Design, Analysis and Control of Solar Heating System with Seasonal Thermal Energy Storage

by

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Abstract

The majority of the electricity consumption in Canadian single-family house is for space heating and water heating. Currently, around 99% house in Canada using the conventional grid electricity for those purposes. To utilize the sun's free energy for space heating and domestic water heating, first a sessional solar thermal energy storage system (SSTES) has been designed and investigated to determine their thermal and electrical performance of a house consists of four persons in the Canadian climate environment. The detailed mathematical formulation and sizing of each SSTES system component have been developed. Similarly, the components mathematical modelling, sizing of solar collector-based TES system, a hybrid solar Photovoltaic thermal (PV/T) based TES system, a Photovoltaic based TES system has been designed. To validate the feasibility and numerical studies of the developed STES configurations, all configurations have been simulated in a professional thermal simulation software named as PolySun, and only solar collector-based TES system has been designed and simulated at MATLAB/Simulink environment packages. The proposed TES system performance have been compared with the existing conventional system. All configurations have been tested using the solar radiation and other weather data of St. John's city/NL city in Canada. The main objective to design a suitable TES system for space heating and water heating so that the residence can save high monthly electricity bill. For experimental validation, an open source IoT platform named openHAB smart home automation is used as a home server, an ESP32 Thing microcontroller board has been used as Microcontroller unit where all sensors and output devices (relays, thermostat settings channels) are connected for data acquisition and control. The proposed setup is able to monitor the TES system parameters, and able to control locally/remotely and manually/automatically. The proposed system is the low cost, low power consumption prototype which will be a commercial solution of TES system monitoring and remote control.

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List of Abbreviations and symbols

TES	Thermal Energy Storage System
STES	Solar Thermal Energy Storage System
SSTES	Seasonal Solar Thermal Energy Storage System
A.H	Auxiliary Heater
NRCan	Natural Resource Canada
DHW	Domestic Hot Water
GHG	Greenhouse Gas
PV	Photovoltaic
PV/T	Photovoltaic Thermal
ASHP	Air Source Heat Pumps
GSHP	Ground Source Heat Pump
HE	Heat Exchanger
SCADA	Supervisory Control and Data Acquisition
IoT	Internet of Things
MTU	Master Terminal Unit
API	Application Programming Interface
GUI	Graphical User Interface
ADC	Analog-to-Digital Converter
I/O	Input/Output
MQTT	Message Queuing Telemetry Transport
HOMER	Hybrid Optimization of Multiple Energy Resources
BEOpt	Building Energy Optimization

Chapter 1

Introduction and Literature Review

Introduction

1.1. Energy Availability and Consumption

Among all electricity consumption in Canada, residential consumption is around 12%. On average, all typical Canadian single-family houses with four persons are using, on average, 60% of grid electricity for space heating and, on average, 20% for domestic hot water (DHW) supply. The Natural Resource Canada (NRCan) is preparing the energy outlook report every year and is estimating the past and future DHW energy consumption, energy intensity, and greenhouse gas emissions forecast. Based on the several estimation models such as NRCan's residential End-Use Model (REUM) and 2018-2019 survey of household spending (NRCan, 2019), it has been estimated that energy consumption for the space heating to be the largest and the energy consumption for DHW to be the second largest for Canadian households as shown in Fig. 1[1].

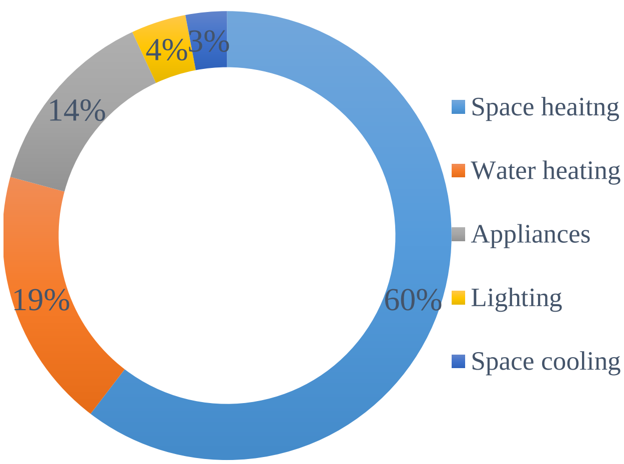

Table:1.1 Space heating by fuel.

Fuel types	DHW	Space heating
Natural gas	68%	50%
Electricity	29%	25%
Heating oil	2%	7%
Wood	1%	17%
Other	2%	1%

Fig. 1.1 Electrical energy consumption pattern.

Currently, a majority of Canada's house are using fossil fuel-based heating systems for mitigating the space and water heating requirements. Canadians` homes consume more energy because of the worst temperatures in the long winter, extensive landscape, and diversified population. The residential consumers are consuming about 16% of the total energy among all sectors in Canada, and the total of greenhouse gas (GHG) emissions of this sector are 15% of all GHGs emitted in Canada (NRCan, 2019). DHW heating alone contributes a considerable amount of roughly 6 million tons of CO_2 to Canada's GHG every year; that's why it is necessary to turn the generation from renewable-based.

Canada has a large landmass and diversified geography and lots of renewable resources that can be used to produce to generate electrical energy to mitigate the partial demand for space heating and water heating. Currently, renewable energy production is around 18.9% of the primary energy supply and around 3~4% of the total generation. The source of renewable energy productions is wind, solar, hydro, geothermal, biofuels, etc. In 2020, solar electricity production is nearly 1% of the total electricity generation and almost 6300 MW. As we all know, solar energy is completely free, convenience, no GHG emission. Energy from the sun can be actively collected for use by two primary methods: solar thermal energy and solar photovoltaic (PV) energy. Solar thermal energy converts energy from the sun into useful heat, while solar PV creates electricity. Solar thermal energy can be used for both heating and cooling purposes. Solar thermal heating is a simple and mature technology that can be used to meet a variety of water and space heating needs for residential, commercial, institutional, and industrial sites. From much researches, it is verified that the solar water heating system can save up to 60% of the energy consumption for a typical home in Canada, although it may vary a little bit, depending on local weather conditions and DHW demand for four members in a family. The space heating demand can also be mitigated by storing solar energy through the solar collector based thermal energy storage systems (TES). But, this energy is not constant and intermittent always naturally, so this energy can be stored for a continuous supply. Solar thermal energy storage (STES) system is becoming very popular nowadays all over the world, especially the cold climate countries because of environmental concern with the fossil fuel-based water system. The STES are very useful to store thermal energy in various mediums such as water, latent heat, sensible heat, phase change materials, chemical processes, magnetic and mechanical processes, thermochemical, etc. Among all of them, the thermochemical process is highly efficient but costly, and the solar thermal heating is the most cost-effective solution for the energy savings on house heating and for the on-site renewable energy generation. People can easily use solar energy for a variety of heating applications like water heating for DHW supply and space heating purposes, air heating, and pool heating, industrial heating, and so on.

All over the world, including Canada, the goal is to prompt renewable energy generation by working jointly with the related industry, university to find the economically viable solution that will contribute to reducing GHG emissions. Canada plans to reduce its GHG emissions by 30% below 2005 levels by 2030[2]. After all, this branch of research can play a significant role in fulfilling this vision.

1.2 Solar Resources Analysis

The Canadian solar industry association (CanSIA) set some goals in their vision statement that it is hoping that by the end of 2025, the solar industry would be widely developed throughout Canada, will achieve the market competitiveness compared to the other countries that will remove the need for government incentives. It can also reduce 15-31 million tons of GHG gas emissions per year that will be able to provide safer, cleaner solutions of power generation from renewable resources. An EPIA's report (European Photovoltaic energy report) [3] mentioned that in 2019, total PV installation around the world is around 113 GW, the growth rate is above 15%, and the total power generation is about 650 GW which is approximately 4% of total electricity generation. China is still in the top position. Based on the Canadian solar irradiation projection[4], among all of them, the Saskatchewan province is the best (higher irradiation, e.g., 1330 kWh/kW/yr) and Yukon Territory is the worst (lower irradiation, e.g., 965 kWh/kW/yr) province. Surprisingly, many areas of Canada have the same solar potential as like as Beijing (China) and Berlin (Germany). However, the total installed PV is much lower in 2019 compared to those cities with less than 3.05 GW. It is rerating to say that one of the Atlantic cities in Canada named St. John's, the capital of Newfoundland and Labrador province, has more potential than Berlin, London, and Tokyo. However, solar recourses are lower here compare to the other province in Canada[5].

The total solar power generation in Canada is around 6300 MW that is equivalent to 1% of all electricity generation. Although solar resources are available in Newfoundland province, the total solar generation is not that much because of the availability of hydro and wind generation, but it is increasing continuously. The solar energy map is shown in Fig. 1.2[6].

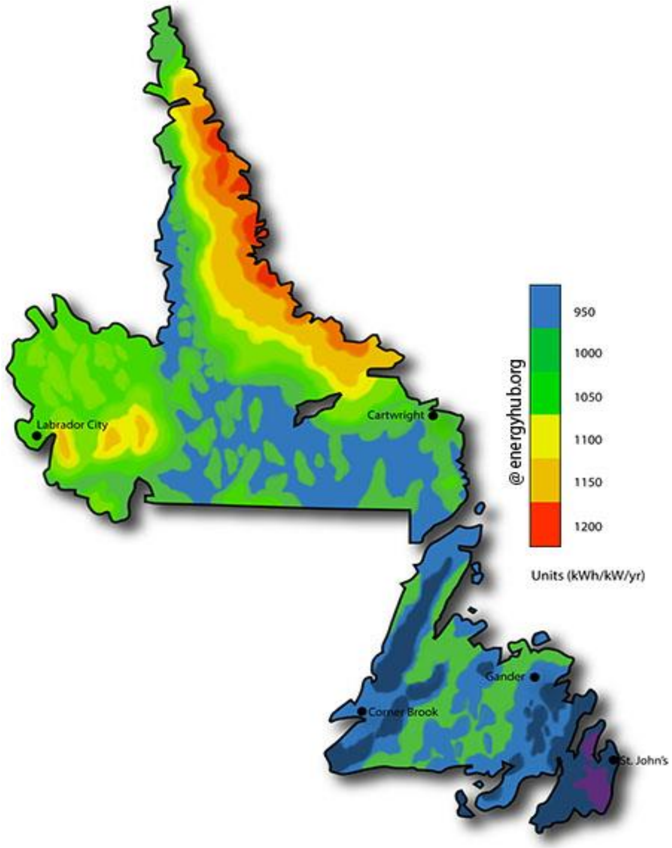

Fig.1.2 Solar potential in Newfoundland Province

The average annual solar irradiance in Newfoundland province is around 1000 kWh/kW/yr, and about 94.3% of power generation is from renewable energy, especially from the hydro, which is approximately 6,848 MW. Newfoundland and Labrador's GHG generation intensity is much lower than most of Canada, emitting 32 grams of GHGs per kWh compared to the Canadian mean of 140 g GHG/kWh. In 2019, the Newfoundland and Labrador (NL) was the tenth best province based on solar irradiation.

The average per capita electricity consumption in Newfoundland province was 1294 kWh in 2019, which was the fourth-highest consumption rate in Canada (NEB, 2018c), as I mentioned before that the residential sector is consuming around 16% of total electricity consumption (NEB 2018c)[7]. Based on the solar resource potential, the NL province received an F rating that means a 5 kW photovoltaic system able to produce around 4,713 kWh per year, and the generation could be increased if there will be no fog and cloud on the sky (Solar Panel Power Canada, 2018). However, similar to the other province, the NL province has a net metering policy so that people can sell excess energy to the grid and can take energy from the grid when they need it. This net metering system will be very useful in installing solar photovoltaic panels for water heating purposes as well.

The PV systems installation cost depends on various factors, as follows:

- ✓ The system's size (the small system is expensive on a per Watt basis)
- ✓ The job complexity
- ✓ The equipment's type and quality (recommended to use the energy star equipment)
- ✓ The contracting company quality,

1.3 Solar Thermal Collector

Solar collectors are being used for many years, and its demand is increasing tremendously for the purpose of domestic water heating (DWH). It can convert sun energy to heat energy, which can be used in a variety of applications such as water heating, space heating, pool heating, and industrial processes. As I discussed in section 1.2 that Canada has abundant solar resources comparable to other countries so that this sector may be the global leader. Aside from cost and greenhouse gas emissions savings, solar collectors are known for their relative simplicity and durability. Usually, two types of collectors are used for producing hot water: flat plate and evacuated tube collectors. Although in this research, the flat plate collector has been taken into consideration. The basic structure part is a flat plat collector is shown in Fig. 1.3[8].

Fig. 1.3 Flat plat collector (water-based) [8]

There are so many advantages with flat plate collectors, such as no required tracking system, low-maintenance, cheap, available, and simple. The solar radiation directly enters through the transparent cover in the top layer and then reaches the absorber sheet. The fluid is flowing through the pipes in between the water tank and the collector absorber sheet, and in this way, the sun energy is converter into the heat energy. This working fluid can protect the collector from overheating damage. There are two types of losses is considered one is thermal, and another one is optical. Although the optical losses are constant, the thermal losses are proportional to temperature. Similarly, the freezing climate has an adverse effect on collector efficiency.

From 2000 to 2007, the solar collector market growth was 16%, which was equivalent to 247 MW. Later on, from 2008 to 2012, the average annual market sell is growing annually by an estimated 40-50% by the collector area. The highest sell happened in 2010, which is around 1,000,000 m^2 and 1,138,800 m^2 by the end of 2011, which is equivalent to 1 GW (1,000 MW). Similarly, the sale was also increasing from 2013 to 2014 period around 9%, but the industries experienced around 37% sales decrease in 2017 compared to 2016 [9].

1.4 Domestic Water Heating

As mentioned earlier, DWH accounts for approximately 12% of total house consumption in Canada as shown in Fig. 1.4. Over a couple of years, people are changing their water heating systems from oil-fired to natural gas or electrical because of its high efficiency and less carbon emission. Besides, current minimum energy performance standards mean that new water heaters use less energy than older models, especially the energy start water heating systems can save a family of four over $3400 in electricity costs over the lifetime of the water heater[10].

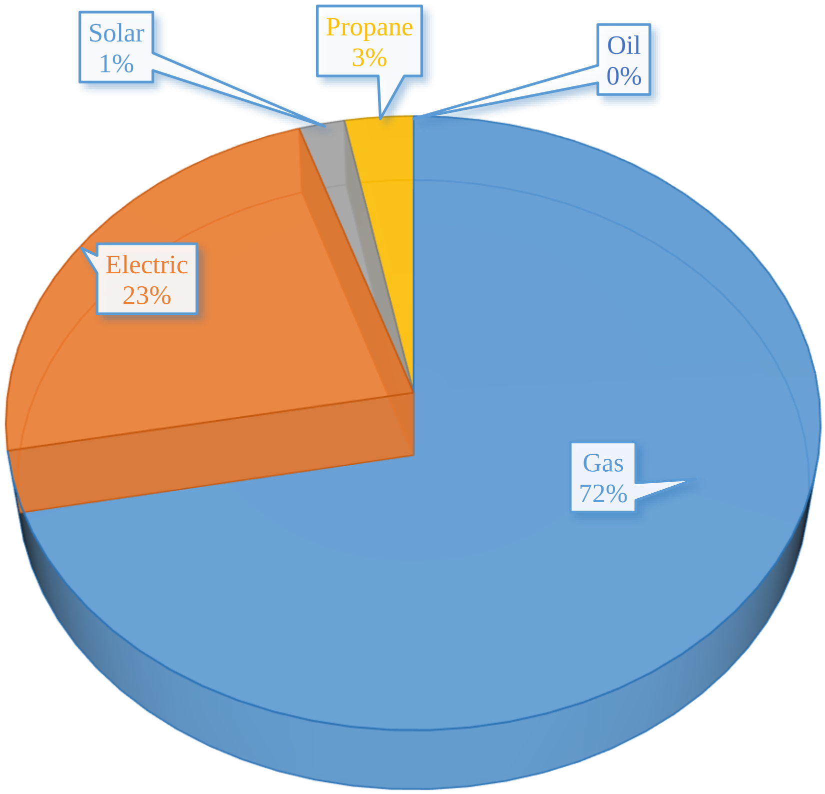

Fig. 1.4 The domestic water heating by fuel type.

Based on NRCan report[1], Over the 1990-2017 period, people are saving around 45% of energy in the residential sector, which is equivalent to 639 PJ of energy and approximately $15 billion costs in 2017. Still, the energy intensity is decreased by 24% per house, and the energy use is also decreased by 35% per square meter. The energy source selection firstly depends on the availability of the energy source and the related costs, usage, and maintenance, such as in Newfoundland province; there is no natural gas. That's why people are using the only electric water heater. From table 1.2, it's clear that the consumption for DHW is reduced in 2017 compared to 1990.

Table 1.2: Water heating consumption scenario by energy source[1].

Particulars/fuel types	1990	1995	2000	2005	2010	2015	2016	2017
Total Water Heating Energy Use (PJ)	3.1	3.1	3.1	2.9	3.1	2.9	3.1	2.8
Energy Use by Energy Source (PJ)								
Electricity	2.0	2.1	2.2	2.2	2.3	2.4	2.5	2.4
Natural Gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heating Oil	1.0	0.8	0.7	0.6	0.8	0.4	0.5	0.4
Other[2]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Wood	0.1	0.1	0.2	0.1	0.1	0.0	0.0	0.0
Shares (%)								
Electricity	65.0	68.1	70.4	76.2	73.5	84.2	81.9	84.3
Natural Gas	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Heating Oil	31.6	27.4	23.1	19.2	24.3	15.0	17.2	15.2
Other[2]	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
Wood	3.3	4.5	6.5	4.6	2.2	0.8	0.9	0.6
Activity								
Total Households (thousands)	173.9	183.7	190.5	199.5	209.2	218.0	219.0	222.0
Energy Intensity (GJ/household)	17.7	16.8	16.3	14.8	15.0	13.2	14.1	12.8

1.5 Domestic Water Heater Types

Domestic water heaters are available in five distinct types. These types are:

1.5.1 Conventional Storage Tanks

Conventional storage tanks are the most common type used in Canada. There are many heating sources for these heaters, such as electricity, natural gas, or heating oil, but in Newfoundland province, mostly, it is electric because there is no natural gas. These systems heat and store water in a well-insulated tank generally placed in the basement of a house, and water enters and leaves the tank simultaneously. The heater is directly connected to the electric grid. Whatever the hot water demand is does not matter, it is necessary to maintain the constant temperature; that's why the auxiliary heater is essential, although it has some standby heat losses. These losses are even higher for residences with low hot water use patterns compared to the large industrial consumer. The more recent energy star models have a much better efficiency compared to the conventional models and can perform as much as 40% better performance (NRCan, 2019). There are several ways we can improve the performance of the storage tanks such as to having better tank insulation for better heat retention and less standby heat loss or to having a better heat exchanger or to the use of efficient solar thermal collector or to the use of dynamic control for optimal operation, which enhances the heat transferred to the water. This type of heating system is very convenient and easy to install and can be located in various areas of the household, and there is no need for venting with various tank volume. People can get hot water within the short waiting time. But the main drawbacks of electric fueled storage tanks usually have one of the highest annual operating costs.

