Techno-economic Assessment of Photovoltaic (PV) and Building Integrated Photovoltaic/Thermal (BIPV/T) System Retrofits in the Canadian Housing Stock

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Abstract

Techno-economic impact of retrofitting houses in the Canadian housing stock with PV and BIPV/T systems is evaluated using the Canadian Hybrid End-use Energy and Emission Model. Houses with south, south-east and south-west facing roofs are considered eligible for the retrofit since solar irradiation is maximum on south facing surfaces in the northern hemisphere. The PV system is used to produce electricity and supply the electrical demand of the house, with the excess electricity sold to the grid in a net-metering arrangement. The BIPV/T system produces electricity as well as thermal energy to supply the electrical as well as the thermal demands for space and domestic hot water heating. The PV system consists of PV panels installed on the available roof surface while the BIPV/T system adds a heat pump, thermal storage tank, auxiliary heater, domestic hot water heating equipment and hydronic heat delivery system, and replaces the existing heating system in eligible houses. The study predicts the energy savings, GHG emission reductions and tolerable capital costs for regions across Canada. Results indicate that the PV system retrofit yields 3% energy savings and 5% GHG emission reduction, while the BIPV/T system yields 18% energy savings and 17% GHG emission reduction in the Canadian housing stock. While the annual electricity use slightly increases, the fossil fuel use of the eligible houses substantially decreases due to BIPV/T system retrofit.

Keywords: Photovoltaic Electricity, Solar Heating, Energy Simulation, Low Energy Design, Residential Energy Use

Nomenclature

ACSH	annual cost savings for the house due to energy savings in a uniform series, continuing for n periods (C$)
AR	roof area (m^2)
ATCCH	average tolerable capital cost per house (C$)
CO_{2e}	equivalent CO_2 (kg)
E	energy saving per period for each fuel type (unit depends on fuel type; kg, liter, kWh, etc.)
$E_{T,eff}$	effective irradiance incident on the surface (W/m^2)
$E_{T,ref}$	reference irradiance (W/m^2)
e	fuel cost escalation rate (decimal)
F	fuel price per unit of each fuel type (C$/unit)
H_{ref}	reference insolation (W/m^2)
I	circuit output current (A)
I_D	diode current (A)
I_L	difference between the light generated current (A)
$I_{mp,ref}$	maximum power point current (A)
I_{sc}	short circuit current (A)
$I_{sc,ref}$	reference short circuit current (A)
i	interest rate (decimal)
m	number of different fuels used in a house
NH	number of houses
N_{PV}	number of PV panels (integer)
n	acceptable payback period (year)
$P_{el,pump.DHW}$	pump power for DHW heating loop (W)
$P_{el,pump.SH}$	pump power for heat delivery to the space (W)
P_{in}	power input (W)

P_{indv}	nominal power of individual module (W)
P_{mp}	maximum power (W)
P_{nom}	nominal power (W)
$P_{nom,burner}$	nominal capacity of auxiliary boiler (W)
P_0	power loss when there is a voltage across inverter (W)
R_i	internal resistance of inverter (Ω)
TCC	tolerable capital cost (C$)
TCCH	tolerable capital cost of the upgrade for each house (C$)
TTCC	total tolerable capital cost (C$)
T_{amb}	ambient temperature (K)
T_{cell}	cell temperature (°C)
$T_{cell,ref}$	reference cell temperature (°C)
T_{sup}	air supply temperature (°C)
T_{ref}	reference temperature (°C)
T_{ret}	return water temperature (°C)
T_w	water temperature (°C)
$V_{mp,ref}$	maximum power point voltage (V)
V_{oc}	open circuit voltage (V)
$V_{oc,ref}$	reference open circuit voltage (V)
U_{out}	voltage output (V),
U_s	set-point voltage (V)

Greek symbols

η	efficiency (decimal)
η_b	boiler efficiency (decimal)
η_{ref}	full load boiler efficiency at the reference temperature (decimal)
α	Temperature coefficient of I_{sc} (K^{-1})
β	Empirical coefficient beta used in calculation of V_{oc} (-)
γ	Temperature coefficient of V_{oc} (K^{-1})

φ	slope of the efficiency curve

Abbreviations

AB	Alberta
AL	appliance and lighting
AT	Atlantic provinces (i.e. NF, NS, PE and NB)
ASHP	air source heat pump
AWHP	air to water heat pump
BC	British Columbia
BIPV/T	building integrated photovoltaic and thermal
CHS	Canadian housing stock
CHREM	Canadian Hybrid Residential End-Use Energy and GHG Emissions model
COP	coefficient of performance
CSDDRD	Canadian single detached and double/row database
DHW	domestic hot water
EIF	emission intensity factor
GHG	greenhouse gas
HHV	higher heating value
HP	heat pump
HVAC	heating, ventilation and air conditioning
ICE	internal combustion engine
LHV	lower heating value
MB	Manitoba
NB	New Brunswick
NF	Newfoundland and Labrador
NG	natural gas
NS	Nova Scotia
NZE	net zero energy
OT	Ontario

PCM	phase change material
PE	Prince Edward Island
PR	Prairie provinces (i.e. MB, SK and AB)
PV	photovoltaic
PV/T	photovoltaic thermal
QC	Quebec
SAHP	solar assisted heat pump
SDHW	solar domestic hot water
SE	Stirling engine
SK	Saskatchewan

1. Introduction

Solar energy is a significant source of renewable energy for residential buildings. Solar energy can be harvested and utilised in buildings by different approaches. Photovoltaics (PV) convert solar energy directly into electricity. After inversion, PV generated electricity may be used by appliances and lighting, or in hybrid systems for space heating/cooling and DHW heating. The electricity generation efficiency of PV systems is affected by PV panel temperature. As the panel temperature increases the electricity generation efficiency decreases due to increasing resistance. To overcome this reduction, PV thermal (PV/T) systems were introduced in 1970's [1]. In a PV/T system the panels are cooled using a heat transfer medium. By integrating a PV/T system into the building façade (thus referred to as a BIPV/T system) the captured heat can be used as a source of thermal energy. In a BIPV/T system the PV panels can be connected to a heat pump, in which case the heat transfer fluid pre-heated by the PV panel is directed into the evaporator of the heat pump where the heat is extracted and delivered to the HVAC system. In addition to lowering the panel temperature and increasing PV efficiency, this arrangement increases the performance of the heat pump since the heat pump works with a higher temperature medium (compared to surrounding air) resulting in a higher coefficient of performance (COP). If the heat pump supplies thermal energy for both space and DHW heating, this approach is beneficial during the whole year. Nevertheless, the feasibility of BIPV/T system performance is highly influenced by climatic and geographical conditions as well as building characteristics.

Several authors have focused on the performance of different BIPV/T system configurations in various locations and operating conditions. For example, in one of the early studies, Anderson et al. [2] developed a numerical model for BIPV/T systems and validated its accuracy using experimental results. They showed that a series of parameters can be varied in the design of a BIPV/T collector to maximise performance. Yang and Athienitis [3] studied a prototype single inlet open loop air-based BIPV/T system in a full scale solar simulator. Experimental results were used to validate a numerical control-volume model for the BIPV/T system. They used the numerical model to estimate the impact of multiple inlets and other means of heat transfer enhancement on the performance of the BIPV/T system. Results of numerical simulations showed that the thermal efficiency may increase by about 5% and electrical efficiency may increase marginally due to using two inlets on a BIPV/T collector. Also, it was found that adding a vertical glazed solar air collector and wire mesh packing in the collector improves the thermal efficiency of system. Hailu et al. [4] studied a two stage variable capacity air source heat pump (ASHP) coupled with a wall integrated BIPV/T system using the TRNSYS [5] software. The COP of the integrated ASHP and BIPV/T system was evaluated and compared to an identical standalone ASHP operating under the same conditions. Results show that the COP was significantly improved for ambient temperatures between -3°C to 10°C. Buonomano et al. [6] developed a numerical model in TRNSYS to evaluate the energy and economic performance of residential BIPV/T systems capable of generating electricity and thermal energy for space and DHW heating in various

European climates. Results show that depending on climatic conditions, the BIPV/T system can yield 67-89% primary energy savings, with a payback period between 11 to 20 years. They concluded that a public funding strategy may improve the economic profitability of BIPV/T systems in the European housing market. Lee et al. [7] experimentally studied a BIPV/T system in a test building constructed to achieve zero energy status. The power generation of the BIPV/T system and building load were monitored to evaluate the energy self-sufficiency of the building. Results show that the system was capable of generating enough energy year round to achieve net zero energy status. Kim et al. [8] used a TRNSYS model to study the performance of a BIPV/T system and examine the efficiency of a PV panel on a cold and a warm roof of a low-rise residential building assuming that the BIPV/T back surface temperature is equal to the roof temperature. Results indicated that the BIPV/T system installed on a cold roof has a superior performance compared to a system installed on a warm roof. He et al. [9] compared the performance of PV, conventional solar thermal and PV/T systems under similar operating conditions. The effective areas of the solar thermal and PV/T systems were identical and solar cell covered area of PV/T and PV systems were the same. Results indicated that the thermal efficiency of the conventional solar thermal system was higher compared to that of the PV/T system. However, the primary energy savings due to the PV/T system were considerably higher compared to standalone solar systems. Saadon et al. [10] studied a ventilated PV façade installed in an energy efficient building. The installation enables the BIPV/T system to provide cooling in summer and heat recovery in winter. A numerical model was developed and validated for the simulation of the BIPV/T system during the cooling season. The model was incorporated into TRNSYS and used for an integrated analysis. Results show that the BIPV/T system is a useful technology for net zero energy building design. Yin et al. [11] designed a building integrated solar thermal roofing system to utilize solar energy for electricity and heat generation. The system is comprised of a PV panel augmented with a hydronic cooling system for thermal management of the PV panels. The heated water can be used in the radiant floor heating system. Results show that the BIPV/T system provides significant advantages over the conventional asphalt shingle roof and standalone PV systems.

