

$$N_{ZE} = Q_{export,elec} - \sum_{i} Q_{import,i} \quad (3)$$

where $Q_{export,elec}$ is the annual exported energy to the grid, and $Q_{import,i}$ is the imported energy of fuel type i into the community. Imported energy may be expressed in terms of site or source energy.

To express energy imported to the community as source energy, the NREL annual-averaged site-to-source factors from Deru and Torcellini (2007) were used. These factors represent a ratio of source-to-site energy. The factors relevant to this study are provided in Table 1.

Table 1
NREL annual-average source energy factors for the eastern interconnect, from Deru and Torcellini (2007)

ENERGY CARRIER	SOURCE-TO-SITE FACTOR
Electricity	3.443
NG[1]	1.103

[1] factor adjusted to reflect ESP-r heating value

SIMULATION MODEL

Virtual community

A set of 50 single-detached (SD) dwellings located in Toronto, Ontario, Canada were selected for this preliminary study. The selected dwellings have a vintage between 1981 and 1990. As of 2006, this vintage group represented 20.9% of the SD Toronto stock (Statistics Canada, 2006). Dwelling data from the CSDDRD was used, which contain 641 records of Toronto SD dwellings built during the period of interest. Dwellings were randomly selected from these records to form the virtual community. The CHREM was then used to generate and simulate the ESP-r models.

The final set of dwellings has a total heated floor area of 15,400 m^2. Of the 50 dwellings in the final model set, eight did not have an air-source heat pump space cooling system. Space heating and DHW preparation is provided by NG for 90% of the dwellings, while the remainder use electricity for all end-uses. The baseline total annual electricity and NG energy consumption for the community is 1.87 TJ and 5.89 TJ, respectively. The community annual energy end-use fractions are summarized in Figure 1.

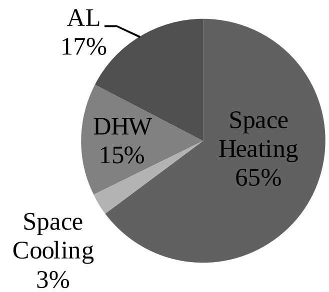

Figure 1 Virtual community annual energy end-use

PV upgrade

The Canadian Solar CSP-250P polycrystalline silicon PV module was selected for this study (Canadian Solar Inc., 2014). The model inputs are summarized in Table 2. To model roof-mounted PV in the virtual community, a new algorithm was introduced into the CHREM which determined eligible roof surfaces for PV and generated the imputs to model the PV systems. Eligibility was determined by roof surface area and orientation. Only sloped roof surfaces, with a compass azimuth angles from 90° to 270°, were considered eligible for PV. The CHREM assumes all sloped roof surfaces are 23° (Swan, 2010).

Table 2
PV model inputs for the CSP-250P module

PARAMETER	VAULE
Rated Power	250 W
Open-circuit voltage	37.2 V
Short-circuit current	8.87 A
Max. power-point voltage	30.1 V
Max. power-point current	8.3 A
Short-circuit current temperature coefficient	6.5E-4 °C^{-1}
Open-circuit voltage temperature coefficient	-3.4E-3 °C-1
Number of cells	60
Idealty factor	1.047

Additonal toggles were implemented into the algorithm to provide user control for PV mounting. The user could specify a maximum percentage of usable model roof area on each surface to address roof obstructions and simplifications in model geometry. The user could also specify a per-dwelling maximum PV power rating.

The quantity of collectors that could be applied to an eligible surface was determined using a finite bin packing procedure similar to those described by Berkey and Wang (1987). Packing bin geometries considered in the algorithm included rectangles, triangles, and trapezoids to reflect the roof geometries present in the CHREM. PV modules were packed both all in horizontal and vertical orientations to determine the maximum number of modules that could be mounted on the surface.

If the total PV power rating of the dwelling exceeded the user specified maximum, panels were first removed from east and west facing arrays. These were expected to have less annual PV energy production than south-facing PV modules.