Fig. 1.5 The conventional electric water heating tank[11]

But in other areas in Canada, they used many types of fuels for water heating, as mentioned in table 1.1. Among all of them, the natural gas water heaters can quickly produce hot water and should be vented through a chimney or wall compared to the other fuel. But the limitation of this type if, other than having access to natural gas, the location of such heaters in a house may be restricted by access to the gas line or chimney. Heating oil water heaters are the fastest in producing hot water, which allows the option for smaller tanks, and people typically use it in small families. But the limitation of this type of heater is that the carbon emission is more. There is a range of low to high-efficiency storage tanks available in the market with various sizes and costs that include such brands as Rheem, John Wood, General Electric, Kenmore, Bradford White, and AO Smith.

1.5.2 Tankless Water Heaters

The other name of the tankless water heating system is called as on-demand or instantaneous water heaters, as shown in Fig. 1.6, so there is no storage tank. The water is heated only when it is needed, and thus, there are no standby heat losses (NRCan, 2019). These heaters usually have a gas burner or an electric element surrounded by flowing water. When the customer turns on the hot water tap, the switch is close, and the burner or element ignites. This heater can be installed at any location in the house, preferable is in the endpoint of use.

Fig. 1.6 The structure of the tankless water heater[12].

When the hot water tap is turned on, water moved through the pipe directly into the unit where it is heated by either gas burner or electrical heating element. As there is no concrete storage tank, the flow rate is not that much, although the consumer always gets the hot water instantaneously. The main advantages of this type of water heaters are plentiful continuous heated hot water. But there are some limitations as well, and the main restriction is about 7 to 15 liters of hot water per minute. That's why proper sizing is essential; otherwise, the customer may face a hot water shortage. Regularly the single-family small house with 1/2 persons where the hot water uses less than 41 gallons of hot water daily that could be 24% to 34% more energy-efficient compared to the storage style. A single-family residential typical house with four people could save up to $100 a year if they installed the energy star equipment. Still, they may face the shortage of water flow rate as the savings are not significant, so it is only suggested for the family with one or two persons but not recommended for the typical or big family.

1.5.3 Integrated Water Heaters

Integrated water heating systems consist of a tank and tankless systems, thus saving installation cost compared to the storage tank-based systems. This type of heaters can be divided into two separate classes: 1- Tankless coil water heaters and 2- Indirect water heaters.

Firstly, a copper coil or heat exchanger installed inside of a central furnace or boiler which heat the continuous flow water instantly[13]. The performance of this type of heating system is very efficient in the wintertime but less useful in the summer time because it is temperature-dependent.

Secondly, it offers a more energy-efficient choice for households with and without a storage tank. There are so many options for complicated systems such as it can be run by gas, oil, electricity, solar energy, or a combination of these. Sometimes it is the more efficient option compared to the tankless options because it turns on/off the water tank less often.

1.5.4 Heat Pump Water Heaters

Heat pumps exchange energy in between two different heat sources, such as low-temperature heat source to a high-temperature heat sink. Mostly two kinds of heat pumps are using practically, 1) Air source heat pumps (ASHP) and the Ground source heat pump (GSHP). The ASHP takes the ambient temperature as input and produces more heat air in the output, which will flow further through the water tank, and the water will be warm-up. These water heaters are widely used for water heating, including Canada. Its performance is affected by the temperature, and the best performance is in the warm temperature. Most of these heaters have back-up heating elements to heat water during cold periods.

Similarly, GSHP draws heat from the ground through the buried loops close to the household for space heating during winter months and from the indoor air during the summer for space cooling. A desuperheater needs to be added to the GSHP system if the system is to be used for water heating purposes. According to the manufacturer recommendations, heat pump water heaters require a specific range of temperatures for better performance, which is 4.4ºC to 32.2ºC and requires 28.3 cubic meters of air space. Similarly, the GSHP is not suitable where the ground and ambient temperature difference is not at least $\pm 5\%$. If this temperature difference is more than that, the performance will be better.

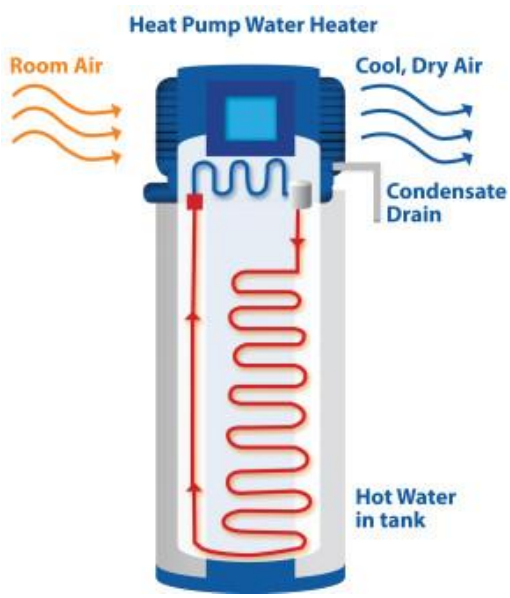

Fig. 1.7 Heat pump water heater[14]

1.5.5 Solar Water Heaters

The simple solar water heating systems are shown in Fig. 1.8, use the sun's energy for water and space heating. The main components in these systems are a solar collector, a water storage tank of solar heat, circulating pumps, a heat exchanger (in most systems), pipes containing water or other fluids, a control system for safety and optimum operation, water supply, and an auxiliary (back-up) heating system. There are so many configurations that are available in the literature, but among them generally, four system layouts are used conventionally such as

- ✓ Passive or active.
- ✓ Direct or indirect.
- ✓ Filled or drain back;
- ✓ External or internal solar storage tank.

Active systems use pumps to circulate the fluid within the solar loop, which, in return, allows more choices on component locations and enables better solar heat management. Passive systems, on the other hand, use no pumps, no controllers, and no circulation of heat, as shown in Fig. 1.9. Direct systems use the water entering the building as the heat transfer fluid. Reversely, indirect methods use heat exchangers, and heat exchangers use separate fluid for the heat transfer. Infilled systems, the collector, is fully furnished with the liquid, and all air is removed from the collector and pipes, as shown in Fig. 1.9. Conversely, in drain back systems, the working fluid is removed from the collector when the pump is switched off, and some air is always retained. In this system, the collector should be higher than the pipes and tank(s).

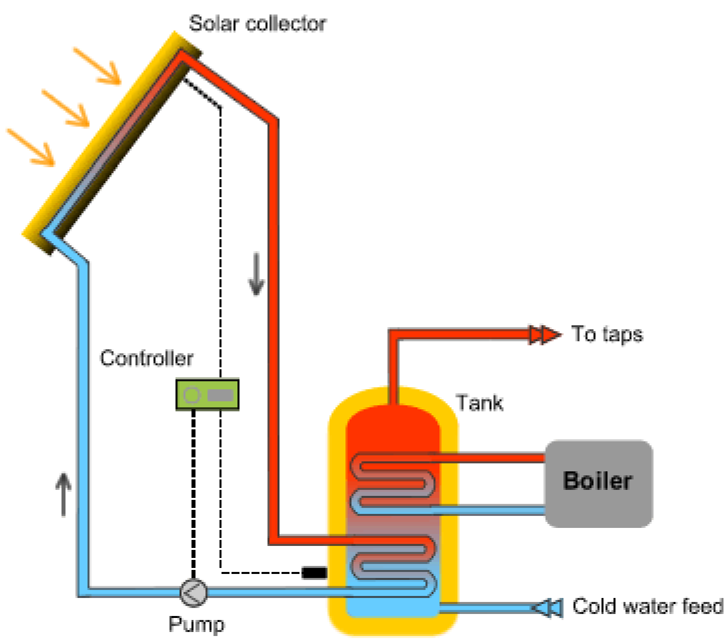

Fig. 1.8 The solar domestic hot water system[15]

1.6 Efficiency of Domestic Water Heaters

The energy factor (EF) is an indication of the overall efficiency of a domestic hot water (DHW) unit. It represents the ratio of the energy output to the energy consumption of a water heater. The sizing of the water heater can be calculated using the EF, which can be described as follows:

$$\mathrm{EF} = \sum_{i=1}^{6} \frac{M_i C_{pi}(T_{out} - T_{in})}{Q_{dm}} \tag{1.1}$$

where Q_{dm} is the modified daily water heating energy consumption (Btu), M_i is the mass withdrawn from the i^{th} draw (lb), and C_{pi} is the specific heat of the water of the i^{th} draw Btu/lb°F.

EF also takes into account the heater standby losses and the stored water heat loss per hour. The heater efficiency is proportional to the EF ratings, but the operating cost is conversely related to the EF.

A thermal collector has two types of efficiency, one is electrical, and another one is thermal. The electrical efficiency is to measure the heater useful energy gain, Q_u. The useful heat gain Q_u is given as

$$Q_u = A_c F_R[I_t(\tau_o \alpha_o) - U_L(T_t - T_a)] \tag{1.2}$$

Where,

U_L is the overall heat transfer coefficient

F_R is the heat removal factor

T_t is the collector plate temperature

T_a is the ambient temperature

The thermal efficiency of a collector is the ratio of the useful heat gain to the total input energy, which can be described as follows:

$$\eta = F_R\left[(\tau_o \alpha_o) - \frac{U_L(T_t - T_a)}{I_\tau}\right] \tag{1.3}$$

The angle of the incident is considered as 90^o.

1.7 Thermal Energy Storage System

The thermal energy storage (TES) system is mainly used for space heating and domestic hot water supply. The primary function of the storage system is that it receives energy during the sunny day and supply heat during the nighttime or off-peak period or when solar is not available. Solar and wind energy is not constant; it is always intermittent. The author in [16] mentioned that the solar energy is converted into thermal energy by solar water heating (SWH) systems. The primary application of solar energy is in TES in a cold climate zone. The passive system (uncontrolled type) was used previously. Still, nowadays, the active integrated system (controlled type) is applying to a large extent because a dynamic system reduces the energy mismatch between supply and demand through the controller, as shown in Fig. 1.9.

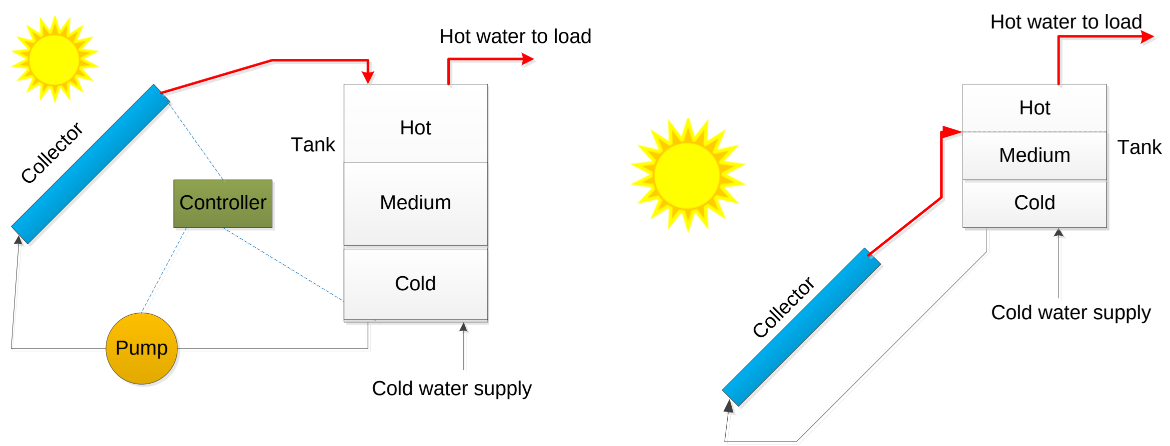

Fig. 1.9 Basic structure of active and passive solar thermal system[17].

1.7.1 Description of Different Other Components

1. Pressure Gauge: The function of pressure gauge is that it uses the semiconductor device, which can generate electrical signals due to exertion of pressure. The various ranges of pressure gauges available in the market in the field of 101.3 to 650 kph, which is used to measure the working fluid pressure.

2. Water flow meter: The current water flows exist in a variety of sections in TES systems, and it can measure the current water flow rate. It is one kind of programmable meter with a range of 0.5 to 25 LPM, and the temperature limit is up to 800 C.

5. Circulating pump: Circulating pump is necessary to continue the flow from the collector, tank, and the user end although the passive system does not have. To maintain the continuous flow and optimum operation, the controller can drive the pump.

6. Anemometer: An anemometer can be used to measure the ambient air velocity and the temperature in the range of 0.4 to 45.0 m/s and -10 to 600 ^{o}C, respectively. It is the replacement of the airflow sensor that was used before.

7. Fan: Sometimes, in large systems, a fan may be used to generate artificial airflow to reduce the unexpected heat and damage. A temperature sensor may send a signal to the controller to turn on/off this fan to avoid the unnecessary moving.

8. Valve: This part is essential in TES systems to control the water flow in the various branches. Based on the demand requirement, it will control the water flow.

9. Preheat tank: It is also one type of temporary storage tank. The radiation is very always, and sometimes the collector output temperature is not very high compared to the primary storage tank. Due to the high temperature in the main storage tank, a preheating tank is used in any configuration to transfer the collector out heat to the preheat tank, and then water will warm a little bit, then this preheated fluid will flow to the main storage tank.

10. Main storage tank – This is the main storage tank in TES systems with various ranges, such as 500 L to 10000 L or more. The hot water from the collector will store in this tank and will move forward to the kitchen tab, bathroom tab, or the radiator for space heating. It is necessary to maintain the constant temperature here, but the solar radiation and the collector output is intermittent, that's why an auxiliary heater/burner is needed. There are several configurations of these tanks available that are discussed in section 1.5.

11. External Heat Exchanger: The working fluid in the collector and the storage tank may not always be the same fluid. That's why this element is an essential element in TES systems as well. It is capable of transferring heat from the two different mediums, such as from the collector to the storage tank.

12. Main Controller –The responsibility of the main controller is great. It has some sots of sensors, and they will monitor the status of each and every part. Based on the sensor result, it takes decisions

based on the program. The controller is used to control all circulating pumps, valves, auxiliary heater switch, and so on.

1.7.2 General Assumptions

There are several analyses has been done in this research such as solar photovoltaic based water heating systems, a solar collector based water and space heating systems, Seasonal storage systems design and remote control with four or five different software's. To perform these experiments, there are a variety of assumptions that have been taken into consideration, although these assumptions are not against the basic operating principles for more straight forward analysis and to simplify the systems.

a) The flat plate collectors have been considered, and those are in a steady-state condition.
b) Uniform flow is considered to the riser tubes.
c) Temperature gradients and heat losses around the tubes are neglected.
d) All component's material properties are considered as temperature independent.
e) The absorbed energy, dust and shading effects, opaque to infrared radiation, and temperature drop in the glass cover in the collector are neglected.

1.8 Energy Consumption Pattern in a Single-Family House

The single-family detached house is generally made for living one or two families. It has four directional exposed walls. It may be one story or two stories with the roof. For energy saving purposes due to space heating, the half portion of the ground floor is designed for the underground. It usually has five or more numbers of rooms, two bathrooms, almost ten numbers of completely transparent windows, seven numbers of doors on each floor. A single thermostat is enough in the cooling system for a single story, but for the two-story separate thermostat is needed for each floor. The rooms have a centralized air return system where the air and load are mixed. As the air supplied to every room based on their load, so the load calculation should be more accurate.

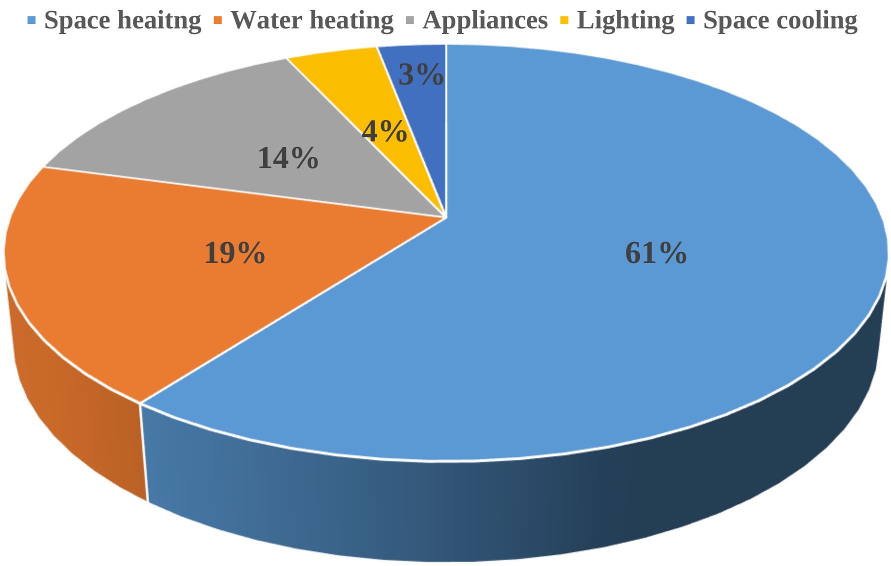

Fig. 1.10 A typical single-family house energy consumption pattern[1]

It is found that the highest energy consumption is in space heating and domestic water heating. The other energy is used to run household appliances such as stoves, refrigerators, air conditioners, televisions, computers, and other electronic devices. Conventionally, this energy comes from electricity, natural gas, oil, propane, and wood, etc. The energy consumption depends on many factors, such as climate change, fuel prices, household size, and a number of devices, dwelling size, and many more. So, great care may be taken to improve the heating system design, especially.

In Canada, the residential electric bill is enormous due to space heating and water heating. In Newfoundland and Labrador, space heating is by far most significant compared to any other energy use in homes, accounting from about two-thirds of all the energy consumption. The overall energy consumption pattern is shown below (NRCan, 2019):

Table: 1.3 Energy consumption patterns

Sectors	Ratios
Transportation	49%
Industrial	22%
Residential	17%
Commercial and Institutional	10%

Sectors	Ratios
Space Heating	67%
Appliances	15%
Water Heating	15%
Lighting	3%

The winter electricity consumption is much higher than the summer energy consumption because of the extreme lower temperature (most of the time it is negative) and the other reason as described as follows[18]:

- The house wall thermal insulation is poor.
- There may be too many large windows, which is also not installed properly.
- The house orientation may not follow the sun's path, such as south-facing is the perfect orientation.
- The lower quality technologies may use.
- The high velocity of wind in the long winter.

1.9 Energy Saving Concepts of a Single House

Due to the horrible weather in the long wintertime, the consumption is very high, around 4000 kW/year. All houses are designed based on well insulated and fully wired with computerized monitoring equipment. A control system may be developed that will turn on and off the appliances, lighting, and equipment's as people are doing. Sometimes people may forget to switch off the appliances than the controller will automatically turn off the appliances. This system is called "simulated occupancy." This energy will be saved from unnecessary consumption. Energy efficient home: There are several factors that will define the home energy-efficient design such as (i) airtight construction, (ii) air-sealing (example around windows, doors, electrical outlets, vents), (iii) High performing or energy star equipment (example furnace, AC, water heater), (iv) high performing or energy star windows (example transparent windows) (v) LED or energy star lighting, (vi) energy star home appliances (example refrigerator, clothes washer, electric stove) (vii) well insulation (example walls, attic, basement shade). A programmable thermostat may be used to manage the inside heating and cooling, and based on the thermostat values, the controller will control the circulating pump and whole system. With all of these, if highly efficient heating and cooling equipment have installed at the house, then the electric bill will be lower. All energy-efficient equipment at home reduces energy consumption, the electric bill, and GHG emissions. The exhaust fan may be installed, which has an ENERGY STAR certificate at the bathroom, kitchen and vent them outdoors. A sensor with timers may be connected with a fan to reduce the unexpectedly long time running and power consumption. Energy-saving leakage-free toilets, faucet aerators, and showerheads may be installed. In all pugs, the timer may be introduced so that when a device is not in use, then it will be switched off, and then the devices will not consume standby power. The first two meters of pipes may be covered with foam sleeves or insulating wrap to reduce the water heating energy because in a house frequently, it turns on and turns off. In a proper design, the one area factor affects the others. For instance, if air leaks from the ceiling, then ventilation design will be influenced. If the house is not correctly insulated, then it will not become energy efficient. The energy consumption scenario of a typical single-family detached home is shown in Fig. 1.10.