Kamel et al. [12] designed a full-scale test apparatus of a BIPV/T system integrated with an ASHP and thermal energy storage for a building in Toronto, Canada. The system used 25 PV/T collectors and a concrete slab for thermal energy storage. The preheated air was used in the evaporator of the ASHP to enhance its COP. A numerical approach was used to evaluate the design parameters that may affect heat and electricity generation as well as ASHP COP and power draw. They suggested that the BIPV/T system integrated with an ASHP and thermal storage system might be a suitable technology to approach net zero energy building status. In another study, Kamel and Fung [13] developed a numerical model in TRNSYS to analyze a BIPV/T system integrated with an air source heat pump (ASHP) in Ontario, Canada. The preheated air from BIPV/T system is used in the evaporator of the ASHP. Their results showed that integrating the BIPV/T system and ASHP reduces the electricity demand of the ASHP due to its enhanced COP. They concluded that the proposed system reduces the annual operating cost and GHG emission. Vuong et al. [14] developed a BIPV/T model in EnergyPlus [15] based on the modeling scheme of BIPV/T systems in TRNSYS. Annual simulations were conducted in both TRNSYS and EnergyPlus and it was concluded that the slight discrepancy in the results was caused by different weather data interpolation methodologies, sky temperature computations, and electrical models used by the two modeling software.

This study investigates a large scale adaption of PV and BIPV/T systems in the Canadian housing stock (CHS) as part of ongoing efforts to identify feasible strategies and incentive measures to approach net zero energy (NZE) status for existing Canadian houses. In earlier studies various high efficiency alternative and renewable energy technologies including envelope modifications, installation of solar domestic hot water (SDHW) systems, phase change material (PCM) thermal energy storage, internal combustion engine (ICE) and Stirling engine (SE) based cogeneration systems, solar combisystem, air to water heat pump (AWHP) system, and solar assisted heat pump (SAHP) system were investigated [16-26].

2. Methodology

This study assesses the performance of PV and BIPV/T systems in existing Canadian houses using the Canadian Hybrid Residential End-Use Energy and GHG Emissions Model (CHREM). CHREM is statistically representative of the Canadian housing stock (CHS) with close to 17,000 unique house models [27-29]. The simulation engine of CHREM is the thoroughly validated, high-resolution building energy simulation software ESP-r [30, 31]. The appliances and lighting (AL) and DHW energy consumption of the houses in CHREM are estimated using a neural network model of Canadian households [32] and a set of AL and DHW load profiles representing the usage profiles in Canadian households. The reductions in GHG emissions due to reduced on-site fossil fuel consumption and reduced off-site fossil fuel consumption for electricity generation are separately calculated for each household. The validity of the predictions of CHREM was verified earlier [27, 28].

The energy savings and associated GHG emissions reductions due to retrofitting PV and BIPV/T systems were estimated using CHREM as follows:

(i) To maximize the incident solar energy for both PV and BIPV/T retrofits, houses that have a major roof surface facing south-east, south or south-west were selected as eligible houses.

For the BIPV/T retrofit, the presence of a basement or mechanical room (plant room) is an additional requirement for eligible houses to provide a suitable space for the equipment required. Since the presence of a mechanical room is not explicitly identified in the CHREM, houses with heating, ventilation and air conditioning systems that require a mechanical room were selected as eligible houses. Due to the differences in construction characteristics of houses across Canada and the non-uniform population density, the number of eligible houses varies substantially from province to province. Also, due to additional basement or mechanical room requirement for the BIPV/T system, the number of eligible houses for the PV retrofit is larger compared to the number of eligible houses for BIPV/T system retrofit.

(ii) The ESP-r input files of the selected eligible houses were modified to add the PV and BIPV/T retrofits, and the post-processing code was revised.

(iii) The energy savings and reduction (or increase) of GHG emissions of the CHS with the PV and BIPV/T retrofits were evaluated by comparing the estimated energy consumption and GHG emissions with the "base case" (i.e. current) values. The variation in GHG emissions was estimated using published marginal GHG emission intensity factors [33]. The energy savings and reduction (or increase) of GHG emissions estimated by CHREM were extrapolated to the entire CHS using scaling factors [27, 28].

2.1. Numerical model

In this study, first a PV system model is incorporated into CHREM. A roof-mounted PV module can be modeled in ESP-r as part of the roof construction, or as a separate zone with a small thickness, attached to the roof. In the former strategy, the air gap between the PV and the roof is modeled as one layer of the multi-layer construction. In the latter approach the air gap between top and bottom layers is modeled by an air-flow network. The first approach is simpler and less accurate than the second because of the higher temperatures predicted in the air gap due to neglecting the heat transfer rate increase as a result of the air-flow in the gap. Also, it is less suitable for the modelling of BIPV/T systems because the air flow in the gap between the PV module and the roof is a critical component of the system that delivers thermal energy. Therefore, PV panels are modelled in this work as a separate zone with a narrow air gap above the roof, and the air gap is modelled by an airflow network. [34]. The BIPV/T system is modeled using three interconnected networks (i.e. air flow network, plant network and electric network), as shown in Figure 3 [35].

2.1.1. PV array

The current vs. voltage curve (I-V curve) is generally used to characterize a PV system. Power generation of a PV cell can be determined from its operating voltage and current. Mottillo et al. [36] used the special materials approach developed by Evans and Kelly [37] and incorporated the PV model into ESP-r based on an equivalent one-diode circuit model (WATSUN-PV model) recommended by Thevenard [38]. The equivalent one-diode circuit is shown in Figure 1. The circuit output current, I, is the difference between the light generated current, I_L, and diode current, I_D. The diode current represents the resistance of the cell's junction to current flow [36]. This model is based on the short circuit current, the open circuit voltage and maximum power point the at the reference conditions. The reference curve is adjusted to match the operating conditions. The equations defining the short circuit current, I_{sc}, and open circuit voltage, V_{oc}, in the WATSUN-PV model are given in Equations 1 and 2.

$$I_{sc}=I_{sc,ref}\frac{E_{T,eff}}{E_{T,ref}}\left[1+\alpha\left(T_{cell}-T_{cell,ref}\right)\right] \tag{1}$$

$$V_{oc}=V_{oc,ref}\left[1-\gamma\left(T_{cell}-T_{cell,ref}\right)\right]\times Max\left\{0,1+\beta\ln\left(\frac{E_{T,eff}}{E_{T,ref}}\right)\right\} \tag{2}$$

where $E_{T,eff}$, is the effective irradiance incident on the surface (W/m^2), T_{cell}, is the cell temperature (°C), and α, β, γ are empirical coefficients. Beam and diffuse solar radiation (inclusive the reflectance of the front surface of the module) are considered in determining the effective irradiance. Reference irradiance and cell temperature are considered to be 1000W/m^2 and 25°C, respectively [36], and the values of the coefficients are given in Table 1 as per [39].

The cell voltage and current at the maximum power point (shown by subscript *mp*) are assumed to be proportional with the short circuit current and open circuit voltage in the WATSUN-PV model. Therefore, the maximum power is defined as:

$$P_{mp}=I_{mp,ref}\times V_{mp,ref}\left(\frac{I_{sc}\times V_{oc}}{I_{sc,ref}\times V_{oc,ref}}\right) \tag{3}$$

The PV module surface is represented as a multi-layered construction of several material layers. Individual layers are modeled with one or more nodes. A node within the surface is defined as a special material and represents the location of the PV cells within the structure. Cell temperature is determined by solving the energy balance equation for the special material node.

The power conditioning unit (PCU) model [40] was used to simulate the DC-AC inverter as given in Equation 4.

$$\frac{P_{in}}{P_{nom}}=\frac{P_0}{P_{nom}}+\left(1+\frac{U_s}{U_{out}}\right)\frac{P_{out}}{P_{nom}}+\frac{R_i P_{nom}}{U_{out}^2}\left(\frac{P_{out}}{P_{nom}}\right)^2 \tag{4}$$

where P_{in}, is the power input (W), P_{nom}, is the nominal power (W), P_0, is the power loss when there is a voltage across inverter (W), U_s, is the set-point voltage (V), U_{out}, is the voltage output (V), R_i, is the internal resistance of inverter (Ω) and $\frac{P_0}{P_{nom}}$ is collectively named idling constant.

The Crystalline-Silicone type PV modules with ethylene vinyl acetate (EVA) encapsulation, low-iron glass cover and metal back sheet are modelled in CHREM due to their higher efficiency and commercial availability [34].

The number of PV panels for a given roof area is determined as:

$$N_{PV} \leq \frac{H_{ref} \times \eta \times AR}{P_{indv}} \tag{5}$$

where N_{PV}, is the number of PV panels (integer), H_{ref}, is the Reference insolation (W/m^2), η, is the user defined efficiency, AR, is the roof area (m^2) and P_{indv}, is the nominal power of individual module (W). The input data used in modelling the PV modules are given in Table 1 [34].

2.1.2. Heating system

The preheated outside air exiting the roof integrated PV system is fed into the evaporator of the heat pump as shown in Figure 2. The heat pump is modeled as a grey-box component. Under the grey-box modeling strategy the system behaviour is expressed by performance related equations including the power consumption and COP of the heat pump. This strategy has been used for modeling several plant components in ESP-r [41, 42]. The empirical expressions used for the COP of the heat pump are given in Equation 6

$$\mathrm{COP} = \begin{cases} \mathrm{a}_0 + \mathrm{a}_1\left(T_w - T_{sup}\right) + \mathrm{a}_2\left(T_w - T_{sup}\right)^2; & -15^\circ\mathrm{C} < \mathrm{T}_{\mathrm{sup}} < 35^\circ\mathrm{C} \\ \mathrm{a}_0 + \mathrm{a}_1(T_w - 35) + \mathrm{a}_2(T_w - 35)^2; & \mathrm{T}_{\mathrm{sup}} \geq 35^\circ\mathrm{C} \end{cases} \tag{6}$$

where T_w, is the water temperature and T_{sup}, is the air supply temperature. The heat pump operation is limited to the supply air temperature above -15°C. At temperatures below -15°C, the heat pump is turned off and the auxiliary boiler supplies heat. The values of the coefficients are determined using manufacture’s data given in Table 1 [43].

Hot water leaving the condenser of the heat pump is stored in the hot water tank, which is used for energy storage and heat transfer within the hydronic system. The space and DHW heating loops are served by two heat exchangers immersed in the thermal storage tank, modeled as a stratified tank [44]. When the heat pump energy supply is not enough to satisfy the demand, the auxiliary boiler shown in Figure 2 supplies the shortfall. The auxiliary boiler is modeled as a condensing boiler in locations where natural gas is available, and as a non-condensing boiler where natural gas is not available and oil is used. The boiler performance data given in Table 1 are used in the model [45, 46].

