JREE: Vol. 5, No. 1, (Winter 2018) 35-42

Journal of Renewable Energy and Environment

Research Article

Journal Homepage: www.jree.ir

Comprehensive Evaluation of Using Solar Water Heater on a Household Scale in Canada

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PAPER INFO

Paper history:
Received 14 November 2018
Accepted in revised form 11 March 2019

Keywords:
Solar Water Heater
Buffer Tank
Heating Load
Average Daily Consumption
Heated Useable Area

ABSTRACT

Canadian researchers are now trying to exploit much more energy from solar sources, hydropower, wind, and biomass. Given the fact that reducing the carbon pollutant level is a political priority in Canada, this paper studies the feasibility of providing sanitary hot water and space heating demands of a four-member family in 10 provinces in this country. The feasibility analysis was performed by T*SOL Pro 5.5 software, and radiation data were obtained by MeteoSyn software. Results indicated that the most suitable station in terms of using solar water heater was Regina, which supplied 35 % of the total heat load for space heating and sanitary hot water purposes. This accounted for 5074 kWh of heat for space heating (25 % of demand) and 3112 kWh energy for sanitary hot water (94 % of demand) using a 40 m^2 solar collector. In addition, results are indicative of an annual amount of saving up to 2080 kg of CO_2 in the Regina station and an annual reduction of 984 m^3 in natural gas for this station. In conclusion, Canada has a potentially alluring market to utilize solar water heaters for providing sanitary hot water for the residential sector.

1. INTRODUCTION

Energy consumption in Canada has increased by 23 % over the last two decades [1]. The primary energy consumption in Canada occurs in residential, commercial, and industrial sectors [2]. By 2020, a 15 % increase in Greenhouse Gas (GHG) emissions from residential buildings in Canada will be expected, as compared to 2012, which is equivalent to 6 Mt CO_2 eq [3]. In 2015, the government of Canada announced that it will remain committed to the Paris agreement target (COP21) so as to reduce its GHG emissions by 30 % by 2030 [4, 5]. It is obvious that lower energy demand from residential buildings will have a significant effect on emissions and energy security of communities [6]. The residential sector in Canada uses energy primarily for space heating (63 %), water heating (19 %), home appliances (12 %), lighting (4 %), and space cooling (1 %). As is clear, more than 80 % of total energy is consumed for heating water and spaces [1]. Integration of the renewable energies with the conventional fossil fuel systems will significantly reduce energy consumption and GHGs emission. Among the solutions proposed for world energy problem, solar energy is undoubtedly one of the most encouraging ones from an environmental point of view [7]. In many countries around the world, heating water consumes too much energy. Solar water heaters (SWHs) are popular technologies and are well validated in the residential sector [8]. Therefore, in residential application schemes, solar energy for heating domestic hot water can lead to significant savings in energy and improvement of the performance of regular water heaters and energy heat recovery [9-12]. Generally, SWHs are simple systems since they only use solar radiation for heating domestic water [13]. These systems are used as a substitution for classic hot water systems. Water heating systems using solar energy are considered the most efficient and, specifically, the most cost-effective and unique systems for cold climates such as Northern Europe, Russia, and especially Canada. In the following, a literature review of solar domestic hot water (SDHW) systems in Canada will be presented.

Hobbi and Siddiqui in 2009 analyzed a forced circulation SWH system for a single residential household in Montreal [14]. Results indicated that the optimized system could cover 83-97 % of hot water demand in May-September and 30-68 % of demand in October-February with an annual value of 68 %. In addition, it was found that even a single locally made non-selective-coated collector could provide around 54 % of the annual water heating energy requirement through solar energy.

Among other studies on SDHW systems in Canada from 2009 to 2011 are support of the Ministry responsible for natural resources and wildlife in Quebec from a pilot project aimed at developing the solar domestic water heater (SDWH) in this province [15] and

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a study on the performance of two SDHW systems installed at the Archetype Sustainable Twin Houses (ASH) at Kortnight Center, Vaughan, Ontario [16].