Every roof surface with PV was treated as a separate PV array. For every array, the algorithm generated a corresponding stand-alone surface in the ESP-r dwelling model. Each array was connected to an individual AC-DC inverter. All inverters were then connected to a common household AC bus with a reference voltage of 240 V, shown in Figure 2:

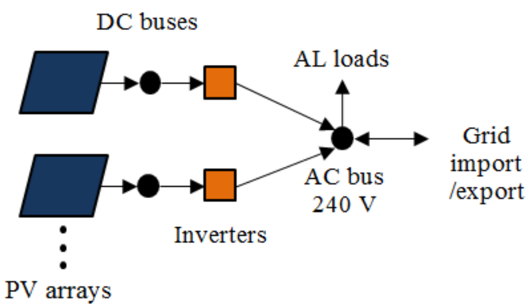

Figure 2 Virtual community annual energy end-use

Inverter model input parameters were selected from the inverter performance database created by Driesse (2009). Since the PV array size and corresponding power rating is variable, 17 inverters were selected from the database with nominal power ratings between 200 W and 250kW. The full load inverter efficiencies varied between 90.5% and 96.2%. The PV upgrade algorithm determined rated array power and selects an inverter such that the nominal inverter power rating does not exceed array rating. An example of inverter model parameters are provided in Table 3. If no PV power generation is supplied to the inverter, the inverter is "OFF" and component energy consumption is zero.

Table 3
SunPower Corp SPR-3000m (240V) inverter model parameters, from Driesse (2009)

PARAMETER	VAULE
Nominal power rating, $\dot{Q}_{nom}$	3000 W
Idling constant, C_{idle}	6.151E-3
Setpoint voltage, U_s	2.694 V
Internal resistance, R_i	1.943 kΩ

Upgrade cases

Two community PV upgrade cases were considered in this study. The first limited each house to a maximum dwelling PV power rating of 2.5 kW. Tonkoski et al. (2012) simulated potential voltage rise issues from integrated distributed residential PV generation in Canada. They found that average PV penetration of approximately 2.5 kW on a distribution system will not push the system outside of an acceptable voltage range. They acknowlegded however, that this was a conservative value.

The second case considered a maximum per-dwelling PV upgrade of up to 10 kW. The micro feed-in tariff (microFIT) program in Ontario, Canada was introduced in 2009 as an initiative to increase renewable energy production in the province (IESO, 2015). Homeowners with a renewable enegy project, such as solar or wind, with a capacity of 10 kW or less were able to participate in the program. For both cases, the grid was modelled as an infinte energy source and sink.

The distribution of PV module orientations for both cases is provided in Figure 3. Each eligible surface for PV mounting was assumed to have 100% usable surface area. For the 2.5 kW and 10 kW maximum PV per dwelling cases, there are 500 and 1802 PV modules, respectively. This corresponds to a community-scale PV systems rated at 125 kW and 450.5 kW, respectively. For the second case, the community average PV system rating per house is 9 kW indicating there is insufficient avaliable roof area.

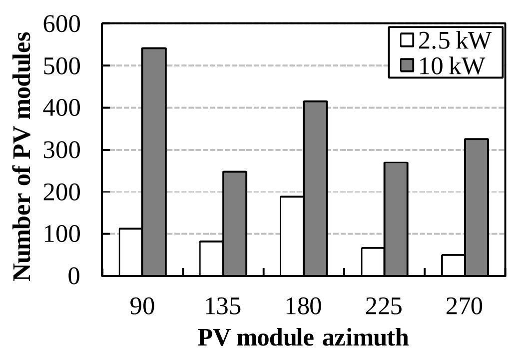

Figure 3 Distribution of collector module orientations

RESULTS AND DISCUSSION

PV system performance

The community PV systems for the 2.5 kW and 10 kW upgrade cases produced 670 GJ and 2370 GJ of annual electrical energy, respectively. The annual-averaged AC-DC inverter efficiency for the community was 95.2% and 95.4%, respectively.

Net-zero site energy performance

The community annual site energy balance for both PV upgrade cases are shown in Figure 3, and summarized in Table 4. Both upgrade cases were unable to achieve site net-zero energy. Equation 3 was used to determine the site N_{ZE} in Table 4. The negative values of N_{ZE} indicate the additional amount of energy export required annually to meet the net-zero target.