Literature Review

1.10 Literature Review of TES

There are many ways the energy has been stored previously such as (i) flow batteries, (ii) solid-state batteries (iii) pumped hydro (iv) thermal storage (TES), superconducting magnetic energy storage (v) electromagnetic capacitors (vi) hydrogen (including the power to gas). But, the main focus of this research is in solar thermal energy storage systems (STES).

The main targets of thermal energy storage are to get free energy from renewable energy resources, to increase the system efficiency, to provide energy security. Based on thermodynamics, thermal energy storage can be classified as chemical, latent, and sensible heat storage (SHS). Latent heat TES storage densities are 3 to 15 times greater than sensible storage. Another way, SHS is used widely compared to others because it can be stored/released by increasing/decreasing the storage materials temperature without the use of a phase change or chemical reaction. Perhaps the SHS for hot and cold water storage tanks in all types of buildings [19]. The major components of the underground TES system are solar collector, short-term energy storage, Seasonal BTES, and a district heating system. UTES collects heat and stores energy in the underground in the summertime and returns heat during winter. ATES, BTES, and gravel water TES all are commonly called UTES.

Over the past decades, some TES system has been developed. Ahmed Aisa [20] investigated the performance of the heat pump based TES systems in a swimming pool, proposed a model, and found that up to 80% energy saving is possible and the rate of return is less than five years. Authors in [21] measure the TES system performance in Korea with 1179 households similar to the Drack

Landing project in Canada, he found the payback period was around 12 years. Authors installed large TES systems in British Columbia, Canada, including 260 m^2 collectors for fish farms, and they found the payback period is less than five years[22]. From much research, it is observed that the control and monitoring system may reduce the cost and may increase the overall efficiency of solar domestic water heating systems. Liang et al., [23] proposed the tracking systems on the TES systems to increase the output up to 30%, but the tracking system may consume extra energy and need some maintenance as well. That's why it may not be suitable for all systems. The authors in [16], investigated the basic concepts, system designs, and the latest developments of TES systems, especially for sensible and latent heat types. The paper [16] presented the dynamic performance of STES systems, balancing of heat generation and domestic water heating and space heating, the characteristics of various TES materials. A techno-economic feasibility study of TES systems has been studied in [24], and it is suggested the details calculation of the investment for residential or commercial heating. A life cycle assessment of a phase change materials (PCM) based TES systems have been conducted in[22]. The energy savings issue for various energy storage systems has also been studied and compared. The mathematical modeling of a molten salt and quartzite rock-based TES system performance has been evaluated in [25]. The heat energy supply and demand mismatch have been studied with the application of the PCM based TES system. Finally, the authors commented that the PCM system is more economical in domestic water heating. For the residential water heating application, the details study has been done in between domestic hot water consumption and STES heat generation capability and finally optimized the storage tank. The authors in [16] studied the sheat loss reduction with a variety of TES systems. In a single-family residential house in Virginia, USA, one underground Seasonal STES has been designed and simulated using TRNSIS software. They installed 15 m^3 bed volume, south-facing roof, 11.356 pm water flowrate, and found the system overall efficiency in the range from 50% to 70%[26]. A solar assistant heat pump based PCM TES system has been designed and simulated in [27] where authors considered 30 m^2 solar collector area, 75 m^2 floor area with 1500 kG PCM and found 70% system efficiency. Ahmed Aisa and Tariq Iqbal [20], designed a Seasonal STES systems for a residential house in Matlab/Simulink environment and found that the house total demand is 12,268 kWh/yr, whereas the designed system is capable of supplying total 19,537 kWh/yr.

Besides the single-family residential house, there is another research studied in an urban large residential building with Seasonal STES systems, and the designed model is capable of supplying at least 91% of heat supply from solar water heating systems. There are much research is also conducted by using a borehole based STES system, and one of them is in [28] where the heat storage storge heat in the depth of 30-200 m by using soil/rock through the borehole. There is a lot of design available with hybrid photovoltaic thermal (PV/T) system. In [29], the residential house has been considered as a load, designed a PV/T based systems, the authors found that the efficiency is increased by 5.3% and the collector output is suitable for domestic hot water supply.

Authors in [16] think that TES system is commonly four types like water tank TES, aquifer, borehole with the heat exchanger (HE), and water gravel pit storage. Among them, aquifer and borehole types are commonly used because of cost-effectiveness. Some projects have already been implemented in Alberta, Canada (Drake Landing, n.d). The details comparison is given in table 1.1. Guo et al. [30] Investigated some large scale operational TES systems in detail. They also developed some model for BTES such as full-scale model, multi-stage model, numerical network-based model, the two-region analytical model for U-shaped quasi-three-dimensional steady-state heat transfer analytical model. Authors in [16] classified the variation of temperature with different TES system and their suitable applications. They emphasized on solar assistant ground source heat pump (GSHP) system is the combination of solar collectors and GSHP. The determination of the proper sizing of TES is essential for efficient design. Several papers have described it with necessary equations such as in [16].

The TES system needs large and inexpensive storage volumes because of the long time frame. Authors mentioned that the parameters of TES systems are an efficient solar panel, thermal storage temperature, heat pump capacity, solar collector area, storage volume, borehole depth (if BTES type), types of the heat exchanger, heat demand, and life-cycle cost. The cost of TES depends on the application, size, and thermal insulation types, etc. This research has been developing for a long time, so it's time to optimize the system components, to enhance the performance, to reduce the costs, to increase the efficiency[22] [16].

Conventionally for residential single-family house domestic hot water demand consisting of two 4' x 8' (6 m^2) glazed solar collectors, average 150 L/d hot water usage, with a 300 L hot water storage tank.

Some solar collector based power generation plant design, specification, and parameters is shown Fig. 1.11[31].

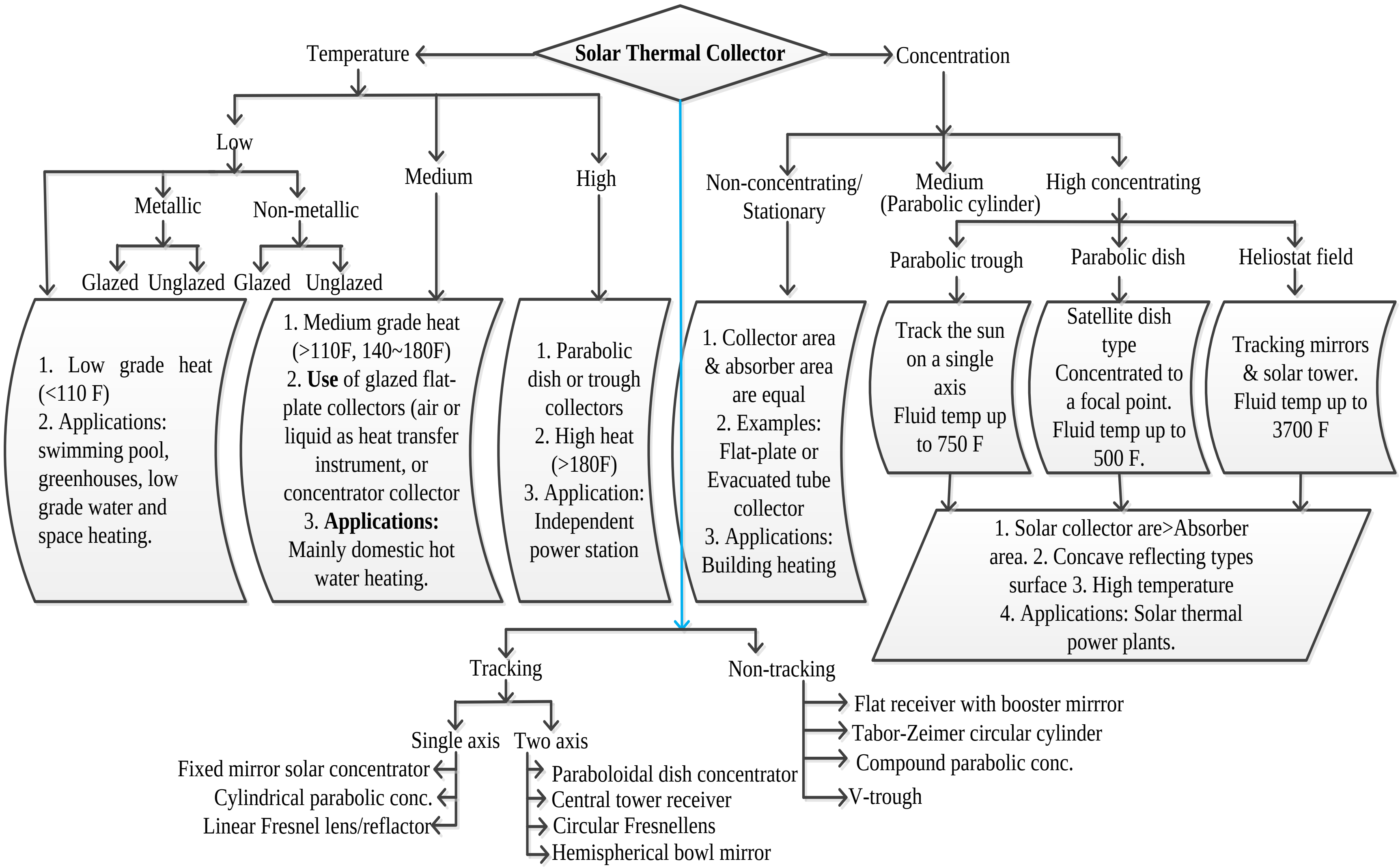

Fig. 1.11 Overview of solar thermal collector

1.11 Classification of Energy Storage

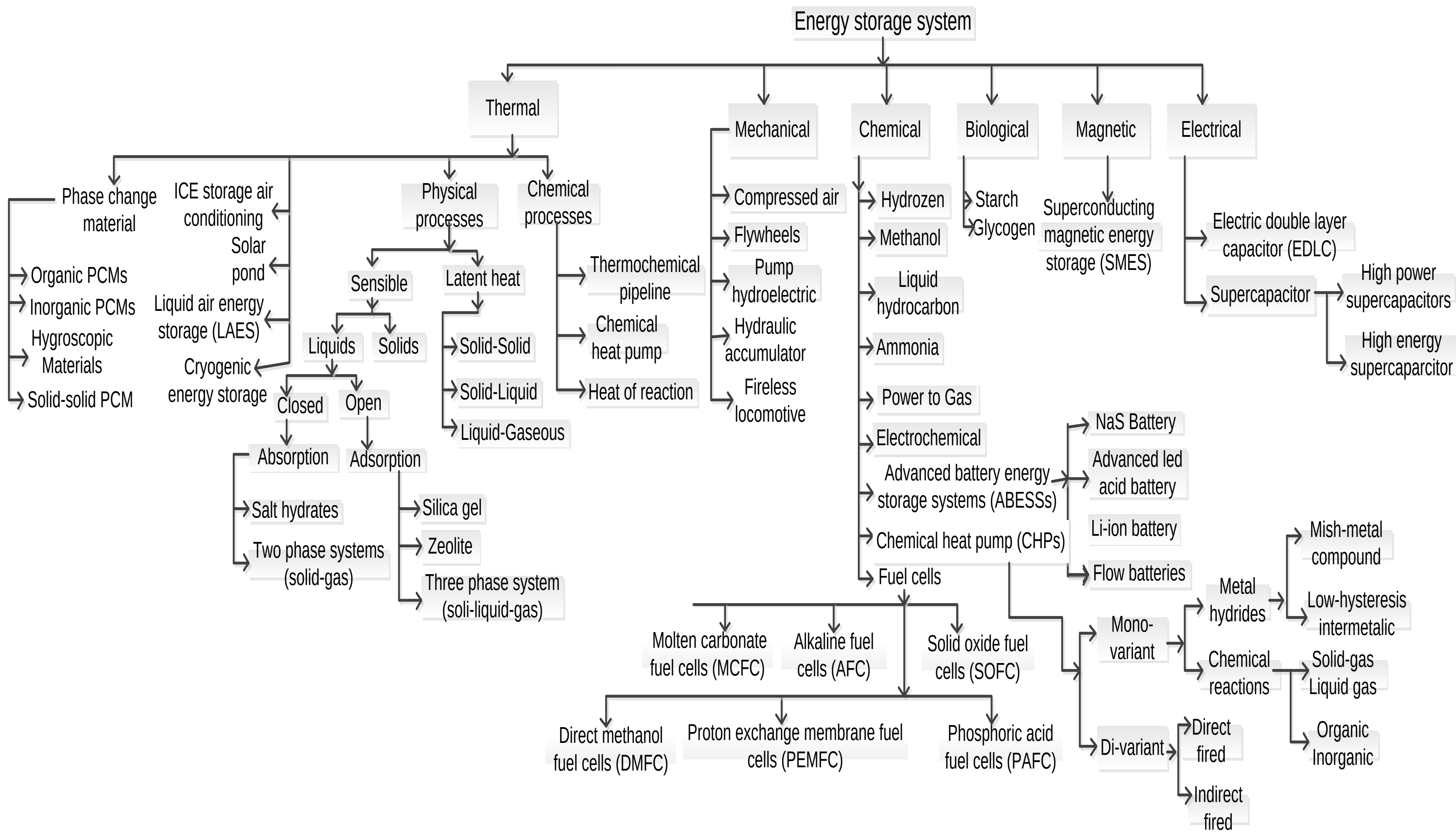

Fig. 1.12 The complete overview of the energy storage system.

Table 1.4: Comparison of different TES systems

Storage issues	Water tank TES	Gravel-water TES	Aquifer TES	Borehole TES (BTES)	Sensible heat storage	Latent heat TES	Thermochemical
Storage medium	Water	Gravel water	Sand/water-gravel	Soil/rock	water, air, soil, rock beds, bricks, concrete or sand	Phase change material (solid, liquid, and gas)	Zeolite and Silica Zel
Efficiency	40~60%	50~60%	50~70%	60~70%	60~90%	70~90%	80~99%
Solar collector capacity	Depends on heat demand	Depends on heat demand	Depends on heat demand	Depends on heat demand	Depends on heat demand	Depends on heat demand	Depends on heat demand
Heat capacity (kWh/m^3)	60-80	30-50	30-40	15-30	10-50	3~32 GJ/m3	~250
Storage volume	7~15 m3 per m2 of collector area	7~15 m3 per m2 of collector area	5~16 m3 per m2 of collector area	4~13 m3 per m2 of collector area	~10 m3	~1500 m3	1~1.5 m3 per m2 of collector area

Geothermal requirement	Stable ground	Stable ground	Natural, high hydraulic conductivity	Durable, high heat/thermal capacity	High heat/thermal capacity	Low heat capacity rocks and ceramics	Low temperature, mid-deep
Energy Input	Auxiliary burner, collector heat.	Parabolic collector heat.	Ground source heat pump, waste heat, CHP.	Solar thermal, ground source heat pump, CHP, gas turbines, waste heat.	Heat energy from the sun storage medium	Heat energy from the sun to PCM	50% sodium hydroxide (NaOH) solution
Advantages	Install any location	More cost-effective than WTES	Low cost and maintenance	High heat capacity/thermal conductivity, Suitable for low ~high applications	Low cost	Rapid charge and discharge. Need fewer numbers of heat pipes.	Low/medium/ high-temperature applications, long-term storage
Limitations	High cost/heat loss/corrosion	High cost, required large size, leakage	High heat loss, required large size, need a specific temperature	Not suitable for all location, high initial cost	Not suitable for very high temperature	Not suitable for very high temperature and large-scale	Storage capacity changing with evaporator and absorber temperature

Applications	Space and domestic heating	Space and domestic for large-scale	Commercial building for heating and cooling, Seasonal type	Heating for the greenhouse, Seasonal type	Where a lot of energy can be stored in a minimal volume	Greenhouse solar cooking building, agricultural greenhouse, cooling helmet	Seasonal house heating, the storage capacity changing with evaporator and absorber temperature
Project Example	Marstal district heating system (Denmark)	Gujarat Solar One (India), Gemasolar Plant (Spain)	Electric Thermal Storage Heaters in Kentucky (United States)	Drake Landing Solar Community, Canada	Solar Reserve's Crescent Dunes project in Nevada	Beijing international financial center (China)	Mono Sorp project, INSA de Lyon

Table: 1.5 The market summary of various solar thermal collector [31]

Solar Thermal Collector Types	Respondent		Total Sales Revenue ($ thousands)		Collector Area (Sq. meter)		Thermal Capacity (MW)		Growth Rate		Residential use		Industrial /Commercial /Institutional use	
	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017	2016	2017
Air Glazed	7%	7%	1117	547	7358	3489	5.2	2.5	-99%	-86%	0%	0%	100%	100%
Air Unglazed	7%	14%	3644	2072	20313	11574	14.2	8.1	-28.00%	-36%	0%	0%	100%	100%
Liquid Evacuated	40%	29%	1352	528	2815	1135	2	0.8	-30%	-52%	40%	98%	60%	2%
Liquid Glazed	20%	29%	917	454	1693	836	1.2	0.6	-51%	-50%	63%	70%	37%	30%
Liquid Unglazed	27%	21%	3537	2648	37466	28049	26.3	19.7	-3%	-25%	96%	99%	4%	1%

The solar thermal power plants are available around the world and the contribution of solar energy is not small. In Table 1.6, the summery of some thermal power plant around the world has been shown as well as their efficiency, pros and cons. In Fig. 1.13, the market overview of solar thermal collector in Canada has been shown from 2001 to 2017 where it seen that the 2010 was the highest sells and revenue earning years.

Table: 1.6: The summery of large solar power generation and their comparison.

Technology	Overview	Optimum capacity	Conversion efficiency	Storage	Pros/Constraints
Parabolic Trough	Long curved mirrors pivot sunlight onto tubes filled with heat transfer medium (water or oil)	150-250 MW	Annual average efficiency is 12-14%	Molten salt based	Storage, well understood technology, needs water for efficient cooling
Fresnel Reflectors	Almost same as the parabolic Trough but uses flat mirror strips instead of curved mirrors	60-125 MW	Less than 12%	Storage can be used to some extend but has not been perfected.	Less efficient than other CSP systems, cheap
Dish Stirling	It uses a parabolic mirror which focuses heat directly on a Stirling engine, which operates using any heat source	Around 25 kW per dish	Annual average is around 22%. The newest system has 31.5%	Does not accommodate thermal storage	High efficiency, no thermal storage
Solar Power Tower	It consists of an array of dual-axis tracking reflectors (heliostat) that can concentrate light on a central receiver top of a tower. The receiver contains a heat transfer medium (sea water)	Around 30 MW	Annual average is around 12%	Molten heat storage system	Cheaper than solar trough. Needs water for efficient cooling.

