A Comparison of Solar Photovoltaic and Solar Thermal Collector for Residential Water Heating and Space Heating System

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***Abstract*—Almost all single-family detached houses in Canada consume enormous electrical energy for space heating and domestic hot water (DHW) purposes. There are many possibilities to design an energy-efficient house. A solar water heating system can be used for domestic water and space heating. Water temperature can be kept constant always by connecting a heat pump or oil burner to the main tank because solar energy is intermittent. The sizing of solar photovoltaic and collector, tank, heat pump is essential to design an effective system based on the system energy consumption. The existing house is just a conventional house where space and water heating are provided by the grid electricity only. In this research, two possible ways of thermal energy storage systems have been designed for a residential single-family house with solar collector and solar photovoltaic. It is proved that the proposed PV based energy storage system is highly suitable considering lower cost, high output power, flexibility, and easy installation.**

***Index Terms*—Solar Photovoltaic, Thermal Collector, Water Heating, Space Heating, Performance, Cost Analysis.**

I. Introduction

Solar PV installation in Canada is rapidly growing. Currently, the residential and commercial solar breakeven is comparatively much less than the grid electricity prices, for example, the solar energy cost is 6.8 cents/kWh average whereas the grid electricity price is 12 cents/kWh [1]. It is assumed that the rooftop PV or collector panel could mitigate about half of Canada's residential energy requirement [2]. The price of PV technology has significantly decreased over the last few decades, and the efficiency of the PV panel increased. Some manufacturers demanded that efficiency is around 23% [3]. Among all methods of power generation in Canada, solar energy is contributing more than 1%, and the total generation is more than 3000 MW [4]. This heat energy can be used to provide domestic hot water (DHW) supply, and space heating purposes as almost all Canadian single-family houses are using electricity for both.

Thermal energy storage (TES) system is a structure to store thermal energy for space heating and domestic hot water supply in different mediums such as water, latent heat, sensible heat, and many more [5] [6]. Because of several advantages nowadays, the active control of the integrated system with photovoltaic thermal (PVT) is used to a large extent to reduce the energy mismatch between supply and demand through a controller [7]. Canada's Energy Future (2018) published a report and mentioned that the present per capita greenhouse emission (GHG) is around 22 %. Considering its reduction planning to reduce it to below 5% by 2030 [8]. Based on the Government of Canada, the solar contribution will increase to around 5% by 2025, which will significantly help to reduce the CHG emission [9].

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II. Literature Review

Renewable energy sources provide more than 17% of Canada's total primary energy supply currently [10]. Lots of research is conducted on solar thermal energy storage systems with renewable sources. M. Ghorab et al. [11] verified that the solar fraction, as well as output, would increase proportionally with the increase of the solar collector area.

They also suggested that hybrid residential energy end-use and emissions model is beneficial to make an efficient detached house. M. C. Rodríguez-Hidalgo et al. [12] investigated in his research that for the long-term performance, the TES systems with multisource heat pump, and solar collectors are efficient, and cheapest way to produce heat for space heating. S.Z. Mozabieh et al. [13] highlighted that the cumulative lifecycle energy and carbon analysis, as well as energy payback periods and net energy ratios, are also crucial for making an energy-efficient house.

A single-family house can make energy-efficient, even net-zero carbon emission by using an all-electric solution. J. L. Garcia et al. [14] mentioned that the solar collector based DHW system performance depends on water flow rate, draw time and duration, city water temperature, control of water circulation loop, and system layout. From their experiments, they found that most of the collected energy goes to the loads. They used a concentrating solar collector and rock-bed storage with air as a working medium for a long-term house heating system. The authors [11] suggested making an energy-efficient house by improving the house design parameters such as walls, insulation, windows, ceiling fan, and so on.

Some Universities in Canada are doing some research related to the sessional energy storage systems. For instance, the University of Ontario Institute of Technology built a low-temperature borehole thermal energy storage system (BTES) in 1990, which had 384 holes, provide the basis for a highly efficient heating and cooling system for eight University buildings [15],[16].

