La 5e conférence d'IBPSA - Canada
The 5th IBPSA - Canada Conference
Québec 21-22 mai

FEASIBILITY ANALYSIS OF DOMESTIC HOT WATER SYSTEMS USING TRNSYS

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ABSTRACT

The heating of water for domestic uses presently accounts for 24 percent of Canadian residential energy consumption and 25 percent of Canadian residential greenhouse gases (GHG) emissions (Natural Resources Canada, 2006). The objective of this paper is to simulate different domestic hot water (DHW) systems to study their fuel consumptions, GHG emissions and 30-year lifecycle costs.

Using TRNSYS simulation model, tests are performed for seventeen different DHW systems. These systems include two panel solar-based systems with electric and gas back up tanks, modulating gas combo boiler, on-demand gas water heater, and as well as conventional electric and gas hot water tanks.

Results showed that DHW system with solar pre heat and electrical secondary with timers is the best system for energy consumption and GHG emissions. It uses 1.22 MWh of electricity and produces 266 kg of GHG emissions. DHW system with High efficiency on demand modulating gas combo boiler with gray water heat recovery is the best system in terms 30-year life cycle cost ($12,332).

INTRODUCTION

Comparison of different domestic hot water systems is subjected to many studies in the past. National Renewable Energy Laboratory, Colorado, USA performed performance comparison of residential hot water systems. Authors Wiehagen et al. (2002) presented performance testing and annual simulations of electric water-heating systems. Test experiment was conducted to measure the energy performance of two different types of water heaters - electric storage tank and electric on-demand tank. Using TRNSYS simulation model, they showed that electrical energy savings for the on-demand system over the electric tank system were 34%. More recent study by Biaou et al. (2005) using TRNSYS compared four different DHW systems for zero net energy homes. Their results showed that heating water with solar thermal collectors with an electric backup is best solution for zero net energy homes. Another experiment by Spur et al. (2005) studied the influence of the domestic hot-water daily draw-off profile. They concluded that realistic daily profiles should be used in the performance testing to reflect conditions experienced in the field. A case study by Jordan et al. (2000) analyzed the influence of domestic hot water load profiles with a constant total yearly heat demand for a solar combisystem. Using TRNSYS model they generated more realistic profile on one-minute time scale. They concluded that the influence of the DHW-load profile might not be disregarded, when combistores are compared. Crawford et al. (2003) studied the net energy analysis of solar and conventional domestic hot water systems. They concluded that energy payback period of the electric and natural gas-based solar hot water systems were found to be 0.5 and 2 years for the respective same fuel based conventional hot water systems.

In this case study, conventional and solar-based DHW systems are simulated and their results are compared. Another feature of this study is to model and analyze the effect of time of use (TOU) pricing of electricity. TOU electricity plan is developed by Ontario Energy Board (OEB) to provide stable and predictable electricity pricing, which also encourages conservation and ensures the price consumers pay for electricity better reflects the actual cost of producing the electricity they use. Electricity prices charged per "kilowatt-hour" change throughout the day to better reflect the changes in the costs to produce electricity at different times of the day (OEB, 2008). As an initiative of the province of Ontario, all homes and businesses will be equipped with smart meters using TOU pricing by 2010. Our objective is to study the effects of TOU feature by optimizing its use to reduce overall energy costs and GHG emissions.

CASE STUDY

This study is based on an energy-efficient house (R-2000) located in Whitby, Ontario, Canada. The house is based on the design of CCHT house in

Ottawa, Ontario, Canada. This paper will discuss three solar-based and four conventional systems. These different systems are: I) Solar pre-heat with .56 efficiency natural gas back up tank; II) Solar pre-heat with .94 efficiency electric back up tank; III) Timers (off during peak times 7am till 10 pm) with solar pre-heat and electric (.94 efficiency) secondary; IV) Electric tank (0.94 efficiency); V) Natural gas tank (0.56 efficiency); VI) On-demand (0.83 natural gas) VII) Modulating gas combo boiler (0.78 efficiency). Monthly city water temperature profile was used as input city water temperature. Time of use of electricity application was modeled in the systems involving timers. This feature sends control signals to the elements of heating tank, and uses off-peak rates of electricity for water heating, thus reducing the costs. TRNSYS output results provide in depth hourly results, thus analysis of system behaviour throughout the year at any given time, is feasible. Characteristics of CCHT house are given in the Table 1 (Government of Canada, 2004).