In another research, NikooFard et al. in 2014 studied the effect of energy consumption, GHGs emission, and the economic feasibility of using an SDHW system for all of the households in Canada [17]. It was assumed that all of the houses were equipped with a single-tank hot water system and had roof spaces facing the south, southwest, or southeast in order for a solar water heating system to be installed on. The achieved results suggested 2.1 % (22.7 PJ/year) and 2.2 % (1 Mt of CO_2) reductions in energy consumption and GHG emissions in the residential sector of Canada. Furthermore, through governmental support and motivation, SDHW systems would be economically more attractive for Canadian households, which would lead to more requests of such system to the residential sector.

Edwards et al. in 2015 measured DHW profiles from 73 households in Quebec city at a time resolution of 5 min for four DHW consumption levels (mean, median, sparing, and profligate) and 3 temporal consumption patterns (consumption primarily in the morning, primarily in the evening, and dispersive consumption) [18]. These measurements were taken between early November 2006 to mid-April 2007. Significant temporal variability in the consumption patterns was also observed among houses so that about one-fourth of the houses primarily consumed in the morning, nearly one third had a higher DHW consumption rate in the evening, and the rest (around 40 %) did not fit into these temporal patterns. The obtained DHW profiles were used to numerically study the performance of a typical solar DHW system, and the results indicated that these obtained profiles could provide more efficient conditions in the simulation-based studies than the typical daily repeated profile.

Semple et al., in 2016, explored the potential of using large-scale solar heating systems to prevent carbon emissions from the greenhouse sector in Ontario, Canada [19]. Their analysis was carried out by TRNSYS software using actual gas consumption data. The results showed a 35 % reduction in annual heating energy demand, and it was stated that per hectare of a greenhouse, annually, 120 tons of CO_2 would be reduced.

To gain a better understanding of the real performance of SDHW systems, Ghorab et al. (2017) studied these systems with regard to a selected house in Alberta, Canada, for a family of four (2 adults and 2 kids) with an annual DHW load of 246 L/day [20]. This system comprised two solar collectors installed on the roof of each house with a total area of 7.716 m^2, 272 L solar tank, and 172 L auxiliary gas tank, and it was of a closed-loop type. Results indicated that outdoor conditions (solar radiation and temperature) significantly affected the DHW temperature inside the solar tank. Among other results, it was found that around 91.5 % of solar energy collected by solar tanks was consumed for DHW heating load. The share of DHW heating load accounted for around 69.4 % of natural gas and 30.6 % of solar energy.

Narval et al., in 2018, carried out a comparative study on solar thermal storage in residential applications [21]. The sample was a Canadian four-person family, and the parameters studied included various thermal adsorbents. Their results showed that Zeolit 4A-water and Zeolit 13X-water were the most economical and efficient adsorbents, with the lowest amount of mass, with 290 and 226 kg, respectively.

McNally et al., in Canada, examined the absorption cooling and solar heating for home-use cooling applications [22]. Their experimental results showed that if the solar collector system's capacity to maintain a good average temperature was correct, the chiller function would be suitable for residential applications.

In 2019, Rahmatmand et al. carried out an experimental study on the removal of snow and ice from the collector of solar cell system using hot water circulation behind the solar panel [23]. Their results showed that the proposed method could clean the panel surface in a shorter amount of time. It also provided a dimensionless number that represents the energy used to remove snow from the panel to the energy produced by the panel after the removal of snow. In the end, they also mentioned that the proposed system removed the ice and snow in the middle of the panel sooner than its upper and lower.

According to surveys, so far, no comprehensive work has been done to find an optimal location in Canada for the use of SWH. Further, the simultaneous supply of heat requiring for both heating space and sanitary hot water is another innovation of this paper. The results indicate that each location has the potential for supplying the heat required by SWH. As a matter of fact, this issue will help private sector investors and the general public to contribute as much as possible. This issue will be used for other similar climates and generalized. Therefore, this paper uses T*SOL Pro 5.5 software to investigate the potential of using SWHs in 10 provinces of Canada. The studied stations are shown in Figure 1.