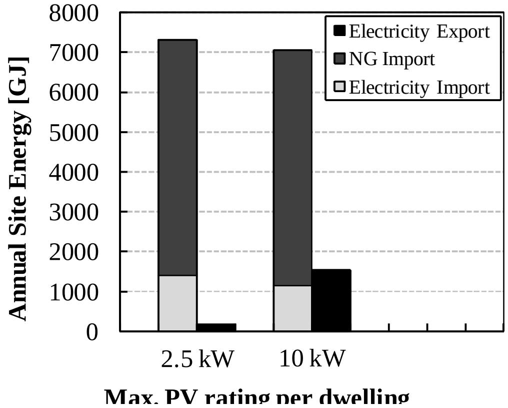

Figure 3 Annual site energy balance for the community

Table 4
Annual site energy balance results

ENERGY	2.5 KW	10 KW
Imported Electricity	1400 GJ	1150 GJ
Imported NG	5900 GJ	5900 GJ
Exported Electricity	**175 GJ**	**1540 GJ**
Site N_{ZE}	-7.13 TJ	-5.51 TJ

When 2.5 kW PV arrays were applied to each dwelling in the base case, the annual electrical grid energy import decreased by 24.9% due to self-consumption of PV energy. Using the emission factor for delivered electricity from Deru and Torcellini (2007), this decrease in annual import energy corresponds to an annual decrease of 102 tonnes of CO_{2e} emissions. Increasing the array sizes to a maximum of 10 kW per dwelling further decreased the imported electricty by 17.9%.

Despite the missed net-zero target, the 10 kW case was able to achieve a net-positive annual site electricity energy balance. Exported electrical energy exceeded site-imported by 390 GJ.

Net-zero source energy performance

The community annual source energy balances for both PV upgrade cases are shown in Figure 4, and summarized in Table 5. Neither case was able to achieve either source energy balance or source electricity balance over the year. For the 2.5 kW case, the source N_{ZE} decreased by 56.6% compared to the site N_{ZE}. Similarly, the 10 kW case source N_{ZE} decreased by 62.2% compared the site N_{ZE}.

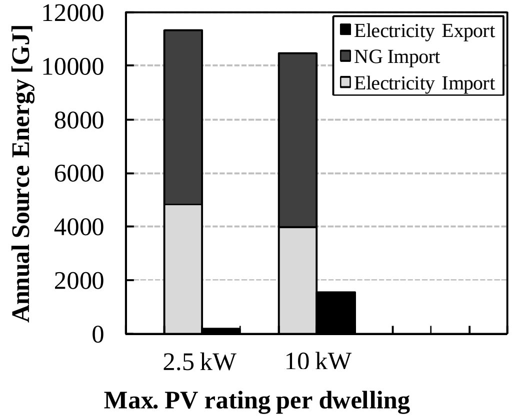

Figure 4 Annual source energy balance for the community

The prevalence of NG use in the virtual community presents a challenge for achieving a source net-zero balance. Mentioned previously, 90% of the dwellings in the virtual community used NG for space heating and DHW preparation. These end-uses accounted for a combined 80% of the total community secondary energy consumption, as shown previously in Figure 1.

It is desirable to consume on-site generated energy in order to avoid source energy import factors. For this community however, on-site PV production largely cannot be used to directly meet the space heating and DHW preparation loads which primarily use NG. All NG must be imported to the site with a source energy penalty.

Thus, the PV system must be scaled up to offset all NG energy entering the community over the year. However, increasing the roof-mounted PV is likely not an option. The PV upgrade algorithm implemented in the CHREM was only able to mount an average amount of 9 kW of PV per dwelling as opposed to the desired 10 kW. This indicates that eligible roof area for PV mounting was saturated. Other interventions in the community will need to made in order to achieve community net-zero energy.