Table 1: Characteristics of CCHT house

Component	Characteristic
Construction Standard	R-2000
Liveable Area	210 m^2, 2 stories
Insulation	Attic: RSI8.6, Walls: RSI3.5
Basement	Poured concrete
Window Area	35 m^2, South facing: 16.2 m^2

For electric models, variable hourly GHG emission factor for electricity generation in Ontario was used. GHG emission factors from a study by Gordon et al. (2007) were used. Yearly simulation tests were performed for all systems with 175 and 225 litres of daily hot water demand. The feasibility analysis data was extracted from the TRNSYS in the excel format. The results were compared with baseline electric and natural gas models for calculating the payback period.

SOLAR DOMESTIC HOT WATER

Solar domestic hot water (SDHW) is modeled using 2-panel EnerWorks system. The system consists of flat plate solar collectors, solar hot water collector, an external heat exchanger, a solar pump, gray water heat recovery heat exchanger and a back-up electric or natural gas auxiliary tank. The Figure 1 shows the solar domestic hot water model.

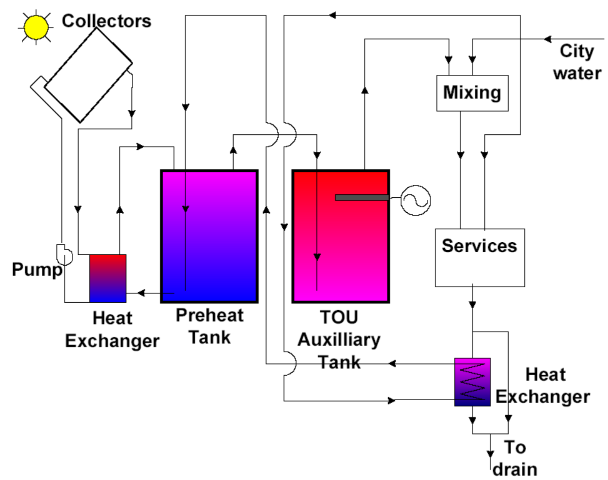

Figure 1: Schematic of Solar DHW Model

The propylene glycol is used as heat transfer fluid, which is composed of 40 percent propylene glycol and 60 percent distilled water. The solar boiler module contains approximately 4L of propylene glycol/distilled water mixture. The system has an on/off differential controller (Type 2b). The solar pump is turned on/off by using this controller. It uses the temperature difference between the heat exchanger fluid exiting the solar collector array, and the water flowing from the bottom of the solar storage tank and returning to the heat source (the temperature of the bottom node). The on/off differential controller has a 100ºC high limit cut off temperature (monitoring temperature). The controller will set the solar pump to the off position, if the temperature being monitored exceeds the high limit cut-off limit. The temperature being monitored in this case is the temperature of the water flowing from the top of the solar storage tank to the load (the temperature of the top node). The controller will remain off until the monitored temperature falls below the high limit cut-off temperature (100ºC).

SDHW MODELING

Two panel EnerWorks solar collector copper tube on aluminium sheet absorber with absorptance 94% ± 2%, emittance 5% ± 2% is used for the study. The Type1b solar thermal collector is modelled from TRNSYS library. The Type 1b models a quadratic efficiency equation. This collector type was used by Thevenard et al. (2004) and compared with ESP-r model results. They concluded that this model performs well in simulation models. Table 2 shows the characteristics of solar hot water system. TRNSYS weather base data, Meteonorm was used in solar models. Meteonorm weather database has more than 1000 locations, in more than 150 countries. Solar collector thermal efficiency is given by the following equation:

$$\eta_{col} = \dot{m} . c_p \, (T_{o\text{-}col} - T_{i\text{-}col}) \, / \, A_{col} \, I_t$$

Where:

η_{col} = Collectors efficiency
$\dot{m}$ = Flow rate
c_p = Fluid specific heat
$T_{o\text{-}col}$ = Outlet temperature of fluid from collector
$T_{i\text{-}col}$ = Inlet temperature of fluid to collector
A_{col} = Collector area
I_t = Global radiation incident on the solar collector

