MODELLING AND TECHNICAL FEASIBILITY ANALYSIS OF A LOW-EMISSION RESIDENTIAL ENERGY SYSTEM

J. Good[1], V.I. Ugursal[1], and A. Fung[2]
[1]Dalhousie University, Halifax, Canada
[2]Ryerson University, Toronto, Canada

ABSTRACT

The residential sector contributes 17 per cent of Canada's secondary energy use, with more than 80 per cent of this contribution allocated to space and domestic hot water heating. Technological advancements in low-grade residential heat sources and distribution systems coupled with distributed renewable energy generation create an opportunity for overall end-use energy savings in the residential sector.

In this work, an energy-efficient, renewable energy based HVAC and DHW heating system for houses is proposed and modelled to assess its end-use energy savings potential. For this purpose, an integrated building model was developed using the open-source building simulation software ESP-r to simulate the proposed system. The system consists of a ground heat exchanger, ground source heat pump, in-floor radiant heating, and a heat recovery ventilation system. The proposed DHW system utilizes the excess thermal energy from the heat pump to preheat the domestic hot water. As well, a renewable energy source in the form of photovoltaic generation and net-metered grid storage were modelled to compliment the building's electrical network.

A building simulation of a common energy-efficient home in central Canada revealed that potential end-use energy savings of 50 per cent were attainable when the proposed HVAC system was compared with the base case scenario. Incorporating modest renewable energy generation furthered the net energy savings potential to over 60 per cent.

INTRODUCTION

Canada's residential housing stock is a large consumer of energy, attributable for nearly 20 per cent of the country's total secondary energy. Space and domestic hot water heating alone contribute more than 80 percent of this consumption. As traditional residential energy systems rely heavily on fossil-fuel combustion, this consumption is directly contributing to greenhouse gas emissions and the potential ecological catastrophes associated with them. Although partially attributable to circumstances such as cold winters and a dispersed geography, significant improvements are possible to reduce wasted energy as well as to tend away from fossil-fuel dependence to meet the heating demands of Canadian homes and contribute to our Kyoto commitments.

The high combustion temperatures produced by traditional systems (i.e. approximately 2000°C for a natural gas boiler) are excessive when applied to residential heating (typical temperature requirements of 60°C or less). Alternative residential heating systems must be explored that are better suited for low-temperature heating applications while still maintaining the dependability and comfort levels afforded by traditional fossil-fuel fired heating, ventilation, and air-conditioning (HVAC) systems. The energetic and emission performance of one such alternative, a hybrid residential energy system, is the focus of this study.

The proposed system is a hybrid system incorporating low-exergetic and renewable technologies. While exergetic efficiency is not calculated, exergetic efficiency is inherently higher due to smaller temperature difference in the heat transfer process. The proposed system includes a ground source heat exchanger that utilizes the near constant year round temperatures of the earth (approximately 4 to 12°C), this temperature is then upgraded by a heat pump. The heat pump provides conditioned water (approximately 35 to 40°C) to supply a radiant in-floor loop that provides sensible heating to the conditioned zones as well as to a domestic hot water (DHW) loop which will be preheated by any excess thermal energy available from the ground source heat pump (GSHP). A heat recovery ventilation (HRV) system is incorporated to minimize the heating load necessitated with conditioning outdoor air directly. A schematic of the proposed HVAC system is shown in Figure 1[1].

[1] Due to the small percentage of residential end-use energy consumption that is attributed to cooling in Canada, approximately one percent (NRCan, 2003), this work concentrates on the more intensive energy consumers: space heating, DHW, and occupant-driven electricity consumption.