Table 5
Annual source energy balance results

ENERGY	2.5 KW	10 KW
Imported Electricity	4830 GJ	3970 GJ
Imported NG	6510 GJ	6510 GJ
Exported Electricity	**175 GJ**	**1540 GJ**
Source N_{ZE}	-11.16 TJ	-8.93 TJ

Individual dwelling net-zero performance

The source energy N_{ZE} was calculated for each individual dwelling for the 10 kW case, and is plotted in Figure 5. The community source N_{ZE} divided by the number of dwellings in the community is also shown in the figure, with a value of 180 GJ/dwelling.

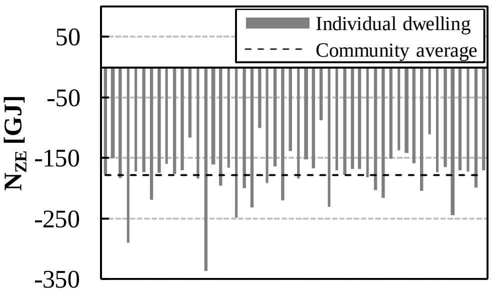

Figure 5 10 kW case annual source energy balance for each dwelling

It can be seen that none of the 50 dwellings were relatively close to source net-zero energy. The worst performing dwelling had a source N_{ZE} of -340 GJ, and strictly used electricity for all end-uses with electric baseboard heating. The second worst performing dwelling was also fully-electric, with a source N_{ZE} of -290 GJ.

Space heating demands are most prominent during the winter, when solar availability is relatively low. This presents a challenge for fully-electric dwellings, which in this study contained no energy storage to match load to PV generation. To illustrate this mismatch, the monthly site electricity import/ export energy for the worst-performing dwelling is shown in Figure 6.

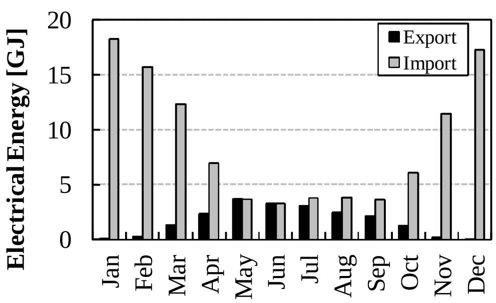

Figure 6 Site electricity monthly import/export for fully-electric dwelling, N_{ZE} = -340 GJ

In the absence of energy storage, fully-electric dwellings must import electricity from the grid during periods of heating demand and low solar availability. This presents a challenge for achieving source net-zero compared to dwellings which use NG for space heating. Shown previously in Table 1, the source energy factor for electricity is three times the NG source factor.

The best performing dwelling had a source N_{ZE} of -89 GJ. This dwelling was fully electric, however it used a ground source heat pump for primary heating with a nominal COP of 3.0. Additonally, the heated floor area of 115 m^2 is relatively small compared to the community average heated floor area per dwelling of 204 m^2/dwelling. This is related to the relatively small annual space heating load of 16.2 GJ per year compared to the community average space heating load of 100 GJ/dwelling/year.

CONCLUSION

This paper presents a preliminary simulation study of retrofitting 50 SD dwellings located in Toronto, Canada with roof-mounted solar PV arrays. All dwellings have a vintage between 1981 and 1990, and were randomly selected from the CSDDRD. Performance was evaluated in terms of site and source net-zero energy balances.

It was found that when an average of 2.5 kW and 9 kW of PV per house was roof-mounted in the community, additional annual on-site generation of 11.16 TJ and 8.93 TJ, respectively, was still required to achieve source net-zero energy. For the 9 kW case, on-site energy export needed to increase by 356% to achieve site net-zero energy. When considering source net-zero, the on-site energy export capacity needed to increase by 578% to meet the target.

The estimate of available roof area in this model was optimistic, and the amount of eligible area for PV was determined to be near saturation at 9 kW per house. This indicates that in order to achieve a net-zero energy balance in an existing Canadian community, additional retrofits, energy storage, controls, and energy conservation initiatives need to be undertaken.

FUTURE WORK

This work demonstrates that the application of PV alone is insufficient for achieving net-zero in an existing Canadian community. Future work will investigate other dwelling upgrade measures and community-scale technologies such as central heating plants. Additionally, the PV was modelled with on-site power storage to match periods of high energy demand to periods of high solar energy production. It is shown in this paper that decreasing grid imports not only benefits the net-zero balance, but also reduces GHG emissions.