Table 2: Characteristics of Solar Hot Water System

Mode	Value
Collector Area	5.382 m^2
Fluid specific heat	3.747 kJ/kg.K
Tested Flow Rate	26.756 kg/hr.m^2
Efficiency Slope	4.063 W/m^2.K
Efficiency Curvature	0.0061 W/m^2.K^2
Collector Slope	22.5° from horizontal
Collector Orientation	South
Solar Hot Water Tank	300 litres
Auxiliary Tank	227 litres (60 gallons)
Auxiliary Tank Set Point	60ºC, 80ºC (with mixing)
Solar pump Rated Flow Rate	72 kg/hr
Solar Pump Rated Power	23 W
Solar Pump Total Efficiency	0.9
Solar Pump Motor Efficiency	0.95
Heat Exchanger	3 (shell passes)

CONVENTIONAL MODELS

The conventional electric hot water tank is modeled by using Type 4a (Stratified Storage Tank) in TRNSYS. The model optionally includes two electric resistance-heating elements, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during selected periods of each day. Both heaters are used to maximize the TOU electricity rate. One element (set at 55ºC) is used during on-peak and mid-peak hours, and second (set at 65ºC or 70ºC) is used during off-peak hours to get maximum benefit of off peak rate. The Figure 2 shows the conventional electric hot water tank.

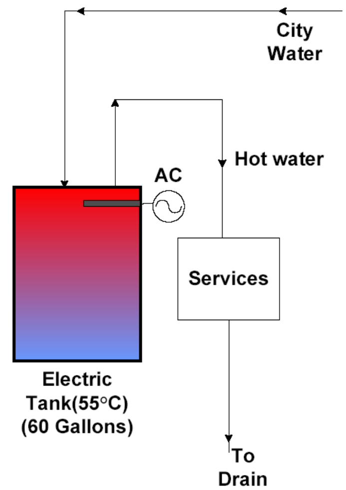

Figure 2: Schematic of Conventional Electric Tank Model

The conventional natural gas hot water tank is modeled by using Type 60d (Stratified Storage Tank) in TRNSYS. This model allows the tanks with a gas auxiliary heater. The model treats gas auxiliary energy the same as electric energy, so the heat rate when the burner is firing is the same as if it was electric power. Table 3 shows the characteristics of conventional DHW models.

Table 3: Characteristics of Conventional DHW Models

Mode	Value
Electric Tank Volume	227 liters (60 gallons)
Electric Tank Efficiency	0.94
Maximum Heating Rate	3000 W
Natural Gas Tank Volume	227 liters (60 gallons)
Natural gas tank efficiency	0.56
Natural gas tank height	1.25 m
On-demand heater efficiency	0.83
On-demand heating rate	10800 kJ/hr (max)
Combo boiler rated capacity	100000 kJ/hr
Boiler Efficiency	0.78
Combustion Efficiency	0.85

The on-demand gas hot water heater is modeled using Type 6-auxilliary heaters from the TRNSYS library. The heater is designed to add heat to the flow stream at a rate less than or equal to Q_{max}, which is a user determined quantity. Modulating gas combo boiler is modeled using Type 700 from TESS library. In this model, the boiler efficiency and the combustion efficiency are supplied as inputs to the model. The

WASTE HEAT RECOVERY

A zero capacitance sensible heat exchanger (Type 91) with a constant effectiveness of 60 percent is modeled in TRNSYS. For the constant effectiveness mode, the maximum possible heat transfer is calculated based on the minimum capacity rate fluid and the cold side and hot side fluid inlet temperatures. Waste temperature of water coming out of house is assumed to be at 37ºC.