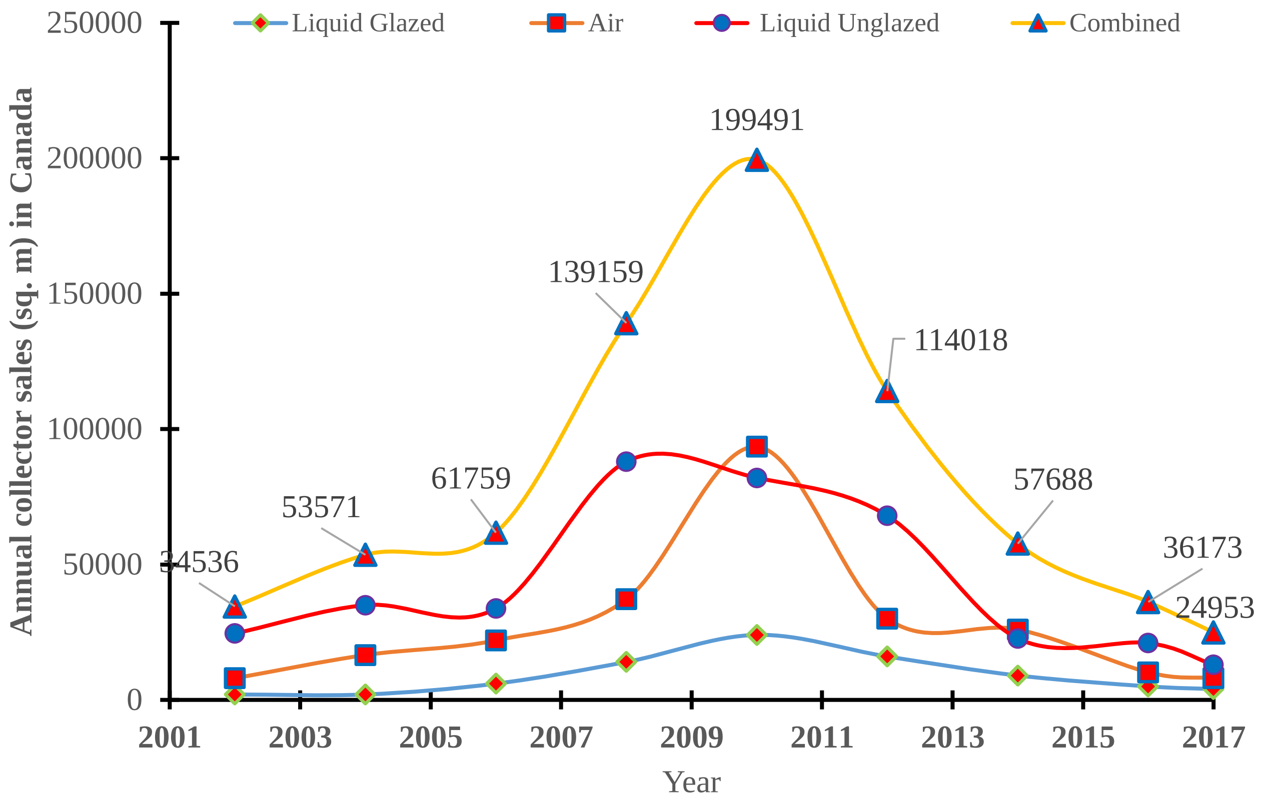

Fig. 1.13 The overview of the solar collector industry in Canada.

1.12 Research Background

The whole worlds, including Canada, are now in great concern to generate more power from renewable resources and to reduce carbon emission. Canadians are paying the highest amount of monthly electricity bills due to water heating and space heating. Several reports such as the conference board of Canada (2013)[32], National Energy Board (2016)[33], Canada's Energy Future (2016) [34] says that the per capita greenhouse emission (GHG) in around 17% from the residential sectors, but they are optimistic about reducing to below 5% by 2030. It is the main challenge to modify the existing systems and to develop renewable energy-based energy storage systems. Another problem is that in some provinces three or four months, there is no sun, so at that time, it will be challenging to get energy from solar resources; that's why Seasonal energy storage systems can solve these issues.

Some Canadian Universities are working to develop some research relating to energy storage in summer and supply the stored energy in the extreme wintertime. Thus, electricity demand will be reduced. For instance, the University of Ontario Institute of Technology developed a low-temperature borehole thermal energy storage system (BTES) system in 1990 which has 384 holes, each 213 meters (700 feet) deep, provide the basis for a highly efficient heating and cooling system for eight University buildings[35].

The Carleton University developed an energy storage system for cooling and heating and operated using a heat pump in the low-temperature range, and it is successfully in operation since 1990. This system was designed[36]. The University of Alberta is successfully built a BTES based energy storage system in 2015, and it is operating correctly still now[37]. One of the examples of the gigantic project in Canada is the Drake Landing Solar Community (DLSC) in 2007, which is supplying 90% of heat demand and 60% hot water demand in total 52 numbers of single house detached families. Eight hundred solar flat plate panels (2.45 m $\times$ 1.18m) are producing 1.5 MW of thermal power and supply heat to the district heating system[38]. The panels are connected with an underground pipe that carries the heated energy to the community's thermal energy storage system. The storage system is BTES types, and it has 144 holes, each stretching depth is 37 meters, 35 meters diameters. In DLSC, every house is a typical Canadian single-family detached house with 1492 to 1664 square feet in size[38]. A gigantic energy-saving building (1,68,000 square feet) has been constructed by East Port Properties, Canada, before 25 years in St. John's, Newfoundland. It is the first building in Newfoundland, which is using seawater tides for space heating and cooling with 50% energy efficiency[39]. To meet government GHG reduction targets, the Newfoundland provincial government is increasing the renewable energy-based power plants and are reducing the fossil fuel-based power plants. The Newfoundland government is also focusing on green building energy projects like solar-based thermal energy storage system design, net-zero energy building, energy efficiency, and many more relating to green energy production [40] .K & P contracting Ltd. first successfully built up a net-zero energy home in St. John's, Newfoundland on 2013[41]. They installed the necessary solar panel to the rooftop and a wind turbine. During the sunny day, solar energy is collected, and during the windy day, the energy comes from wind, and both energies are stored in the thermal energy storage tank. When no renewable energy is available, then the energy is supplied from storage. To keep the temperature at a specific level, a fossil fuel-based auxiliary burner is used. Every month, in this way the necessary energy is used but no electricity bill is paid. The feature is that it is entirely designed as a highly energy-efficient home appliance, high insulation levels, and thicker walls, double low triple glazed windows, better floor insulation, the ceiling, and a small, efficient heating system.

1.13 About Research

In this research, a single-family detached house located in 5, Blue River Place, St. John's, NL, Canada, is considered. By selecting all necessary parameters of a house, annual energy demand has been calculated, such as domestic hot water demand, space heating demand, and electrical load demand form BEopt software, and it is verified by using the Newfoundland power monthly electric bills and NRCan, 2019 demand estimation. The weather potentials such as solar, wind, ambient temperature, underground temperature have been determined form Homer software and verified from the local weather office data. Based on this, there are various system designed to mitigate the high energy demand such a solar Photovoltaic based water heating systems, solar collector based and Seasonal solar thermal energy storage systems. The sizing of each component has been done carefully based on mathematical modeling and optimize the component sizing. As almost 83% of total energy is used in a single-family residential house for space heating and domestic hot water heating and in the long wintertime sometimes there is no sun, so during the summertime, the bulk amount of renewable energy will be collected and stored, and during the wintertime, the stored energy can be supplied to the house for space heating and hot water. Thus the electricity bill will be reduced. The techno-economic analysis has conducted so that it will be helpful to choose the optimum low-cost and energy-efficient systems. A controller is necessary to monitor the ambient, indoor, and ground temperature, to control the collector water flow rate, to control the centrifugal pump, to turn on the auxiliary heater, to control the flow of water for domestic hot water and space heating. A robust controller is used in every configuration to improve system performance and efficiency. The openHAB smart home automation software can be used as an IoT platform, and a Sparkfun ESP32 Thing board can be used as a microcontroller unit, MQTT can be used to establish the communication in between openHAB home server and ESP32 Thing via local Wi-Fi router. The sensors may be connected to the analog and digital pins of ESP32 to collect the data from the environment, and similarly, the solid-state relay can be connected with the output pin of ESP32 Thing to control the heater and circulating pump. The thermostat control and settings can also be the control using the proposed systems. The controller has been designed to control and monitor, as discussed above, in three different ways, such as manual control, automatic control, and remote control. The consumer will decide which option is suitable based on his choice and comfortability. Finally, an energy-efficient, low cost, and Seasonal energy storage systems with remote control systems is the primary goal of this thesis. This research is funded by the Memorial University of Newfoundland and the Natural Science and Engineering Research Council of Canada.

1.14 Research Objectives

The objectives of this research are to investigate renewable energy potential, especially solar energy and it's an application in energy storage for domestic water heating and space heating purposes at St. John's, NL area, Canada. The detailed review of the solar energy storage systems and some real-life projects have been investigated. The main propose to design a smart energy saving single-family detached house for all Canadians with necessary remote-control system design. In this study, a typical single-family detached house has been considered and analyzed the solar potential then properly designed the component sizing such as solar photovoltaic, solar collector, circulating pump, Seasonal thermal energy storage system. A control system has been designed that will monitor and control the whole system to reduce the system losses and improve the overall system efficiency. The system components have been selected and sized properly as best practices from the literature review and manufacturers' datasheets.

Lots of software are available for simulation and optimization in literature. To perform this research objective, the details of the software and hardware is described below:

- ✓ BEopt software: The house parameters have been given as input and calculated the house energy demand such as electrical demand, domestic hot water demand, and energy rating index as well.
- ✓ Homer software: It is used to determine the solar potential in the ST. John's area, NL, Canada, and determine the proper size of the system components. The data is also verified from the local weather office.
- ✓ PolySun software: PolySun 6.2, the latest version, has been used in this research. There are a lot of components available in the library, such as solar PV, collector, battery, pump, storage tank, auxiliary heater, and controller, and carefully selected and modify the values based on the mathematical and sizing. This is an excellent software for renewable energy modeling and simulation, especially solar PV and solar collector based short term, long term, and Seasonal thermal energy storage systems. The performance and simulation results are accurate.
- ✓ Matlab/Simulink software: Matlab 2019b version has been used for simulation of solar thermal energy storage systems. In the Simulink library, there are a lot of components available, but some elements are not directly available, that's why the existing model has been chosen and customize the model based on the requirements such as solar collector, circulating pump, storage tanks auxiliary heater and controller.

- ✓ openHAB software: open Home Automation Bus (openHAB) is an open-source home automation software that is written in Java language. There are so many options to install, such as Windows, Linux, RaspberryPi, and so on, but I choose Windows. Its development is able to connect the devices and services from many vendors. The devices can be connected to each other by developing the Java language. With openHAB, the sensor devices output can be monitored and can be controlled from remote, and it may be manual or automatic. This software can be installed on the cell phone, and then anybody can control the house from anywhere in the world using a regular cell phone.
- ✓ Overview of the experimental setup: This project demo has been implemented for verification. In the setup, the temperature sensors have been connected with the Sprukfun ESP32 Thing, and the room and ambient temperature have been displaying in the openHAB via MQTT protocol. Again the thermostat control switch is in the openHAB dashboard; when the state changed, it sent a message at MQTT protocol. The relay's and the heater remote are connected to the digital pin at Sprukfun ESP32 Thing. The MQTT is connected to the ESP32 board through Wi-Fi. In this way, bidirectional communication happened. The dashboard can be accessible in so many different ways from anywhere in the world, such as through the IP address port forwarding, Teamviewer, and openHAB cloud. For this project, openHAB cloud has been used with a secured authentication, and now it is possible to control and monitor the TES systems anywhere in the world.

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Chapter 2

Design and Analysis of Solar Water Heating System with Seasonal Storage

Preface

This chapter is the continuation of research NESTNet Project 1.4. Only the system sizing section of this chapter and the system sizing section of the conference paper are almost similar, except that whole chapter is my own work and different. The paper has been published as a conference proceeding in the Canadian Society for Mechanical Engineering (CSME) and the CFD Society of Canada (CFDSC) at the Western University in London, ON, Canada. I was the second author, and I carried out the figure drawing, worked with the first author to finalize system sizing, and simulation. The Co-author, Dr. M. Tariq Iqbal, supervised the research, reviewed the draft paper, acquired and made available the research funding.

This chapter sizing section is a part of a conference proceedings named, "Rabbani Rasha, Habibur Rahaman, Tariq Iqbal, Sizing, modeling and analysis of a solar seasonal energy storage for space heating in Newfoundland, presented at CSME-CFDSC 2019, London, ON, Canada".

Abstract

The majority of the electricity consumption in Canadian single-family house is for space heating and water heating. Currently, around 99% house in Canada using the conventional grid electricity for those purposes, and it is emitting large greenhouse gas. The sun has unlimited energy. We can utilize that energy for the same purpose, but it is internment in nature. In this chapter, Seasonal solar thermal energy storage (SSTES) configurations that have been designed and investigated to determine their thermal and electrical performance of a house consists of four persons in the Canadian climate environment. The detailed mathematical formulation and sizing of each SSTES system component have been developed. To validate the feasibility and numerical studies of the developed SSTES systems, the configurations have been simulated in a professional thermal simulation software named as PolySun, compared to its performance with the existing system, and showed a good argument among them. The SSTES systems have been tested using the solar radiation data of St. John's city/NL, Canada. Comparing performance, it can conclude that the Seasonal STES system has better electrical and thermal efficiency, and besides that, the required collector area and carbon emission are lower. The sustainability is higher for Seasonal STES systems, and less roof space is required, and there is no freezing effect on it.

Keywords: Hybrid solar photovoltaic, thermal systems, domestic hot water, solar collector, electric load, auxiliary heater, heat pump, Seasonal thermal energy systems.

2.1. Introduction

Canada has a large landmass and diversified geographical structures, which is suitable for many renewable energy resources. Renewable energy technology helps to reduce fossil fuel-based energy consumption in many different ways. Gradually all countries in the world are turning into the renewable energy hybrid systems form the small load to commercial load. The renewable energy-based hybrid systems have been recently developed to penetrate renewable generation, reduce greenhouse gas emissions, and flexibly balance the supply-demand requirements.

The main renewable energy resources in Canada are hydro, biomass, wind, and solar. The total contribution of solar photovoltaic energy in Canada is around 1%, and the installed capacity is approximately 6000 MW[1]. Solar energy is free and a promising technology alternative to fossil fuels to provide electricity or heating for the building. Solar PV and solar collectors can mitigate this energy demand partially or fully. Solar photovoltaic array (typical efficiency is around 11~16%) can directly convert solar energy into the electric energy, which is directly using for electrical appliances and water heating or space heating. There are some heat losses (around 80~85%) under the panel, and the efficiency is decreased at high or low temperatures [2]. The solar thermal collector (ability is around 60~80%) can convert solar energy directly to heat energy, which is also used for water and space heating, but it is too expensive[3].

The heat energy produced from the solar resources can be sent to the storage tank. The storage tank hot water can directly be used for domestic purposes and space heating purposes. This technology is not new, but recently the researcher found that this is the most economical way to save energy. Similarly, storing solar thermal energy for a long time is not a new technology and has become relatively advanced, and the user can get heat instantaneously[5]. The total available solar radiation is shown in Fig. 2.3, and the hot water and space-heating demand of the selected home is shown in Fig. 2.13 and 2.14, respectively. From those curves, it is found that the demand in winter is higher, but solar radiation is low. The opposite scenario in the summertime, the demand is low, but the radiation is high. That is why for continuous and immediate hot water and space heating supply, the thermal energy storage system with an auxiliary heater is essential. Storing the solar thermal energy for space heating during the peak demand can reduce the overloading of the electric grid that way, the consumer can reduce the monthly electric bill.

In a single-family residential house, the majority of energy is consumed for space heating (around 60%) and water heating (18%) among all energy consumed, as shown in Fig. 2.9. Based on the energy face book 2015 report [6], more than 99% of homes in Canada used fossil fuel (60%), grid electricity (30%), wood, and others (10%) for space heating and domestic hot water supply. It is also responsible for releasing massive carbon dioxide into the atmosphere from a single home. In Newfoundland, the sun provides the earth with an average of approximately 250 to 350 W/m^2 of power every day on the ground surface [7]. There is an excellent opportunity to utilize this unlimited power for space-eating and water heating in our homes. Due to the increasing demand for energy and the decreasing supply of fossil fuel, it is becoming more economical, and the research justifies that. The carbon dioxide emission will be reduced too.

The objective of this research is to investigate the suitable Seasonal solar thermal energy storage (SSTES) system, to minimize the fuel consumption and conventional electric boiler consumption, to maximize the energy savings, to reduce carbon dioxide emissions.

In this chapter, the literature review of the SSTES system has been conducted; the monthly and annual demand of a single-family residential house has been calculated, such as electric, domestic hot water, and space heating demand. The detailed weather in St. John's, Newfoundland, has been analyzed by using Homer and PolySun software and verified with the local weather office. SSTES system configurations have been introduced to mitigate the high demand. The numerical analysis of SSTES components has been presented; simulation has been conducted in PolySun software, Results have been analyzed and compared with the existing system to show the simulation output will mitigate the overall demand of the selected house.

The chapter is organized as follows. In section 2, the recent research and development, methodologies, researcher's contribution, limitations and research score related to Seasonal solar thermal energy storage systems has been summarized. The purpose of this research in this chapter and research assumption has been mentioned in section 3. In chapter 4, the mathematical formulation of SSTES components has been described and found the suitable components with suitable sizing. The weather data, renewable energy potential, house parameters and energy demand analysis (electrical demand, hot water demand and space heating demand) have been conducted in section 5. The existing house parameters and heating elements has been considered as a reference system which has been simulated in section 6, and the energy demand and monthly/annual energy consumption, CO_2 emission have also been conducted there. When simulation start running, how PolySun software works that mention in section 7. The Seasonal solar thermal energy storage system designed, simulation, energy generation and demand scenario have been mentioning in section 7. Finally, the comparison, performance analysis of both system is described in section 9, and the conclusion are drawn in section 10.

2.2 Literature Review

In the last few decades, the researchers are thinking more about the renewable energy-based hybrid and Seasonal solar thermal energy storage systems (SSTES) for space heating and water purpose because the customer has to pay the largest portion of the electricity bill is related to that purpose in Canada. The system may be several configurations, including solar collector based, ground source heat pump based, aquifer based, borehole based SSTES systems, and many more[8]. The solar collector-based systems can be water-based, air-based, air-water combine, phase change materials, nanofluid methods. Among all of them, the water-based systems have better thermal and electrical efficiencies, like 65~70% [9]. To avoid the freezing problems in wintertime when the ambient temperature is harmful for the long time, the water circulation can be conducted with the borehole technology and the ground source heat pump technology. The solar energy is not constant, but it is necessary to supply hot water and space heating continuously. That's why heat pump or auxiliary electric heater must be connected for uninterruptable hot water and space heating supply at a particular set temperature. Andrea et al.[13], simulated thermal energy storage for the residential applications where authors optimized the model parameters by using a graph-based methodology, they fund that the energy cost reduced up to 41%, and carbon emission reduced up to 73% of a heat pump is used instead of natural gas boiler.