In the Drake Landing Solar Community (DLSC) project [17] in 2007, which is supplying 90% of heat demand and 60% hot water demand in total 52 numbers of single house detached families.

In this work, a thermal energy storage system with a necessary control system has been designed for a single-family residential house. Finally, the performance and installation costs of both systems have been compared.

III. DATA COLLECTION AND ANALYSIS

A. Weather Analysis

The tested house location is 5, Blue River Place, St. John's, NL, Canada. Based on the PolySun software analysis, the minimum wind speed for power generation is 2m/s, and the maximum value is 10 m/s. The average daily solar radiation is 3.06 kWh per m2 per day, which is enough to generate heat or electricity.

B. House Analysis

The considered house is a typical single-family house in Canada, and the details of this house are described in Table I. In the tested house, the hot water supplied by an electric boiler and space heating is provided by the grid electricity. Thus the vast grid electricity is required, and consumers are paying a large number of electric bills every year.

TABLE I: THE SELECTED HOUSE PARAMETERS

House Particulars	Values
Facility full size (13.7 m × 9.144 m)	125.27 m^2
Annual energy demand	153.56 KWh/m^2
Hot water temperature	50 ^{0}C
Space heating setpoint temperature	24ºC
Annual electricity demand (Based on NL power)	19007 kWh
Annual electricity demand (BEopt. analysis)	19511 kWh

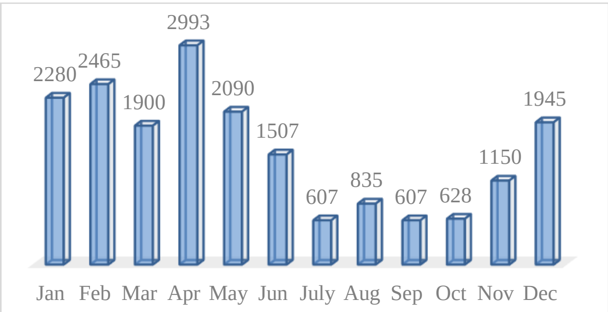

Fig. 1. The annual consumption (NL power data)

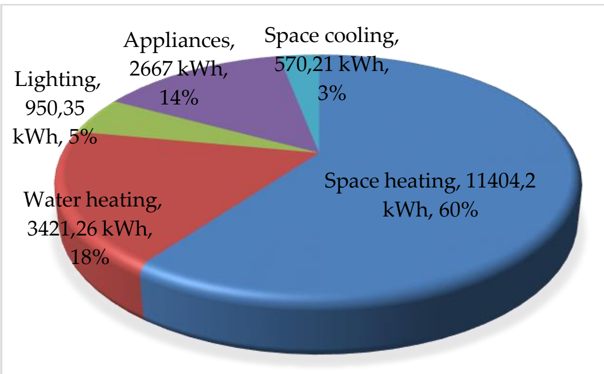

Fig. 2. The actual electricity consumption distribution [18]

Based on NL power annual bill summary, the considered house present annual demand is around 19007 kWh of electricity for space heating, DHW, and other electrical appliances, as shown in Fig. 1. The distribution of this consumption shown in Fig. 2 where it is shown that most of the electricity consumed for space heating and DHW.

C. House Analysis in BEopt Software

This house again was analyzed by using the BEopt Software. All input parameters have been selected carefully based on the existing house materials. The simulation output is shown in Fig. 3.

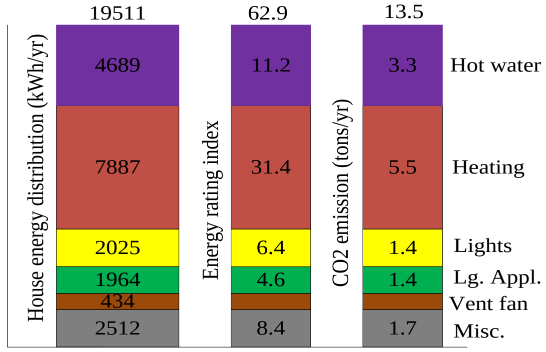

Fig. 3. House standard annual energy demand

It is a result that the actual energy consumption in the house in Fig. 1 is almost like the electrical and thermal consumption of the house, as shown in Fig. 3.

