International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:5, 2016

Technical Analysis of Combined Solar Water Heating Systems for Cold Climate Regions

Hossein Lotfizadeh, André McDonald, Amit Kumar

***Abstract*—**Renewable energy resources, which can supplement space and water heating for residential buildings, can have a noticeable impact on natural gas consumption and air pollution. This study considers a technical analysis of a combined solar water heating system with evacuated tube solar collectors for different solar coverage, ranging from 20% to 100% of the total roof area of a typical residential building located in Edmonton, Alberta, Canada. The alternative heating systems were conventional (non-condensing) and condensing tankless water heaters and condensing boilers that were coupled to solar water heating systems. The performance of the alternative heating systems was compared to a traditional heating system, consisting of a conventional boiler, applied to houses of various gross floor areas. A comparison among the annual natural gas consumption, carbon dioxide (CO_2) mitigation, and emissions for the various house sizes indicated that the combined solar heating system can reduce the natural gas consumption and CO_2 emissions, and increase CO_2 mitigation for all the systems that were studied. The results suggest that solar water heating systems are potentially beneficial for residential heating system applications in terms of energy savings and CO_2 mitigation.

***Keywords*—**CO_2 emissions, CO_2 mitigation, natural gas consumption, solar water heating system, tankless water heater.

I. Introduction

In recent years, solar energy has become a valuable source of renewable energy. It is renewable, clean, and widely available in comparison to traditional energy including fossil fuel and nuclear fuel [1]. Also, availability of large-scale solar energy resources can reduce the building energy consumptions [2], [3]. Moreover, the use of solar energy in the residential sector has the potential to reduce harmful emissions and fossil fuel consumption [3]. Thus, it is worthwhile to study the possibility of applying different solar energy systems in residential buildings and their impact on energy savings and reduction in air pollution.

Solar water heating systems (SWHS) usage is increasing, owing to the fact that they decrease fossil fuel consumption and greenhouse gas emissions of residential buildings [4]. Generally, two types of liquid collectors can be used in SWHS, including flat plate and evacuated tube solar collectors [5]. Many researchers have shown that the evacuated tube solar collectors (ETSCs) have greater efficiencies than flat plate solar collectors (FPCs), notably at low temperatures [6], [7].

Hossein Lotfizadeh and Amit Kumar are with the Department of Mechanical Engineering, University of Alberta, T6G 1H9 Canada (e-mail: hlotfiza@ ualberta.ca, Amit.Kumar@ualberta.ca).
André McDonald is with the Department of Mechanical Engineering, University of Alberta, T6G 1H9 Canada (phone: +1 780 492 2675; fax: +1 780 492 2200; e-mail: andre.mcdonald@ualberta.ca).

In the current study, a technical analysis of alternative heating systems, including condensing boilers and conventional (non-condensing boiler) and condensing tankless water heaters that are combined to solar water heating systems with evacuated tube solar collectors for different roof areas, ranging from 700 to 2500 ft^2 in Edmonton, Alberta, Canada was studied.

II. Model Houses

A set of model houses was considered to examine how increasing only the space heating load affects the annual natural gas consumption, CO2 emissions, and CO2 mitigation in all the heating systems that were explored. The houses have a square floor geometry, with areas of 700, 1000, 1500, 2000, and 2500 ft^2.

III. Assumptions

It was assumed that the houses were located in Edmonton, AB, Canada. The construction characteristics were assumed to be in accord with the minimum requirements of ASHRAE Standard 90.1 for Zone 7 [8]. It was further assumed that the indoor comfort conditions were 21.2°C (70 °F)/30% RH [9] with Ti = 21.2 °C as the design dry bulb temperature. The outdoor design temperature of To = -29.6 °C (-21.3 °F) was chosen for Edmonton [10].