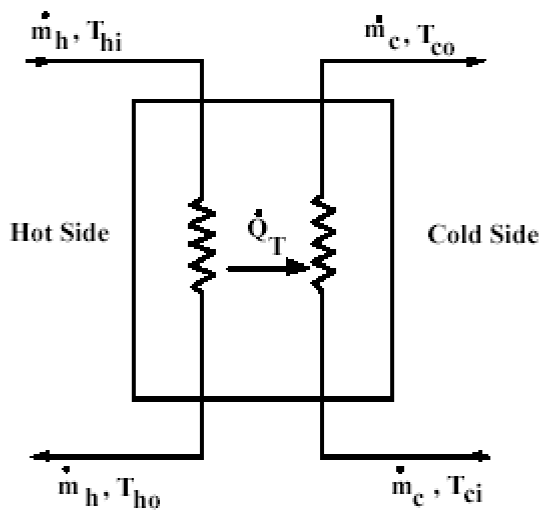

Figure 3: Heat Exchanger Schematic

The following expressions are given to determine the maximum possible amount of heat transfer at a given time step.

If $C_{min} = C_h$, $Q_{max} = C_h (T_{hi} – T_{ci})$

If $C_{min} = C_c$, $Q_{max} = C_c (T_{hi} - T_{ci})$

The actual heat transfer then depends upon the user specified effectiveness.

$Q_T = \varepsilon Q_{max}$

Where:

C_c – Capacity rate of fluid on cold side, mcCpc
C_h – Capacity rate of fluid on hot side, mhCph
C_{pc} – Specific heat of cold side fluid
C_{ph} – Specific heat of hot side fluid
C_{min} – Minimum capacity rate
ε – Heat exchanger effectiveness
m_c – Fluid mass flow rate on cold side
m_h – Fluid mass flow rate on hot side
Q_T – Total heat transfer rate across heat exchanger
Q_{max} – The maximum heat transfer rate across exchanger
T_{ci} – Cold side inlet temperature
T_{hi} – Hot side inlet temperature

WATER DRAW PROFILE

The daily hot water draw profile has been subjected to many studies in the past. Perlman and Mills (1985) monitored the data from Canadian residences. They provide two sets of data, one for all families and one for typical families. They defined typical family as two adults and two children, with clothes washer and dishwasher present. Typical hot water draw profile is most widely used. Becker and Stogsdill (1990) gathered, analyzed and reported on nine different data sets consisting of more than 3 million data points on hot water use in residences. Becker's database included measurements from 110 single-family residences in both Canada and U.S. Each of these data sets contains measured hot water use data of one year or greater in duration. Bouchelle and Parker (2000) reported on hot water demand profiles for large 204 homes sample study conducted in central Florida. Becker (1990) is most comprehensive compilation of U.S measured data. In this case study, hot water draw profile from Perlman et al. (shown in Figure 4) is used as it is based solely on the Canadian data.

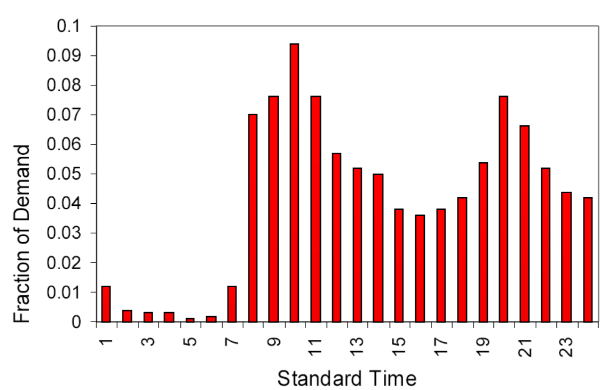

Figure 4: Hot Water Draw Profile

SIMULATION

DHW systems were simulated in TRNSYS (Type 56) for the whole year (8760 hours) using one-hour time step. Daily hot water demand of 175L and 225L was used for simulation. In the solar models, a set point temperature of 60ºC (no mixing) and 80ºC (with mixing valve) was used in the auxiliary tank for sensitivity analysis. The yearly results were extracted in excel format using one hour time step. The instantaneous value of energy (in kJ) required to heat the water was analyzed. If water is not being heated at particular hour, then given value is zero. The temperature of hot water flowing into the house at any hour is also studied. The required water temperature for the house is 55ºC. By monitoring the data of hot water temperature to house helps to conclude if system will meet the requirements for whole year. The energy required to heat the water is converted from kJ to kWh in electric models and from kJ to m^3 in gas models. The GHG emissions are calculated using hourly emission factor for electricity generation in Ontario (Gordon and Fung, 2007a and 2007b). The yearly average emission factor is 226.35 (tonnes CO_2/total GWh generation). If no electricity is used to heat the water at particular hour, then corresponding CO_2 emission is zero. The constant emission factor of 1.856 kg/m^3 equivalent CO_2 was used in the gas models for GHG emission calculations.