2. THE STUDIED AREA

As shown in Figure 1, Canada is the largest country of North America. Its land reaches from the Atlantic Ocean in the east to the Pacific Ocean in the west and from the Arctic Ocean to the north. Canada ranks number 38 in the list of countries by population with an estimated population of over 35 million in 2017 [24]. In addition, Canada has a total area of 9.98 million km^2, making it the world's second largest country by total area. Canada is often associated with cold weather and snow; however, in reality, its climate is as diverse as its landscape. Generally, Canadians enjoy four very distinct seasons, particularly in the more populated regions along the US border. In these regions, daytime summer temperatures can rise to 35˚C and higher, while lows of -25˚C are not uncommon in winter [25]. Canada has the largest hydrocarbon reserves in North America. It ranks number 5 and 4 in the world market in terms of production and export of crude oil and natural gas, respectively. In addition, it ranks as the world's third and fifth country by hydroelectricity and biofuels, respectively [26]. Currently, hydroelectricity, biomass, wind, and solar contribute significantly to energy production in Canada [27]. Canada also has high potential for solar energy use and, since 2007, there have been an estimated 544000 m^2 of solar collectors installed in this country [28]. As is obvious in Figure 1, the southern parts of Canada, particularly Manitoba, Saskatchewan, and Alberta, and also some parts of Ontario province have good potential for implementing solar projects.

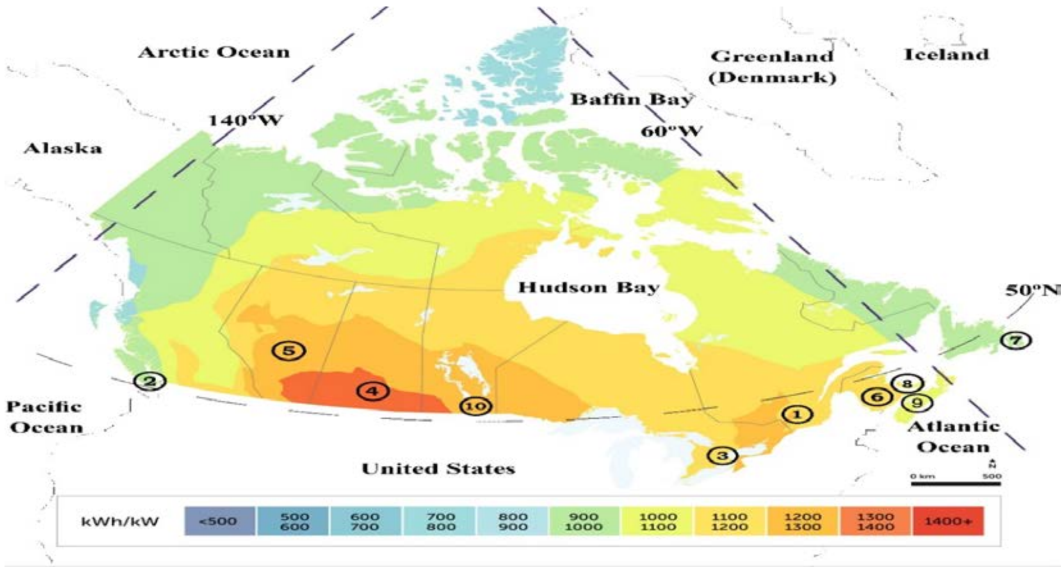

Figure 1. Hours of sunshine for Canada and the positions of studied stations and Canada location in the world.

3. THE SOFTWARE AND THE RELATED EQUATIONS

To study the SDHWS performance, it is required to use dynamic analysis tools to accurately describe the system responses to rapid changes in environmental conditions. T*SOL Pro 5.5 is one of these tools, which is a professional simulation program for the design and planning of solar thermal systems [29]. It has facilitated the simulation and calculation process in these systems by providing tools and components of solar systems and, also, the relevant components such as hot water supply, swimming pool, heating process, buffer tanks, etc. This software enables the optimal design of solar thermal systems, temperature simulation, and their energy performance at lower cost and in shorter time [30]. In T*SOL Pro 5.5, calculations are performed according to the balance of energy flows and provides yield prognosis according to the hourly meteorological data provided [30].