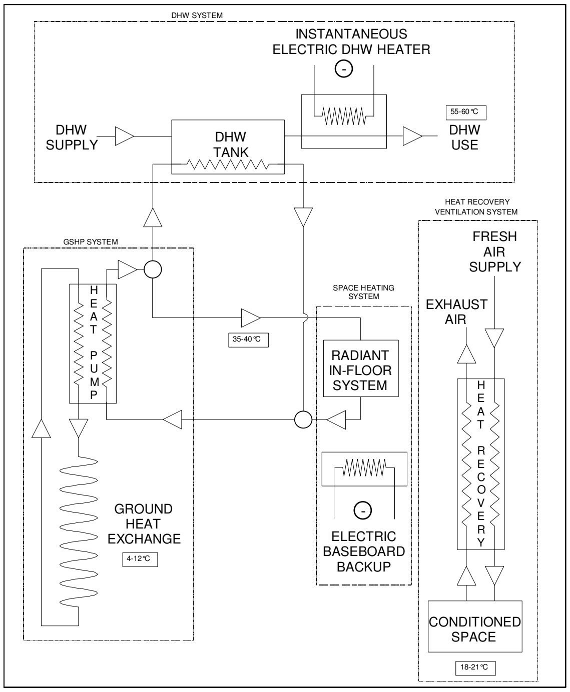

Figure 1: Schematic of Proposed Hybrid HVAC System

The proposed system is inherently "low-emission" compared to conventional systems (e.g. combustion or resistance electric based) because of the use of geothermal heat, HRV, heap pumps and radiant heating (resulting in a lower setpoint temp). To reduce the reliance on grid-generated electricity, and the mandatory losses and emissions associated with its production, the electrical demands necessary of the residence are met through a combination of renewable electricity generation (via photovoltaic modules) and grid-generated electricity interacting in a net-metering scenario.

The pursuit of alternative residential energy systems is well documented in recent research, as many hybrid systems focusing on sustainable energy production and reduction in exergetic losses have been investigated. For example, the merits of combining flat plate thermal collectors with air source heat pumps (Kaygusuz, 1999), solar assisted heat pumps with seasonal energy storage (Yumrutas et al., 2003), and ground coupled heat exchangers with hybrid cooling systems (Phetteplace and Sullivan, 1998) have all been investigated. Combinations of electricity-producing renewable hybrids have also received attention as Kilkis (1999) performed a study similar to the hybrid system proposed in this work by combining a GSHP with a 6 kW wind turbine and radiant paneling for Turkish residences. His findings suggest that the system has great end-use energy saving potential when coupled with the right climatic conditions; northern climates, such as Canada's were found to be the best suited. Literature relevant to each individual system will be presented along with the description of each model. For a complete literature review refer to Good (2005).

This paper builds upon a simulation strategy developed for modelling in-floor radiant heating (Good et al., 2005) by discussing the process in which the proposed residential HVAC and electrical system was modelled. The results will be compared to those achieved with common Canadian residential energy systems.

BUILDING SIMULATION

To assess the performance of the proposed hybrid residential energy system a model was employed. The building simulation platform ESP-r was selected as a result of its powerful energy flow modelling capabilities, capable of solving for the thermal and electrical flows and balances throughout an entire building. A multi-domain approach allows the modeller the freedom of varying the level of complexity of both the model and the solution. As well, the open source code allows for continual evolution and expansion of the original software kernel as developed and validated by the Energy Systems Research Unit at the University of Strathclyde (see ESRU, 2000; Strachan, 2000; Clarke, 2001). ESP-r was also selected as it has been established by CANMET Energy Technology Centre (CETC) as the preferred simulation engine for future Canadian standards of building simulation tools (see Haltrecht et al., 1999).

Residential Model

The residential model for the proposed simulation and analysis was based on a set of twin test houses built according to R-2000 energy design standards in Ottawa, Ontario by the Canadian Centre for Housing Technology (CCHT) (see Swinton et al., 2001). The CCHT test house has already been modelled in ESP-r by Purdy and Beausoleil-Morrison (2001), with only minor modifications required for the current base case application. The CCHT model consists of five zones representing a basement, main-floor, garage, second-floor, and attic totaling 210 m^2 of livable area. The occupied zones (main and second floors) were ideally controlled to achieve a set-point temperature of 21°C during the day (8am to 8pm) with a night temperature setback to 18°C. The remaining zones in the model were not directly controlled, but allowed to "free-float" with thermal influence of the adjacent zones and exterior environment. Selected characteristics for the building are given in Table 1.

