INVESTIGATING THE PERFORMANCE OF A HYBRID SOLAR DOMESTIC HOT WATER SYSTEM THROUGH COMPUTER SIMULATION AND DATA ANALYSIS

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ABSTRACT
The objective of this paper is to simulate the performance of a Solar Domestic Hot Water system and to investigate the contributions of different components in lowering the annual electricity demand for domestic hot water production. The system is for one of the Archetype Houses located at the Kortright Centre in Vaughan, Ontario. Simulation results showed that with solar thermal collector and drain water heat recovery, the system’s annual electricity demand can be reduced from 3672 kWh to 1988 kWh which is 46% of savings. It was also concluded that changing solar loop control strategy can lower energy losses from solar preheat tank.

INTRODUCTION
Decreasing energy requirements and conserving energy, alongside with exploring renewable and environmentally friendly sources of energy is becoming more important as the concerns for limited energy resources in the near future continues to grow, especially in a cold climate country like Canada. According to Natural Resources Canada (NRCan, 2009) domestic water heating (DWH) is estimated to be the second largest energy end-use for Canadian households, exceeded only by space heating, which accounts for about 18% of total household energy consumption. Although there has been an approximate decrease of 20% in per household annual energy used to heat water since 1990, the overall energy required for this purpose has increased by about 6% from 243.0 PJ to 257.9 PJ (NRCan, 2009). This paper focuses on a hybrid Solar Domestic Hot Water (SDHW) system with drain water heat recovery (DWHR) system and electric heating backup in a semi-detached house located in Vaughan, Ontario. The DWHR system is for recuperating part of the energy contained in drain water coming from different sources. Both main pipe and coil of the DWHR heat exchanger are made from copper to enhance the heat transfer between the two flows. The solar collector is a heat pipe based evacuated tube collector type with 20 evacuated tubes.

LITERATURE REVIEW
The performances of SDHW systems and DWHR units have been subjected to many studies in the past. In a research project by Florida Solar Energy Centre (FSEC), Merrigan and Parker (1990) investigated the water heating electrical energy consumption, efficiency and time of day demand of eighty single family residences in Florida with four different heating systems through monitoring systems for two years. The four systems were conventional electric heaters, heat pumps, heat pump desuperheaters and solar hot water systems; all of which were equally divided among the residences. The results from the collected data showed that daily electricity consumption of electric resistance water heaters was 8.3 kWh on average. The annual average electricity consumption of SDHW system was determined to be the lowest with 2.7 kWh per day. Electrical demand taken at 15-minute intervals showed that the electric heaters contributed approximately 1.1 kW and 0.2 kW per customer to the utility winter peak and summer peak respectively which accounted for about 25% of the utility winter peak demand and 5% of the summer peak demand in Florida. It was concluded that the SDHW system had the highest peak demand reduction of 0.7 kW and 0.2 kW per customer in the winter and summer, respectively. The average coefficient of performance (COP) for the SDWH system was shown to be 2.35 with an annual load factor of 41%. COP is defined as the hot water energy use divided by the electrical energy consumption.

Druck et al. (2004) from University of Stuttgart, Germany performed a series of comparison tests on sixteen different solar thermal collectors used for water heating. Twelve systems were equipped with flat plate collectors and four with evacuated tube collectors and the systems were tested for their thermal performance, durability and reliability, environmental and safety aspects. The effective collector areas varied from 3.2 m² to 5.7 m² for all solar collectors. The effective usable storage volume of the domestic hot water was in the range of 268 litres up to 419 litres. The transferred solar energy to the domestic hot water (DHW) was through a plain
tube heat exchanger. The systems were simulated for a single-family house located at Wurzburg, Germany using TRNSYS simulation software. The results showed that the DWH system with the evacuated tube collector of 3.2 m² in area had the lowest energy payback period of 1.3 years.

Picard et al. (2004) investigated two methods for reducing the amount of energy required for DWH in residences through TRNSYS simulations. The first method was using a DWHR unit and the second one was a classic SDHW heating system. TRNSYS simulations were performed using a typical Canadian residence hot water consumption profile and the annual temperatures of water mains of the city of Montreal. From the simulation results, it was concluded that the DWHR unit can recover 36% to 49% of the energy needed to heat water for showers, depending on its location in the plumbing system which are equivalent to 12% to 17% of savings in the total energy needed for producing DWH. The SDHW system was shown to be able to provide about 56% of the energy needed for the DWH heating. It was concluded that with the addition of the DWHR unit to the solar system, the total renewable fraction could reach to 69% for the DWHR configuration with the highest energy recovery.