The heat load was calculated based on the average temperature of the indoor and outdoor design conditions and the thermal properties. In this study, an estimate of the heating load for the model houses was determined by using Newton's law of cooling $\left(\dot{Q} = UA(T_{\text{in}} - T_{\text{out}})\right)$ to calculate the rate of heat loss from the building through the walls, roof, windows, doors, floor, and infiltration $\left(\dot{Q} = \rho c_{\text{p}} V(ACH)(T_{\text{in}} - T_{\text{out}})\right)$. The daily consumption of water was calculated by multiplying the daily consumption per person by the number of people living in the houses (four people in each house). The total volume flow rate of consumed water was calculated based on the fixture unit method [11].

In regards to solar irradiation, for Edmonton, the average solar radiation is 47.152 Btu/hr-ft^2 [12]. For the evacuated tube solar collectors, the average efficiency was as assumed to be 61% based on work from Ayompe and Duffy [13]. The useful energy provided by evacuated tube solar collectors is given as:

$$Q_u = \eta \times A_c \times I_T \tag{1}$$

where Q_u is the useful energy provided by the ETSCs, η is the efficiency, A_C is the collector area, and I_T is the solar radiation incident on the collector plate.

IV. Calculations

A. Natural Gas (NG) Consumption

The annual NG consumption can be calculated from the rate of NG input to the heating plants and the annual heating time. The annual heating period can be subdivided into the time required for space heating and that for domestic hot water (DHW) heating.

For DHW heating, the heating time is the time for "on demand" heating or to the heating phase of the gas tank water heater cycle in the traditional system. "On demand" heating takes place when a high-efficiency heat exchanger is utilized to supplement hot water instantaneously.

For space heating, the annual heating period can be determined by using the heating degree-days (HDD) method which compares the daily mean temperature for every day in the heating season to a reference temperature, T_{ref} [8]. It should be noted that only days during which heating is required and when the daily mean temperature less than the reference temperature is considered. Therefore,

$$\mathrm{HDD} = \sum_{m=1}^{N} \left(T_{\mathrm{ref}} - \bar{T}_m \right), \quad (2)$$

where N is the number of days in the heating season and T_m is the mean daily temperature on the mth day of the season. Therefore, the heating period is calculated as:

$$t_{\text{Annual Heating}} \approx \frac{\mathrm{HDD}_{18}}{T_{\text{indoor}} - T_{\text{outdoor}}}, \quad (3)$$

where the subscript indicates that the reference temperature was taken as 18.3 °C (65 °F).

In order to calculate the heating time for "on demand" water usage, the daily consumption of water was estimated by multiplying the number of people living in the house by the daily consumption per person. The total volume flow rate of consumed water was calculated based on the fixture unit method [11]. The heating time for "on demand" usage can be determined using the daily water consumption and the volumetric flow rate obtained by the fixture unit method as:

$$t_{\text{DHW, on demand}} = \frac{(365\ \text{days/year}) \times V_{\text{Daily}}}{\text{Demand Factor} \times \dot{V}_{\text{Hourly}}}, \quad (4)$$

where V_{Daily} and V_{Hourly} are the daily and hourly flow rate, respectively. The demand factor is used to obtain the water demand that is most likely to occur for a given application. The demand factor was taken as 0.3 for residential applications [11].

For a gas tank water heater cycle, it was assumed that the water was heated to a maximum of 54.4 °C (130 °F) in order to prevent scalding from occurring and the low set point temperature (the temperature at which the heater turns on) was 46.1 °C (115 °F) to avoid the risk of growth of Legionella bacteria, where temperatures greater than 45°C (113 °F) are required [14].

The heating time of the cycle for the gas tank water heater can be determined using the heating input rate,

$$t_{\text{cycle heating}} = \frac{Q_{\text{heating required}}}{\dot{Q}_{\text{heating input}}} = \frac{\rho_{\mathrm{w}} V_{\text{tank}} C_{\mathrm{p,w}} \left(T_{\mathrm{h}} - T_{\mathrm{l}} \right)}{\dot{Q}_{\text{heating input}}}, \quad (5)$$

where ρ_w is water density, V_{tank} is the tank volume, c_p is the specific heat capacity of water, T_h is the final temperature, and T_l is the initial temperature.