TIME OF USE (TOU)

All TRNSYS models that involve timers are modeled considering time of use. There are different periods of TOU (Toronto Hydro, 2007) for winters and for summer. Winter timing is from Nov-1 – Apr-30 whereas summer timing is from May-1 – Oct-31. All weekends as well as all statutory holidays will pay off peak rates for all hours of the day. To incorporate statutory holidays, year 2005 calendar is used. Figure 5 shows the different rates (in ¢/kWh) during 24 hours.

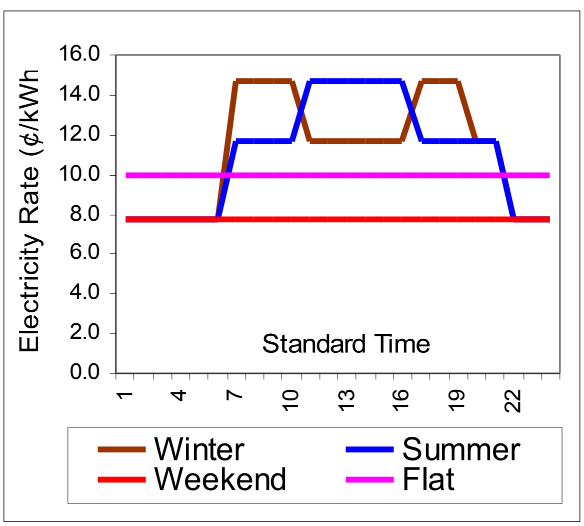

Figure 5: Electricity Rates (¢/kWh)

ENERGY PRICES AND CO_2 FACTORS

Energy Prices: The following energy prices were used in the study. These prices are the final prices paid by the customer including delivery charges.

Electric (Flat Rate) – $0.10/kWh ((Toronto Hydro, 2007)
Electric (TOU) – $0.077/kWh off peak
Electric (TOU) – $0.117/kWh mid peak
Electric (TOU) – $0.147/kWh on peak
Natural Gas – $0.488/$m^3$ (Enbridge Gas, 2007)
CO_2 Factors:
Natural Gas – 1.856 kg/m^3 equivalent CO_2

Electricity – Variable for every hour of the year for electricity production in Ontario (Gordon and Fung, 2007a and 2007b). The average emission factor is 226.35 (tonnes CO_2/total GWh generation).

RESULTS

Heat transfer rate: Figure 6 shows the total heat transfer rate between the fluids in the cross flow heat exchanger of solar model. Maximum heat transfer rate was found to be in 9372 kJ/hr in the month of June. The average heat transfer rate for the whole year is 960 kJ/hr.

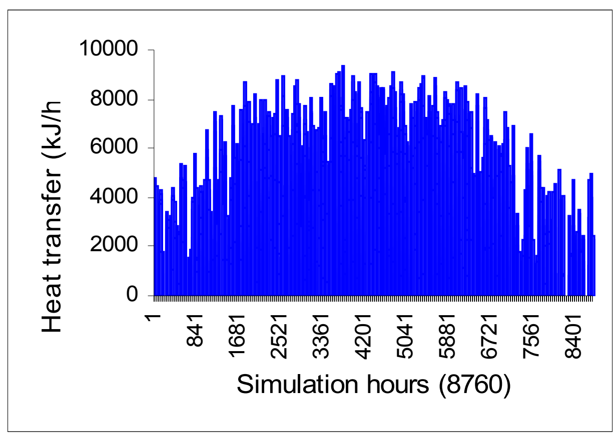

Figure 6: Total Heat Transfer Rate between the Fluids in Heat Exchanger

Auxiliary tank heating: Figure 7 shows the heating rate of TOU electric auxiliary tank. It demonstrates the effect of solar panels during the summer period. The solar model is able to keep up with daily hot water demand during this period, thus hardly require using the back up hot water electric tank. It was found that that during the summer months (May 1 – October 31), only 202 kWh of electricity is needed for TOU auxiliary tank. This result is obtained assuming 225 litres of daily hot water demand and 60ºC set point temperature in auxiliary tank.