The total radiation received on a collector surface is a summation of direct and diffuse radiations. Direct radiation is available in the supplied climate files, and the calculations of diffuse radiation striking collector surface are performed using α angle and hourly clearness index K_t according to the following equations [31]:

$$0 \le k_t \le 0 \cdot 3 \ : \ \frac{I_d}{I} = 1 \cdot 02 - 0 \cdot 245\, k_t + 0.0123 \sin\alpha \quad (1)$$

$$0 \cdot 3 < k_t \le 0 \cdot 78 \ : \ \frac{I_d}{I} = 1 \cdot 4 - 1 \cdot 749\, k_t + 0.177 \sin\alpha \quad (2)$$

$$k_t \ge 0 \cdot 78 \ : \ \frac{I_d}{I} = 0 \cdot 486\, k_t - 0 \cdot 182 \sin\alpha \quad (3)$$

where I is the total hourly radiation on a horizontal surface (KJ/m^2), and I_d is the hourly diffuse radiation on a horizontal surface (KJ/m^2). It is noteworthy that some incident radiation on the collector surface is wasted. The software calculates collector losses by [31]:

$$\rho = G_{dir} \cdot \eta_0 \cdot f_{IAM} + G_{diff} \cdot \eta_0 \cdot f_{IAM.diff} - k_0\,(T_{km} - T_A) - k_q\,(T_{km} - T_A)^2 \quad (4)$$

where G_{dir} is the part of solar radiation striking a tilted surface, η_0 is the collector's zero-loss efficiency, f_{IAM} is the incidence angle modifier factor, G_{diff} is the diffuse solar radiation striking a tilted surface, $f_{IAM,diff}$ is the diffuse incidence angle modifier factor, k_0 is the heat transfer coefficient (in $\frac{w}{m^2-k}$), T_{km} is the average temperature of collector, T_A is the air temperature, and k_q is the heat transfer coefficient (in $\frac{w}{m^2-k^2}$).

The software considers solar system's CO_2 emissions savings of 5.14355 g per KJ of energy generated [31]. Solar fraction of energy supplied by collectors is obtained by dividing the energy transferred from solar system to the standby tank by total energy supply of standby tank (solar system+auxiliary heating) according to the following equation [31]:

$$\text{Solar fraction. total} = \frac{Q_{CL.DHW} + Q_{S.HL}}{Q_{CL.DHW} + Q_{S.HL} + Q_{AuxH.DHW} + Q_{AuxH.HL}} \quad (5)$$

Other equations used in simulations, shown schematically in Figure 2, are as follows [31]:

$$\text{Solar fraction DHW} = \frac{Q_{CL.DHW}}{Q_{CL.DHW} + Q_{AuxH.DHW}} \quad (6)$$

$$\text{Solar fraction heating} = \frac{Q_{S.HL}}{Q_{S.HL} + Q_{AuxH.HL}} \quad (7)$$

4. SIMULATION DATA

Information on the temperature, geographical position, municipal water temperature, and total annual global radiation for the studied stations is presented in Table 1. These stations are also shown in Figure 1. Daily average sanitary hot water consumption of 110 L, sanitary hot water temperature of 60 ˚C, and operating period of the whole year were considered. Furthermore, the space heating load of 10 kW, space temperature of 21 ˚C, and heated useable area of 80 m^2 were applied.

Double glazed windows with areas of 1.6, 4, 8, and 5.6 m^2 were considered for north, east, south, and west facing windows, respectively. heat gain of 5 W/m^2 due to internal heat sources was also considered. Of note, heating load requirements of the building were assumed as constant throughout the year. Since Canada has a very cold climate, the thermal requirement was the same for all months of a year and equal to the average heat requirement. Moreover, "thick" wall type was considered. Solar water heater type, solar water heater area, and other accessory equipment such as buffer tanks, piping's, boiler, etc. were all the same in 10 provinces for comparison purposes.

The used solar water heater was of a standard flat-plate type with an area of 40 m^2 and 0 ˚ azimuth angle. The Flat Panel Solar Collector is a standard choice of black chrome with a useful heat absorption area of 1 m^2 and a special thermal capacity of 6000$\frac{ws}{m^2k}$. The coefficient of optical loss and its correction coefficient for direct and diffused radiation are 78 %, 88 %, and 83 %, respectively. The simple heat transfer coefficients and their square degree are 3.8 $\frac{w}{m^2k}$ and 0.03 $\frac{w}{m^2k}$ for use in Equation (4), respectively.