Table 1:
Selected Characteristics of the CCHT Test Houses

Component	Characteristic
Construction Standard	R-2000
Storeys	2
Livable Area	210 m^2
Basement	Poured concrete, full basement
Garage	Two-car, recessed into the floor plan; isolated control room in the garage
Attic	RSI 8.6
Walls	RSI 3.5
Rim Joists	RSI 3.5
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor.
Basement Walls	RSI 3.5 in a framed wall. No vapour barrier.
Basement Floor	Concrete slab, no insulation
Windows	Low-e, insulated spacer, argon filled, with argon concentration measured to 95%
Window Area	South Facing: 16.2 m^2 Total: 35.0 m^2
Air Barrier System	Exterior, taped fiberboard sheathing with laminated weather resistant barrier. Taped penetrations, including windows.
Airtightness	Reference 1.07 ach @ 50 Pa; Test House 0.97 ach @ 50 Pa
Heat Recovery Ventilator	High Efficiency (84% nominal)
Furnace	Condensing gas @ 91% efficiency (as measured)
Hot Water Heater	Conventional, induced draft @ 67% efficiency (as measured)
Air Conditioning	High efficiency – SEER 12 (nominal)

This configuration represents a common system of central Canadian residences (Aydinalp et al., 2000). This selection accounts for a significant percentage of the residential housing stock in Canada and was therefore used as the base case for which the proposed residential energy system could be compared. Varying climatic conditions were introduced to the simulation using hourly weather information from Canadian Weather for Energy Calculation (CWEC) files, available within ESP-r.

SYSTEMS SIMULATION

As mentioned previously, the proposed residential system is comprised of two main components. The first of these is the hybrid HVAC system that transports heat from the ground in the heating season and distributes this thermal energy throughout the residence. The second component is the hybrid renewable electricity system that provides the electricity required to run the HVAC system and occupant-driven demands from photovoltaic electricity generation complimented by storage and control schemes. The proposed systems were modelled by integrating existing ESP-r modules, modifying existing modules, and developing new modules.

Ground Source Heat Pump Model

Two models exist in ESP-r to model ground source heat exchange. The first, incorporated from the GHX sizing program GS2000 (Morrison, 1997), performs heat transfer calculations on a daily basis, superimposing single pipe results for a multi pipe configuration. A recently developed module by Pinel (2002) has increased the simulation frequency to hourly and considers the heat transfer between boreholes but is not compatible with other modules required for the analysis. Therefore, the GS2000 adaptation was used to estimate entering water temperatures (EWT) to the heat pump. Validation and comparison with other models is available elsewhere (Purdy, 2002; Shonder et al., 1999).

A sensitivity analysis was performed to identify optimum heat exchanger configurations using common lengths and EWT as a deciding metric[2] (see Good, 2005). This revealed that, for constant lengths, vertical and horizontal slinky configurations performed equitably (both outperforming straight horizontal) despite the significant financial savings of the horizontal slinky configuration. Considering the significant capital cost savings of the horizontal slinky configuration over the vertical, the horizontal slinky configuration was selected to supply the ground temperature antifreeze solution to the heat pump. The heat pump was sized to meet 75% of the design heating load, with electric baseboards providing the supplemental heating requirements[3]. Table 2 provides the details of the modeled ground heat exchanger (GHX) and GSHP systems.

Table 2: GSHP and GHX Modelling Parameters

Heat Exchanger Parameters	
GSHP System Type:	Horizontal Slinky
Pipe Inner Diameter (mm):	21.9
Pipe Outer Diameter (mm):	26.9
Pipe Thermal Conductivity (W/mK):	0.38
Pipe Length (m):	200
Fluid	CPTherm-G, 35% conc.
Fluid Density (kg/m^3):	1160
Fluid Heat Capacity (kJ/kgK):	2.805
Fluid Flow Rate (L/s):	0.7
Earth Mean Temperature (°C):	10
Surface Temperature Amplitude (°C):	12.5
Time of Minimum Surface Temp:	41st day of year
Soil Conductivity - Summer (W/mK):	0.87
Soil Conductivity - Winter (W/mK):	1.3
Soil Diffusivity - Summer (m^2/s):	0.52 x 10^{-6}
Soil Diffusivity - Winter (m^2/s):	0.64 x 10^{-6}
Depth of Heat Exchanger Pipes (m):	1.8
Diameter of Slinky Spirals (m):	0.9
Heat Pump Parameters	
HVAC system type:	Ground Source Heat Pump
Heat pump heating capacity (kW):	12.8
Heat pump heating mode COP:	2.9
Flow rate (L/s):	0.75

2 A higher EWT results in a higher heat pump COP, resulting in lower energy consumption.
3 It is acknowledged that an electric baseboard system would be impractical as a backup for an in-floor, hydronic system. The selection was based upon the ease of modelling this system within ESP-r and the close approximation it makes of a more realistic (but difficult to model) backup scenario, electric resistance heating.