Additions and enhancements to the CHREM are also planned for future work. The AL profiles currently used in the CHREM are the synthetic profiles from Armstrong et al. (2009). Swan (2010) dissaggregated these profiles to create nine unique usage profiles. Additional profiles will be added to the CHREM to reflect the diversity of time-of-use electricity patterns in communities. Saldanha and Beausoleil-Morrison (2012) gathered measured electrical usage data from twelve Ottawa dwellings, and this data is to be integrated into the CHREM.

Also, the DHW profiles used within the CHREM are based upon European data from Jordan and Vajen (2001). Recently, Edwards et al. (2015) developed an annual DHW profile dataset containing four consumption levels and three temporal consumption patterns. These profiles were based upon data measured from 73 houses in Québec. These profiles will also be integrated into the CHREM.

NOMENCLATURE

AL	= appliance and lighting
C_{idle}	= PCU idling constant
CHREM	= Canadian Hybrid Residential Energy End-use and Emissions Model
CSDDRD	= Canadian Single-Detached and Double/Row Database
DHW	= domestic hot water
GHG	= greenhouse gas emissions
net ZEB	= net-zero energy building
net ZEC	= net-zero energy community
NG	= natural gas
N_{ZE}	= net-zero energy balance
PCU	= power conditioning unit
PV	= photovoltaic
$\dot{Q}_0$	= power loss when voltage across PCU
$Q_{export,elec}$	= annual electrical energy export
$Q_{import,i}$	= annual energy import of fuel carrier i
$\dot{Q}_{in}$	= PCU input power
$\dot{Q}_{nom}$	= PCU nominal power rating
R_i	= PCU internal resistance
SD	= single-detached
U_{out}	= PCU output voltage
U_s	= PCU setpoint voltage

ACKNOWLEDGEMENT

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the NSERC Smart Net–zero Energy Buildings Strategic Research Network (SNEBRN) for supporting this work.

REFERENCES

Armstrong, M. M., Swinton, M. C., Ribberink, H., Beausoleil-Morrison, I. & Millette, J. (2009), ‘Synthetically derived profiles for representing occupant-driven electric loads in Canadian housing’, Journal of Building Performance Simulation 2(1), 15–30.

Aydinalp, M., Ugursal, V. I. & Fung, A. S. (2002), ‘Modeling of the appliance, lighting, and space-cooling energy consumptions in the residential sector using neural networks’, Applied Energy 71(2), 87–110.

Berkey, J. & Wang, P. (1987), ‘Two-dimensional finite bin-packing algorithms’, Journal of the Operational Research Society 38(5), 423-429.

Canadian Solar Inc. (2014), ‘Datasheet: CS6P-250|255|260P’, Technical report, Guelph, Ontario.

Deru, M. & Torcellini, P. (2007), ‘Source energy and emission factors for energy use in buildings’, Technical report, National Renewable Energy Laboratory and Department of Energy, Golden, Colorado.

Edwards, S., Beausoleil-Morrison, I. & Laperrière, A. (2015), ‘Representative hot water draw profiles at high temporal resolution for simulating the performance of solar thermal systems’, Solar Energy 111, 43–52.

EPA (2013), ‘Portfolio Manager Technical Reference: Source Energy’, Technical report, U.S. Environmental Protection Agency, ENERGY STAR, Washington, DC.

ESRU (2015), ‘ESP-r’, University of Strathclyde, Energy Systems Research Unit. Available at: http://www.esru.strath.ac.uk/Programs/ESP-r.htm [Accessed May 9, 2015].

Farhat, A. A. M. & Ugursal, V. I. (2010), ‘Greenhouse gas emission intensity factors for marginal electricity generation in Canada’, International Journal of Energy Research 34(15), 1309–1327.

Finkelor, B., Sudhakaran, B., Hayakawa, M., Kurtovich, M., Zail, N., Dickinson, B., England, S., Segar, B., Dakin, B., Idrees, O. & Branch, E. (2010), ‘West village: A process & business model for achieving zero-net energy at the community-scale’, in Proc. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, California.