Fung and Gill (2011) studied seventeen DHW systems for their fuel consumption, greenhouse gas (GHG) emissions and 30-year lifecycle costs. Results from TRNSYS simulations showed that the system with flat plate solar collector and electrical backup with time of use (TOU) option is the best option for reducing energy consumption and GHG emissions with the annual energy consumption of 1.22 MWh and 266 kg of GHG emissions. In the second part of this study, 96 different scenarios of hybrid water heating systems were simulated using TRNSYS and sensitivity analysis was performed. It was concluded that the hybrid system with DWHR unit has the ability to achieve 80% reduction in electricity cost and GHG emissions when compared to a conventional natural gas system without heat recovery. It was also indicated that the lowest payback period is when the daily hot water consumption is 225 litres with the auxiliary set point temperature of 60°C.

Zaloum et al. (2007) investigated the performance of eight different DWHR units through experimental analysis. The experiments were performed for two different flow configurations, three different flow rates and three different shower temperatures under equal operating conditions to assess the performance and heat transfer rate of each unit. The performance of the units was measured in terms of Number of Thermal Units (NTU) and effectiveness with the NTU versus flow rates curves showing a better correlation. It was concluded that the NTU-curves were independent of the flow configurations and an energy saving calculator, showing the performance and benefits of different units was also developed. It was also shown that there is an optimal balance between the performance and size of the units; that is the shorter units perform best on a per foot basis.

**SIMULATION**

The current study is based on the SDHW system of one of the two semi-detached “Sustainable Archetype Houses” located at the Kortright Centre in Vaughan, Ontario, Canada. The two houses are named as House A and House B and the project has been implemented by Toronto and Region Conservation Authority (TRCA) along with the Building Industry and Land Development (BILD) Association. The aim of this project has been to demonstrate different sustainable housing technologies in the near and medium term future. Figure 1 shows an overview of the twin archetype houses. House B is the semi-detached house located on the right.

![Figure 1- TRCA Archetype Houses Overview](image)

A comprehensive energy monitoring system has been implemented in the houses to investigate the effectiveness and efficiency of the mechanical systems (Zhang et al., 2011). The SDHW system of House B consists of an evacuated tube solar collector in conjunction with an electric water heater and DWHR unit. This system is a dual tank system, the second of which is the solar pre-heat tank. The solar system is an active, indirect system which is closed from the atmosphere and the circulating fluid is a mixture of 60% distilled water and 40% propylene glycol. Figure 2 displays the schematics of solar domestic hot water model.

The solar collector is south facing with an inclined angle of 25°. The model presented in Figure 2 is simulated in TRNSYS with one-minute time step to be able to better investigate the DWHR unit’s performance. Standard components from TRNSYS library are use except for the DWHR unit for which a new model was created. As seen in Figure 2, the system is configured in a way that the DWHR only preheats the water to solar preheat tank.
The collector is assumed to be a stratified tank with a volume of 300 litres and with two immersed heat exchangers. The lower heat exchanger is used for solar loop and the upper one can be used for an auxiliary heating source like the desuperheater loop of Ground Source Heat Pump/Co-generation unit. The stored water in the tank gets warmed up with heat exchange from antifreeze fluid in the heat exchanger. The model used for the tank is Type 60t with one immersed heat exchanger since this paper's focus is only on the performance of the SDHW system with the electric tank as the backup. In other words, it has been assumed in this paper that there is no other auxiliary heating source hooked up to the tank. The heat exchanger coil is 0.025 m in diameter and the heat exchanger area is 1.5 m² with 10 litres of fluid content. The tank has no heating elements. The pump starts to run when the temperature difference between the solar preheat tank sensor, located inside the heat exchanger coil and close to the outlet port of the tank, and the solar collector header outlet reaches 6.7°C and stops when the temperature difference is less than 4.5°C. There is also a high limit cut-off to stop the pump when solar preheat tank outlet temperature exceeds 60°C.