The cooling time of the cycle for the gas tank water heater was determined based on the law of conservation of energy.

The time required to complete the gas tank water heater cycle is as:

$$t_{\text{cycle total}} = t_{\text{cycle heating}} + t_{\text{cycle cooling}} \quad (6)$$

It was assumed that the duration of the cycle was always the same and that the cycle was repeated continuously throughout the entire year.

The rate of NG consumption was determined as:

$$\left(\mathrm{kg\ CH_4/hr}\right) = \left(\frac{1\ \mathrm{kJ}}{0.94782\ \mathrm{Btu}} \right) \times \frac{\dot{Q}_{\text{input}}}{\mathrm{HHV}_{\mathrm{CH_4}}}, \quad (7)$$

where $\dot{Q}_{input}$ is the input heat transfer rate. It should be noted that the higher heating value (HHV) was used with the condensing systems and the lower heating value (LHV) was used with the non-condensing systems. Therefore, the annual NG consumption can be calculated by multiplying the rate of NG by the annual heating time for the different floor areas.

In the combined SWHS, the amount of heat provided by the SWHS was subtracted from the input heat transfer rate in order to indicate the influence of solar energy on the NG consumption in all of the heating systems.

B. CO_2 Emissions

The rate of CO_2 emission was found as:

$$\mathrm{CH_4(g)} + 2\left(\mathrm{O_2(g)} + 3.76\mathrm{N_2(g)}\right) \xrightarrow{\Delta H \uparrow} \mathrm{CO_2(g)} + 7.52\mathrm{N_2(g)} + 2\mathrm{H_2O(g)} \quad (8)$$

Equation (8) shows the chemical equation for the stoichiometric combustion of methane (CH_4). It was assumed that NG was 100% CH_4 due to the fact that the composition of NG is approximately 95% CH_4 [15]. According to (8), 2.743 kg CO_2 is emitted per kg CH_4. Therefore, the rate of CO_2 emission is calculated by multiplying the rate of NG consumption by 2.743 kg CO_2/kg CH_4. Similarly, the annual CO_2 emission can be calculated by multiplying the rate of CO_2 emission by the annual heating time.

C. CO_2 Mitigation

The annual CO_2 mitigation can be calculated by multiplying the difference in the hourly rate of emission of CO_2 between the conventional boiler (benchmark system) and the alternative systems by the annual heating time:

$$\left(\frac{\text{kg CO}_2}{\text{year}}\right) = \left(\left(\dot{m}_{CO_2}\right)_{\text{Traditional}} - \left(\dot{m}_{CO_2}\right)_{\text{Alternative}}\right) \times t_{\text{Annual}} \qquad (9)$$

where t_{Annual} is the heating time, which is determined by using the heating degree-days (HDD) method which compares the daily mean temperature for every day in the heating season to a reference temperature, T_{ref} [9].