Managan, K. (2012), ‘Issue brief: Net zero communities, one building at a time’, Technical report, Institute for Building Efficiency, Johnson Controls, Washington, DC.

Marszal, A. J. & Heiselberg, P. (2011), ‘Zero energy building definition - a literature review’, Technical report, International Energy Agency Solar Heating & Cooling Programme, Aalborg, Denmark.

McDowell, T. P. & Thorton, J. W. (2008), ‘Simulation and model calibration of a large-scale solar seasonal storage system’, in Proc. Third National Conference of IBPSA-USA, IBPSA-USA, Berkeley, California.

Mottillo, M., Beausoleil-Morrison, I., Couture, L. & Poissant, Y. (2006), ‘A comparison and validation of two photovoltaic models’, in Proc. Canadian Solar Buildings Conference, Montréal, QC.

Now House (2015), ‘Community-scale retrofit projects’. Available at:

http://www.nowhouseproject.com/workCommunityScaleRetrofit.php [Accessed May 9, 2015].

NRCan (2015), 'Comprehensive Energy Use Database Tables'. Natural Resources Canada, Office of Energy Efficiency. Available at: http://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/menus/trends/comprehensive_tables/list.cfm, [Accessed May 9, 2015].

Saldanha N. & Beausoleil-Morrison, I (2012), 'Measured end-use electric profiles for 12 Canadian houses at high temporal resolution', Energy and Buildings 49, 519–530.

Salom, J., Widén, J., Candanedo, J., Sartori, I., Voss, K. & Marszal, A. (2011), 'Understanding net zero energy buildings: Evaluation of load matching and grid interaction indicators', in Proc. of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, IBPSA, Sydney, Australia.

Sartori, I., Napolitano, A. & Voss, K. (2012), 'Net zero energy buildings: A consistent definition framework', Energy and Buildings 48, 220-232.

Statistics Canada (2006), '2006 Census: Catalogue Number 97-554-XCB2006021'. Available at: http://www5.statcan.gc.ca/olc-cel/olc.action?objId=97-554-X2006021&objType=46&lang=en&limit=0 [Accessed May 9, 2015].

Swan, L. G. (2010), 'Residential Sector Energy and GHG Emissions Model for the Assessment of New Technologies', Ph.D. thesis, Dalhousie University, Halifax, Nova Scotia.

Swan, L. G., Ugursal, V. I. & Beausoleil-Morrison, I. (2009), 'A database of house descriptions representative of the canadian housing stock for coupling to building energy performance simulation', Journal of Building Performance Simulation 2(2), 75–84.

Swan, L. G., Ugursal, V. I. & Beausoleil-Morrison, I. (2013), 'Hybrid residential end-use energy and greenhouse gas emissions model–development and verification for Canada', Journal of Building Performance Simulation 6(1), 1–23.

Thevenard, D. (2005), 'Review and recommendations for improving the modelling of building integrated photovoltaic systems', in 'Proc. Ninth International IBPSA Conference, IBPSA, Montréal, Québec.

Thevenard, D., Dixon, S., Rueb, K. & Chandrashekar, M. (1992), 'The current-voltage model for PV modules in the WATSUN-PV simulation software', in Proc. 18th Annual Conference SESCI, Edmonton, Alberta.

Tonkoski, R., Turcotte, D. & El-Fouly, T. H. (2012), 'Impact of high pv penetration on voltage profiles in residential neighborhoods', Sustainable Energy, IEEE Transactions on 3(3), 518–527.

Torcellini, P., Pless, S. & Deru, M. (2006), 'Zero energy buildings: A critical look at definition', Technical report, National Renewable Energy Laboratory and Department of Energy, Golden, Colorado.

Ulleberg, Ø. (1998), 'Stand-alone power systems for the future: optimal design, operation and control of solar-hydrogen energy systems', Ph.D. thesis, Norwegian University of Science and Technology, Trondheim, Norway.

Wamboldt, J. (2009), 'Central solar heating plants with seasonal storage for residential applications in Canada: A case study of the Drake Landing Solar Community', M.Es., Queen's University, Kingston, Ontario.