IV. SOLAR COLLECTOR BASED SYSTEMS

Currently, the house is just a typical single-family house. All energy demand is provided form the grid electricity. To modify it, a solar thermal collector relates to two water tanks. As solar energy is always variable, the preheating tank water temperature may always not reach the desired value. That is why an auxiliary burner is added with the main tank that will help to keep the water temperature at the desired level. The modified space heating and hot water supply diagram in a single-family house given in Fig. 4.

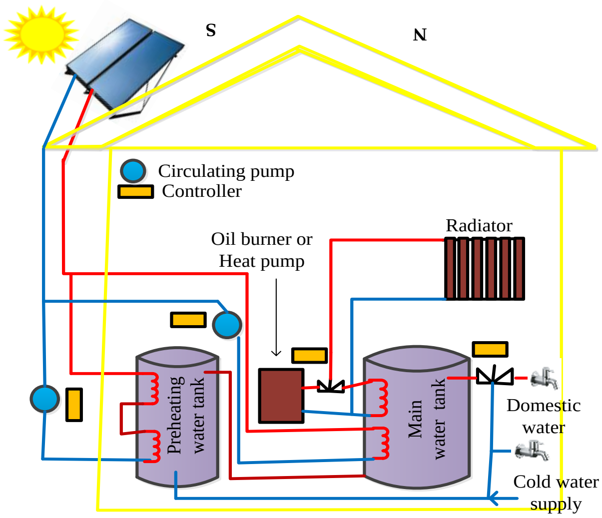

Fig. 4. The proposed model for the tested house.

A. Design of Solar Collector

In this research, the water medium is considered in the tanks. The stored hot water carried to the radiator for space heating purposes and to the hot water taps (kitchen, bathrooms). The DHW distribution scenario is taken for 24 hours, as mentioned in Fig. 5. The design calculation for hot water heating is given below [18]:

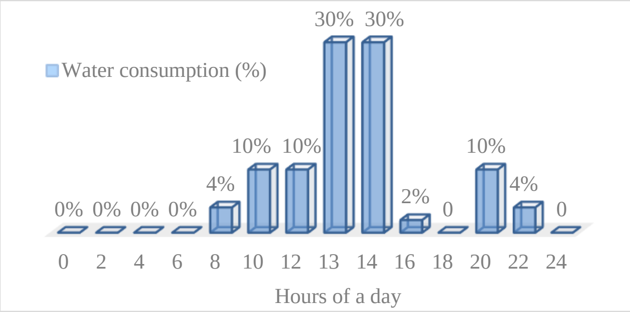

Fig. 5. The daily water consumption scenario

Average solar radiation for high solar fractions=3.06 (Kwh/m2/d).

Storage volume,

V_{st}=[(B×O×DHW)+ 〖HWD$_k$]×1.2=132 liter=0.132 m^3 (1)

Energy demand for hot water,

$Q_s=V_{st}\times Cp\times\Delta T$=0.132×1.16×45=6.89 kWh/day (2)

The calculated global solar radiation at St. John's, NL, Canada is S_r= 2.9 kWh/day.m2

Collector yield,

$C_Y = S_R \times \eta_K \times \eta_{sys}$=2.9×0.6×0.8=1.392 kWh/$m^2$ (3)

Where η_k is the collector efficiency and η_sys is system efficiency. If 100% solar fraction, the maximum value considered then,

Collector array,

$C_A=Q/C_Y$ =(6.89 kWh)/(1.392 kWh/m^2) = 4.95 m2 (4)

The design calculation for space heating given below:

A standard flat plate collector can produce 9085.23 kW/m^2/day [18], and the daily requirement is 202.7 kW/m^2/day

The required number of collectors=

(Daily requirement)/(Collector output)=0.0223 (m^2/day) (5)

The total number of collectors=0.02231(m^2/day) × 125.27 m^2=2.7 per day.