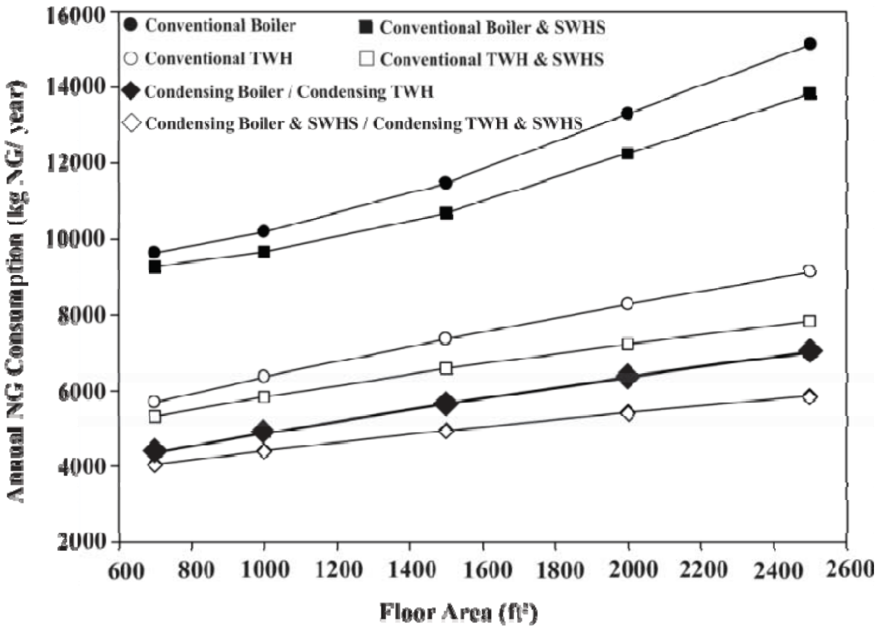

Fig. 1 Annual Natural gas consumption for 20% solar coverage

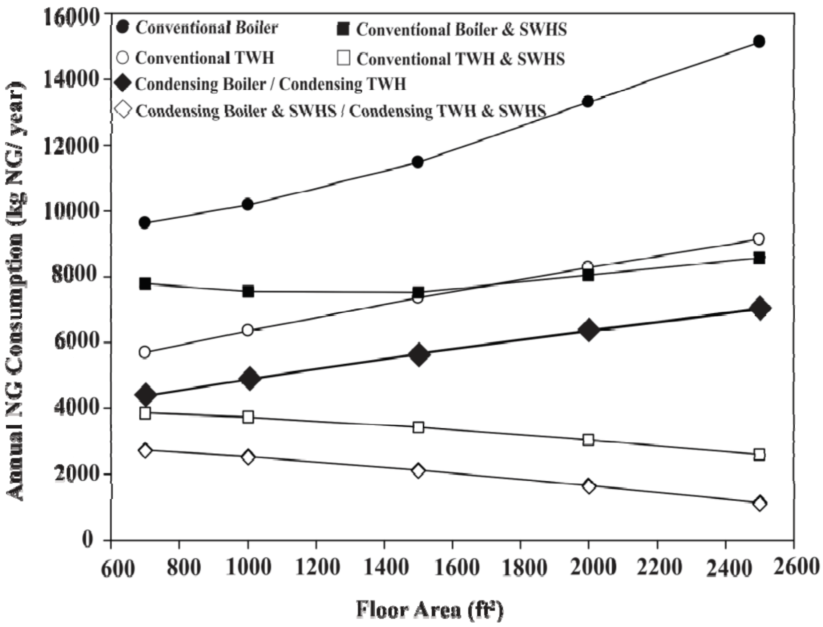

Fig. 2 Annual Natural gas consumption for 100% solar coverage

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:5, 2016

V. Results and Discussion

A. Natural Gas (NG) Consumption

The results of annual NG consumption for 20% and 100% solar coverage have been shown in Figs. 1 and 2, respectively. These figures show the annual NG consumption as a function of floor area. As shown in the figures, as the floor area of the residential building increases, the annual NG consumption increases. The largest natural gas consumption rate corresponds to use of the conventional boiler alone, whereas the lowest consumption corresponds to the use of the two combined SWHSs, including the condensing boiler with SWHS and condensing tankless water heater (TWH) with SWHS. The use of the SWHS has resulted in reduction of the annual NG consumption. In addition, as can be seen in Figs. 1 and 2, with the increase of solar coverage from 20% to 100%, the reduction of annual NG consumption is noticeable in all of the heating systems due to the fact that more solar radiation is available due to the larger solar coverage. The increased solar energy provides greater energy required for space and water heating.