At each simulation time step, first the boiler efficiency is determined based on the return water temperature as shown in Equation 7 [47].

$$\eta_b = \left[\eta_0 - \tan\varphi \times \left(T_{ref} - T_{ret}\right)\right] \quad (7)$$

where η_b is the boiler efficiency, η_0 is the full load boiler efficiency at the reference temperature, φ is the slope of the efficiency curve, T_{ref} is the reference temperature, and T_{ret} is the return water temperature. Then, the heat supply of the boiler is calculated using the boiler efficiency, fuel heating value (HHV for NG and LHV for oil), and instantaneous fuel use, and added to the energy balance equation as a source term. Boiler heat supply, water flow rate, and heat loss to the environment are used to determine the boiler output temperature. To model the transient operation, the thermal mass of the boiler is included in the energy balance.

A hydronic heat delivery system using commercially available radiators [48] is assumed for space heating. The number of radiators in each zone is determined to satisfy the design heating load. The power for the hot water circulation pump is estimated using empirical equations as shown in Equation 8 and 9 [24].

$$P_{el,pump.SH} = 90\text{W} + 2\times10^{-4} P_{nom,burner} \tag{8}$$

$$P_{el,pump.DHW} = 49.4\text{W}\times\exp\left(0.0083\,\frac{P_{nom,burner}}{\text{kW}}\right) \tag{9}$$

where $P_{el,pump.SH}$ and $P_{el,pump.DHW}$ are the power of the pump operating in the space and DHW heating circuit, respectively. The $P_{nom,burner}$ is the nominal capacity of the auxiliary boiler.

2.2. Control strategy

The BIPV/T system control sensors and actuators are described in Table 2. The system shown in Figure 2 is controlled by the space and DHW heating demand. The hot water tank stores heat and transfers it to the space and DHW heating loops. The temperature of the hot water tank is maintained between 50°C and 55°C by controlling the hot water pump operation. When the temperature drops below 50°C, the pump turns on and continues to operate until the temperature reaches 55°C.

When the outlet temperature from the heat pump evaporator is above the cut-out temperature of the heat pump (-15°C), the heat pump compressor turns on to extract heat from the supply air and heats the water in the hot water tank. If the temperature of the water leaving the heat pump is below 50°C, the auxiliary boiler turns on to increase the water temperature to 55°C. With this control scheme, the auxiliary boiler operates only at the BIPV/T system shortfall.

If the main zone temperature drops below the thermostat set-point of 20°C, the pump supplies hot water from the hot water tank to the radiators. Since the other zones including the basement are slave to the main zone, hot water is supplied to all radiators in the house, until the main zone temperature exceeds the upper temperature threshold of 22°C.

The DHW supply temperature is maintained in the range of 55±1°C. To simplify the model, the operation of the combination of DHW service valves is simulated as a small fully mixed adiabatic tank held at 55±1°C, and the DHW draw and equivalent main water supply are applied into this tank, emulating the operation of the valves in a real system.

2.3. GHG emission estimation

The GHG emissions of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are converted to and reported as "equivalent CO_2" (CO_{2e}) based on their global warming potential calculated according to Equation 10 [28, 33].

$$CO_{2e}=CO_2+25CH_4+298N_2O \tag{10}$$

The amount of CO_{2e} emission for onsite fossil fuel and electricity consumption is determined using the applicable GHG emission intensity factors (GHG EIF). The GHG EIF is the level of CO_{2e} emission per unit energy of fuel. The GHG EIF for onsite NG and oil consumption is defined based on the chemical reactions that occur in the combustion of these fuels in residential boilers. Thus, GHG emissions due to onsite fuel consumption is calculated in each simulation time step based on the fuel type and efficiency of the energy conversion device [28]. Wood combustion is considered carbon neutral because the combustion of wood returns to the atmosphere the CO_2 that was recently removed by photosynthesis [33].

Electricity generation in Canada is by provincial utilities, and based on the available primary energy sources, each provincial utility uses a different fuel mixture. Furthermore, the efficiency of energy conversion as well as the transmission and distribution losses are also widely different. Thus, CHREM calculates the GHG emissions associated with electricity consumption separately for each province using provincial GHG EIFs. The GHG EIF for electricity generation is defined as the level of CO_{2e} emissions for the generation and delivery of one kWh electricity to the end-user. Since different types of technologies are used for base-load and peak electricity generation, published values of provincial average and marginal GHG EIFs given in Table 3 [33] are used.

2.5. Connection of the PV system to the electrical grid

Energy storage is an essential part of renewable energy systems. While the hot water tank is a practical option for thermal energy storage for dwellings, electricity storage is a more complicated issue. Onsite electricity storage can be managed using batteries at households. However, the space requirements, initial investment and additional maintenance may decrease the favourability of this option. Grid connected low energy buildings can be considered as an alternative. As shown in Figure 2, onsite electricity generation is consumed by the heat pump, fan, pumps and AL operation. If the onsite electricity generation is not sufficient to meet the demand, the required electricity is imported from the grid with the meter recording electricity draw from the grid. When the onsite electricity generation exceeds the electricity demand of the household, the surplus electricity can be exported to the grid. In this case the meter spins backwards and subtracts the value of the exported electricity. This billing strategy is known as net metering and allows residential customers to earn credit for onsite electricity generation. With this strategy, the grid acts as an infinite and lossless electricity storage system for individual houses. The specific policies for net metering is defined by local authorities. Since several parameters can affect the energy market and electricity trade in each jurisdiction, balanced net metering approach is assumed in this study. Under the balanced net metering approach, the onsite electricity generation and grid electricity supply have the same price, GHG EIF and source energy intensity. Net metering is approved by utility companies across Canada for micro scale electricity generation [49-53]. Whether the electricity grid could support the large electricity export due to widespread PV system adoption is a question that must be investigated in future research.

3. Economic analysis

There are substantial uncertainties in estimating the investment cost for PV and BIPV/T system retrofits in Canada. The cost of purchase, delivery and installation of system components (e.g. piping and pumps, storage tanks, auxiliary heaters, heat pumps) vary substantially from province to province due to widely different economic parameters including market size, population density, geographical area, competitive market conditions, special site requirements and prevailing labor rates. Furthermore, the price of PV panels has been dropping significantly during the past decade, and further reductions are expected in the near future [54]. Additionally, while it is expected that a solar system retrofit would increase the market value of a house, helping to recover part of the investment cost, the magnitude of the increase is uncertain as it is affected by factors such as buyer perception and sophistication, market forces, and energy prices.

Due to these uncertainties, it is not realistic or practical to use a conventional economic feasibility analysis to assess the economic feasibility of PV and BIPV/T retrofits. Therefore, as in other similar studies [16, 18, 19, 21, 24-26], a reverse payback analysis method, referred to as "tolerable capital cost" (TCC) of the upgrades [55], was used here. TCC is the acceptable initial investment (including the present value of the additional annual maintenance cost over the system's lifetime) for an energy saving upgrade that will be recovered based on the annual cost savings, the number of desired years for payback, and the estimated annual interest of borrowing money and fuel cost escalation rates.

The prices of natural gas, heating oil, electricity and wood used for each province are presented in Table 4 [56, 57]. Since the future of fuel price escalation and interest rates are also uncertain, a sensitivity analysis was conducted to evaluate the uncertainty. The interest rates of 3%, 6% and 9% were selected as the range of consumer loan rates based the Bank of Canada Prime Rate [58], which was about 1% in June, 2015. Similarly, for each fuel type, a set of low, medium and high fuel cost escalation rates shown in Table 5 were used in the sensitivity analysis. These values are based on the medium rates extracted from the National Energy Board of Canada [59] and Energy Escalation Rate Calculator [60]. For payback, six and ten year periods were used, both shorter than the expected life of the PV and BIPV/T systems.

Since data on individual houses have no utility from a macro level of interest, the “average tolerable capital cost per house” (ATCCH) was used to evaluate the economic feasibility of the PV and BIPV/T system retrofits. ATCCH is calculated by dividing the total TCC by the number of houses:

$$\mathrm{ATCCH}=\mathrm{TTCC}/\mathrm{NH} \tag{11}$$

where, TTCC is the total tolerable capital cost as a result of the PV or BIPV/T system upgrade (C$), calculated as follows:

$$\mathrm{TTCC}=\sum_{i=1}^{\mathrm{NH}}\mathrm{TCCH}_i \tag{12}$$

NH = number of houses that received the upgrade.

4. Results and discussion

CHREM estimates of the energy consumption and GHG emissions for the current status of the CHS (‘base case’) are presented in Table 6. The validity of these estimates was verified earlier [28] by comparing them with available statistical data on Canadian energy use. In this study, first the impact of PV retrofit on energy consumption and GHG emissions is investigated. For this purpose, all houses that are eligible for PV retrofit are assumed to receive this retrofit and the energy consumption and GHG emissions are estimated using CHREM. The same approach is used to evaluate the BIPV/T system retrofit for the CHS.

4.1. Energy savings

The amount of electricity generated by the PV systems retrofitted in all eligible houses (about 35% of the houses in the CHS) and the associated GHG reductions are presented in Table 7. Electricity is used by appliances and lighting (AL), and in some houses additionally for space and DHW heating. Unlike modern, low-energy houses designed to enhance the suitable area for PV panel installation, existing houses were not designed with solar energy utilization in mind, and have limited roof area for PV installation. Thus, the average PV electricity generation per house is considerably low for existing houses. As shown in Table 7, the average electricity generation per house is 10-15 GJ per year in the CHS. To provide a comparison, the average per house electricity consumption by appliances and lighting in eligible houses is also presented in Table 7. Depending on the province, the average PV electricity generation is about half or less than half of the average AL load per house in the CHS. Thus, a standalone PV retrofit will not be sufficient to convert existing houses into low energy buildings.

As discussed earlier, the BIPV/T system is an alternative approach that combines the benefits of the PV and heat pump systems in a hybrid system. The total energy savings and associated GHG emission reductions with the BIPV/T retrofit is given in Table 8. Since the BIPV/T system requires the additional eligibility criterion of a suitable mechanical room in a house, the number of eligible houses for BIPV/T retrofit in the CHS is less than that for PV retrofit, also as shown in Table 8.

However, the energy savings due to the BIPV/T system retrofit is much higher compared to the electricity generation by PV retrofit although fewer houses are eligible for the BIPV/T retrofit.