Auxiliary Tank: The tank is assumed to be a stratified tank with a volume of 184 litres. The tank is modelled by assuming that it consists of eight fully mixed equal volume segments with an equal height of 0.15 m. Each segment has an assigned node. The type used to model the tank is Type 4a with two electric resistance heating elements. The first element located in the eighth node with node one being the top most node with a set point temperature of 52°C and a dead band of 5°C and with a maximum heating rate of 3000 W. The second element is located in the fourth node with a set point temperature of 60°C and a dead band of 5°C and with a maximum heating rate of 3000 W. The tank loss coefficient is set to be 0.5 kJ/hr-m²-K.

Solar Loop Circulation Pump: The pump is used to circulate the propylene glycol solution within the solar loop. The model used is Type 110 which is a variable speed pump that is able to maintain any outlet mass flow rate between zero and a rated value. The rated flow rate for the pump is 120 kg/hr and the rated power is 50 W. A differential controller with hysteresis (Type 2b) is used to activate the pump. The pump starts to run when the temperature difference between the solar preheat tank sensor, located inside the heat exchanger coil and close to the outlet port of the tank, and the solar collector header outlet reaches 6.7°C and stops when the temperature difference is less than 4.5°C. There is also a high limit cut-off to stop the pump when solar preheat tank outlet temperature exceeds 60°C.

Drain Water Heat Recovery: Figure 3 displays the schematic of the DWHR heat exchanger. The physical characteristics of this model correspond to an actual model, R3-36 by Power Pipe Company. The performance and the effectiveness of the unit have been obtained through a series of experiments.

TRNSYS Models

The used components are as followed:

Evacuated Tube Solar Collector: The collector is Vitosol 200, manufactured by Viessmann which consists of 20 evacuated tubes. An absorber with sol-titanium coating is an integral part of the tubes to ensure high absorption of solar radiation. The gross area of collector is 2.88 m² and the absorber area is 2.05 m². Flow rate at test conditions is 0.02 kg/s-m². The operational efficiency equation used for the model is:

\[ \eta_{col} = \eta_0 - k_1 \left( \frac{T_m - T_a}{t_i} \right) - k_2 \left( \frac{T_m - T_a}{t_i} \right)^2 \]  \hspace{1cm} (1)

Where \( T_m \) is the collector’s inlet and outlet average temperature, \( T_a \) is the ambient temperature and \( I \) is the solar irradiation. \( \eta_0 \) is the optical efficiency and \( k_1 \) and \( k_2 \) are thermal loss coefficients. These values are as stated below:

\[ \eta_0 = 83.8\% \]
\[ k_1 = 1.18 \frac{W}{(m^2 K)} \]
\[ k_2 = 0.0066 \frac{W}{(m^2 K^2)} \]

The above values have been determined by the manufacturer in accordance with EN 12975. The thermal efficiency of the collector can also be obtained as shown in Equation (2):

\[ \eta_{col} = \frac{\dot{m} C_p (T_{0,Col} - T_{i,Col})}{A_{col} I_t} \] \hspace{1cm} (2)

Where \( \dot{m} \) is the flow rate, \( C_p \) is the fluid specific heat, \( T_0 \) and \( T_i \) outlet and inlet temperature of fluid through the collector and \( A_{col} \) is the collector area.

Solar Preheat Tank: The tank is assumed to be a stratified tank with a volume of 300 litres and with two immersed heat exchangers. The lower heat exchanger is used for solar loop and the upper one can be used for an auxiliary heating source like the desuperheater loop of Ground Source Heat Pump/Co-generation unit. The stored water in the tank gets warmed up with heat exchange from antifreeze fluid in the heat exchanger. The model used for the tank is Type 60t with one immersed heat exchanger since this paper’s focus is only on the performance of the SDHW system with the electric tank as the backup. In other words, it has been assumed in this paper that there is no other auxiliary heating source hooked up to the tank. The heat exchanger coil is 0.025 m in diameter and the heat exchanger area is 1.5 m² with 10 litres of fluid content. The tank has no heating elements.

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Figure 2- Schematic of the SDHW System of House B

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performed at the site and the average effectiveness for different flow rates has been defined. The main pipe is 7.6 cm (3 inches) in diameter and 91 cm (36 inches) in length and the wrapping tubes are ½ inch in diameter.