Authors in [14] investigated Canadian single-family solar collector based thermal Cobi-systems by using TRANSIS software, and they demanded that their system can save 19% of energy and can reduce greenhouse emission up to 19%, but the other parameters are missing. Authors in [15] briefly described the available technology for Seasonal solar thermal energy storage, and a borehole-based system has been described, but this is for a large scale like district heating systems. Authors in [16] proposed hydrogen-based systems for a single-family residential house in Canada, and the proposed methodology can reduce CO_2 emission, but it is costly and unsuitable for practical application. If the system cost is more than a house cost, then usually nobody will agree to install. A low, medium, and high-temperature district heating concept has been investigated for a group of a Canadian family and evaluate the performance of the system [17]. The authors in [18] reviewed various configurations of borehole SSTES systems for Canadian house space heating and cooling purpose. The author in [19] designed an SSTES system for a single-family house in Ottawa, Canada, but they showed the performance of the system only for space heating purposes, not for hot water purposes. Sweet et al.[20] found that if SSTES is introduced, then smaller solar collector size is required compared to the other thermal energy storage systems. Hooper et. al.[21] investigated the same SSTES systems and came to similar conclusions, stating that a Canadian single-family home equipped with seasonal storage required less collector area compared to a system with short-term storage.

Authors in [22] proposed a solar collector based systems in Alberta in 2005, which mitigated the space heating demand, wall temperatures, and natural gas savings only. They did not mention the other configuration possibilities. A follow-up project was developed an inter-Seasonal STES system for a Canadian residential community by using borehole and aquifer STES systems in 2006 [23]. The authors only showed the design and optimization of the water heating chiller and output of the boiler. Various STES system has been studied in Canadian weather in [24]. One of the most excellent models has been proposed in Montreal by using solar combi systems based on thermal energy storage systems in 2010, but based on their output result, the performance of the system is not well enough [25]. The systems cost was high, and their payback period was extremely high as long as it ranges from 38 to 55 years that is not economical.

Following the above projects, some Canadian universities are working related to energy storage systems. For instance, the University of Ontario Institute of Technology built a low-temperature borehole thermal energy storage system (BTES) system in 1990 which has 384 holes, each 213 meters (700 feet) deep, provide the basis for a highly efficient heating and cooling system for eight University buildings [26]. The performance of borehole and ground heat exchangers based STES has been studied in Denmark considering various locations, including Canada [27]. Authors in [28] studied for 52 residential community houses with a total demand of 1900 GJ/s and their systems include 2293 m^2 of solar collector, 35000 m^3 of storage volume and they found the solar fraction is 90%, but system cost is exceptionally high compared to Canada's Drack Landing community (DLSC) project in 2007 [29]. DLSC is supplying 90% of heat demand and 60% hot water demand in total 52 numbers of single house detached family. Eight hundred solar flat plate panels (2.45 m$\times$1.18m) are producing 1.5 MW of thermal power and supply heat to the district heating system. The panels are connected with an underground pipe that carries the heated energy to the community's thermal energy storage system. Habibur and Iqbal et al. [30] designed a STES system for a single-family house and analyzed the techno-economic suitability in 2018. In 2019, Habibur and Tariq Iqbal proposed two possible configurations i) Solar collector and heat pump and ii) solar PV and heat pump for solar thermal-based energy storage systems for a single-family house and compared their performances such as component sizing, installation cost, total energy production, consumption, and energy balance, percentage of energy-saving etc[31].

In this research, a typical Canadian single-family detached house has been considered, and the electrical and thermal consumptions (hot water and space heating) has been studied. The mathematical modeling, design, and simulation of Seasonal STES systems have been proposed and concluded the percentage of energy efficiency.

2.3. Problem Description and Assumptions

In this study, only solar thermal energy storage systems have been considered. A residential house has been selected as an example, and the schematic diagram of the physical problem has been shown in Fig. 2.16. Currently, the hot water and space heating demand are mitigating from an electric heater and an electric hot water tank. The majority of electric bill and energy consumption is for space heating (60%) and hot water (18%). In next chapter (chapter 3), it is shown that we designed two solar thermal energy storage systems and verified which system will be more energy-saving i) solar collector or ii) solar photovoltaic (PV) based[30]. There it is concluded that the solar PV based proposed system is cheaper and more energy saving. But the designed total PV arrays area were very large (43 m^2). Now the same house has been redesigned with the SSTES configurations with a flat plate solar collector, external auxiliary heater, storage tank, circulating pumps, air-source heat pump, and other components. Thermal energy storage with the necessary control systems. Based on the weather condition, only the renewable energy source may not be enough to mitigate the electrical appliances demand, hot water demand, space heating demand for 24 hours around the year. That's why the external auxiliary heater has been considered. From the various configuration, it is the objective to find out suitable solar thermal energy storage systems that will mitigate the house energy demand, will reduce the monthly bill and CO_2 emission. The system should be cost-effective, lower payback period, lower rooftop space required, convenient, and maximum energy savings. All configurations will work on the same weather data (solar radiation, wind speed, and ambient temperature) located at 5, Blue, River Place, St. John's, NL, Canada.

The Seasonal solar thermal energy storage systems have been developed in the present studies is based on the following assumptions [31]:

1. The water flow has been considered under steady-state conditions.
2. The tube flow has been assumed fully developed flow.
3. The collector's layer temperature has been neglected.

4. All other parameters have been assumed, temperature independent.
5. There is no heat gain (or loss) when the water through the pumps and pipes.
6. It is assumed that there is no shading and dust on the collector panel.

2.4. Mathematical Formulation

In this section, the Seasonal solar thermal energy storage configurations have been considered. The mathematical model should be developed for the essential components like a solar thermal collector, storage tank, heat pump. Based on the mathematical model, the total electrical energy output, thermal energy output, energy consumption, electrical and thermal efficiency, and storage tank temperature have been estimated and tried to compare with the total energy demand for a single-family residential house considering four people living in St. John's, Newfoundland, Canada. The mathematical model of each system component has been developed below.

2.4.1 Seasonal Energy Storage System Components Sizing

The main components of a Seasonal solar thermal energy storage system (SSTES) is a flat plate collector, one small tank for domestic hot water supply, and another big tank for space heating. For design consideration, it is considered that the auxiliary heater will be controlled in such a way that around 30% of heat energy will be released in the DWH small tank, and the rest of the 70% of heat energy will go through the Seasonal storage tank. In reference [44], the authors have also calculated the required area of the solar collector 16 $m^{2,}$ and the Seasonal tank size depends on the tank volume to the solar collector. In order to get the 70% of solar fraction, the optimal volume to collector area ration should be 2 m^3/m^2 although it may be affected by the tank height and foundation limitations. So, taking all the consideration, the authors suggested the optimal Seasonal tank volume is 30 m^3 to make the volume to collector area ration is close to 2. The small tank for DWH is considered as 0.189 m^3.

Finally, the Seasonal tank volume, $V = (\pi \times D^2 \times H)/4$ (2.1)

Where the tank height, H=3 m and the volume, V= 30 m^3. Using equation (2.1), the calculated tank diameter is, D= 3.36 m. So, H/D=3⁄3.36 =0.89. It showed a good agreement with literature to design the cylindrical storage tank diameter.

2.4.2 Heat Pump Model Equation

The heat pump can be air source (ASHP) or the ground source (GSHP). The input of ASHP is the ambient air, and the input of the GSHP is the underground soil temperature. The performance of the heat pump is generally measured with the coefficient of performance (COP).

Heat supplied to the tank, $Q_h = W \times COP$

COP of the heat pump may be expressed as:

$$COP = \frac{Q_h}{W} = \frac{Q_h}{Q_h - Q_L} \tag{2.2}$$

The Carnot efficiency, η_c is equal to the ratio of actual COP of a heat pump to Carnot COP_e, which can be expressed as a function of inlet (T_i) and outlet (T_o) temperatures as:

$$\eta_c = \frac{COP}{COP_e} \tag{2.3}$$

$$COP_e = \frac{T_o}{T_o - T_i} \tag{2.4}$$

Putting those value in equation (), the COP can be calculated as follows:

$$COP = \eta_c \times \left(\frac{T_o}{T_o - T_i}\right) \tag{2.5}$$

In (18), the carnot COP calculation equation is described. Based on that formula and table 1.3, the carnot COP is calculated 2.5, so the COP of the heat pump is calculated 3.0. The earth's surface or ambient temperature variation coincides with the air temperature variation, and it is changing instantaneously. The range is around -15 to 20^{o}C, which is shown in Fig. 2.3. While the underground temperature fluctuation is not so frequent, and the variation range in between 3 to 4.5^{o}C at a depth of up to 10 meters in St. John's, NL. The ground temperature with periodic heat action can be calculated using the exponential behavior model [33].

$$t_o = t_d + A_d \exp\{-y[\Omega/(2a)]\} \cos\{\Omega\tau - y[\Omega/(2a)]\} \tag{2.6}$$

Where t_o is the ground's natural temperature (^{o}C) at depth y(m) at time τ, t_d is the mean earth's surface temperature (^{o}C) between the winter and summer months, A_d is the ambient temperature (^{o}C), Ω is the frequency (rad/s), and a is the thermal diffusivity [W/(m^{o}C)]. Based on the equation (18), the ground temperature has been determined using equation 19 at the selected location at various depths which is shown in Fig. 2.2.

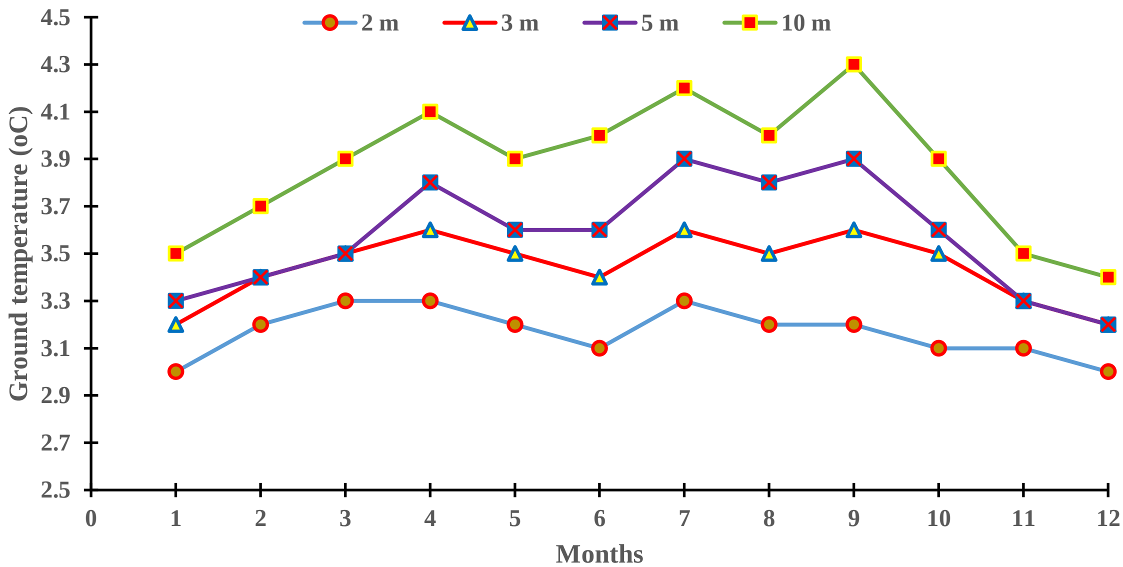

Fig. 2.1 Ground temperature variation with depth.

The city water in St. John's is carrying through the underground pipelines. That's why although the ambient temperature varies from -20 to 20 ^{o}C, but the supply water temperature is always around 5 to 15 ^{o}C. The ground source loop is considered as the source of energy, and then the efficiency will not be high. There is not much temperature difference between the inlet and the outlet of the ground source loop. That's why the ground source heat pump is not suitable for the weather.

2.4.3 Diurnal Energy Storage Tank Sizing

The multilayer water-based storage tank has been considered in this research where the two inlets are considered one is for cold water, and another one is hot water inlet from the heat exchanger. The energy flow of the water tank is affected by the two flows, one side is the collector loop and the other side is the demanding loop. There are two outlets has been considered in the demanding loop, one is for hot water supply, and another one is for space heating purpose. In this research, the various combinations have been performed with the storage tank like the circulating pump, heat exchanger, and radiator. Sizing of the water tank depends on water consumption. Since the solar radiation and the water consumption are in the various schedule as mention in Fig. 2.4 and Fig. 2.12, the time difference needs to be bridged, that's why the storage tank size and water volume should be larger then the conventional storage tank and an auxiliary heater (heat pump or electric heater) is needed [34]. However, the large storage tank needs more energy to reach the water temperature to the setpoint temperature, and the energy loss is more too. The size, capital cost, and loss must be optimized. The aperture area and the volume of the storage tank are calculated using a trial and error approach to meet a desired solar fraction. Conventionally, a 0.2 m^3 water tank is installed in the house premises, but in this research, for a single-family with four people houses, to mitigate the demand generally 0.189 m^3 water tank is considered except the Seasonal storage.

2.5. Data Collection and Analysis

2.5.1. Weather Analysis

The tested house location is 5, Blue River Place, St. John's, NL, Canada. There is a vast temperature difference between the ambient and the ground temperature. It is found that the environment temperature range is from -10 ^oC to 15 ^oC, and the ground temperature range is from 3 ^oC to 4 ^oC at a depth of up to 5 meters, as shown in Fig. 2.3. The average daily solar radiation is 3.06 kWh per m^2 per day, as shown in Fig. 2.4, which is enough to generate heat or electricity. The environment Canada is recording the hourly solar radiation data every year, which is shown in Fig. 2.5, and it is found that solar radiation is available every month, and the recorded radiation range is from 0.1 to 0.95 kWh/m^2.

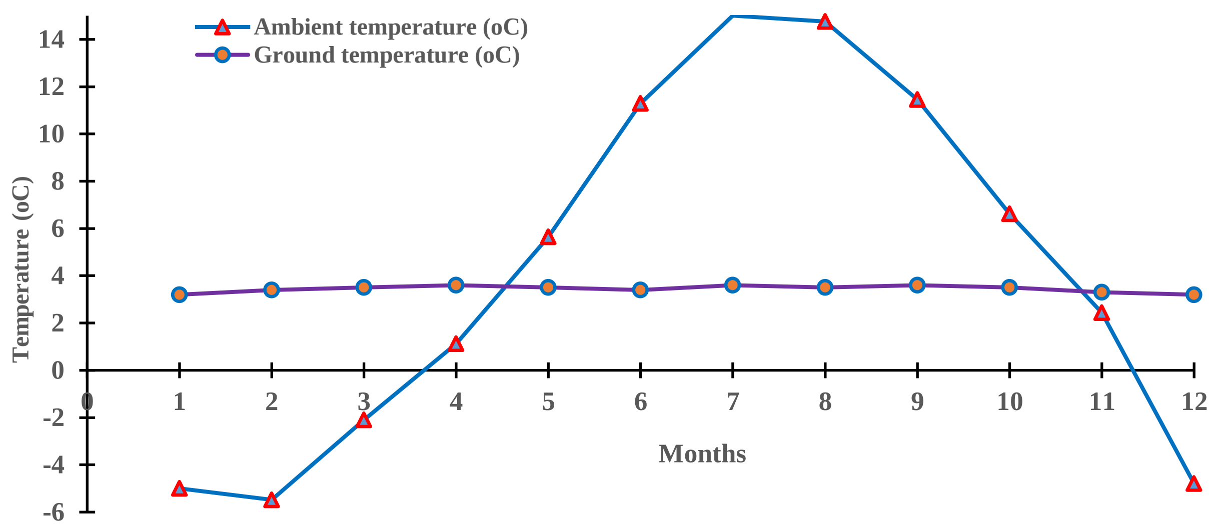

Fig. 2.2 The ambient and ground temperature of the selected location

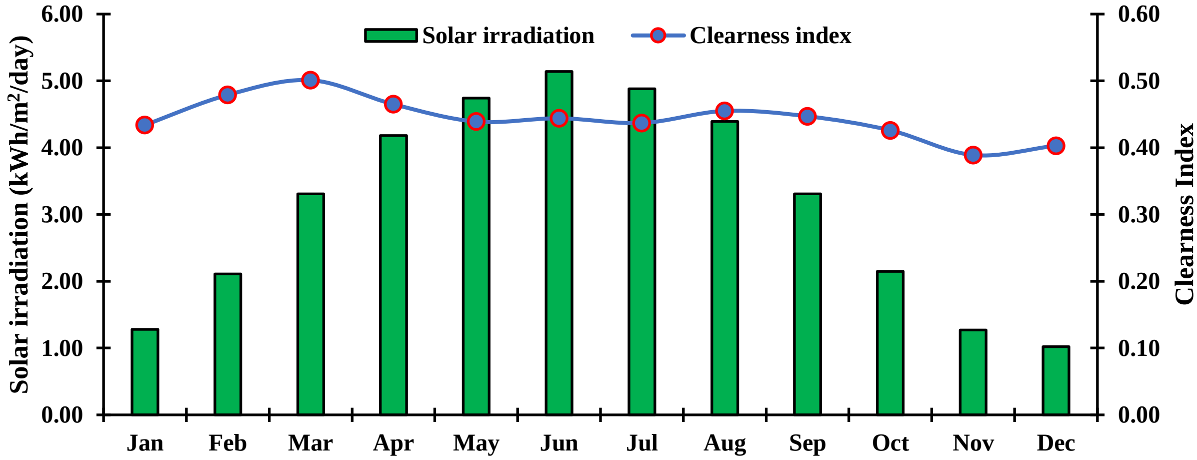

Fig. 2.3 Yearly solar radiation and temperature data

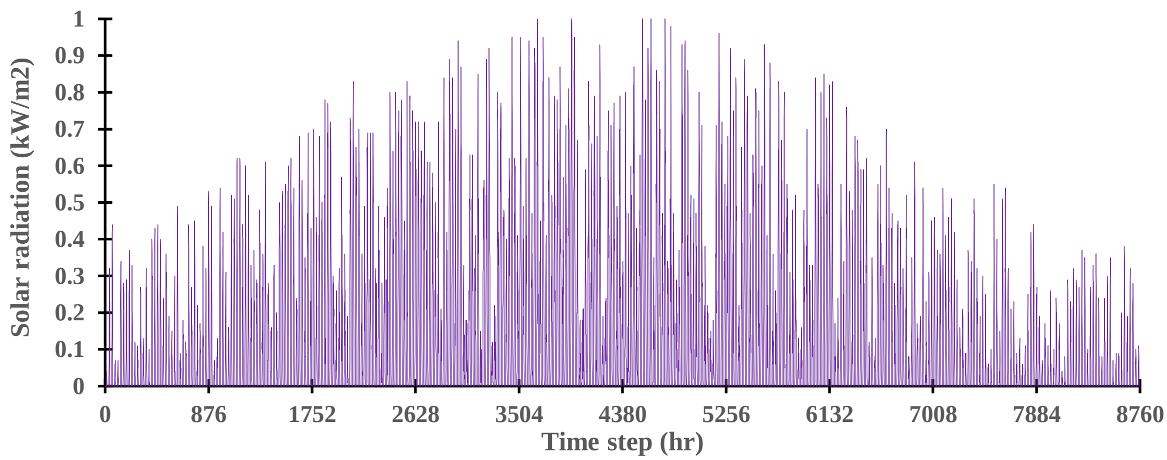

Fig. 2.4 Yearly solar radiation data.