Double coil buffer tanks for sanitary hot water and space heating were used having 300 L and 1000 L capacities, respectively (As shown in Figure 2). Since the SWH cannot meet all the thermal requirements, a boiler is used as a backup system. Therefore, a gas boiler with a rated capacity of 9 kW was utilized. Water/polypropylene glycol in 60/40 ratio and a rate of 40 L/m^2 was used as the intermediate heat transfer fluid. In case of high requirement for space heating, in/outlet temperature difference of 20 ˚C and for other cases 15 ˚C were considered. The general schematic of the simulated system is shown in Figure 2. It should be noted that the tilt angle of solar panels was equal to the latitude of the studied area [32].

There are two tanks in this study: one is for sanitary hot water and another for hot water needed for space heating. To connect each of these reservoirs with a solar collector (returning water from reservoirs to solar collectors), a pump is required. A pump for circulating water inside radiators is also required. Therefore, a total of 3 pumps are required.

Table 1. Information on the studied stations.

NO.	Station	Latitude	Longitude	Total annual global irradiation (kWh/m²)	Cold water temperature (Feb./Aug.) °C	Diffuse radiation percentage (%)
1	Montreal	45.7	74	1322	2/10.5	49.9
2	Victoria	48.7	123.4	1134.9	8.5/12	54.3
3	Toronto	43.7	79.4	1296.5	5.5/12.5	51.4
4	Regina	50.4	104.7	1401.4	1/8	44.9
5	Edmonton	53.3	113.6	1268.4	1/7	46.7
6	Fredericton	45.9	66.6	1259.6	2.5/10	52.3
7	St. John's	47.5	52.8	1128.9	3.5/8	56.4
8	Summerside	46.4	63.8	1252.7	3/9.5	51.5
9	Truro	45.4	63.3	1254.5	3.5/9.5	53.8
10	Winnipeg	49.9	97.2	1378.2	1/8.5	44.2

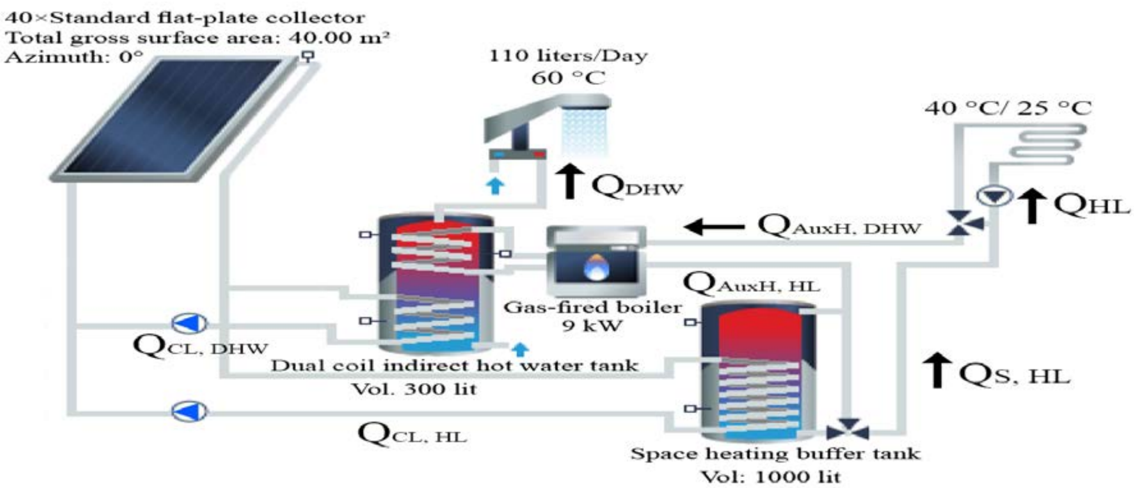

Figure 2. Schematic view, specifications, and components of the simulated solar system.