The surface area of collector array=No of collectors × size of each collector in m^2 =2.7 × 1.9 m^2 = 5.13 m^2 (6)

Total collector area for space heating and DHW=10.08 m^2 ≅10 m^2 (eq. 4 and eq. 6) [19].

B. Installation cost analysis

The setup cost distribution for the solar collector and energy storage system described in Fig. 6.

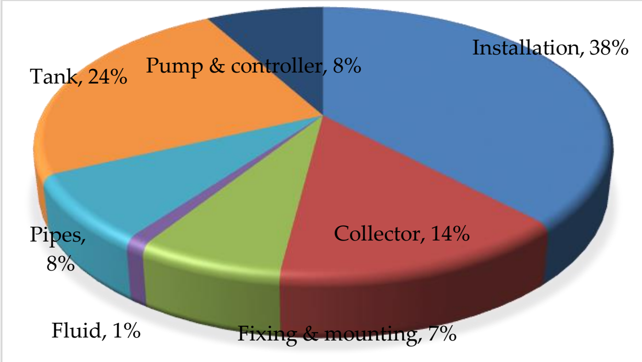

Fig. 6. Installation cost distribution by section [18]

The calculation has been done based on the above design and the latest market price according to Amazon.ca. It is found that the total investment cost with oil burner is CA $53,600 and with heat pump is CA $54,600.

C. Simulation Result

The modified single-family house, as shown in Fig. 4 has been designed and simulated in a professional PolySun designer environment. In this simulation, there are two models considered, for example, model 1: a collector, an oil burner for heat sources, and model 2: a collector, heat pump for heat sources. The system other parts remain the same for both cases. The simulation was done carefully for every month of a year. The collector output is available around the year, as shown in Fig.7.

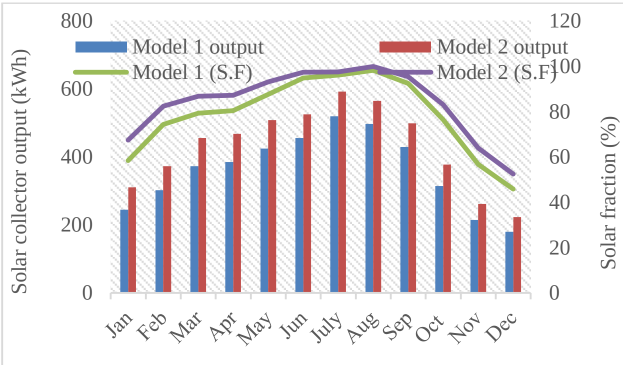

Fig. 7. Solar collector and fraction comparison.

The average efficiency of the oil burner is 95% and the heat pump efficiency is 300% to 500%. Usually, from Jun to Aug is the hottest months in NL, Canada, so the overall demand is lower than the other months, as shown in Fig. 8. The performance of both systems is compared in Table II. In NL, Canada, the electricity price is 0.12 CAD/kWh that considered for electric bill calculation. Usually, one liter of furnace oil price is 0.82 CAD, which is also equivalent to 10.27 kWh of energy is also considered in the calculation.

V. Solar PV Based Systems

The central systems in Fig. 4 is considered again with the solar PV module instead of solar thermal collector, and the design steps are given below [19]:

A. Sizing PV for Water Heating

Required load for water heating= 6.89 kWh/day (standard two rooms for 4 people)

Total PV panels energy needed= 6.89 kWh/day × 1.3=

8.957 kWh/day.

Total Wp of PV panel capacity needed= 8957 Wh/day/3.4=2634 Wp.

Number of PV module=2634 Wp/150 W= 17.56 modules ≅ 18 modules.