In the wintertime (example January month), the average solar power generation time is around 4 hours, the radiation is very low due to the heavy cloud in the sky, and the environment temperature is in between -11 ^{o}C to -4 ^{o}C. That's why the collector and the PV module efficiency, power generation capability is very low, as shown in Fig. 2.6. On the other hand, in the summertime (example July month), the average solar power generation time is around 10 hours, the radiation is well enough to generate power. The ambient temperature is also favorable at approximately 10 ^{o}C. That's why the solar collector or the solar PV module can generate sufficient power, as shown in Fig. 2.5. In the nighttime all-round the year, there is no power generation from a solar resource.

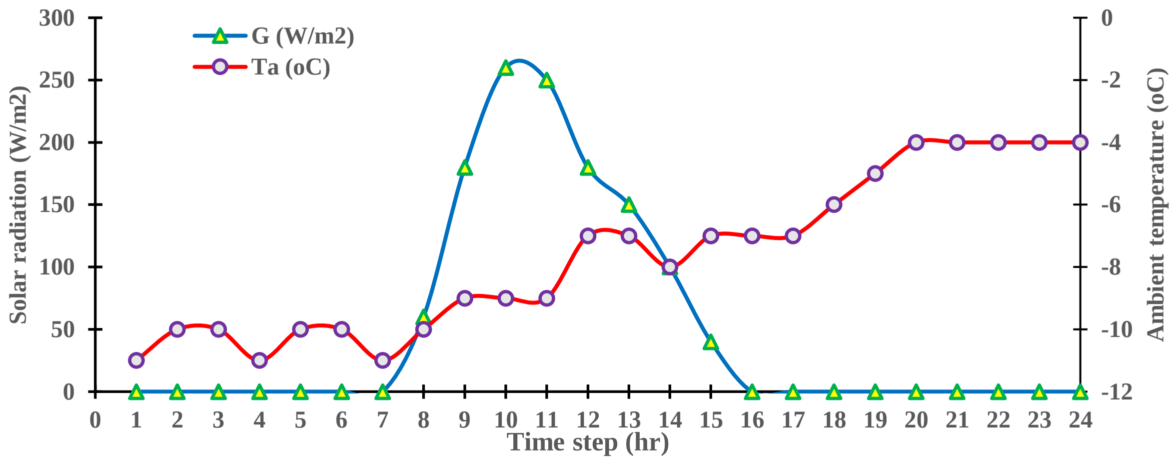

Fig. 2.5 A typical winter (Jan)

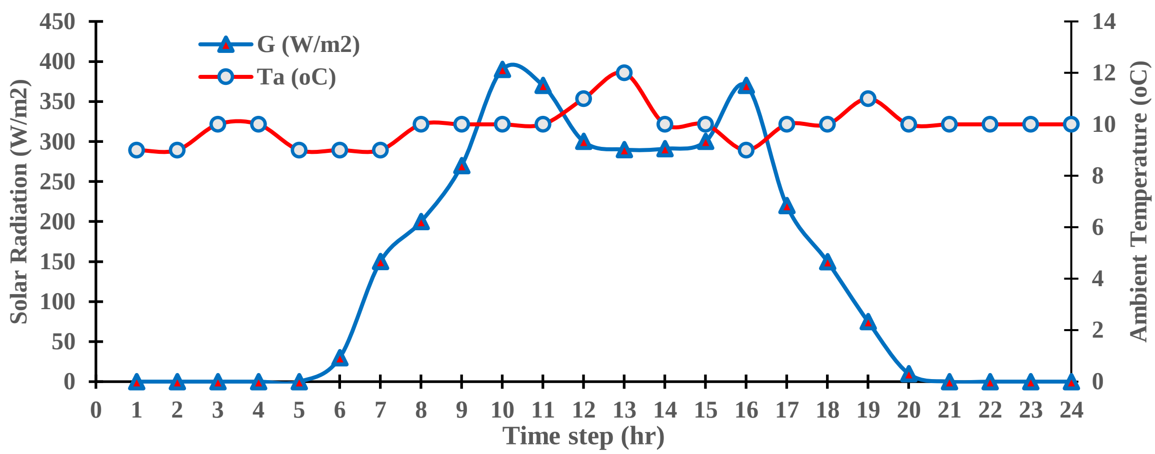

Fig. 2.6 A typical summer (July)

2.5.2 House Parameters Analysis

The considered house is a typical single-family house in Canada. The schematic diagram of this house is shown in Fig. 2.8, and the details of this house parameters are described in table 2.1. In the tested house, the grid electricity provides the hot water supplied by a conventional electric boiler and space heating through the electrical resistance heater that is the most common scenario of all Newfoundland single-family houses. Thus, the considerable grid electricity is required, and consumers are paying a large amount of electric bills every month.

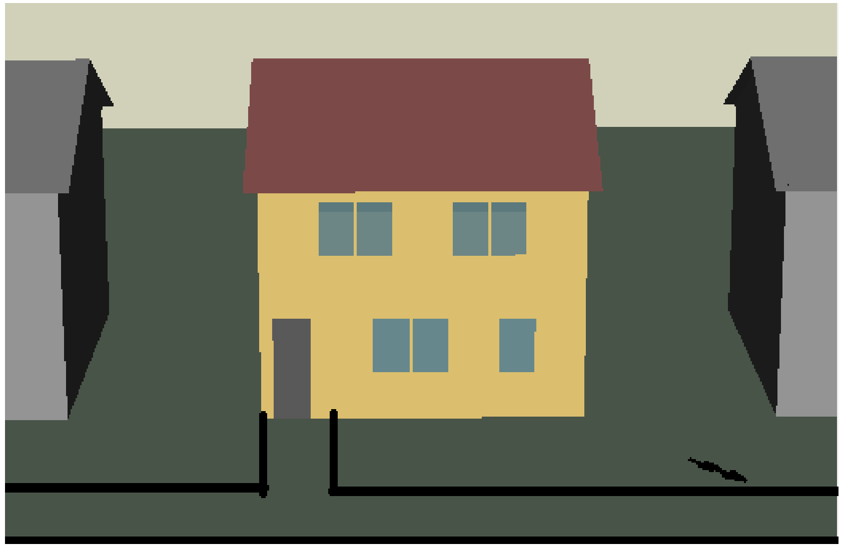

Fig. 2.7. The geometry and the schematic view of the selected house

Table 2.1. The tested single-family house details

Building envelop surface	Components	Materials specification
Building	Orientation	Northwest
	Neighbors	Left/Right at 4.57 m.
	Facility full size (13.7 m × 9.144 m)	125.27 m^2
	Annual energy demand (space heating & domestic hot water)	153.56 KWh/m^2
Wall	Wood stud	R- 15 Fiberglass Batt, 2*4, 16 in o.c
	Wall sheathing	OSB
	Exterior finish	Vinyl, light
Ceilings/Roofs	Unfinished attic	Ceiling R-38 Fiberglass, Vented
	Roof material	Asphalt Shingles, Medium
Foundation/Floors	Finished basement	Whole wall R-13 Fiberglass Batt, 2*4, 16 in o.c
	Interzonal floor	Uninsulated
Thermal mass	Carpet	0% Carpet, R value is 2.08
	Floor mass	Wood Surface
	Exterior wall mass	½ in. Drywall

	Partition wall mass	½ in. Drywall
	Ceiling wall mass	½ in. Drywall
	Window areas	16.44 ^{m2} total (12 numbers)
	Windows	Clear, Double, Non-metal, Air, H gain
Windows & Doors	Door Area	1.85 m^2
	Doors	Wood
	Eaves	0.3 m.
	Air leakage	4 ACH50
Airflow	Mechanical ventilation	2010, HRV, 70%
	Natural Ventilation	Cooling months only, 7 days/week
Space conditioning	Electric baseboard	100% Efficiency
	Ducts	7.5 % Leakage, Uninsulated
Space conditioning	Heating setpoint	68 F or 24^{o}C (My Test)
	Water heater	Electric Standard
Water Heating	Distribution	Uninsulated, Home Run, PEX
	Hot water setpoint temperature	50 ^{0}C
	Lighting	34% CFL Hardwired, 34% CFL plugin
	Refrigerator	Top freezer, EF= 21.9
	Cooking range	Electric
	Dishwasher	219 Rated Kwh, 80% usages
Appliances and fixtures	Clothes washer	Energy start, Cold water only
	Clothes dryer	Electric
	Hot water fixtures	A new input has been inserted (My Test)

The house monthly electric bill has been collected from the NL power customer profile page and analyzed based on the NREL report[6]. The considered house present annual demand is around 19007 kWh of electricity for space heating, domestic hot water, and other electrical appliances, as shown in Fig. 2.9. The distribution of this consumption is shown in Fig. 2.10, where it is found that the majority of electricity is consumed for space heating (11404.2 kWh) and domestic hot water (3421.26 kWh).

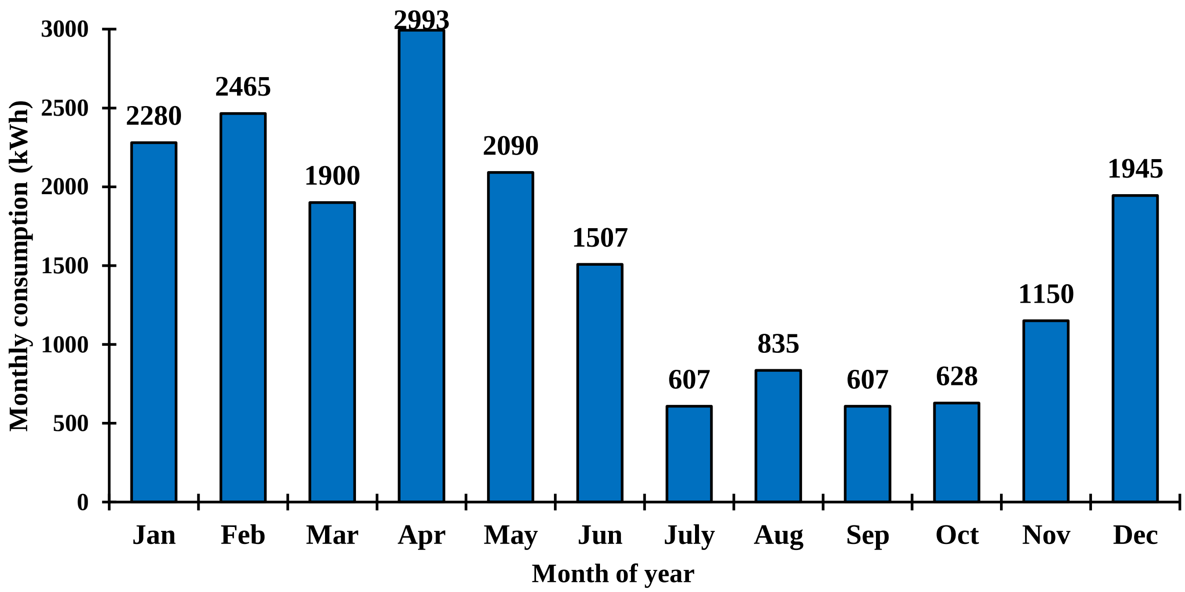

Fig. 2.8 Monthly average energy consumption of a standard residential house in Canada

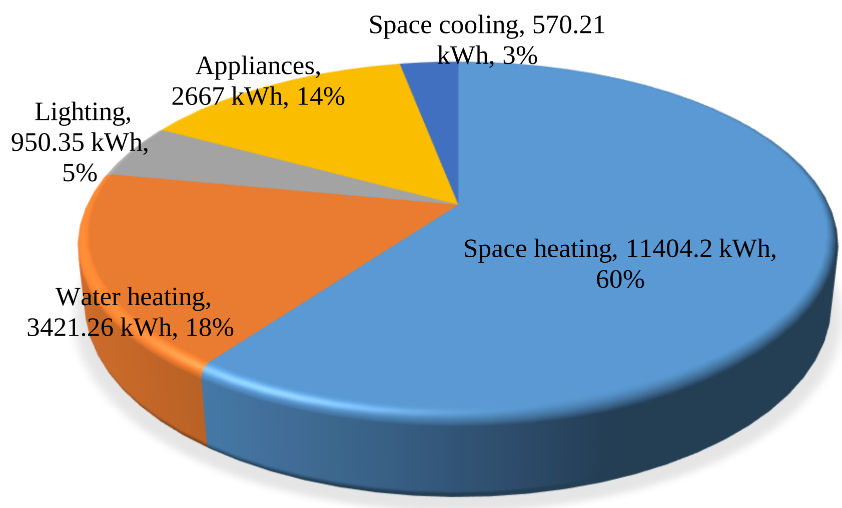

Fig. 2.9 The actual electricity consumption distribution [37]

2.5.2.1 House Energy Demand Calculation

This house again was analyzed by using the BEopt (Building Energy Optimization) software. All input parameters have been selected carefully based on the existing house materials and connected loads, as mention in table 2.1. The simulation output is shown in Fig. 2.11.

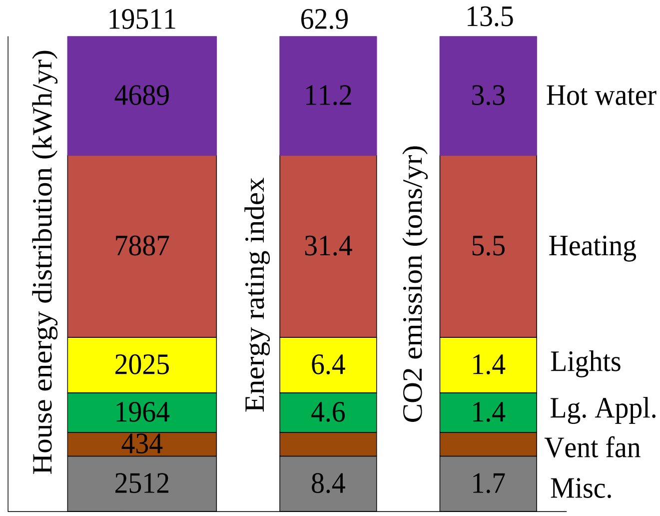

Fig. 2.10 The tested house standard annual energy demand.

It is found that the actual energy consumption in the house is 19511 kWh in Fig. 2.11, which is almost similar to the electrical and thermal consumption of the house collected from the Newfoundland (NL) power, as shown in Fig. 2.9. From the above Fig, 11, it is shown that the hot water demand is 4689 kWh/year, the space heating demand is 7887 kWh/year, and the demand for lighting and other appliances is around 6935 kWh/year in total. The per-hour space heating, water heating, and electrical appliance consumption scenario are shown in Fig. 2.12.

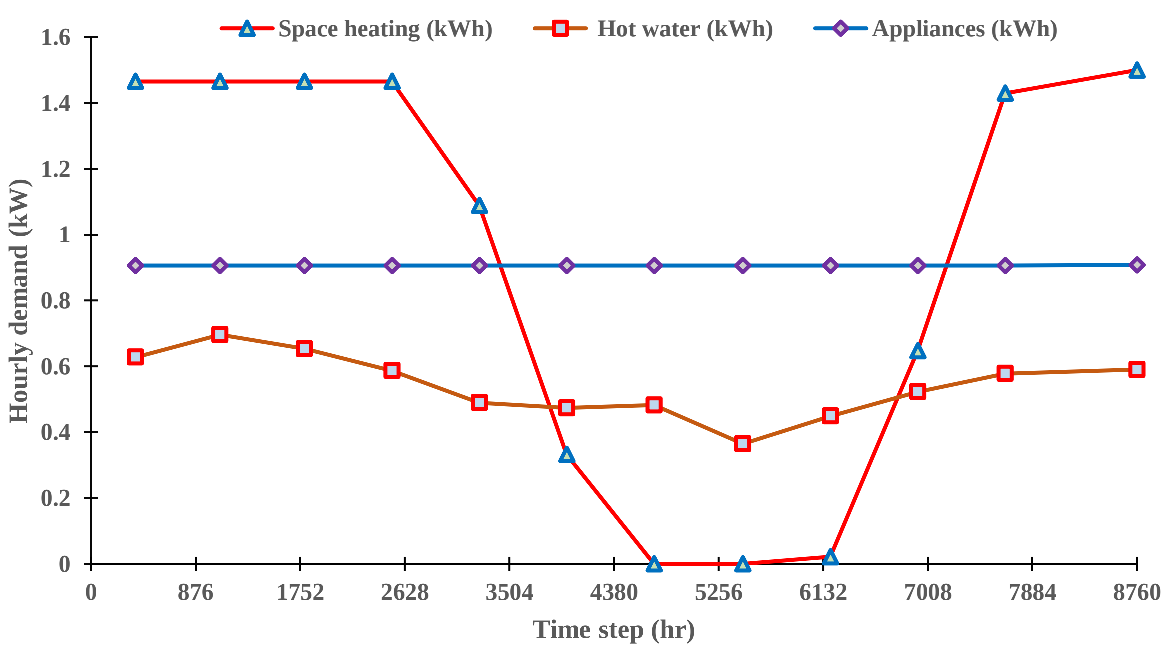

Fig. 2.11 The hourly demand of a typical single-family house

2.5.2.2 Hot Water Demand

The domestic hot water demand was calculated based on the numbers of occupants (N), it is defined in the BRE Domestic Energy Model (BREDEM) as mention in [36]. Hot water demand=38+25N.

Based on the BREDEM model and the average daily hot water demand, the hourly profile has been created for a full 24 hours period, as mentioned in Fig. 2.12. The design calculation for hot water heating is given below[37]:

Occupant, N= 200% (considered, four people are living)

Per person hot water demand, DHW= 0.02 m^3/day

Hot water demand in kitchen, HWD_k= 0.03 m^3/day

Coldwater temperature=10 ^{0}C.

Storage hot water temperature= 55 ^{0}C.

The hourly hot water demand in a day is given in Fig. 2.12.