Figure 2 presents the operation of primary and secondary heating systems over a sample day in the heating season. It can be seen that when the GSHP reaches capacity, the secondary electric system is initiated, with the primary system meeting 86% of the total annual load. Slight fluctuations between the heating energy required and that delivered are accounted for by the throttling range of the PID controller (Good et al., 2005).

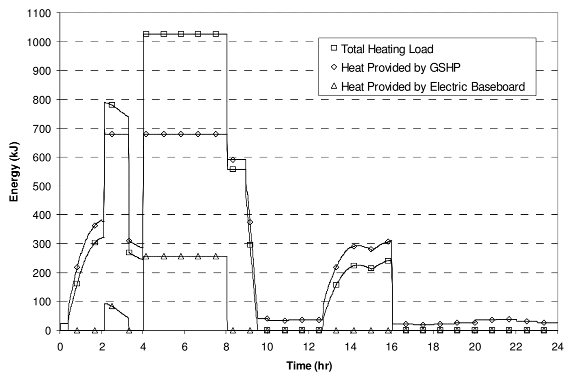

Figure 2: Primary & Secondary HVAC End-Use Energy Consumption (Ottawa, Jan 9th)

In-floor Radiant Heating

In the proposed system, the heated water provided by the GSHP is distributed to meet the heating requirements of the building via a system of pipes in-laid in the flooring of the conditioned zones. The use of radiant heating affords increased comfort levels at reduced thermostat settings when compared with forced air distribution systems. By sensing mean radiant temperature instead of dry bulb temperature this effect could be studied. Since a module for modelling in-floor radiant heating that is compatible with the other implicit models used in this work is not available in ESP-r, a simulation strategy and sensitivity analysis of a module that incorporates a thin "fictitious" heat injection zone to simulate hydronic radiant heating was developed. Full details of this approach and its implementation in ESP-r are documented elsewhere (Good et al., 2005; Good, 2005). The results of simulations conducted using this approach indicate that an overall end-use energy consumption savings of 11% is possible by replacing the common forced air system of the CCHT model with an in-floor radiant system. Figure 3 shows the predicted temperature profiles of the compared distribution systems for a sample day in the heating season.

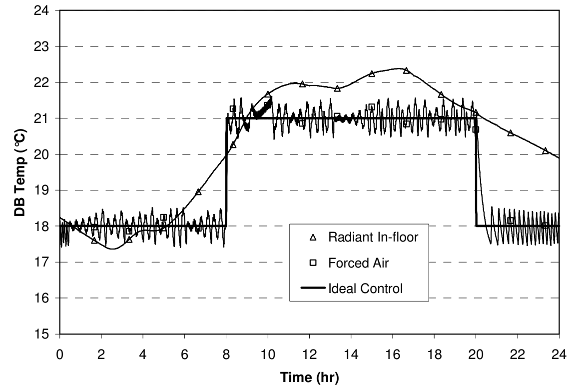

Figure 3: Forced Air & Radiant Temperature Profile Comparison for Mainfloor: DBT Sensed (Ottawa, Jan 9th)

Heat Recovery Ventilation System

A heat recovery ventilation (HRV) system is used to provide the fresh air requirements of the residence. The supply and exhaust fan power as well as the efficiency of heat recovery (85% at design conditions) are calculated using a simple, balanced, air-to-air HRV unit model (Hensen, 1991; Clarke, 2001; Good, 2005).

DHW System with Preheat

The domestic hot water system is responsible for increasing the temperature of the cold water supply at a starting temperature of approximately 10°C[4] to the end use temperature of 55-60°C. Achieving this temperature increase in homes across Canada accounts for 21% of the residential end use energy consumption (NRCan, 2003). Due to the significance of this energy consumption, the proposed system analyzed the use of the excess heat produced by the GSHP system at a high coefficient of performance (COP) for preheating the DHW. For the cases when preheat is not available, or not able to fully achieve temperatures of 55°C, an instantaneous DHW heater is employed (refer to Figure 4). The objective is to achieve further energy savings by eliminating the standard DHW tank, and the standby heat losses inherent with them.