As shown in Table 8 for each province, the average energy savings per house with the BIPV/T retrofit varies between 90-120 GJ per year, compared to the 10-15 GJ per year of electricity produced per house by the PV retrofit. The significant difference between the PV and BIPV/T retrofit benefits illustrates the importance of space and DHW heating load in the CHS and indicates that efforts to convert existing houses into low energy buildings need to include HVAC system upgrade(s) to be effective.

Estimates of the energy consumption in the CHS including the energy consumption in houses not eligible for the BIPV/T retrofit, and energy consumption before and after the retrofit for eligible houses broken down according to the energy sources used are provided in Table 9. As shown in the table, depending on the province, electricity use in eligible houses remains essentially the same (PE and SK), decreases (NF, NB and QC) or increases (NS, OT, MB, AB and BC) after the BIPV/T retrofit. For the entire CHS, electricity consumption increases with the BIPV/T retrofit, indicating that as a whole PV electricity generation is not sufficient for the operation of the heat pumps. However, energy consumption by the eligible houses from every other fuel decreases substantially indicating the overall effectiveness of the BIPV/T system to reduce energy consumption. The 2.2% increase in NG use in QC is because the auxiliary heating with the BIPV/T system is assumed to be from NG rather than the oil used in some existing houses. Thus, all oil consumption by eligible houses is replaced with NG after the BIPV/T retrofit.

Annual energy savings due to BIPV/T system retrofit in the CHS is provided in Table 10. Overall, with the BIPV/T system retrofit, the energy consumption of the eligible houses reduce from 350.8 PJ to 123.8 PJ, corresponding to a reduction of 65%. However, due to the low percentage of eligible houses in the CHS for the BIPV/T system retrofit (25% as shown in Table 8), the energy savings across the entire CHS is about 18% as shown in Table 11. This is about six times more than the savings due to the PV retrofit as shown in the same table.

4.2. Reduction of GHG emissions

The PV and BIPV/T system retrofits not only reduce energy use in the CHS but also replace a portion of the fossil fuel use (including onsite oil and NG as well as offsite fuel use for electricity generation) with more sustainable options. It is assumed here that PV electricity generation only offsets marginal electricity generation. In provinces where marginal electricity generation is mainly from fossil fuels, PV electricity generation translates into a considerable GHG emission reduction as shown in Table 7. However, GHG emission reductions due to PV retrofit is negligible in NF, QC, MB and BC where hydroelectricity is largely responsible for all, including marginal, electricity generation. While PE and SK use fossil fuels for base electricity generation, the marginal GHG EIF is relatively low as shown in Table 3; thus, the GHG emission reductions in those provinces are also negligible.

The estimates for total and average per house GHG emission reductions due to BIPV/T system retrofit are presented in Table 8. Although PV electricity generation offsets the fossil fuel use for marginal electricity generation, the heat pump consumes electricity instead of a fossil fuel for space and DHW heating. Thus, in NF, QC, MB and BC where hydroelectricity is widely available, the BIPV/T system is a favorable option. In Atlantic Provinces where oil is widely used for heating purposes by residential customers and fossil fuels are used for electricity generation, the situation is more complicated. While PV electricity generation is favorable for GHG emission reduction, the heat pump electricity use for heating purposes has an adverse effect on GHG emissions. The most negative impact on GHG emission is predicted in AB where fossil fuels, including coal, are used for electricity generation whereas significantly cleaner NG is mainly used for residential heating purposes.

The GHG emission reductions due to BIPV/T system retrofit by fuel source is provided in Table 10. The GHG emissions of fossil fuels are reduced in all provinces. It should be noted that the GHG emissions associated with oil is replaced with GHG emissions due to NG with BIPV/T retrofits in QC. As a result, the GHG emissions due to NG increases in QC while the overall GHG emissions from fossil fuels decrease. Percent GHG emission reductions due to PV and BIPV/T retrofits are presented in Table 11. Since the largest GHG EIF is in NB and AB, the largest GHG emission reductions by PV retrofit occur in those provinces. However, due to the large marginal GHG EIF in those provinces, the GHG emission reductions due to BIPV/T retrofit is not significant compared to other provinces. Using heat pumps in place of conventional fossil fuel fired heating systems provides a major benefit to reduce GHG emissions in the provinces where hydro-electricity is the main source of marginal electricity generation.

4.3. Economic feasibility

The results of the economic analysis conducted for three fuel escalation rates, three interest rates and two payback periods (as discussed in Section 3) are provided in Tables 12 and 13 for the PV and BIPV/T system retrofits. The TCC is highly influenced by the reduction in fossil fuel use and net electricity purchase from the grid, and it varies substantially in the range of 1,250C$ to 7,600C$ for the PV and 550C$ to 43,000 C$ for BIPV/T systems.

The energy savings due to electricity generation is used in the calculation of the TCC for PV systems. As shown in Table 12, the TCC is the highest in NB largely because the average electricity generation per house is maximum and the price of electricity is relatively high compared to other provinces. On the other end of the spectrum, the TCC for QC is the lowest in Canada. This is because QC has the lowest price of electricity and the per house electricity generation is close to average amongst all provinces as shown in Table 7. While the price of electricity is third highest in AB, the TCC is one of the lowest because AB has the lowest average electricity generation per house.

For BIPV/T systems, TCC is affected by PV electricity generation as well as the change in end-use energy consumption. The significant reduction in oil consumption in AT provinces (i.e. NF, NS, PE and NB) and QC substantially increases the TCC for BIPV/T systems compared to the TCC of PV systems. While the fossil fuel consumption decreases due to BIPV/T retrofit, electricity demand increases as a result of the heat pump operation. Thus, if BIPV/T replaces an inexpensive fossil fuel, i.e. NG, with a relatively higher priced electricity, this results in a low TCC as seen in AB.

The low TCC values for PV retrofit indicate that the PV systems will not be considered attractive by Canadian households in the absence of substantial subsidies. The BIPV/T systems are economically more attractive with higher TCC values, but considering the higher capital costs required by these systems, external economic forces such as energy rebates, government subsidies, incentive measures, and legislation (such as Carbon tax that panelizes fossil fuel use) will likely be necessary to promote their wide scale adoption.

5. Conclusion

The performance of PV and BIPV/T system retrofits in the CHS was investigated considering energy savings, GHG emission reductions and economic feasibility. It was assumed that the retrofits were applied to all houses that are suitable for the installation without the need for major renovations. The findings are as follows:

- About 35% and 25% of existing houses in the CHS are eligible for PV and BIPV/T retrofits, respectively.
- If all eligible houses adopt PV electricity generation, the energy consumption in the CHS will be reduced by 37.5 PJ per year, which is equivalent to 3% annual energy savings. This will results in 3.27 Mt of CO_{2e} equivalent GHG emission reductions, which is 5% of the annual GHG emissions from the CHS. In NF, QC, MB and BC where utility electricity generation is from renewable resources, the impact of PV retrofit on GHG emission reduction is negligible. While the average per house electricity generation by PV systems is similar in all provinces, the reduction in GHG emissions is not. The highest GHG emission reductions occur in regions where the fuel mixture for marginal electricity generation consists mainly of fossil fuels.
- If all eligible houses in the CHS implement BIPV/T system retrofits, the energy consumption in the CHS will be reduced by 227 PJ per year, which is equivalent to 18% annual energy savings. This will remove 10.85 Mt of CO_{2e} equivalent GHG emissions, which is 17% of the annual GHG emissions from the CHS. The change in total electricity use of the CHS is almost negligible while the 99.9% of the annual energy savings is associated with oil and NG consumption. Since replacing existing fossil fuel fired heating systems with heat pumps may increase the electricity demand of some houses, the associated GHG emissions due to electricity use increases in OT and AB. The overall impact of BIPV/T system retrofit is favorable from both energy conservation and GHG emission perspectives.
- The majority of energy savings and GHG emission reductions from the BIPV/T system are found to occur from the heat pump and not the PV electricity generation.

- The economic analysis indicates that the BIPV/T system retrofit is more feasible in the AT region and QC where oil consumption for space and DHW heating is significantly reduced. The lowest TCC is predicted in AB where the relatively inexpensive NG use is substituted with electricity.
- Although the maximum suitable roof area for PV panel installation was considered, the standalone PV electricity generation is not sufficient to convert existing houses into NZEBs. On the other hand, the BIPV/T system retrofit can substantially reduce energy consumption and will be a suitable option to be included in the set of potential strategies to be evaluated to achieve near NZE or NZE status for Canadian houses.

Acknowledgement

The authors gratefully acknowledge the financial support provided to this project through the NSERC funded Smart Net-Zero Energy Buildings Strategic Research Network and V.I. Ugursal’s NSERC Discovery Grant. Rasoul Asaee is thankful to the Atlantic Computational Excellence Network for the ACENET Research Fellowship and the Government of Nova Scotia for the Nova Scotia Graduate Scholarship.

Computational resources for this study are provided by the Atlantic Computational Excellence Network (ACENET), the regional advanced research computing consortium for universities in Atlantic Canada. ACENET is funded by the Canada Foundation for Innovation (CFI), the Atlantic Canada Opportunities Agency (ACOA), and the provinces of Newfoundland and Labrador, Nova Scotia, and New Brunswick.