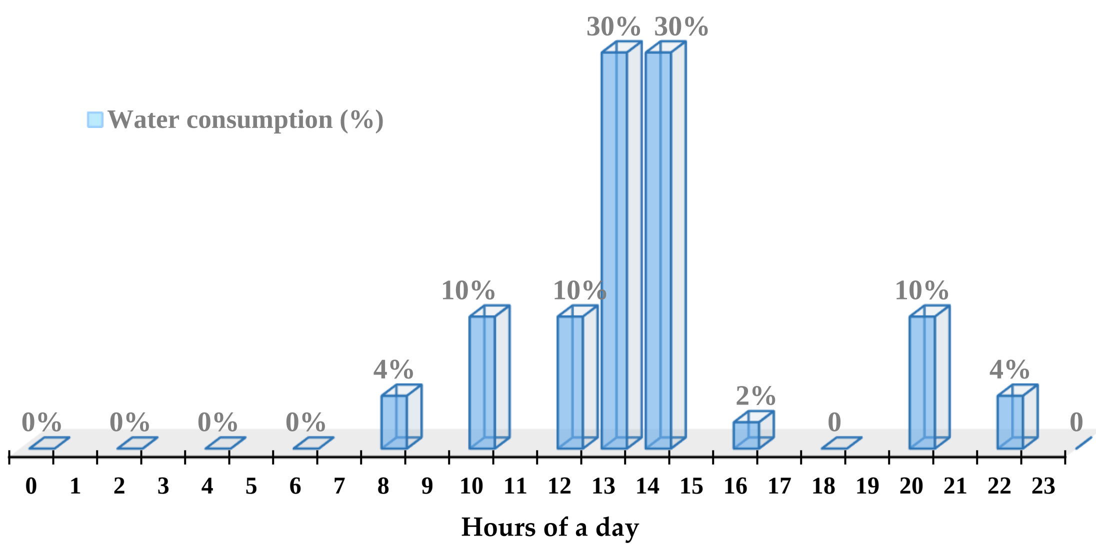

Fig. 2.12. The daily water consumption scenario in the tested house

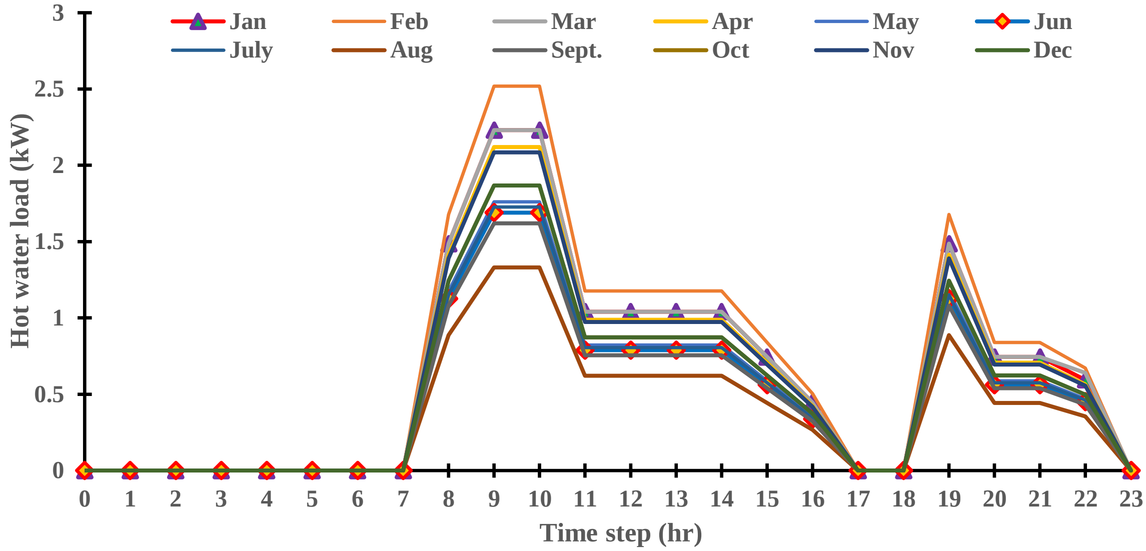

Fig. 2.13 The hourly hot water demand of a typical single-family house

2.5.2.3 Space Heating Demand

In this project, the water-based PVT collector, solar collector, and the water tank has been considered. So, the energy storage medium is water. The radiator has been considered as the source of space heating in each room and surroundings. The design heat loss for the selected house, with uninsulated cavity walls, solid ground floors, single glazing, and loft insulation for a row of this house, was calculated by using the BEopt software. The average internal room temperature is 20 ^{o}C, external temperature is -1 ^{o}C, distribution losses assumed is 16%, and a radiator hot water supply is 55 ^{o}C were considered in this project. Fig. 2.14 described the hourly space heating scenario for the selected house.

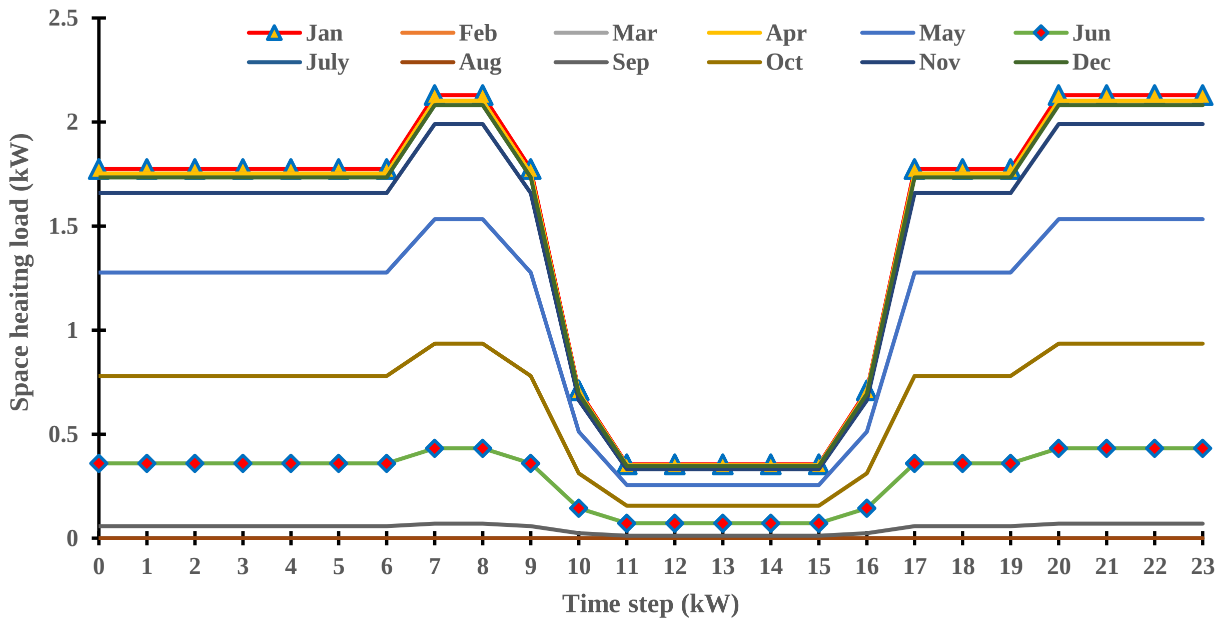

Fig. 2.14 The hourly space heating demand of a typical single-family house

2.5.2.4 Electrical Appliances Energy Demand

A variety of loads is connected to a single-family residential house, as mentioned in table 2.2. It is found that the total demand of all connected electrical load is 9.61 kWh/day. The hourly load demand scenario is shown in Fig. 2.15. The lists of all connected loads are given below.

Table 2.2. The connected load and demand calculation for electrical appliances

Appliances	Rating (W)	Quantity	Operating time (hr/day)	Total Demand (kWh/Day)
LED light	30	6	6	1.08
Bed light	10	3	8	0.24
Refrigerator	150	1	24	3.60
TV	150	1	5	0.75
Microwave oven	2100	1	1	1.58
Rice cooker	400	1	1	0.40
Water heater	1200	1	1	1.20
Blender	400	1	0.5	0.20
Mobile charger	10	3	2	0.06

Washing Machine	500	1	1	0.5
Total load demand				9.61 kWh/day

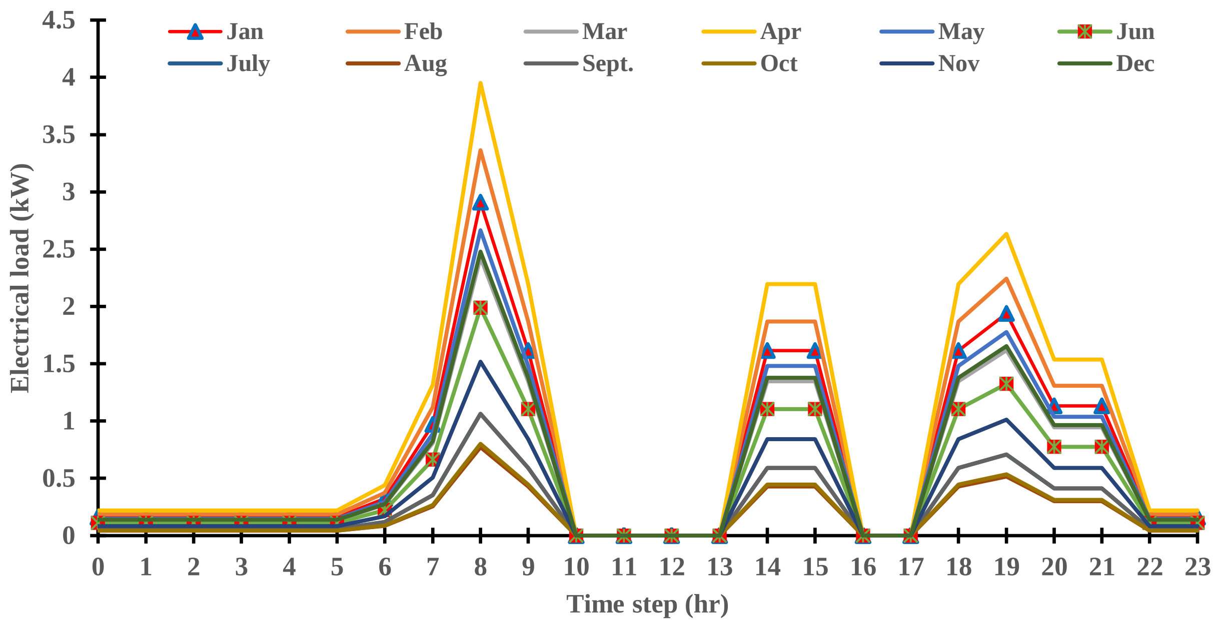

Fig. 2.15 The hourly electrical load demand of a typical single-family house

2.6. The Reference Systems

Currently, the considered house is just a typical Canadian single-family house in which parameters are given in table 2.1 and located in 5, Blue river place, St. John's, NL, Canada. The house energy demand and present consumption are described in section 5.2. Currently, all energy demand is provided form the grid electricity. The schematic of the existing house is shown in Fig. 2.16.

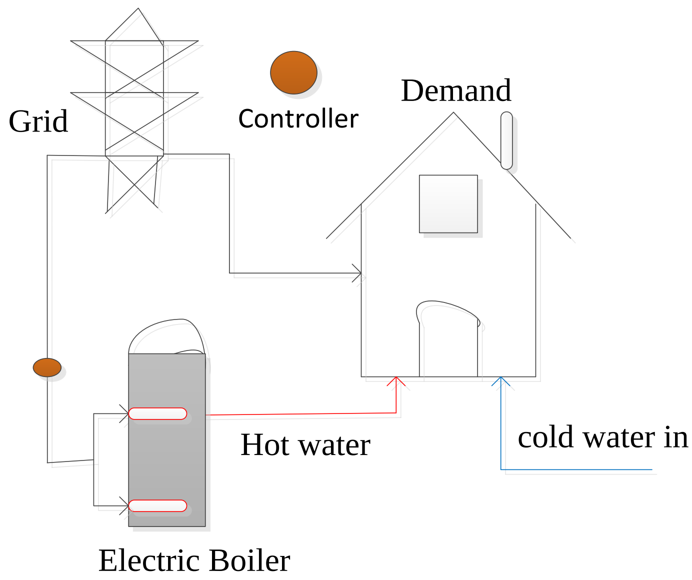

Fig. 2.16 The existing situation of the tested house.

In the existing house, the electric boiler size is smaller because it is supplying the only DHW. The conventional electric resistance heater is providing space heat. The water storage tank size is 189.3 L. The inlet cold water temperature is assumed to be at a fixed temperature of 10 ^{o}C. However, there would be some temperature deviations throughout the year. The hot water tank was model with a high-density 2-inch foam insulation (R=12.5, equal to about 0.08 W/m^2.k) and a sturdy steel jacket. The solar energy is intermittent, so for maintaining the fixed temperature at the output, the auxiliary heater is necessary. Before selection, the consideration of input and output power of each heater is essential. It usually is expected to be a more efficient one. The auxiliary heater operational power was calculated based on the electrical demand required to heat the hourly peak hot water demand (m^3/hour) from 10 ^{o}C to 55 ^{o}C (the setpoint temperature).

Based on the house energy demand, we have to design the solar thermal energy storage systems. In the simulation software PolySun, the demand side components are house, radiator, hot water tab, and electrical load. The energy demand has been adopted in these components, which is given in table 2.3.

Table 2.3. The system components and parameter settings.

Name	Component type	Main parameters	Descriptions
House	Building	Annual energy demand is known: 7887 kWh Heated living area:125 m^2 Warmest month: July Coldest months: January Heating setpoint temperature: 20 ^oC	For the thermophysical properties, please see table 2.2
Space heating	Heating/cooling element	Daily demand: 20.27 kWh/day Radiator inlet temperature: 65 ^oC Radiator outlet temperature: 55 oC Power per heating element: 1000 W Heating element area: 2.5 m^2 Flow rate per heating element: 0.086 m^3/h The volume of per heating element: 0.01 m^3 Annual space heating demand: 7887 kWh	For details of the space heating demand, please see Fig. 2.14
Hot water	Hot water demand	Daily water demand: 6.89 kWh/day. Hot water temperature set point: 55 ^oC Daily demand: 0.189 m^3 Inlet water temperature: 10 ^oC Annual hot water demand: 4689 kWh	For details of the hot water demand, please see Fig. 2.15
Electrical load	Electrical consumer	Residential profile for four-person Annual consumption: 6937 kWh	For details of the demand for the appliances, please see Fig. 2.16

2.6.1 Reference System Simulation

The existing system energy demand has been described in section 5.2 and shown in Fig 17. Currently, space heating and hot water are supplying from the conventional electric grid. Thus, the residence needs to pay a high monthly bill because the electricity demand is high. Carbone emission is also higher, which the environmental hazard for long-term consideration is. The existing system parameters have been summarized below in table 2.4.

Table 2.4. The system components and parameter settings.

Name	Component type	Main parameters	Descriptions
Electric grid	Grid	Electric grid type: 3 phase, Grid voltage: 208 V, Nominal frequency: 60 Hz	Conventional distribution power line
Electric heater	Boiler	Type: Continuous flow of electric Power rating: 6 kW Efficiency: 95% Flow rate: 0.09 m^3/h	This is placed inside the hot water tank.
Water tank 1	Storage tank	Tank volume: 0.189 m^3 Tank height: 1.4 m The thickness of the insulation: 101.6 mm Thickness at the top of the tank: 101.6 mm Manufacturer: Raheem, US	A well-insulated hot water tank with heating element has been considered [39].
Pump 1-2	Pump	Type: Eco, small Flow rate: 0.09 m^3/h Manufacturer: Grundfos	The pump starts, and stop signals were logically calculated by equations and controlled by the programmable controller.

2.6.2 Reference System Simulation Result

After simulating the existing systems, it has been verified the complete scenario of energy consumption profile and hot water temperature profile. The domestic hot water temperature, space heating temperature, house energy demand, and the grid energy consumption is shown in Fig. 2.17.

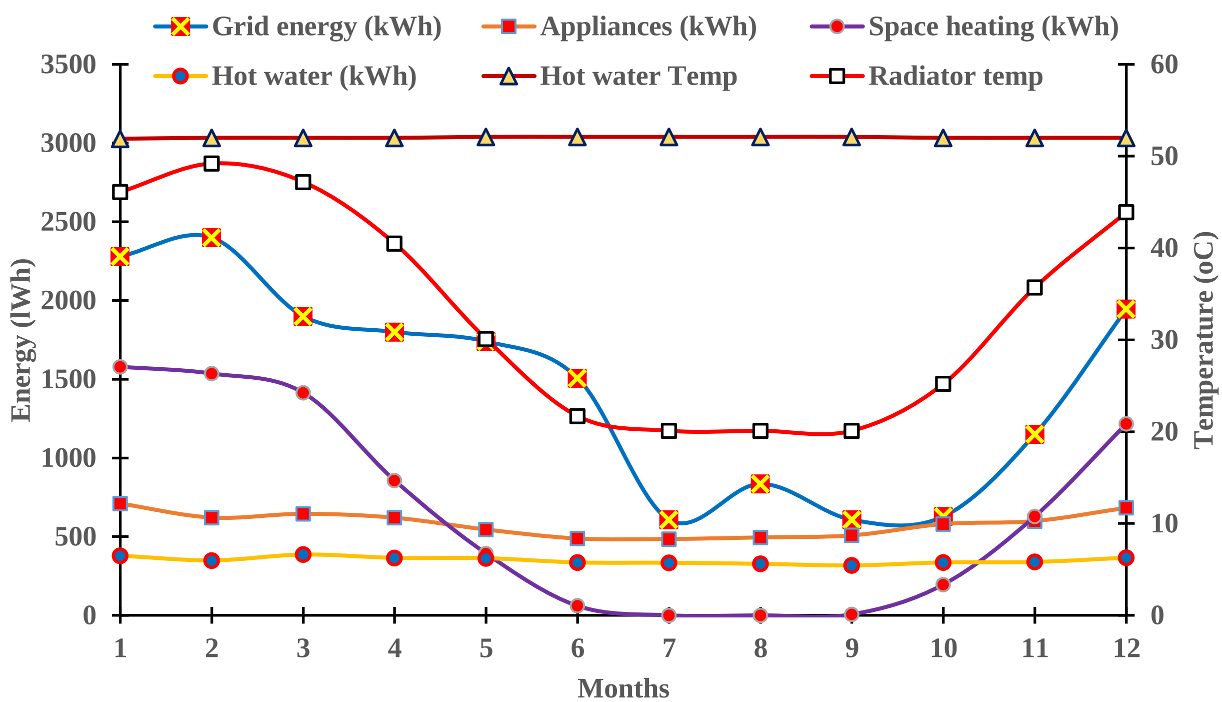

Fig. 2.17 The supply and demand scenario of the existing system

The conventional electric resistance electric heater is using where the room heating setpoint is 20 degrees, and the water heating setpoint is 55 ^{o}C. The system efficiency is 94%, the total CO_2 emission from the existing systems is 6224 kg per year, yearly grid electricity consumption is 19511 kWh among them 6937 kWh is for the electric appliances and 12574 kWh is for both space heating and hot water supply. The availability of space heating and hot water demand is 100% and 100%, respectively.

2.7. Simulation Model Working Principle

All configurations have been designed and simulated in PolySun software. The main objective is to provide hot water and space heating from renewable sources, especially solar. There are two to four circulating pumps has been used in the various model. The collector pump was controlled based on the fluid inlet temperature, outdoor dry build temperature, and the total incident radiation by calculating the critical radiation, which is defined by Duffie and Beckham's solar engineering of thermal processes book in 2006[40]. The pump was turned on when incident irradiation was more significant than the critical radiation, and the tank could gain heat from the solar collector otherwise turned off. The pump in between the water tank and the radiator has been controlled depending on the consumption profile, temperature setpoint, and current water temperature. The working process is described, as shown in Fig. 2.18.