A new model was created for the DWHR used for the SDHW system. DWHR was assumed to be a counter flow heat exchanger. This model is based on the work done by Zaloum et al. (2007). According to their report, different DWHR units can be characterized by the NTU vs. flow rate curve due to the fact that the units flow rates, inlet and outlet temperatures are the most important variables in determining the performance of the units. The correlation is in the format shown in Equation (3):

$$\text{NTU} = A_1 \cdot \dot{m}^{-A_2} \quad (3)$$

From the actual data collected from the DWHR unit at the house, the two coefficients for the NTU vs. flow rate correlation formula for different flow rates was determined to be:

$$A_1 = 1.355$$
$$A_2 = 0.311$$

Once the curve for the NTU is obtained, the unit’s effectiveness and the heat transfer can be achieved.

$$\varepsilon = \frac{1 - \exp(-\text{NTU}(1 - C_r))}{1 - C_r \cdot \exp(-\text{NTU}(1 - C_r))} \quad (C_r \neq 1) \quad (4)$$

$$\varepsilon = \frac{\text{NTU}}{\text{NTU} + 1} \quad (C_r = 1) \quad (5)$$

Where $$C_r = \frac{c_{\text{min}}}{c_{\text{max}}} \quad (6)$$

$$c_{\text{min}}$$ and $$c_{\text{max}}$$ are the minimum and maximum capacity rates in kJ/hr-K. The actual heat transfer rate across the heat exchanger can be defined as followed:

$$Q = \varepsilon c_{\text{min}} (T_{h,i} - T_{c,i}) \quad (7)$$

Where $$T_{h,i}$$ and $$T_{c,i}$$ are the hot side and cold side inlet temperatures respectively.

**Water Draw Profile**

Daily hot water draw profiles have been subjected to several studies during the past years. Stevenson (1983) performed a field survey in over 600 single family households across Canada with different water heaters. The overall hourly hot water draw patterns showed a daily peak usage for the early mornings and evenings with the showers having about 41% of the daily hot water usage. Perlman and Mills (1985) investigated the daily hot water profile patterns by monitoring the data from Canadian residences. The hot water draw profile for the “typical” family, a family with two adults and two children with clothes washer and dishwasher, was an hourly water draw which also showed two sets of peaks, one for the mornings and one for the evenings. The total daily hot water consumption was also concluded to be 240 litres. Parker (2003) performed monitoring of over 200 residences with electrical heaters in Florida, collecting data on water heater energy use and demand on a 15-minute basis. The daily histogram of hot water energy use was derived which showed only one peak occurring in the early morning.

The daily hot water draw profile used in this study is the minutely water draw profile based on Annex 42 schedule by the International Energy Agency (Knight et al., 2007) and is shown in Figure 4. The daily water draw is 225 litres with the end use temperature of 45°C. The temperature drop from the shower heads/faucets is assumed to be 4°C. About 40% of the daily hot water usage is from showers (Jordan and Vajen, 2000). The daily hot water consumption for simultaneous water draw sources is assumed to be about 160 litres (Hendron and Burch, 2007). Figure 5 shows the actual daily hot water draw patterns in minutes. The archetype houses water mains are drawn from the local wells and the average monthly water mains temperatures have been measured from the site, as displayed in Figure 6.
RESULT ANALYSIS

The TRNSYS model performance was validated with the data collected from monitoring the evacuated tube solar collector as seen in Figure 7.

Figure 9 presents the monthly energy demand to heat domestic hot water of the house and the effects of water mains temperatures and solar collector useful energy gain on it throughout the year. As expected, less energy is required for DWH during the summer than during the winter. This is due to higher solar radiations and longer solar energy availability and also higher main water inlet temperatures for summer.

Figure 10 displays the total monthly electricity demand for the SDHW system and three different scenarios modelled.

The results from the TRNSYS simulations including the yearly electrical energy consumption and renewable energy production for different scenarios will be briefly presented. Figure 8 displays the hourly electricity demand for the auxiliary tank with the specified set point temperature and daily hot water demand of 225 litres.
The first scenario is the conventional system (electric how water tank) without solar thermal collector and drain water heat recovery unit, the second is a conventional electric DWH system with drain water heat recovery, the third is a SDHW system without DWHR, and the last scenario is the proposed system. As seen in Figure 10, the monthly electricity demand for all cases follows similar pattern. Figure 10 also shows that the solar collector effect on electricity consumption reduction is low during winter months when there are relatively lower solar radiations. When comparing the conventional system with and without DWHR unit, it can be seen that DWHR unit has a better performance in the winter months and can better reduce the electricity demand in comparison with the solar thermal collector. This is due to colder water mains temperature which allows more energy recovery by the unit.