References

1. Kumar, R., and Rosen, M.A. *A critical review of photovoltaic–thermal solar collectors for air heating.* Applied Energy 2011; **88**(11): p. 3603-3614. DOI: http://dx.doi.org/10.1016/j.apenergy.2011.04.044
2. Anderson, T.N., Duke, M., Morrison, G.L., and Carson, J.K. *Performance of a building integrated photovoltaic/thermal (BIPVT) solar collector.* Solar Energy 2009; **83**(4): p. 445-455. DOI: http://dx.doi.org/10.1016/j.solener.2008.08.013
3. Yang, T., and Athienitis, A.K. *A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets.* Solar Energy 2014; **104**: p. 82-92. DOI: http://dx.doi.org/10.1016/j.solener.2014.01.049
4. Hailu, G., Dash, P., and Fung, A.S. *Performance evaluation of an air source heat pump coupled with a building-integrated photovoltaic/thermal (BIPV/T) system under cold climatic conditions.* Energy Procedia 2015; **78**: p. 1913-1918. DOI: http://dx.doi.org/10.1016/j.egypro.2015.11.370
5. TRNSYS. *Transient system simulation tool.* 2013; [Last accessed: 2013/04/09]; Available from: http://www.trnsys.com/.
6. Buonomano, A., Calise, F., Palombo, A., and Vicidomini, M. *BIPVT systems for residential applications: An energy and economic analysis for European climates.* Applied Energy 2016; **184**: p. 1411-1431. DOI: http://dx.doi.org/10.1016/j.apenergy.2016.02.145
7. Lee, J.B., Park, J.W., Yoon, J.H., Baek, N.C., Kim, D.K., and Shin, U.C. *An empirical study of performance characteristics of BIPV (Building Integrated Photovoltaic) system for the realization of zero energy building.* Energy 2014; **66**: p. 25-34. DOI: http://dx.doi.org/10.1016/j.energy.2013.08.012

8. Kim, H.-R., Boafo, F.E., Kim, J.-H., and Kim, J.-T. *Investigating the effect of roof configurations on the performance of BIPV system.* Energy Procedia 2015; **78**: p. 1974-1979. DOI: http://dx.doi.org/10.1016/j.egypro.2015.11.387

9. He, W., Zhang, Y., and Ji, J. *Comparative experiment study on photovoltaic and thermal solar system under natural circulation of water.* Applied Thermal Engineering 2011; **31**(16): p. 3369-3376. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2011.06.021

10. Saadon, S., Gaillard, L., Giroux-Julien, S., and Ménézo, C. *Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope.* Renewable Energy 2016; **87, Part 1**: p. 517-531. DOI: http://dx.doi.org/10.1016/j.renene.2015.10.016

11. Yin, H.M., Yang, D.J., Kelly, G., and Garant, J. *Design and performance of a novel building integrated PV/thermal system for energy efficiency of buildings.* Solar Energy 2013; **87**: p. 184-195. DOI: http://dx.doi.org/10.1016/j.solener.2012.10.022

12. Kamel, R., Ekrami, N., Dash, P., Fung, A., and Hailu, G. *BIPV/T+ ASHP: Technologies for NZEBs.* Energy Procedia 2015; **78**: p. 424-429. DOI: http://dx.doi.org/10.1016/j.egypro.2015.11.687

13. Kamel, R.S., and Fung, A.S. *Modeling, simulation and feasibility analysis of residential BIPV/T+ASHP system in cold climate—Canada.* Energy and Buildings 2014; **82**: p. 758-770. DOI: http://dx.doi.org/10.1016/j.enbuild.2014.07.081

14. Vuong, E., Kamel, R.S., and Fung, A.S. *Modelling and simulation of BIPV/T in EnergyPlus and TRNSYS.* Energy Procedia 2015; **78**: p. 1883-1888. DOI: http://dx.doi.org/10.1016/j.egypro.2015.11.354

15. NREL. *EnergyPlus*. Building Technologies Office, U.S. Department of Energy 2016; [Last accessed: 2016/6/10]; Available from: https://energyplus.net/.

16. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Technoeconomic assessment of the impact of window improvements on the heating and cooling energy requirement and greenhouse gas emissions of the Canadian housing stock.* Journal of Energy Engineering 2013; **140**(2): p. 04013018. DOI: http://dx.doi.org/10.1061/(ASCE)EY.1943-7897.0000140

17. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Technoeconomic assessment of the impact of window shading retrofits on the heating and cooling energy consumption and GHG emissions of the Canadian housing stock.* Energy and Buildings 2014; **69**: p. 354-366. DOI: http://dx.doi.org/10.1016/j.enbuild.2013.11.023

18. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *An investigation of the technoeconomic feasibility of solar domestic hot water heating for the Canadian housing stock.* Solar Energy 2014; **101**: p. 308-320. DOI: http://dx.doi.org/10.1016/j.solener.2014.01.001

19. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic assessment of the impact of phase change material thermal storage on the energy consumption and GHG emissions of the Canadian Housing Stock.* Building Simulation: An International Journal 2014; **8**(2): p. 225-238. DOI: http://dx.doi.org/10.1007/s12273-014-0204-5

20. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic evaluation of internal combustion engine based cogeneration system retrofits in Canadian houses–A preliminary study.* Applied Energy 2015; **140**: p. 171-183. DOI: http://dx.doi.org/10.1016/j.apenergy.2014.11.068

21. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *An investigation of the techno-economic impact of internal combustion engine based cogeneration systems on the energy*

requirements and greenhouse gas emissions of the Canadian housing stock. Applied Thermal Engineering 2015; **87**: p. 505-518. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2015.05.031

22. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Stirling engine based cogeneration system retrofit impact on the energy requirement and greenhouse gas emissions of the Canadian housing stock*, in *28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*. 2015: Pau, France.

23. Asaee, S.R., Ugursal, V.I., Beausoleil-Morrison, I., and Ben-Abdallah, N. *Preliminary study for solar combisystem potential in Canadian houses.* Applied Energy 2014; **130**: p. 510-518. DOI: http://dx.doi.org/10.1016/j.apenergy.2013.12.048

24. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic study of solar combisystem retrofit in the Canadian housing stock.* Solar Energy 2016; **125**: p. 426-443. DOI: http://dx.doi.org/10.1016/j.solener.2015.12.037

25. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock.* Applied Thermal Engineering 2017; **111**: p. 936-949. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2016.09.117

26. Asaee, S.R., Ugursal, V.I., and Beausoleil-Morrison, I. *Techno-economic assessment of solar assisted heat pump system retrofit in the Canadian housing stock.* Applied Energy 2017; **190**: p. 439-452. DOI: http://dx.doi.org/10.1016/j.apenergy.2016.12.053

27. Swan, L.G. *Residential Sector Energy and GHG Emissions Model for the Assessment of New Technologies*. 2010, Dalhousie University Halifax, NS, Canada.

28. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *Hybrid residential end-use energy and greenhouse gas emissions model – development and verification for Canada.* Journal of Building Performance Simulation 2013; **6**(1): p. 1-23. DOI: 10.1080/19401493.2011.594906

29. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *A database of house descriptions representative of the Canadian housing stock for coupling to building energy performance simulation.* Journal of Building Performance Simulation 2009; **2**(2): p. 75-84. DOI: 10.1080/19401490802491827

30. Strachan, P.A., Kokogiannakis, G., and Macdonald, I.A. *History and development of validation with the ESP-r simulation program.* Building and Environment 2008; **43**(4): p. 601-609. DOI: http://dx.doi.org/10.1016/j.buildenv.2006.06.025

31. ESRU. *ESP-r*. Energy Systems Research Unit (ESRU), University of Strathclyde: Glasgow, UK 2015; [Last accessed: 2015/10/19]; Available from: http://www.esru.strath.ac.uk/Programs/ESP-r.htm.

32. Swan, L.G., Ugursal, V.I., and Beausoleil-Morrison, I. *Occupant related household energy consumption in Canada: Estimation using a bottom-up neural-network technique.* Energy and Buildings 2011; **43**(2–3): p. 326-337. DOI: http://dx.doi.org/10.1016/j.enbuild.2010.09.021

33. Farhat, A.A., and Ugursal, V.I. *Greenhouse gas emission intensity factors for marginal electricity generation in Canada.* International Journal of Energy Research 2010; **34**(15): p. 1309-1327. DOI: http://dx.doi.org/10.1002/er.1676

34. Nikoofard, S. *Techno-economic Assessment of Solar Technologies and Integration Strategies for the Canadian Housing Stock*. 2012, Dalhousie University: Halifax, NS, Canada.

35. Lomanowski, B. *BIPV/T Solar Assisted Heat Pump Systems For Residential Heating Applications*. 2010: CanmetEnergy, Natural Resources Canada, Ottawa, Canada.

36. Mottillo, M., Beausoleil-Morrison, I., Couture, L., and Poissant, Y. *A comparison and validation of two photovoltaic models*, in *Canadian Solar Building Conference*. 2006: Montreal, Canada. p. 6-10.

37. Evans, M., and Kelly, N. *Modelling Active Building Elements with Special Materials*. 1996: Energy Simulation Research Unit - University of Strathclyde, Glasgow.

38. Thevenard, D. *Review and recommendations for improving the modelling of building integrated photovoltaic systems*, in *9th International IBPSA Conference* 2005: Montréal, Canada. p. 1221-1228.

39. Nikoofard, S. *Techno-economic assessment of solar technologies and integration strategies for the Canadian housing stock, PhD Dissertation*, in *Dalhousie University, Nova Scotia, Canada*. 2012.

40. Ulleberg, O. *Stand-alone Power Systems For the Future: Optimal Design, Operation and Control of Solar-hydrogen Energy Systems*. 1998, Norwegian University of Science and Technology (NTNU): Trondheim, Norway.

41. Ferguson, A., Kelly, N., Weber, A., and Griffith, B. *Modelling residential-scale combustion-based cogeneration in building simulation.* Journal of Building Performance Simulation 2009; **2**(1): p. 1-14. DOI: http://dx.doi.org/10.1080/19401490802588424

42. Kelly, N.J., and Cockroft, J. *Analysis of retrofit air source heat pump performance: Results from detailed simulations and comparison to field trial data.* Energy and Buildings 2011; **43**(1): p. 239-245. DOI: http://dx.doi.org/10.1016/j.enbuild.2010.09.018

43. Viessmann. *VITOCAL 350-A: Air/water heat pump*. 2016; [Last accessed: 2016/04/21]; Available from: http://www.viessmann.com/http-svc/web/england/tdis.nsf/0/371A9DC79DA4F398C1257BF80035AADA/%24FILE/vitocal%20350A%20Data.pdf.

44. Thevenard, D., and Haddad, K. *Development of a stratified tank model with immersed heat exchangers in ESP-r*, in *6th IBPSA Canada Conference, Winnipeg*. 2010.

45. Viessmann. *Gas fired boilers*. 2015; [Last accessed: 2015/02/05]; Available from: https://www.viessmann.com/com/en/products/Gas-fired_condensing_boilers.html.

46. Viessmann. *Oil fired boilers*. 2015; [Last accessed: 2015/02/05]; Available from: https://www.viessmann.com/com/en/products/Oil_fired_boilers.html.

47. Hensen, J.L.M. *On the Thermal Interaction of Building Structure and Heating and Ventilating System*. 1991, Technische Universiteitt Eindhoven: Eindhoven, Netherlands.

48. Express Radiant Ltd. *Product catalogue*. 2015; [Last accessed: 2015/02/05]; Available from: http://www.expressradiant.ca/pdfs/product_catalogue.pdf.