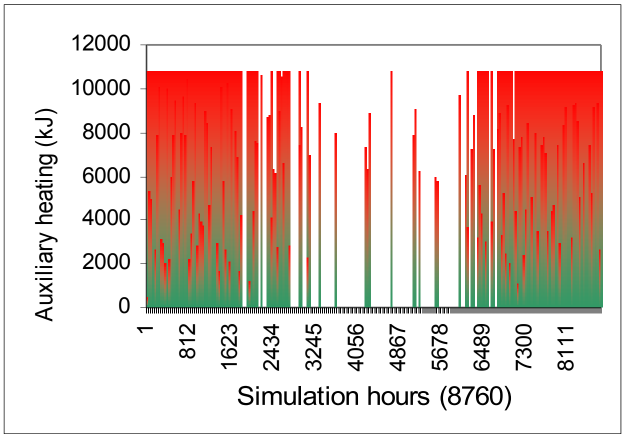

Figure 7: Auxiliary Heating Rate for TOU electric tank in Solar Model

GHG EMISSIONS

The heating of water for domestic purposes contributes 25 percent of total Canadian residential GHG emissions (Natural Resources Canada, 2006). The effect of water heating on environment is subjected to studies in the past. Taborianski and Prado (2004) studied the GHG emissions related to electric, natural gas, LPG and solar water heaters for 20-year life cycle. They concluded that electric water heater is worst GHG emitter. Their study was based on constant input water temperature of 18ºC through out the year and 80 percent efficiency for all conventional systems. Kalogirou and Tripanagnostopoulos (2004) compared solar models with electric models. They concluded that solar-based system has 74 percent GHG savings as compared to conventional system.

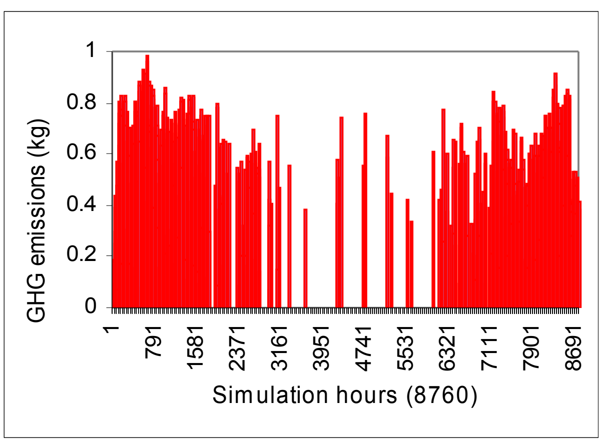

Figure 8: Hourly GHG Emissions for Solar Model with TOU Electric Tank

Figure 8 shows the hourly GHG emissions related to solar DHW model with TOU electric auxiliary tank having 60ºC set point temperature and 225 litres of daily hot water demand. It should be noted that there were only 43 kg of GHG emissions during the summer period (May 1 – October 31). The solar system is able to provide the hot water for domestic uses, thus minimizing GHG emissions during this period.

Table 4 presents the GHG emissions for solar and conventional models. The solar system with gray water heat recovery unit and TOU back up electric tank has lowest emissions. This model has only 266 kg of GHG emissions during the whole year. The conventional natural gas hot water tank (0.56 efficiency) has highest annual GHG emissions (1514 kg) among the natural gas models. The conventional electric hot water (0.94 efficiency) has highest annual GHG emissions (1136 kg) among the electric models.

Table 4: GHG emissions

Model	GHG Emissions (kg)
Solar I	458
Solar II	334
Solar III	266
Electric (0.94)	1136
Natural Gas (0.56)	1514
On-demand (0.83 natural gas)	979
Modulating gas combo boiler (0.78)	1041

FUEL CONSUMPTION

Fuel consumption results related to three solar models and other conventional models are shown in Table 5. Three different solar-based systems are: I) Solar pre-heat with .56 efficiency natural gas back up tank; II) Solar pre-heat with .94 efficiency electric back up tank; III) Timers (off during peak times 7am till 10 pm) with solar pre-heat and electric (.94 efficiency) secondary. Solar model III found to have lowest fuel consumption (4.38 GJ) where as basic natural gas tank (0.56 efficiency) has highest fuel consumption (30.76 GJ). All models were simulated for 225 and 175 litres daily hot water demand. The results shown in the table corresponds to 225L daily hot water demand. The three solar models have lowest fuel consumption among all the models studied. The conventional electric hot water tank (0.94 efficiency) has lowest fuel consumption (17.22 GJ) among the conventional models. The annual energy consumption for on-demand gas water heater (0.83 efficiency) is 19.87 GJ.