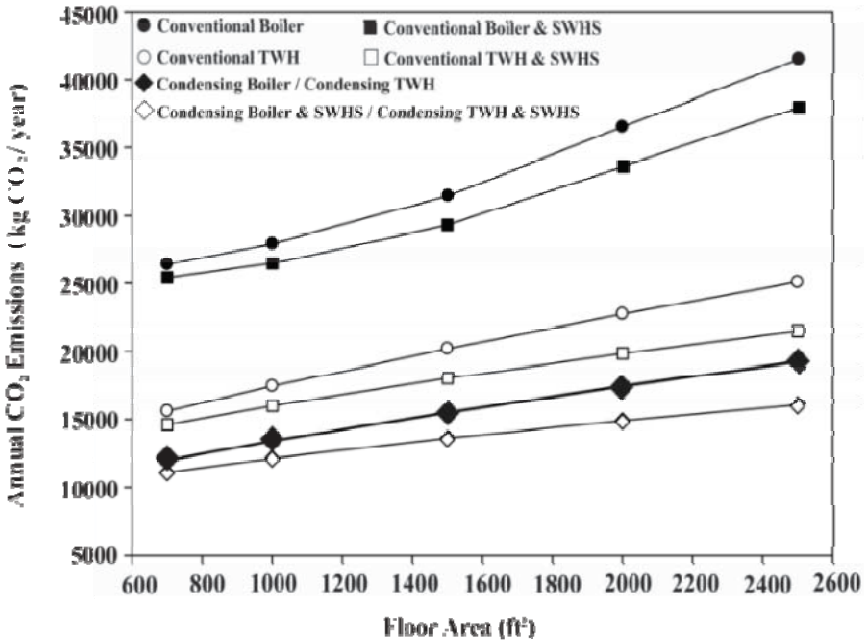

Fig. 3 Annual CO_2 emissions for 20% solar coverage

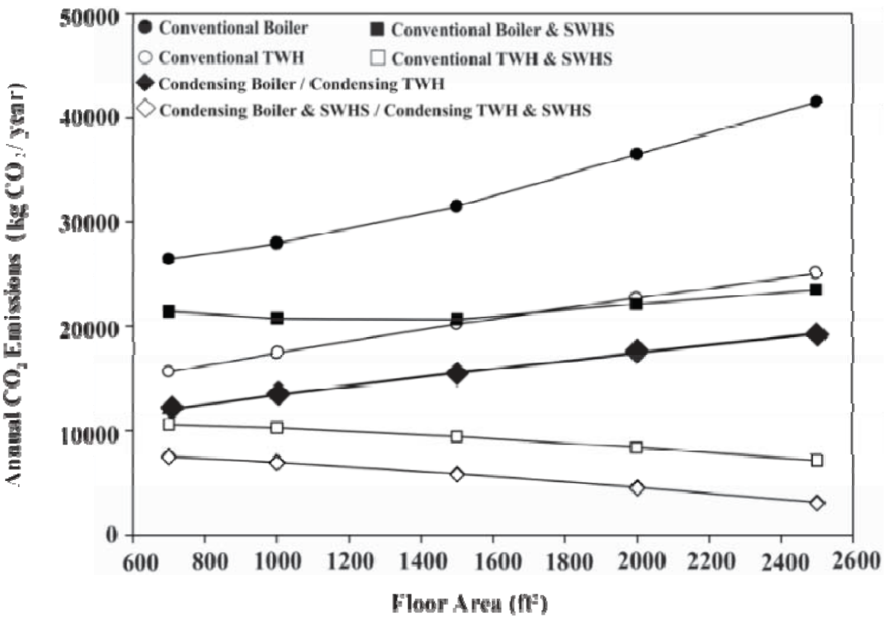

Fig. 4 Annual CO_2 emissions for 100% solar coverage

B. CO_2 Emissions

The results of annual CO_2 emissions for 20% and 100% solar coverage have been shown in Figs. 3 and 4, respectively. These figures show the annual CO_2 emissions as a function of floor area. As shown in the figures, an increase in the floor area results in an increase in the annual CO_2 emissions for the different heating systems.