[4] The model parameters for ground temperatures, and thus inlet water temperatures, for Ottawa are a mean of 11.1°C with an amplitude of 5.9°C (Purdy & Beausoleil-Morrison, 2001)

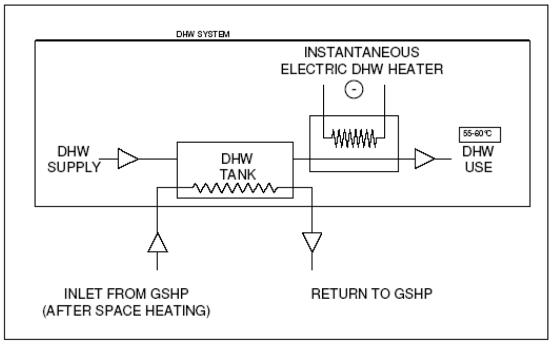

Figure 4: Schematic of DHW System Model

The preheating of DHW by a heat pump is currently not supported in ESP-r; however, a number of modelling options exist for simulating the DHW system of a residential building (Clarke, 2001; Beausoleil-Morrison, 2002; Kelly, 2001). An existing DHW model, developed by Lopez (2001) for CETC's HOT3000 simulation program, provided a reliable basis to incorporate modifications for heat pump preheating capabilities. This DHW model determines the energy requirement necessary for heating the supply water to the desired delivery temperature. The water draw for each simulation time step is then calculated by taking the hourly water draw and dividing it equally between the number of time step iterations in that hour. The amount of energy available from the GSHP system after space heating requirements are met is then determined. If there is excess energy available from the GSHP it is utilized to preheat the DHW up to a maximum temperature of 40°C (the maximum deliverable temperature of the heat pump). The remaining temperature increase up to 55°C is achieved using an instantaneous DHW heater, for which provisions are already made in ESP-r. Details of the modelling procedure and ESP-r code documentation are presented by Good (2005).

The resulting heat pump DHW preheat model was validated by ensuring that DHW end-use temperatures were consistently maintained at 55°C, as well as comparing the energy demand of the proposed system (for a sample week in the heating system) to a base case scenario in which an instantaneous heater met the full DHW load. The result was an identical energy demand between the cases, indicating that the DHW requirements are being fully met by the new model. Alternatively, the energy consumption of the two cases varied significantly, as the preheat model exhibited DHW end-use energy savings of over 40%. The end-use energy consumption and demand of the preheated DHW system are plotted in Figure 5 for a sample day in the heating season.

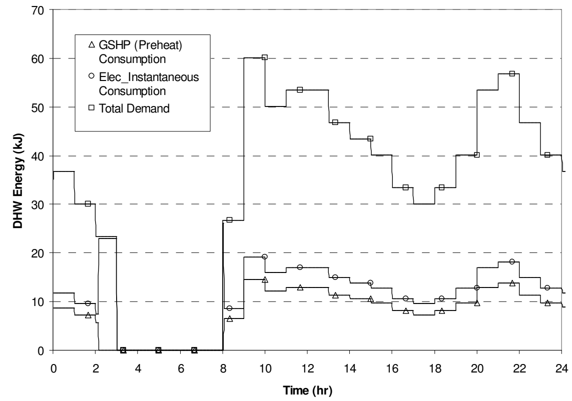

Figure 5: DHW Preheat End-use Energy Consumption forJan 9th

Hybrid Renewable Electricity System

The proposed electrical system balances the fluctuations associated with the photovoltaic (PV) electricity generation system by utilizing the electrical storage provided by the grid through a net-metering scenario. This grid-connected PV system contributes to the residential electric load which consists of two components: an occupant-driven electricity load for a four-person Canadian household (Good et al., 2004) and the HVAC electricity load required to power the hybrid HVAC system described previously.

ESP-r's electrical plant network offers a means of modelling the power flows associated with a building's electrical loads, sources, and distribution system (Kelly, 1998). For the proposed case, the renewable electricity generation was considered an active building element[5] and thus modelled using the silicon solar cell module designated as a special materials function of ESP-r (Evans & Kelly, 1996). A PV cell array was designed to encompass the 41.5 m^2 of south facing roof surface available on the CCHT test house[6]. The multi-crystalline PV modules selected are able to generate a maximum power output of 5.12 kW. As an inverter model is not available within ESP-r, the PV model was altered to consider losses associated with an inverter operating

[5] Elements that alter their thermophysical properties or energy flows (or both) in response to some external excitation.