The total area of PV panel= 11.3 m^2.

B. Sizing for Space Heating

Required load for space heating= 20.27 kWh/day [standard two rooms with 4 people]

Total PV panels energy needed= 20.27 kWh/day × 1.3= 26.35 kWh/day.

Total Wp of PV panel capacity needed= 26350 Wh/day/3.4=7750 Wp.

Number of PV module=7750 Wp/150 W= 51.66 modules ≅ 52 modules.

The total area of PV panel= 0.6277 m^2 × 52= 32.64 m^2

The total number of a solar panel for water and space heating is 70 numbers, which are equal to 43.94 m^2.

TABLE II: THE COMPARISON OF COLLECTOR BASED SYSTEMS

Basic sections	**Particulars**	**Existing/ reference system**	**Model 1 (Oil Burner)**	**Model 2 (Heat pump)**
Solar collector	Total gross area	N/A	10 m^2	10 m^2
	Annual Output	N/A	4345 kWh	5161 kWh
Storage tank	Volume	181 Liter	(132+200) Liter	(132+200) Liter
Auxiliary burner	Type, capacity	Electric (4 kW)	Oil burner (3 kW)	Heat pump (3 kW)
	Energy input/output	Same	1635/1091 kWh	354/882 kWh
Annual energy consumption	DHW and space heating	17009 kWh	9389.5 kWh + 159.2 L Oil	8320.5 kWh
Annual consumer bill	DHW and space heating	1690 CAD	1201 CAD	998.46 CAD
	Savings	**No**	**29%**	**44%**

C. Control and Monitoring Systems

The complete system is shown in Fig. 8, and the controller operating principle is described in Fig. 9. During the day time, when the sunshine is available, the three-position switch transfers the AC power to the water tank. The sensors always monitor the water temperature; when reaching the tree position switch, transfer the power to the room heater-1 and room heater-2. After consumption of some hot water, new cold water comes into the tank; if the temperature is below the set temperature, the three-position switch again connects to the tank. In this way, the water tank temperature always maintains the set temperature. During the night time, auxiliary heater coil supplies heat from the electric grid to the water to maintain the water temperature based on the set temperature. When the water level goes to the desired level, then valve two is not taking cold water. Similarly, when the level goes lower than valve two opens until the tank fills up. The controller will do everything, as shown in Fig. 9.

D. Calculation of the Investment Cost

The whole system is designed and described in section 5.1~5.2. There are factors associated with the installation cost. The percentage of cost distribution, as shown in Fig.10 [22].

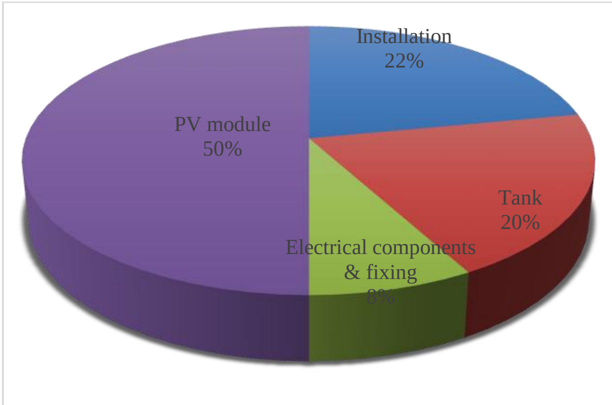

Fig. 10. The cost distribution of solar PV based system

The calculation and the total installation cost has been done based on the above design and the latest market price according to Amazon.ca and it is calculated that the total implementation cost will be CA $22,350.