Table 5: Fuel Consumption

Model	Annual Energy Consumption (GJ)	Cost ($)
Solar I	9.30	$120.5
Solar II	5.21	$144.7
Solar III	4.38	$93.7
Electric (0.94)	17.22	$478.4
Natural Gas (0.56)	30.76	$398.2
On-demand (0.83 natural gas)	19.87	$257.3
Modulating gas combo boiler (0.78)	21.15	$273.8

LIFE CYCLE COST

Table 6 provides 30-year life cycle cost, which is the sum of 30-year equipment, maintenance and fuel costs. In case of combo boiler, 30 percent of cost was allocated towards water heating, while 70 percent is allocated for space heating. To calculate the life cycle cost, following fuel escalation rates were used:

Electricity – 2.14 % per year nominal rate (ref. California Energy Commission)

Natural Gas – 3.75 % per year nominal rate (ref. California Energy Commission)

Table 6: 30-year Life Cycle Cost

Model	Life Cycle Cost ($)
Solar I	$28,075
Solar II	$27,996
Solar III	$25,880
Electric (0.94)	$24,521
Natural Gas (0.56)	$25,705
On-demand (0.83 natural gas)	$19,223
Modulating gas combo boiler (0.78)	$16,920

REALISTIC LOAD PROFILE

In order to take into account fairly realistic conditions, a real time draw given in 1999 ASHRAE handbook was used in this study. This realistic profile is based on three-person house having laundry and dishwasher uses. A study by Jordan et al. (2004) did comparison between simplified and more realistic load profiles. Results showed differences in the fractional energy savings for the investigated system designs of up to more than 3 percentage points.

Table 7 shows the comparison between the results using hourly load profile and detailed load profile in the case of conventional hot water tank (.94 efficiency).

Table 7: Comparison Between Hourly and Detailed Load Profile

175 L daily demand		
	Hourly load profile	Detailed load profile
Fuel consumption	3683 kWh	3573 kWh
GHG emissions	817 kg	795 kg
225 L daily demand		
	Hourly load profile	Detailed load profile
Fuel consumption	4784 kWh	4508 kWh
GHG emissions	1136 kg	1031 kg

Results indicate that using realistic profile have energy and GHG emission savings as compared to hourly load profile. In case of 175 liters daily hot water demand, there are 3 percent savings in fuel consumption and GHG emissions. In case of 225 liters daily hot water demand, there is 6 percent savings in fuel consumption and 9 percent savings in GHG emissions. Thus for increased daily hot water demand, difference is more significant. Similar pattern was observed in other systems. These results collaborate with study by Jordan et al. (2004).

CONCLUSIONS:

This paper studied the feasibility analysis of solar and conventional hot water systems for the house based in Whitby, Ontario and based on the design of CCHT house. The life cycle cost analysis of solar models was compared with conventional models. The 30-year life cycle cost of the solar system is comparable with the conventional models despite having high initial investment costs. Solar models have lowest fuel consumption and GHG emissions as compared to the conventional models. The solar domestic hot water system is a good alternative to the conventional systems because of their environmental benefits. The future uncertainties related to fossil fuel availability as well as their price fluctuations makes solar models an attractive choice. Results indicate that the consumers can take price benefits of low peak period rates by using TOU electric tanks. The utilities will be benefited from shifting the load from peak periods to off peak periods.

The solar system with gray water heat recovery unit and TOU electric backup tank has 202 kWh electric consumption and 43 kg GHG emissions during the summer period (May 1 – October 31). The two-panel solar system is able to keep up with daily hot water demand thus minimizing fuel consumption and CO_2 emissions during that period.

ACKNOWLEDGEMENTS

The authors acknowledge the support and input from Summerhill Group, Toronto.

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