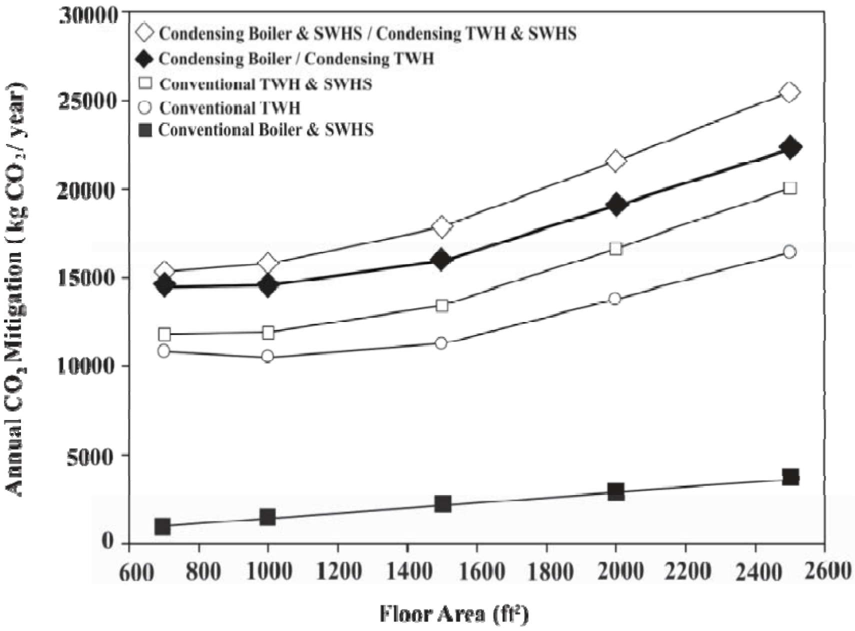

Fig. 5 Annual CO_2 mitigation for 20% solar coverage

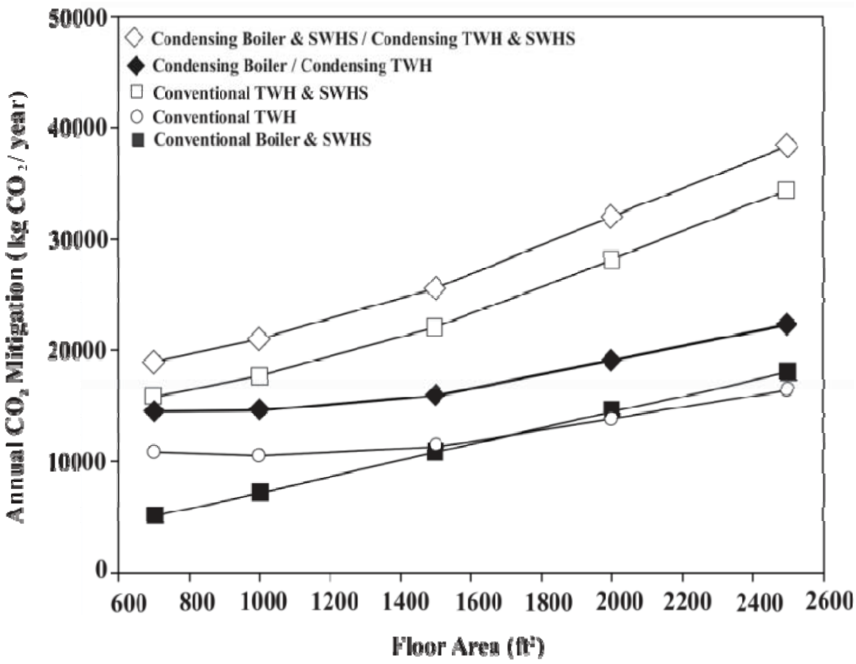

Fig. 6 Annual CO_2 mitigation for 100% solar coverage

C. CO_2 Mitigation

The results of annual CO_2 mitigation for 20% and 100% solar coverage have been shown in Figs. 5 and 6, respectively. These figures show the annual CO_2 mitigation as a function of floor area. According to (4), the annual CO_2 mitigation is calculated by multiplying the annual heating time by the difference in the hourly rate of emission of CO_2 between the conventional boiler (benchmark system) and the alternative systems. Thus, by decreasing the annual CO_2 emissions, the annual CO_2 mitigation increases. As it can be seen in Fig. 5 and 6, the condensing boiler with SWHS, and condensing TWH with SWHS have the highest value of annual CO_2 mitigation owing to the fact that they have the lowest value of CO_2 emissions as shown in Figs. 3 and 4. A similar trend is observed for the other systems. The increase of solar coverage from 20% to 100% resulted in a noticeable increase of the annual CO_2 mitigation for all of the heating systems. This was due to the reduced CO_2 emissions from the systems that were coupled with the SWHSs for space and water heating.

VI. Conclusion

This study provides a technical examination of a combination of solar water heating systems with a variety of alternative heating systems. According to the comparison of the carbon dioxide (CO_2) mitigation, emissions, and natural gas consumption, for the various floor areas, the highest value of NG consumption refers to conventional boiler whereas the lowest value refers to the two combined SWHSs including condensing boiler with SWHS, and condensing TWH with SWHS. Also, with the increase of solar coverage from 20% to 100%, the reduction of annual NG consumption was more noticeable in all of the heating systems. Similarly, the same behavior was observed for CO_2 emissions. In contrast, for CO_2 mitigation, the condensing boiler with SWHS and the condensing TWH with SWHS had the highest value of annual CO_2 mitigation. Moreover, with the increase of solar coverage, the increase in CO_2 mitigation was noticeable. The results suggest that SWHSs are potentially beneficial for residential heating system applications in terms of energy savings and increase in CO_2 mitigation.