TABLE III: THE OVERALL COMPARISON OF BOTH SYSTEMS

Particulars	Reference system	Thermal Collector Based		PV Based
		Model 1	Model 2	
Energy generation from a renewable source	0 kWh/year	4345 kWh/year	4345 kWh/year	26412 kWh
Energy is taken from the grid	17009 kWh/year	9389.5 kWh + 159.2 L Oil	8320.5 kWh	0 kWh/year (If net metering is implemented)
Annual energy savings	0 kWh/year	7619.5 kWh/year	8688.5 kWh/year	17009 kWh/year
Surface requirement	---------	10 m^2	10 m^2	43.94 m^2
Storage tank size	181 L	(132+200) Liter	(132+200) Liter	454 L
Investment cost	Nothing change	53,600 CAD	54,600 CAD	22350 CAD
Yearly savings	0 CAD (0%)	914.34 CAD (29%)	1042.62 CAD (44%)	2041.08 CAD (100%)

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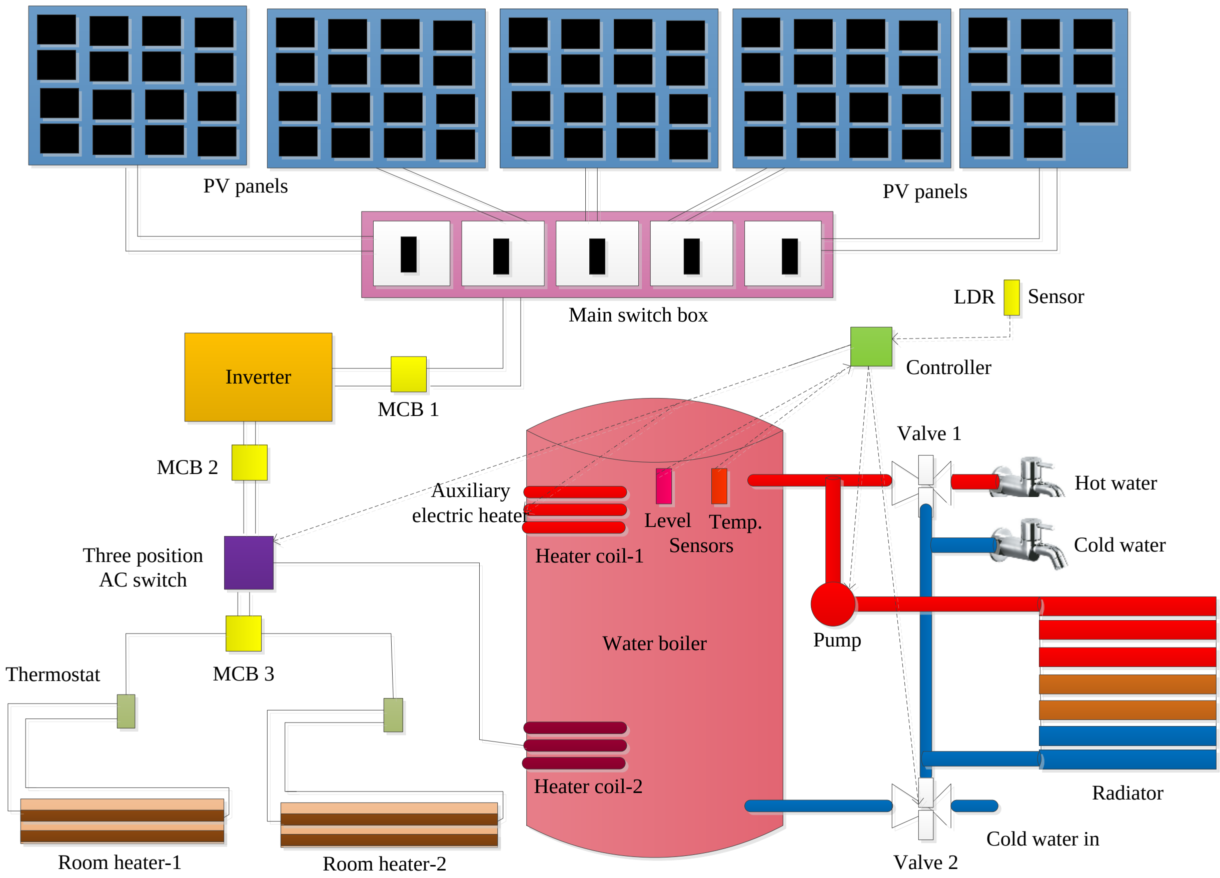