5. RESULTS AND DISCUSSION

Analysis results of 10 studied stations are presented in Table 2. According to the results, it can be observed that Regina, Edmonton, and Winnipeg stations are the most suitable ones that provide 35 %, 34 %, and 32 % of their total heating demand from solar water heaters, respectively. By supplying 25 %, 24 %, and 22 % of space heating demand, these three stations have the highest percentage of building space heating in Canada. According to the data given in Table 2, although Regina station has a slightly higher latitude than the other stations due to its higher air clearness index (thus, the percentage of diffused light is very low), it has a much higher level of radiation per unit area than other stations. It is, therefore, justifiable to be the most suitable station for using SWH.

Regarding the space heating, although Victoria station ranks number 3 by space heating through solar water heater (4472 kWh) due to its higher heat demand, it does not rank among the top three stations in terms of the highest percentage of space heating by solar water heaters.

Regarding the amount of sanitary hot water generated, Regina, Edmonton, and Winnipeg stations rank first to third by 3112 kWh, 3015 kWh, and 3009 kWh, respectively. It should be noted that by providing 97 % of required hot water through solar water heaters, Toronto station is the best one for this purpose. The need for the desired heat to supply sanitary hot water at some stations is higher than others. However, solar water heaters can only provide a small percentage of it. Despite the maximum heat generated by the solar water heater at the Regina station, since its thermal requirement is higher, the heat percentage provided by the solar water heater is not maximized.

In terms of savings in GHG emissions due to not using fossil fuels, three stations of Regina, Edmonton, and Winnipeg with savings up to 2080 kg, 1973 kg, and 1888 kg were the top three stations. Moreover, regarding the use of boiler for providing the reaming energy for space heating and sanitary hot water, it can be said that the application of solar water heaters for space heating and sanitary hot water on average accounts for 19.18 % and 88.7 %, respectively.

This is an excellent justification for using solar water heater for providing sanitary hot water load, compared to space heating. Thus, the best stations with respect to space heating by solar water heater, supply of sanitary hot water by solar water heater, and simultaneous provision of space heating and sanitary hot water by solar water heater are Regina (25 % of its required energy), Toronto (97 % of its required energy), and Regina (35 % of its required energy), respectively.

Notably, the authors recommend investing on solar water heaters in Regina which, based on the results shown in Table 1, has high annual average radiation and low diffuse radiation. Figures 3 and 4 illustrate the solar energy share in the total required energy and energy balance schematic for Regina station, respectively. Figure 3 is one of the most important outputs of the software, showing how much of the building's thermal needs could be met by SWH during the year in each month.

It could be seen from Figure 3 that from May to September, nearly all the required energy is supplied by solar collectors. In Figure 3, the highest need for a boiler occurs in December and January when collectors have supplied 11 % and 15 % of heating loads, respectively. As can be observed in Figure 4, in comparison to optical and thermal losses of collectors (60373 kWh), the energy losses in two tanks and pipings are negligible due to the nearly heat losses of 2055 kWh and 1639 kWh, respectively. The tank losses depend on tank geometry and target values. Particular attention should be given to minimizing these energy losses in practical plans and schemes for each specific scenario.

The only paper available in this regard is the potentiometric use of SWH by the T*SOL Pro 5.5, software which is done by the authors of this paper in which the study focused on Algeria in 2018 [33]. Since the country of Algeria is completely different from Canada, the results are not comparable.

Table 2. The results of studied parameters.

Station	Total solar fraction (%)	Solar contribution to heating (kWh)	Heating solar fraction (%)	Solar contribution to DHW (kWh)	DHW solar fraction (%)	Saving natural gas (H) (m^3)	CO_2 emissions avoided (kg)	Boiler energy to heating (kWh)	Boiler energy to DHW (kWh)
Montreal	29	3386	18.3	2822	89	764	1616	15092	340
Victoria	25	4472	18.4	2386	81	834	1763	19805	550
Toronto	25	2995	15.3	2641	97	705	1491	16571	406
Regina	35	5074	25	3112	94	984	2080	14928	185
Edmonton	34	4806	24	3015	92	933	1973	15199	272
Fredericton	29	3863	19	2823	89	819	1732	16419	331
St. John's	22	3657	14.2	2536	82	739	1562	22026	564
Summerside	27	3760	17.8	2722	86	782	1654	17318	425
Truro	27	3679	17.8	2657	85	772	1632	17008	465
Winnipeg	32	4355	22	3009	92	893	1888	15090	262