Simulation results indicate that the SDHW system of the house along with the heat recovery unit can reduce the annual electricity demand by the auxiliary hot water tank from 3582 kWh to 1898 kWh. If standby losses of the tank are also included, the total electricity consumption values will be 3672 kWh and 1988 kWh respectively. This reduction is equivalent to $202 in cost reductions (based on electricity cost of $0.12/kWh) and about 374 kg in GHG emissions reductions, based on 0.222 kg/kWh equivalent CO2 (Gordon and Fung 2009). The total amount of energy production by the evacuated tube solar collector is 1250 kWh. The amount of energy recovered by the DWHR unit was calculated to be about 806 kWh.

Another observation from the simulation results which is also evident from the actual gathered data is the continuous turning on and off of the solar loop pump when there is not sufficient solar radiation. This is due to the fact that during early mornings, the heat starts to build up in the collector header and the differential controller senses the 6.7°C temperature difference between the header and the solar preheat tank water temperature and forces the pump to start. As the pump runs, the “initial” heat is carried away and the temperature difference falls below the lower dead band temperature and the pump is stopped. This phenomenon causes heat loss from the solar preheat tank, especially during winter months when the solar radiation values are relatively low with low outdoor temperatures. Figure 11 shows this occurring for a typical winter day.

Changing of the control strategy can result in lowering the energy losses from the solar preheat tank and increasing the solar energy fraction.

**CONCLUSION**

This study has simulated the SDHW system simulation for Archetype House B located at Kortright Centre in Vaughan, Ontario. The daily hot water draw of 225 litres with set point temperature of 45°C and the average monthly water mains temperatures were used for performing TRNSYS simulations. Simulation results showed that through the use of an evacuated tube solar collector and drain water heat recovery, the annual electricity demand for DWH can be reduced to 1988 kWh from the 3672 kWh demand for a conventional water heating system which is equal to a saving of 46%. The annual energy provided by the solar collector and recovered by the DWHR unit was shown to be 1250 kWh and 806 kWh, respectively. These amounts of savings are equal to $150 and $97 in annual energy costs reductions. The yearly changes in contributions from the two components were investigated. It was also concluded that revising the temperature control strategy for the solar loop can help reducing the premature energy backflow from the solar preheat tank to the solar collector during early mornings or whenever the solar radiation is insufficient. It should be noted that the Archetype Sustainable House is a technology demonstration, education, training, and research facility, no real occupancy is in the house. Therefore, the sizes of the solar thermal collector and
DWHR unit are smaller than standard for a typical family of four in Canada.

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LIST OF ABBREVIATIONS

BILD - Building Industry and Land Development
COP – Coefficient of Performance
DHW - Domestic Hot Water
DWH - Domestic Water Heating
DWHR - Drain Water Heat Recovery
FSEC - Florida Solar Energy Centre
GHG - Greenhouse Gases
NRCan - Natural Resources Canada
SDHW - Solar Domestic Hot Water
TRCA - Toronto and Region Conservation Authority

LIST OF SYMBOLS

A_{col} - Collector area (m²)
C_{max} - Maximum heat capacity rate (kJ/hr.K)
C_{min} - Minimum heat capacity rate (kJ/hr.K)
C_p - Specific heat (kJ/kg.K)
ε - Heat exchanger effectiveness (%)
I_t - Solar incident radiation on tilted surface (W/m²)
m - Solar loop flow rate (kg/hr.m²)
NTU - Number of Thermal Units
Q - Heat transfer rate (kJ/hr)
T_{col,cold} - Heat exchanger cold-side inlet temperature (°C)
T_{col,hot} - Heat exchanger hot-side inlet temperature (°C)
T_{m,cold} - Collector mean inlet and outlet temperature (°C)
T_{a} - Ambient air temperature (°C)
T_i, col - Collector inlet temperature (°C)
T_{out}, col - Collector outlet temperature (°C)
η_0 - Collector optical efficiency (%)
η_col - Collector efficiency (%)

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