49. OEB. *Information for generators*. Ontario Energy Board 2016; [Last accessed: 2016/09/25]; Available from: http://www.ontarioenergyboard.ca/oeb/Industry/Rules%20and%20Requirements/Information%20for%20Generators/What%20Initiatives%20are%20Available.

50. NSP. *Enhanced net metering*. 2016; [Last accessed: 2016/09/25]; Available from: http://www.nspower.ca/en/home/for-my-home/make-your-own-energy/enhanced-net-metering/default.aspx.

51. Hydro-Quebec. *Net metering option for a rate D or DM customer-generator*. 2016; [Last accessed: 2016/09/25]; Available from: http://www.hydroquebec.com/residential/customer-space/account-and-billing/understanding-bill/residential-rates/net-metering-option.html.

52. Alberta Energy. *What is micro-generation?* 2016; [Last accessed: 2016/09/25]; Available from: http://www.energy.alberta.ca/electricity/microgen.asp.

53. BC Hydro. *Net metering program*. 2016; [Last accessed: 2016/09/25]; Available from: https://www.bchydro.com/energy-in-bc/acquiring_power/current_offerings/net_metering.html?WT.mc_id=rd_netmetering.

54. Poissant, Y., Dignard-Bailey, L., and Bateman, P. *Photovoltaic technology status and prospects: Canadian annual report 2015*. 2016, CanmetENERGY, Natural Resources Canada: Ottawa, Canada.

55. Nikoofard, S., Ugursal, V.I., and Beausoleil-Morrison, I. *Economic analysis of energy upgrades based on tolerable capital cost.* Journal of Energy Engineering 2014; **141**(3): p. 06014002–1–6. DOI: http://dx.doi.org/10.1061/(ASCE)EY.1943-7897.0000203

56. Hydro-Quebec. *Comparison of electricity prices in major North American cities*. 2014; [Last accessed: 2014/02/15]; Available from: http://www.hydroquebec.com/publications/en/comparison_prices/pdf/comp_2013_en.pdf.

57. Statistics Canada. *Energy statistics handbook*. 2013; [Last accessed: 2013/02/15]; Available from: http://www.statcan.gc.ca/pub/57-601-x/57-601-x2012001-eng.pdf.

58. BOC. *Bank of Canada*. 2015; [Last accessed: 2015/10/21]; Available from: http://www.bankofcanada.ca/.

59. NEB. *National energy board of Canada*. 2014; [Last accessed: 2014/07/11]; Available from: http://www.nebone.gc.ca/clf-nsi/rnrgynfmtn/prcng/prcng-eng.html.

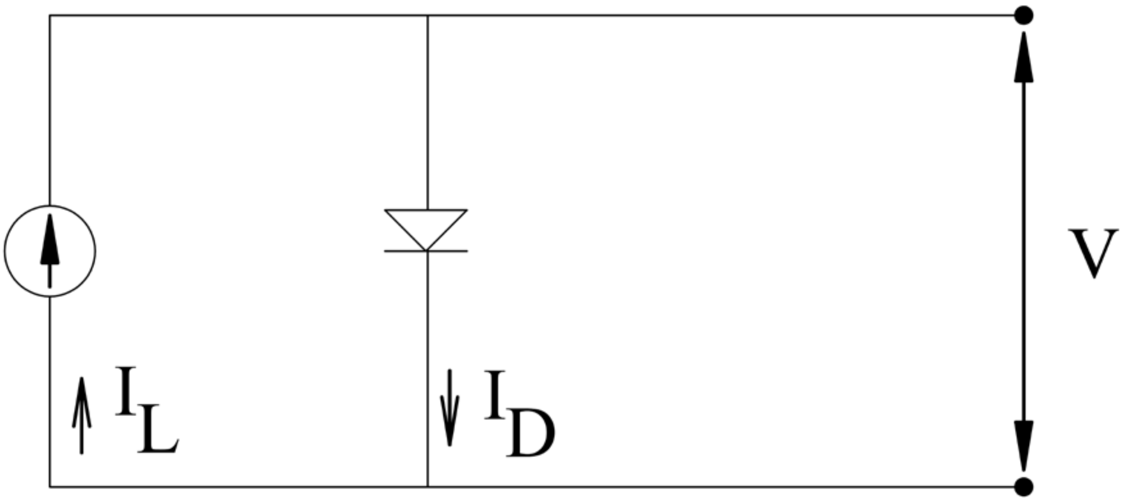
60. WBDG. *WBDG, Energy escalation rate calculator (EERC)* National Institute of Building Sciences 2014; [Last accessed: 2014/08/25]; Available from: http://www.wbdg.org/tools/eerc.php?c=8.

Highlights:

- Techno-economic performance of PV and BIPV/T systems in Canadian houses is evaluated
- Annual energy savings and GHG emission reductions by PV and BIPV/T retrofit are estimated
- Net-metering billing strategy is used for accounting impact of PV electricity generation
- Majority of energy savings from the BIPV/T system occur from the heat pump
- BIPV/T retrofit reduce 18% of annual energy use of the Canadian housing stock

Figure captions:

Figure 1	The equivalent one-diode circuit.
Figure 2	A typical house with BIPV/T system retrofit.
Figure 3	Modelling of PV-roof system in ESP-r.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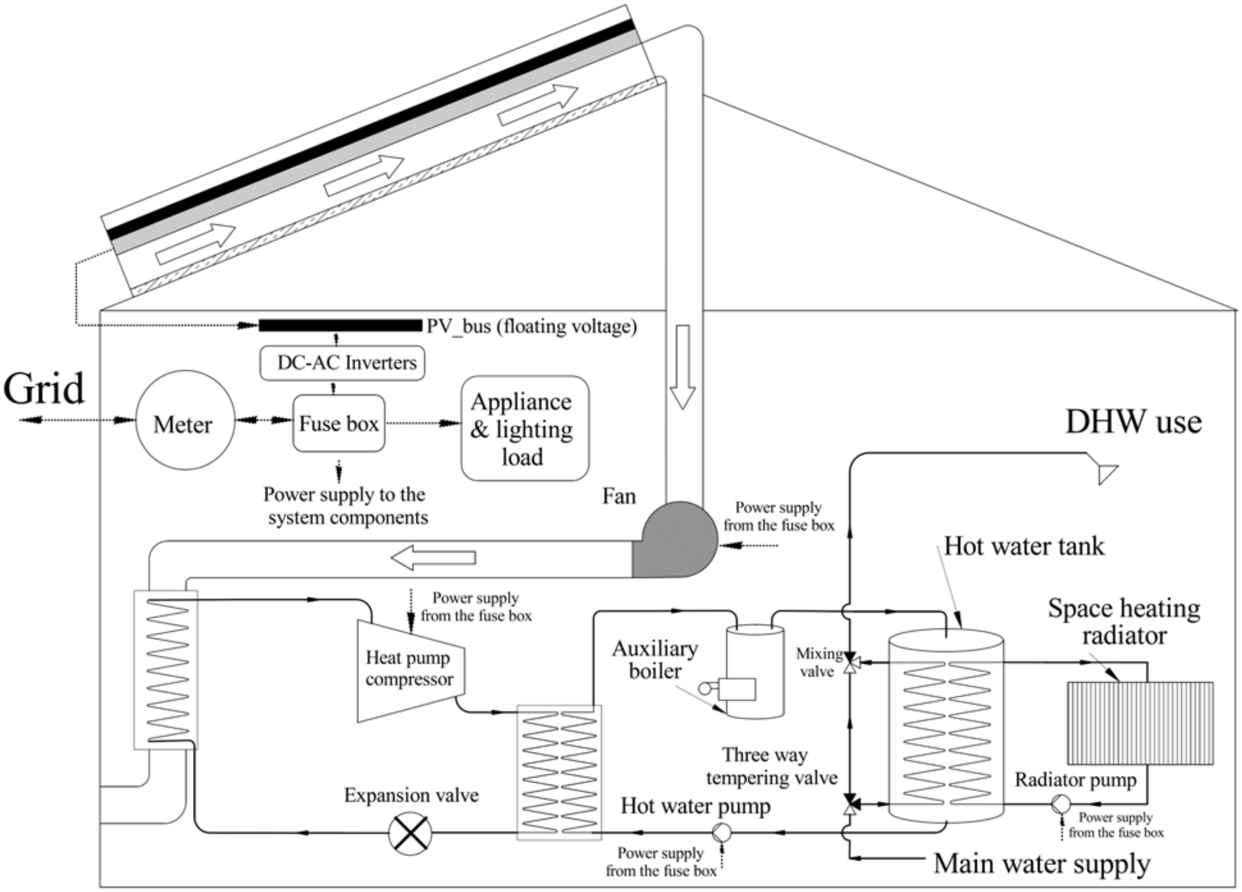
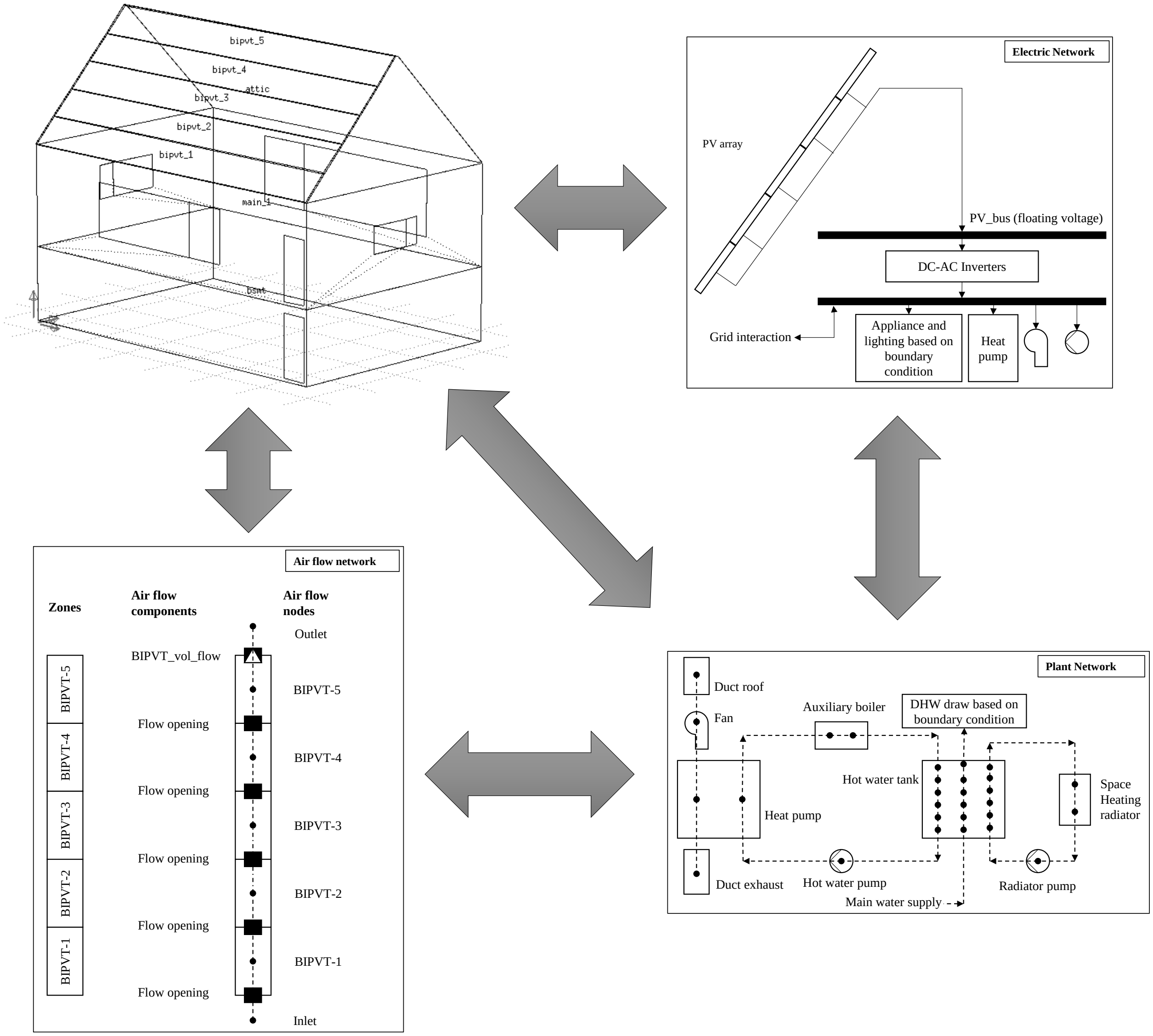