References

[1] Eroglu M, Dursun E, Sevencan S, Song J, Yazici S, Kilic O. A mobile renewable house using PV/wind/fuel cell hybrid power system. Vol 36. International Journal of Hydrogen Energy. 20136, pp.7985-7992.
[2] Martinopoulos G, Tsalikis G. Active solar heating systems for energy efficient buildings in Greece: A technical economic and environmental evaluation. Energy and Buildings. Vol 68, 2014, Part A pp.130-137.
[3] Mateus T, Oliveira AC. Energy and economic analysis of an integrated solar absorption cooling and heating system in different building types and climates. Applied Energy. Vol 86, 2009, pp. 949-957.
[4] Hang Y, Qu M, Zhao F. Economic and environmental life cycle analysis of solar hot water systems in the United States. Energy and Buildings. Vol 45, 2012, pp.181-188.
[5] Active Solar Heating Systems Manual, American Society of Heating Refrigerating, and Air Conditioning Engineers, Inc, 1988.
[6] Kalogirou SA. Solar thermal collectors and applications. Progress in Energy and Combustion Science. Vol 30, 2004, pp. 231-295.
[7] Morrison GL, Budihardjo I, Behnia M. Water-in-glass evacuated tube solar water heaters. Solar Energy. Vol 76, 2004, pp.135-140.
[8] ASHRAE Inc., ANSI/ASHRAE/IES Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings, S-I and I-P Editions; 2013.
[9] ASHRAE Inc., ANSI/ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA2010.
[10] ASHRAE Inc., -Fundamentals, S-I ed., American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA: ASHRAE Handbook 2009.
[11] ASHRAE Inc. Atlanta, GA: HVAC Applications, S-I and I-P Editions, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.; 2011.
[12] Natural Resources of Canada: https:// www.retscreen.net/ang/home.php. Oct 2015.
[13] Ayompe LM, Duffy A. Analysis of the thermal performance of a solar water heating system with flat plate collectors in a temperate climate. Applied Thermal Engineering. Vol 58, 2013, pp. 447-454.
[14] A. G. McDonald HLM. Introduction to Thermo-Fluids Systems Design. Chichester, West Sussex, United Kingdom: John Wiley and Sons, Inc.; 2012.
[15] Components of Natural Gas. Enbridge Gas Distribution Inc: https://www.enbridgegas.com/gas-safety/about-natural-gas/components-natural-gas.aspx. July 2013.