[6] The PV modules enlisted for this project, BP-3160 from BP Solar, were selected based on a review of current panel technologies available on the residential power market in Canada. The selection criteria were based primarily on performance for a given area, as and economic analysis was not performed for this study. Further details of the PV module design process are presented in Good (2005).

at a constant efficiency of 90% (Xantrex, 2005). In Figure 6, the daily electrical generation of the PV panels is compared with the daily residential electrical load for sample days in the heating and cooling seasons.

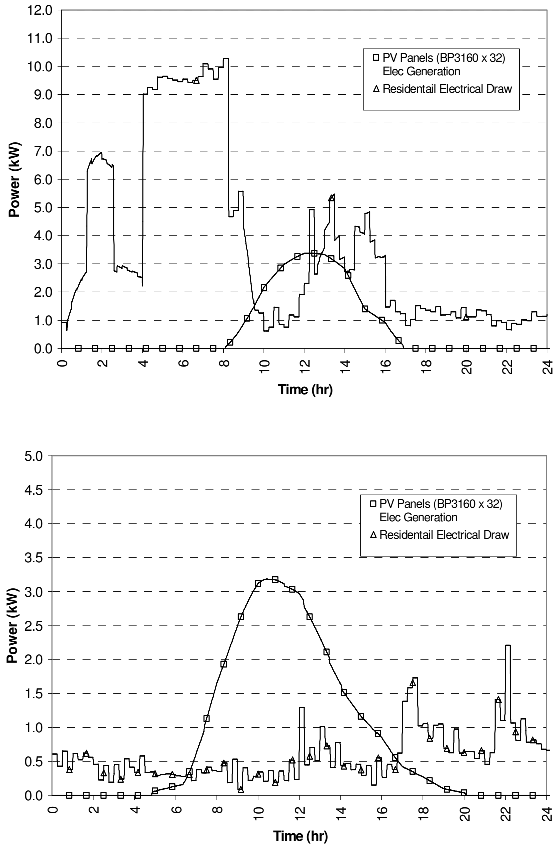

Figure 6: PV Electricity Generation vs. Electrical Draw for Day in Winter (top) and Summer (bottom)

The discrepancy between the time of electricity generation and consumption (only 47% of annual PV generated electricity could be consumed immediately) illustrates the need for demand-supply management. As mentioned previously, for the proposed system the grid acts as an ideal electrical storage device in a net-metering scenario.[7] Figure 7 illustrates the electrical draws from the grid (positive) and to the grid (negative) for the proposed hybrid electrical system.

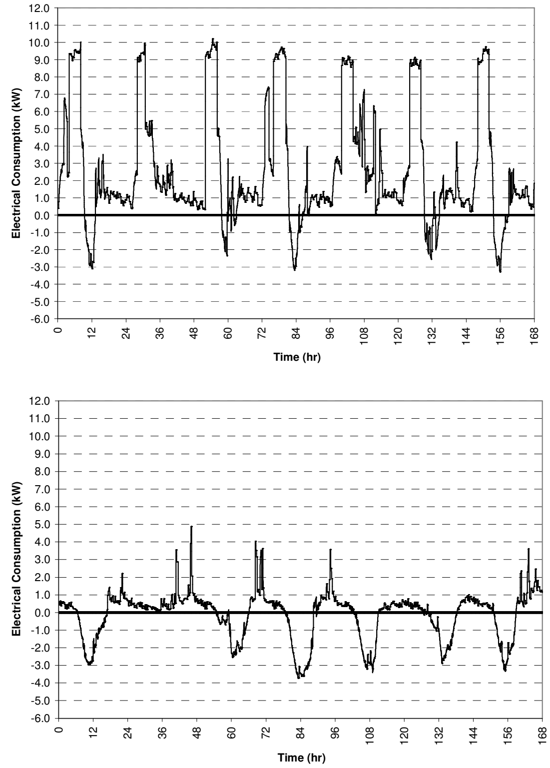

Figure 7: Net Residential Electrical Draw for Week in Winter (top) and Summer (bottom)

END-USE ENERGY RESULTS

The results of the end-use energy consumption for Ottawa, Ontario are shown in Tables 3 and 4 where the operation of the two systems was simulated for an entire year.