PV_bus (floating voltage)
DC-AC Inverters
Grid
Meter
Fuse box
Appliance & lighting load
Power supply to the system components
Fan
Power supply from the fuse box
DHW use
Hot water tank
Space heating radiator
Power supply from the fuse box
Heat pump compressor
Auxiliary boiler
Mixing valve
Three way tempering valve
Radiator pump
Power supply from the fuse box
Expansion valve
Hot water pump
Power supply from the fuse box
Main water supply


bipvt_5
bipvt_4
attic
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bipvt_2
bipvt_1
main_1
bsmt
Electric Network
PV array
PV_bus (floating voltage)
DC-AC Inverters
Grid interaction
Appliance and lighting based on boundary condition
Heat pump
Air flow network
Zones
Air flow components
Air flow nodes
Outlet
BIPVT_vol_flow
BIPVT-5
Flow opening
BIPVT-4
Flow opening
BIPVT-3
Flow opening
BIPVT-2
Flow opening
BIPVT-1
Flow opening
Inlet
Plant Network
Duct roof
Fan
Auxiliary boiler
DHW draw based on boundary condition
Hot water tank
Heat pump
Space Heating radiator
Duct exhaust
Hot water pump
Radiator pump
Main water supply

Table 1. Parameters of BIPV/T system components based on the existing heating system capacity

BIPV/T system components	Parameter	Unit	Existing heating system nominal capacity (kW)			Refs.
			>21	11-16	≤11	
Open circuit voltage at reference	V_{oc}	V	22.1			[37]
Short circuit current at reference	I_{sc}	A	4.8			
Voltage at maximum power point at reference	V_{mpp}	V	17.6			
Current at maximum power point at reference	I_{mpp}	A	4.55			
Reference insolation	H_{ref}	W/m^2	1000			
Reference temperature	-	K	298			
Temperature coefficient of I_{sc}	α	K^{-1}	0.00059			
Temperature coefficient of V_{oc}	γ	K^{-1}	-0.00381			
Empirical coefficient beta used in calculation of V_{oc}	β	-	0.0578			
Number of series connected cells (not panels)	-	-	36			
Number of parallel connected branches	-	-	1			
Number of panels in surface	N	-	10			
Load value	-	V	0			
Miscellaneous loss factor	-	-	0.1			
Efficiency	η	%	11.7			
Invertor nominal power	P_{nom}	W	5000			

BIPV/T system components	Parameter	Unit	Existing heating system nominal capacity (kW)			Refs.
			>21	11-16	≤11	
Idling constant	P_0/P_{nom}	-	0.8975×10^{-5}			
Set-point voltage	U_s	V	3.65			
internal resistance of inverter	R_i	Ω	0.4			
COP of heat pump	a_0	-	5.2202	5.0948	5.6818	[41]
	a_1	K^{-1}	-0.077	-0.0583	-0.0864	
	a_2	K^{-2}	4×10^{-4}	3×10^{-4}	5×10^{-4}	
NG fired boiler	$P_{nom,buner}$	kW	19	18	18	[43]
	η_0		0.92			
	T_{ref}	$^{\circ}C$	50			
	$(\tan\varphi)_{T>50^{\circ}C}$	$^{\circ}C^{-1}$	-0.15			
	$(\tan\varphi)_{T\leq50^{\circ}C}$	$^{\circ}C^{-1}$	-0.25			
Oil fired boiler	$P_{nom,buner}$	kW	18	11	11	[44]
	η_0		0.85			
	T_{ref}	$^{\circ}C$	50			
	$\tan\varphi$	$^{\circ}C^{-1}$	-0.15			
Thermal storage tank	V_{store}	USG	400	265	200	
Radiator	M_{unit}	kg	49			[45]
	C_{avg}	J/kgK	1350			
	Q_0	W	967			
	$T_{s,0}$	$^{\circ}C$	55			
	$T_{r,0}$	$^{\circ}C$	35			
	$T_{env,0}$	$^{\circ}C$	21			

Table 2. Control strategy for space heating and DHW supply

Control loop	Actuator	Period		Sensor location	Setpoint	
		start	end		on	off
BIPV/T loop	Compressor Fan Hot water pump	1 Jan	31 Dec	Top of the hot water tank in the vicinity of outlet	50	55
	Auxiliary boiler	1 Jan	31 Dec	Boiler outlet	50	55
DHW heating and supply	DHW pump [a]	1 Jan	31 Dec	DHW tank	54	56
	DHW tank [a]	1 Jan	31 Dec	DHW draw	--	--
Space heating	Radiator pump	17 Sep	3 Jun	Zone main 1	20	22
		4 Jun	16 Sep		0	1[b]

[a] To avoid unnecessary complexity in the components and control algorithms of plant simulation using ESP-r, the combination of mixing valve and three way tempering valve are modeled using a fully mixed adiabatic tank and a DHW pump.

[b] The heating system will not turn on due to the low temperature setpoint during the cooling only season.

Table 3. The average and marginal GHG intensity factors (g CO2eq/kWh) for each province of Canada [33]

Electrical generation characteristics		Canadian provincial GHG EIF (CO_{2e} per kWh)									
		NB	NF	NS	PE	QC	OT	AB	MB	SK	BC
Annual $\text{EIF}_{\text{Average}}$		433	26	689	191	6	199	921	13	789	22
Annual $\text{EIF}_{\text{Marginal}}$		837	22	360	6				1	225	18
Monthly $\text{EIF}_{\text{Marginal}}$	Jan					23	395	825			
	Feb					0	352	825			
	Mar					0	329	795			
	Apr					0	463	795			
	May					0	501	795			
	Jun					0	514	780			
	Jul					0	489	780			
	Aug					0	491	780			
	Sep					0	455	780			
	Oct					0	458	795			
	Nov					0	379	825			
	Dec					4	371	825			
Transmission and distribution losses		6%	9%	4%	6%	4%	6%	4%	12%	6%	3%

Table 4. Fuel prices in each province of Canada

	unit	NF	PE	NS	NB	QC	OT	MB	SK	AB	BC
Electricity[a]	cents/kWh	13.17	16.95	16.22	13.36	7.89	14.30	8.73	15.12	15.55	9.55
	C$/GJ	36.58	45.06	47.08	37.11	21.92	39.72	24.25	42.00	43.19	26.53
Natural gas[b]	cents/m^3	N/A	N/A	N/A	N/A	46.41	29.87	30.77	29.05	17.26	42.45
	C$/GJ	N/A	N/A	N/A	N/A	12.41	7.99	8.23	7.77	4.62	11.35
Home heating oil[c]	cents/litre	114.9	110.2	113.1	119.3	121.2	127.2	117.6	113.9	N/A	128.3
	C$/GJ	29.63	28.42	29.17	30.76	31.25	32.80	30.33	29.37	N/A	33.08
Wood[d]	C$/tonne	156.3	156.3	156.3	218.8	159.4	187.5	162.5	156.3	312.5	150
	C$/GJ	11.20	11.20	11.20	15.69	11.43	13.44	11.65	11.20	22.40	10.75

[a] Hydro-Quebec [53]

[b] Statistics Canada handbook [54]

[c] Statistics Canada Handbook [54]

[d] Local companies

Table 5. Real fuel escalation type for each fuel type

	Low	Medium	High
Electricity[a]	2	6	10
Natural gas[b]	2	5	8
Light fuel oil[b]	6	10	14
Mixed wood[c]	3	6	9

[a] National Energy Board of Canada [56]

[b] Energy Escalation Rate Calculator (EERC) [57]

[c] Equal to interest rate as there is no source for its escalation rate

Table 6. CHREM estimates of annual energy consumption and GHG emissions for the CHS as a function of energy source

	Energy (PJ)					GHG emissions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	15.2	0.0	9.6	3.3	28.1	0.12	0.0	0.67	0.8
NS	17.7	0.0	22.6	6.0	46.3	3.77	0.0	1.6	5.4
PE	1.8	0.0	4.0	1.5	7.3	0.1	0.0	0.28	0.4
NB	18.7	0.0	9.7	10.7	39.1	2.39	0.0	0.69	3.1
QC	205.3	1.0	30.3	10.4	247.0	0.36	0.05	2.14	2.6
OT	137.2	337.4	47.4	0.0	522.0	8.07	17.12	3.36	28.6
MB	18.9	33.6	0.0	0.0	52.5	0.07	1.7	0.0	1.8
SK	10.6	40.2	0.0	0.0	50.8	2.46	2.04	0.0	4.5
AB	28.3	119.8	0.0	0.0	148.1	7.56	6.08	0.0	13.6
BC	64.6	83.9	0.0	2.1	150.6	0.41	4.25	0.0	4.7
Canada	518.3	615.9	123.6	34.0	1291.8	25.3	31.2	8.7	65.3