Fig. 8. Solar PV based complete system

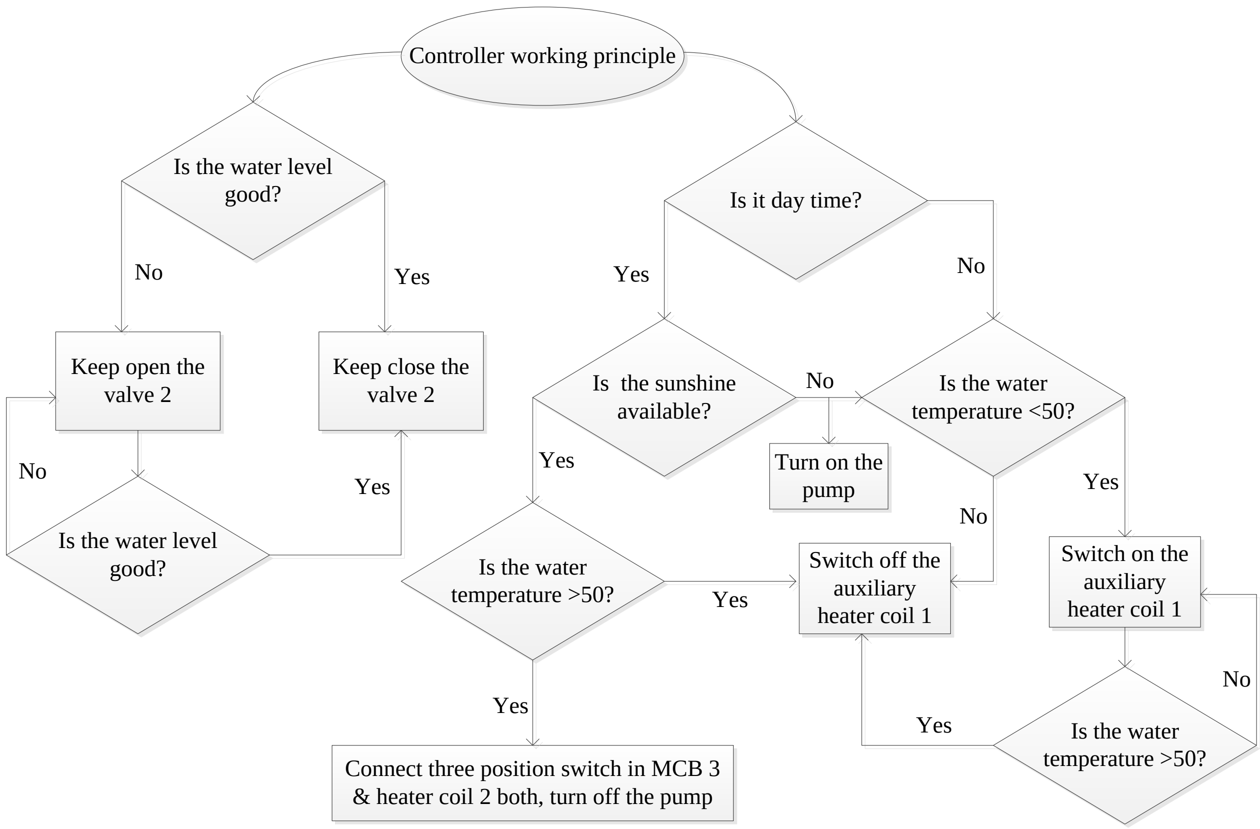

Fig. 9. The operating principle of the controller

E. Simulation Result

The total solar PV based space and water heating system is described in Fig. 8. This complete system has been designed and simulated in the PolySun software environment. The total output of all PV modules shown in Fig. 11 and the house consumption is shown in Fig. 12.