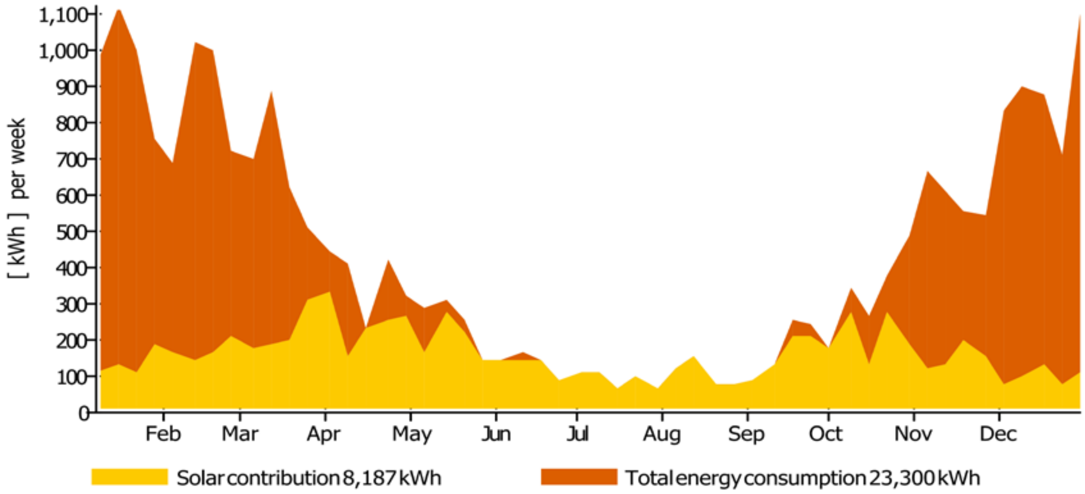

Figure 3. Solar energy consumption as percentage of total consumption for Regina.