Table 7. PV electricity generation, GHG emission reductions in eligible houses

Province	Eligible houses		Electricity generation (PJ)	Average electricity generation per house (GJ)	Average AL load per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent					
NF	80,588	46	1.0	12	34	0.01	124
NS	127,163	43	1.4	11	34	0.15	1,180
PE	25,795	57	0.3	12	31	0.00	0
NB	103,740	44	1.6	15	29	0.37	3,567
QC	730,955	37	8.9	12	24	0.00	0
OT	1,072,692	31	12.7	12	25	1.70	1,585
MB	115,258	34	1.4	12	23	0.00	0
SK	131,471	42	1.6	12	24	0.11	837
AB	384,813	40	3.9	10	26	0.91	2,365
BC	343,207	31	4.7	14	41	0.02	58
Canada	3,115,683	35	37.5			3.27	

Table 8. Energy savings and GHG emission reductions for the CHS due to BIPV/T retrofit

Province	Eligible houses		Total energy saved (PJ)	Average energy saving per house (GJ)	Total GHG reduced (Mt)	Average GHG reduction per house (kg)
	Number	Percent				
NF	35,707	20	3.9	109	0.18	5,120
NS	84,231	28	8.4	100	0.60	7,128
PE	13,882	31	1.7	122	0.09	6,292
NB	56,288	24	6.5	115	0.27	4,761
QC	115,717	6	10.3	89	0.50	4,351
OT	1,077,900	31	111.5	103	5.43	5,041
MB	96,782	28	9.7	100	0.51	5,224
SK	126,942	40	13.2	104	0.73	5,730
AB	382,336	39	37.5	98	1.30	3,408
BC	279,044	25	24.3	87	1.24	4,440
Canada	2,268,829	25	227.0		10.85	

Table 9. CHREM estimates of annual energy consumption (PJ) with existing (Exist) and BIPV/T retrofit (Ret) in houses eligible (EL) and houses not eligible (N-E) for BIPV/T retrofit

	Electricity			NG			Oil			Wood			Total		
	N-E	EL		N-E			N-E			N-E	EL		N-E	EL	
Province		Exist	Ret		Exist	Ret		Exist	Ret		Exist	Ret		Exist	Ret
NF	13.3	1.9	1.6	0.0	0.0	0.0	6.2	3.4	0.8	2.3	1.0	0.0	21.8	6.3	2.4
NS	14.2	3.5	3.6	0.0	0.0	0.0	13.9	8.7	1.3	4.9	1.1	0.0	33.0	13.3	4.9
PE	1.3	0.5	0.5	0.0	0.0	0.0	2.7	1.3	0.2	0.9	0.6	0.0	4.9	2.4	0.7
NB	16.1	2.6	1.9	0.0	0.0	0.0	5.5	4.2	1.1	8.0	2.7	0.0	29.6	9.5	3.0
QC	198.1	7.2	3.9	0.8	0.2	2.4	21.7	8.6	0.0	9.8	0.6	0.0	230.4	16.6	6.3
OT	103.1	34.1	40.2	221.4	116.0	16.0	29.8	17.6	0.0	0.0	0.0	0.0	354.3	167.7	56.2
MB	16.1	2.8	3.1	20.6	13.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	36.7	15.8	6.1
SK	7.2	3.4	3.4	23.7	16.5	3.3	0.0	0.0	0.0	0.0	0.0	0.0	30.9	19.9	6.7
AB	17.1	11.2	14.5	71.8	48.0	7.2	0.0	0.0	0.0	0.0	0.0	0.0	88.9	59.2	21.7
BC	51.5	13.1	13.6	57.0	26.9	2.2	0.0	0.0	0.0	2.0	0.1	0.0	110.5	40.1	15.8
Canada	438.0	80.3	86.3	395.3	220.6	34.1	79.8	43.8	3.4	27.9	6.1	0.0	941.0	350.8	123.8

Table 10. Annual energy savings and GHG emission reductions due to BIPV/T retrofit in the CHS

	Energy savings (PJ)					GHG emission reductions (Mt of CO_{2e})			
Province	Electricity	NG	Oil	Wood	Total	Electricity	NG	Oil	Total
NF	0.3	0.0	2.6	1.0	3.9	0.00	0.00	0.18	0.18
NS	-0.1	0.0	7.4	1.1	8.4	0.08	0.00	0.52	0.60
PE	0.0	0.0	1.1	0.6	1.7	0.01	0.00	0.08	0.09
NB	0.7	0.0	3.1	2.7	6.5	0.05	0.00	0.22	0.27
QC	3.3	-2.2	8.6	0.6	10.3	0.01	-0.11	0.60	0.50
OT	-6.1	100.0	17.6	0.0	111.5	-0.86	5.06	1.24	5.43
MB	-0.3	10.0	0.0	0.0	9.7	0.00	0.51	0.00	0.51
SK	0.0	13.2	0.0	0.0	13.2	0.06	0.67	0.00	0.73
AB	-3.3	40.8	0.0	0.0	37.5	-0.76	2.06	0.00	1.30
BC	-0.5	24.7	0.0	0.1	24.3	-0.01	1.25	0.00	1.24
Canada	-6.0	186.5	40.4	6.1	227.0	-1.42	9.43	2.84	10.85

Table 11. Annual energy savings and GHG emission reductions due to BIPV/T and PV retrofits in the CHS

	Energy Savings (%)		GHG emission reductions (%)	
Province	PV	BIPV/T	PV	BIPV/T
NF	4	14	1	23
NS	3	18	3	11
PE	4	23	0	23
NB	4	17	12	9
QC	4	4	0	20
OT	2	21	6	19
MB	3	18	0	29
SK	3	26	2	16
AB	3	25	7	10
BC	3	16	0	27
Canada	3	18	5	17

Table 12. Average TCC per house for PV retrofit (C$/house)

Province	Payback (yr)	Interest rate								
		3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	4,220	5,032	6,031	3,624	4,283	5,088	3,146	3,685	4,341
	6	2,581	2,845	3,137	2,339	2,570	2,825	2,130	2,333	2,557
NS	10	4,611	5,499	6,590	3,960	4,680	5,560	3,437	4,027	4,743
	6	2,820	3,108	3,427	2,556	2,808	3,086	2,328	2,549	2,794
PE	10	5,090	6,070	7,275	4,371	5,166	6,137	3,795	4,445	5,236
	6	3,113	3,431	3,783	2,821	3,100	3,407	2,570	2,814	3,084
NB	10	5,320	6,345	7,604	4,569	5,400	6,415	3,966	4,646	5,473
	6	3,254	3,587	3,955	2,949	3,240	3,561	2,686	2,942	3,224
QC	10	2,481	2,958	3,545	2,130	2,517	2,991	1,849	2,166	2,552
	6	1,517	1,672	1,844	1,375	1,510	1,660	1,252	1,371	1,503
OT	10	4,371	5,213	6,248	3,754	4,437	5,271	3,259	3,818	4,497
	6	2,674	2,947	3,249	2,423	2,662	2,926	2,207	2,417	2,649
MB	10	2,738	3,265	3,913	2,351	2,779	3,301	2,041	2,391	2,817
	6	1,675	1,846	2,035	1,518	1,667	1,833	1,382	1,514	1,659
SK	10	4,751	5,666	6,791	4,080	4,822	5,729	3,542	4,149	4,888
	6	2,906	3,203	3,532	2,634	2,893	3,180	2,399	2,627	2,879
AB	10	4,069	4,853	5,816	3,495	4,130	4,907	3,034	3,554	4,186
	6	2,489	2,743	3,025	2,256	2,478	2,724	2,054	2,250	2,466
BC	10	3,377	4,027	4,826	2,900	3,427	4,072	2,517	2,949	3,474
	6	2,065	2,276	2,510	1,872	2,056	2,260	1,705	1,867	2,046

Table 13. Average TCC per house for BIPV/T retrofit (C$/house)

Province	Payback (yr)	Interest rate								
		3%			6%			9%		
		Fuel cost escalation rate								
		Low	Medium	High	Low	Medium	High	Low	Medium	High
NF	10	29,819	35,548	42,555	25,417	30,041	35,670	21,904	25,672	30,238
	6	17,094	18,798	20,680	15,450	16,939	18,580	14,037	15,344	16,782
NS	10	28,598	34,197	41,057	24,342	28,858	34,364	20,949	24,626	29,090
	6	16,192	17,831	19,642	14,627	16,059	17,638	13,282	14,538	15,922
PE	10	30,319	36,070	43,090	25,830	30,470	36,108	22,248	26,029	30,601
	6	17,302	19,002	20,876	15,635	17,120	18,754	14,202	15,505	16,938
NB	10	30,376	35,965	42,766	25,927	30,441	35,909	22,372	26,055	30,494
	6	17,623	19,313	21,173	15,937	17,413	19,035	14,485	15,781	17,204
QC	10	29,940	35,942	43,326	25,511	30,355	36,286	21,978	25,926	30,735
	6	17,112	18,893	20,866	15,465	17,021	18,741	14,048	15,414	16,922
OT	10	10,735	12,479	14,562	9,173	10,583	12,259	7,924	9,075	10,436
	6	6,291	6,823	7,403	5,691	6,156	6,663	5,175	5,583	6,028
MB	10	7,203	8,180	9,312	6,186	6,979	7,894	5,370	6,019	6,766
	6	4,406	4,728	5,074	3,993	4,274	4,577	3,637	3,884	4,150
SK	10	7,508	8,564	9,796	6,448	7,304	8,300	5,597	6,299	7,111
	6	4,592	4,939	5,314	4,162	4,465	4,793	3,790	4,058	4,345
AB	10	1,112	1,089	1,020	955	936	882	829	814	771
	6	680	676	664	617	612	603	562	558	550
BC	10	8,934	10,168	11,603	7,673	8,674	9,833	6,661	7,480	8,427
	6	5,464	5,870	6,308	4,952	5,307	5,690	4,510	4,823	5,159