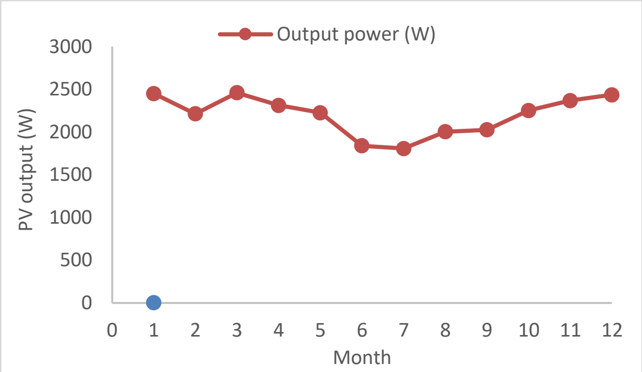

Fig. 11. The output power of designed PV panel

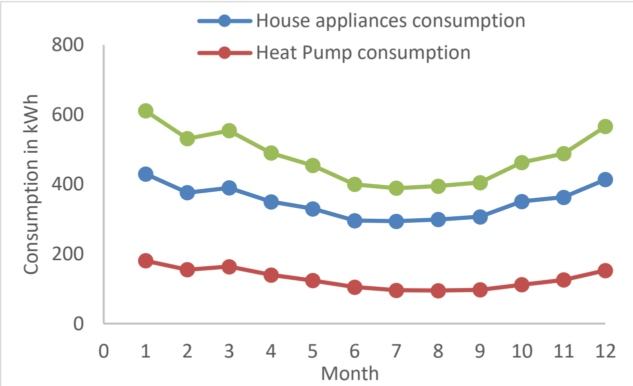

Fig. 12. Selected house electrical consumption

It is investigated that it varies month to month but not more than 600 kWh per month that will mitigate from the batteries when sunshine is not available.

VI. Overall Comparison of Both Systems

Comparing the design, sizing, cost analysis, output power, rate of return of both systems, and the final overview has been summarized in Table III.

Every year, the depreciation cost has been considered as 5% of the investment and calculated the total annual savings up to 30 years, as shown in Fig. 13 where the annual savings comparison for both systems is shown for 30 years.

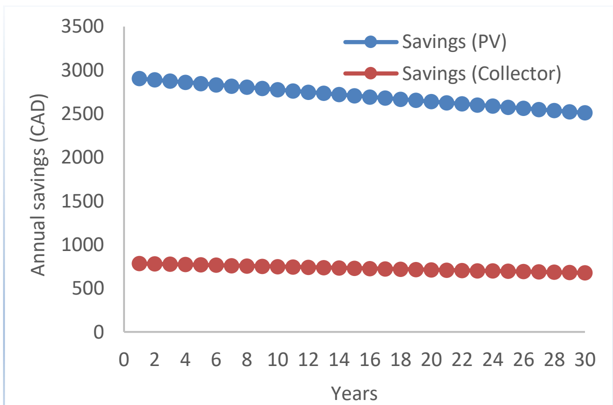

Fig. 13. The annual savings comparison

The PV based system is much cheaper than solar thermal collectors-based systems. The PV based system needs lower maintenance and longer lifetime as well.

VII. Conclusion

By implementing, the solar collector based thermal energy storage system, it is possible to save 50% of electricity and by solar photovoltaic based system, it is possible to save 100% of electricity for residential purposes. From the above design and calculations, it is concluded that the setup cost of a solar collector-based system is higher compared to the PV based system, but the output power is much lower in solar collector-based system. This system is also suitable for other house appliances as well. In the selected house rooftop, space is two times space available compared to the required space, or usually, all Canadian single-family residential houses have this space. Finally, in overall justification, the solar PV based system is a more suitable, cost-effective, and reliable solution for house appliances, water heating, and space heating purposes. This system can be further designed and simulated with solar combi system with another type of control system.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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