Table 3:
End-Use Energy Consumption for HVAC and DHW Heating; Base Case and Proposed System

Ottawa (Jan 1st-Dec 31st)	**Base Case (GJ)**	**Proposed (GJ)**	
	Regular Temperature Setting	*Regular Temperature Setting*	*Reduced Temperature Setting*
Electricity – GSHP		15.31	17.17
Electricity – GSHP Circulation Pumps		3.43	3.50
Electricity – Baseboard Heaters		5.90	0.01
Natural Gas – Furnace	34.38		
Electricity – Circulation Fans	0.73		
Natural Gas – DHW Heater	25.39		
Electricity – Instantaneous DHW Heater		5.83	5.80
Electricity – HRV Fans & Preheat	3.70	3.70	3.70
DHW & HVAC Energy Consumption	**64.20**	**34.16**	**30.18**
DHW & HVAC Energy Savings		**46.8%**	**53.0%**

[7] It is acknowledged that this assumption is an over-simplification of current net-metering practices ignoring technical grid connection and compensation policies. This assumption was deemed acceptable for the current modelling endeavour in an effort to approximate the impact of on-site renewable electricity generation.

Table 4:
End-Use Energy Consumption for Entire Building (HVAC and Elec); Base Case and Proposed System

Ottawa (Jan 1st-Dec 31st)	**Base Case (GJ)**	**Proposed (GJ)**	
	Regular Temperature Setting	*Regular Temperature Setting*	*Reduced Temperature Setting*
Occupant Driven - Electricity	32.18	32.18	32.18
HVAC & DHW – Electricity	4.43	34.16	30.18
HVAC & DHW – Non Electricity	59.77	0	0
PV Generation – Electricity		-23.94	-23.94
Net Electrical	**36.61**	**42.40**	**38.42**
Net Non-Electrical	**59.77**	**0**	**0**
Net Consumption	**96.38**	**42.40**	**38.42**
• **Net Energy Savings**		**56.0 %**	**60.1 %**

For a residential building in Ottawa, it can be seen that significant end-use energy savings (60.1% for the operative (mean radiant) temperature setting) by replacing the base case system with the proposed hybrid HVAC and DHW energy system. It is also seen that due to the small requirements of the backup heating system in the proposed case (3 kWh per year), the sizing of the entire system could be reduced or the backup system could be eliminated altogether.

The PV panels simulated for the Ottawa residence produce nearly 24 GJ of electricity annually, reducing the dependence on grid-generated electricity by up to 45%. Overall end-use energy savings of up to 60% are possible with the incorporation of both the HVAC and electrical component modifications of the residential energy system proposed in this work.

CONCLUSIONS AND RECOMMENDATIONS

This paper documents the implementation of a multi-modular model for simulating the proposed hybrid residential energy system. An approach was documented that successfully links modules in the ESP-r building simulation environment that have previously been isolated from one another. Through the implementation of existing modules (GHX, GSHP, HRV, and PV) for sensitivity analysis and the development of novel modelling approaches (in-floor radiant and DHW with GSHP preheat), a low-emission alternative to conventional residential energy systems was analyzed.

The proposed residential energy system, both HVAC and electrical, have proven to show significant savings when compared with commonly found systems in Canada. The in-floor radiant model exhibited an 11% end-use energy savings over the forced-air base case scenario. The proposed preheated DHW system resulted in a 42% reduction in DHW load over the base case system. When combined, the entire proposed hybrid HVAC system provided end-use energy consumption savings of over 50%, and when the hybrid renewable electrical system was considered as well, the net energy savings increase to over 60%.

The modelling and technical feasibility study of the proposed alternative HVAC system presents an effective solution to reducing the end-use energy consumption and GHG emissions attributed to the Canadian residential sector. The tools developed in this work can be used to evaluate economic, policy and implementation options concerning residential end-use energy and emissions.

While the objectives of this work were achieved, future research exploring thermal storage systems, parallel renewable energy systems, electricity storage, grid connectivity options, and an economic analysis of the proposed system would be required in progressing towards implementation.

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