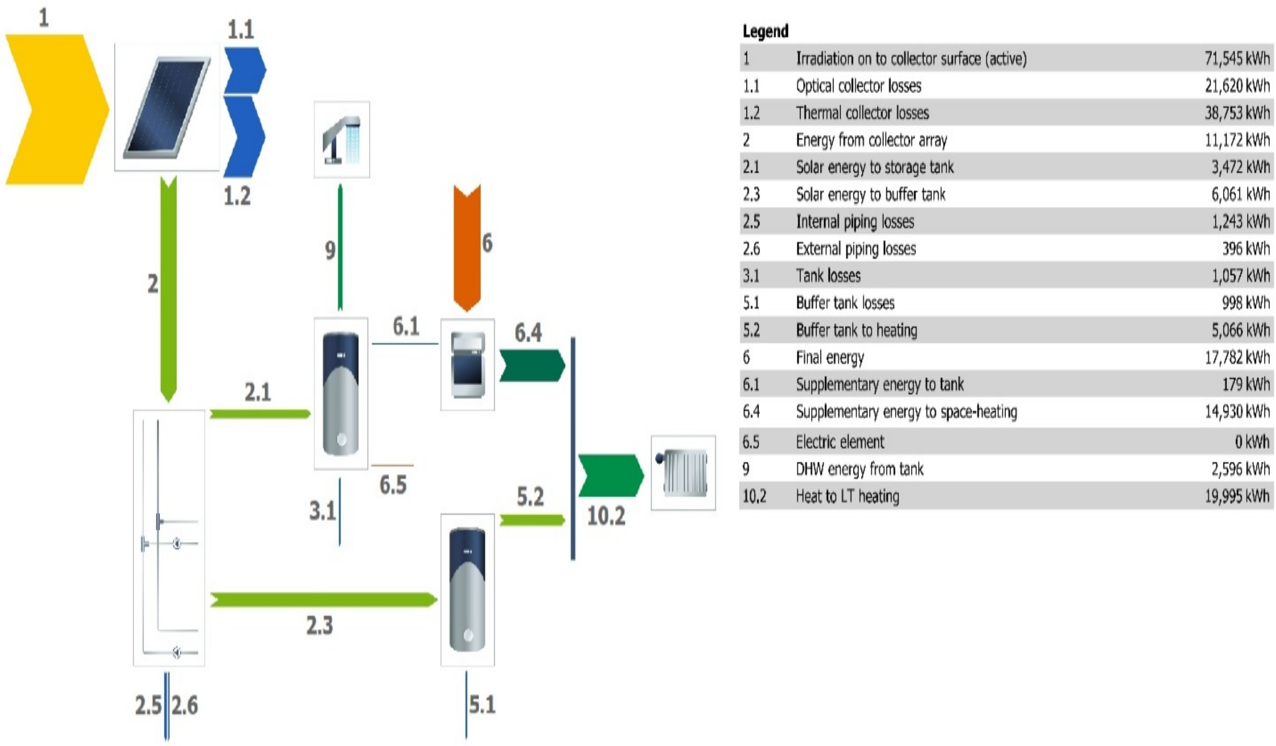

Figure 4. Energy balance schematic for Regina.

6. CONCLUSIONS

The increasing popularity of renewable energies in Canada and regarding the fact that creating new jobs in construction, installation, operation, and maintenance of clean energy systems plays a vital role in social welfare and development of Canadians, this paper attempted to use its findings to achieve governmental support for exploiting solar energy in Canada. This paper investigated the feasibility of using solar water heater for the supply of hot water demand of an 80 m^2 residential house in 10 provinces in Canada using T*SOL pro 5.5 and MeteoSyn software packages. In this study, 4 residents and a 40 m^2 solar water heater with a required hot water temperature of 60 °C are considered. Simulation results are organized as follows:

- Regarding provision of sanitary hot water, Regina (3112 kWh), Edmonton (3015 kWh), and Winnipeg (3009 kWh) stations occupy the top three positions.
- With respect to the heat supply for space heating, Regina (5074 kWh), Edmonton (4806 kWh), and Victoria (4472 kWh) rank as number 1 to 3.
- Concerning annual savings in pollutant gases, Regina (2080 kg), Edmonton (1973 kg), and Winnipeg (1888 kg) stand in the first to third positions.
- Regarding natural gas savings due to the application of solar water heater, Regina (984 m^3), Edmonton (933 m^3), and Winnipeg (893 m^3) stations rank as number 1 to 3.
- On average, for all 10 stations, using a solar water heater for space heating and sanitary hot water

accounts for 19.18 % and 88.7 % of total energy demand, respectively.

- Using solar water heaters for sanitary hot water consumption is a suitable choice in Canada.

It should be noted that the dynamic simulations of the solar thermal system over a year were first carried out in this paper for all Canadian provinces. This study leads to the fact that in addition to introducing the potential of SWH to people to encourage them about its use, the security of private investors increases.

7. ACKNOWLEDGEMENT

The authors would like to thank the Islamic Azad University, Shahrekord Branch and Young Researchers and Elite Club for their moral support.

NOMENCLATURE

k_t	Hourly clearness index
I	Total hourly radiation on a horizontal surface (kJ/m^2)
I_d	Hourly diffuse radiation on a horizontal surface (kJ/m^2)
G_{dir}	Part of solar radiation striking a tilted surface
η_0	Collector's zero-loss efficiency
f_{IAM}	Incidence angle modifier factor
G_{diff}	Diffuse solar radiation striking a tilted surface
$f_{IAM,diff}$	Diffuse incidence angle modifier factor
k_0	Heat transfer coefficient (W/m^2.k)
α	Tilt angle
LT	Low temperature
T_A	Air temperature
T_{km}	Average temperature of a collector
k_q	Heat transfer coefficient (W/m^2.k^2)
$Q_{CL;DHW}$	Collector loop heating for domestic hot water
$Q_{S,HL}$	Solar heating for heating load
$Q_{Aux,DHW}$	Auxiliary heating for domestic hot water
$Q_{Aux,HHL}$	Auxiliary heating for heating load
EWH	Electric water heater
SWH	Solar water heater
ρ	Collector losses
DHW	Domestic hot water

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