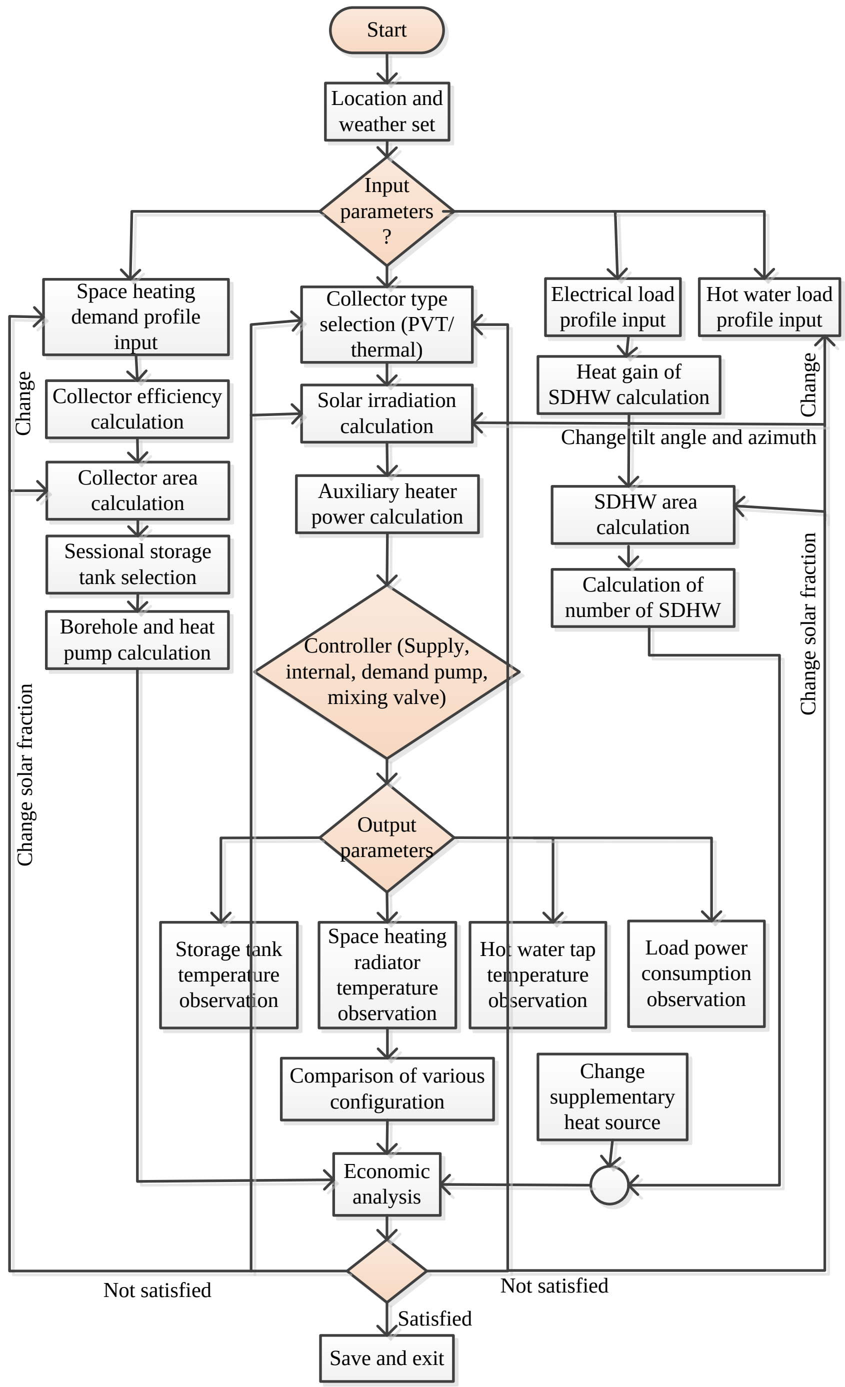

Fig. 2.18 Software design flow chart

Now for further modification of the reference system, various hybrid energy storage technology, including a Seasonal energy storage system, has been considered in various combinations. In this research, various auxiliary heaters have been considered, such as electric heater, heat pump, ground source heat pump.

2.8. Seasonal Solar Thermal Energy Storage (SSTES) System

The SSTES system is modeled in the PolySun software environment as well. As we discussed in section 4.2, why borehole-based ground source loop ground source heat pump-based system is not suitable here in St. John's, Canada, that's why only two tanks with an auxiliary heater have been considered. The water was considered as the working fluid to transfer thermal energy to and from the domestic and Seasonal storage tank. The heat capacity and the density of water used in the radiator models were 4.2 kJ/gK and 1000 kg/m^3, respectively. The controller for the pump sending fluid from the solar collectors to the storage bed is set to turn on when the temperature of the water in the collectors is at least 0.5 ^{o}C greater than the bed temperature and the solar collector loop pump control and auxiliary heater control flowcharts are shown in Fig. 2.19.

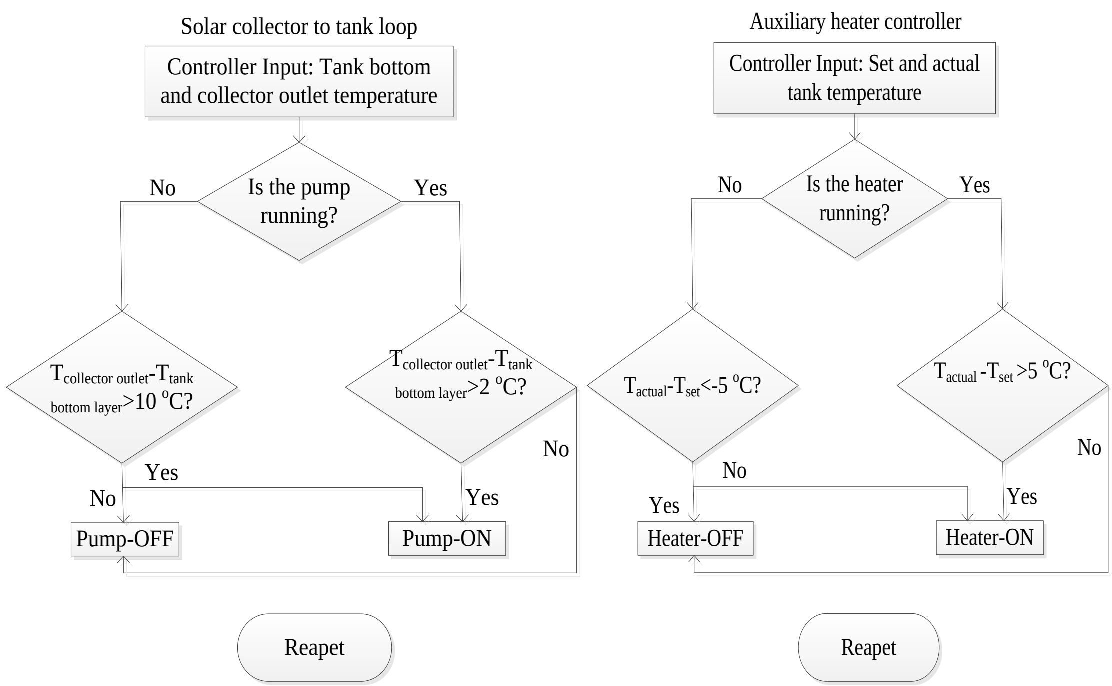

Fig. 2.19 Solar collector loop and auxiliary heater controller control algorithm.

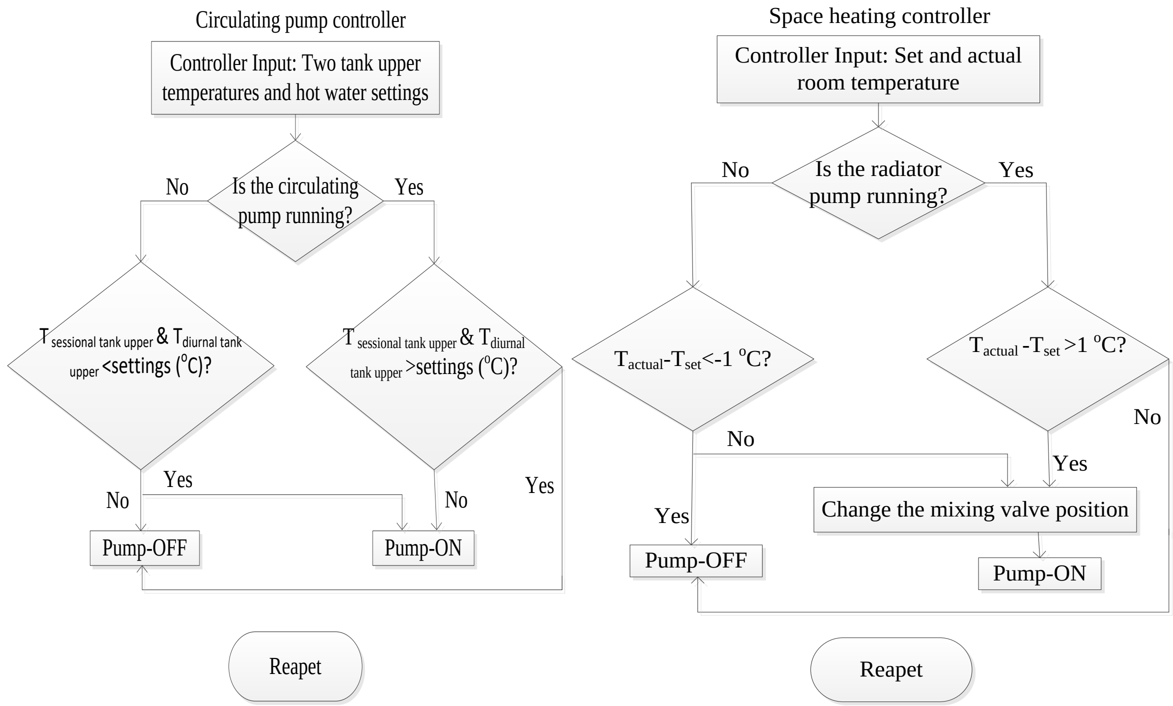

Fig. 2.20 Circulating pump and space heating controller control algorithm.

The standard flow rate used from the collector to the SSTES fine sandstone was 90 kg/h, and the flow rate values of the other pipes were considered by default or the recommended parameters. Based on the section 4.2, it is found that the underground temperature at 5-meter depth is almost 4 °C. The Seasonal storage water tank can be placed in the underground in such a way that the top of the SSTES was 1 meter below the ground surface that would decrease the effect of ambient temperature variation.

Table 2.5. Boiler performance scenario with various SSTES tank sizes considering 16 m^2 collector area.

Parameters	10 m^3	15 m^3	20 m^3	25 m^3	30 m^3
Fuel consumption (kWh)[HP]	4185	3621	3797	3960	4135
Eenrgy to the system (kWh)	11769	10217	10721	11132	11685
Energy saving solar thermal (kWh)	4861	6791	6860	6904	6921
CO2 savings solar thermal (kg)	2608	3643	3680	3703	3712
Seasonal storage tank heat loss (kWh)	2426	2839	3378	3809	4357
Tank top layer temperature (°C)	70.2	69.9	69.8	68.5	68.2
Tank top layer temperature (°C)	43.5	47.2	47	46.9	46.4

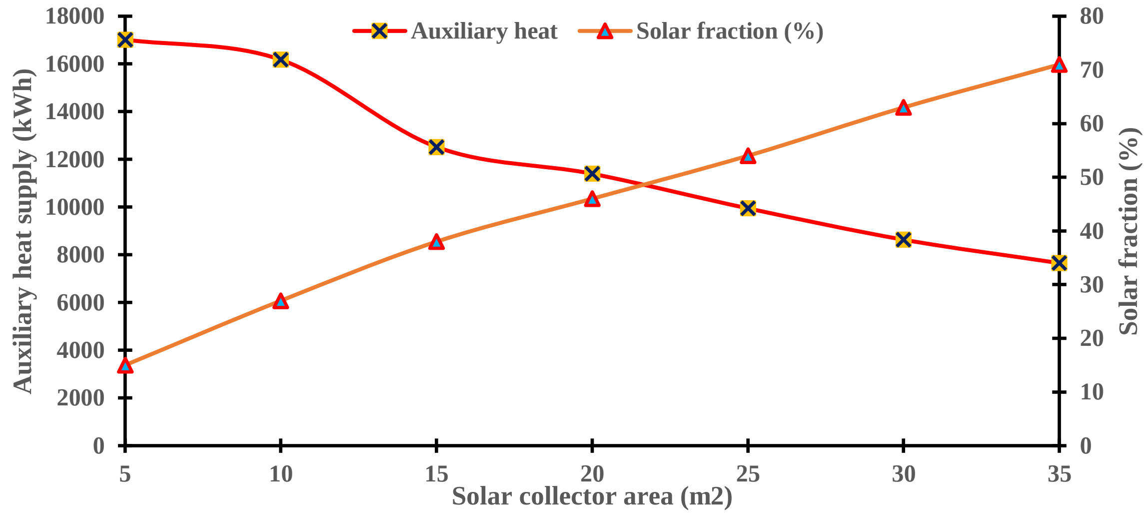

Fig. 2.21 Auxiliary heat demand reduction/Solar fraction to systems VS Collector area. (Considering, 30 m^3 tank and 0.26 GPM flow rate)

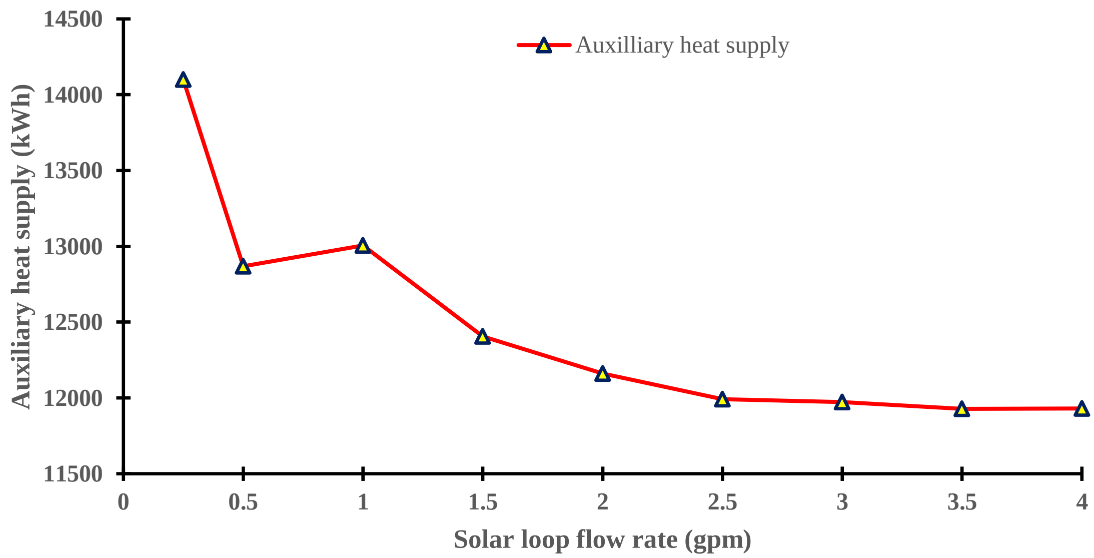

Fig. 2.22 Auxiliary heat demand reduction VS Flow rate. (Considering 30 m^3 tank and 16 m^2 collector area).

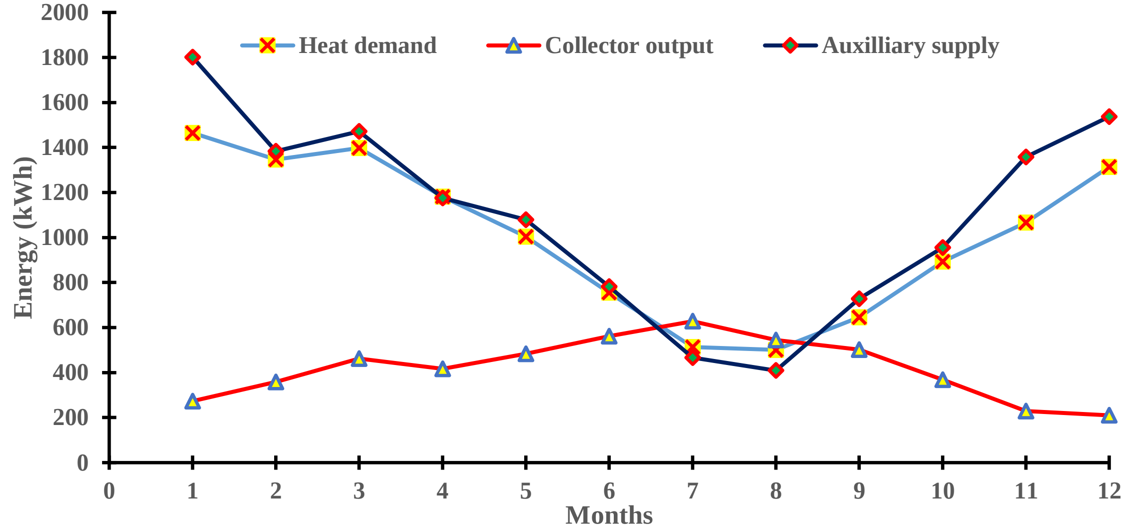

Fig. 2.23 The total heating demand and heat supply to the systems.

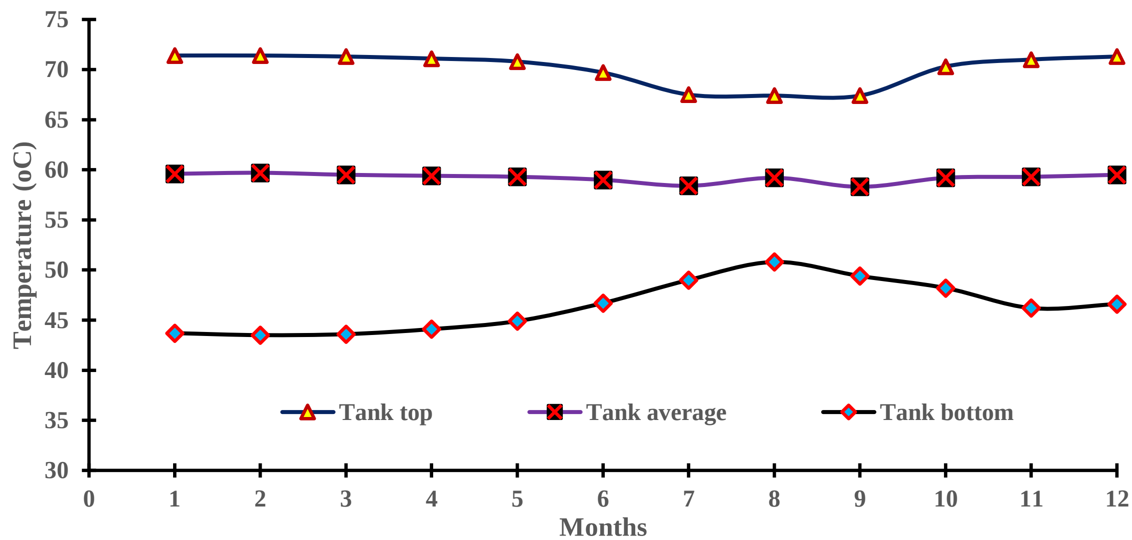

Fig. 2.24 The temperature scenario of the Seasonal storage tank at various layers.

The proposed SSTES system schematic is shown in Fig. 2.25. The flat plate solar collector module has been considered in this research because we need heat for water heating purposes.

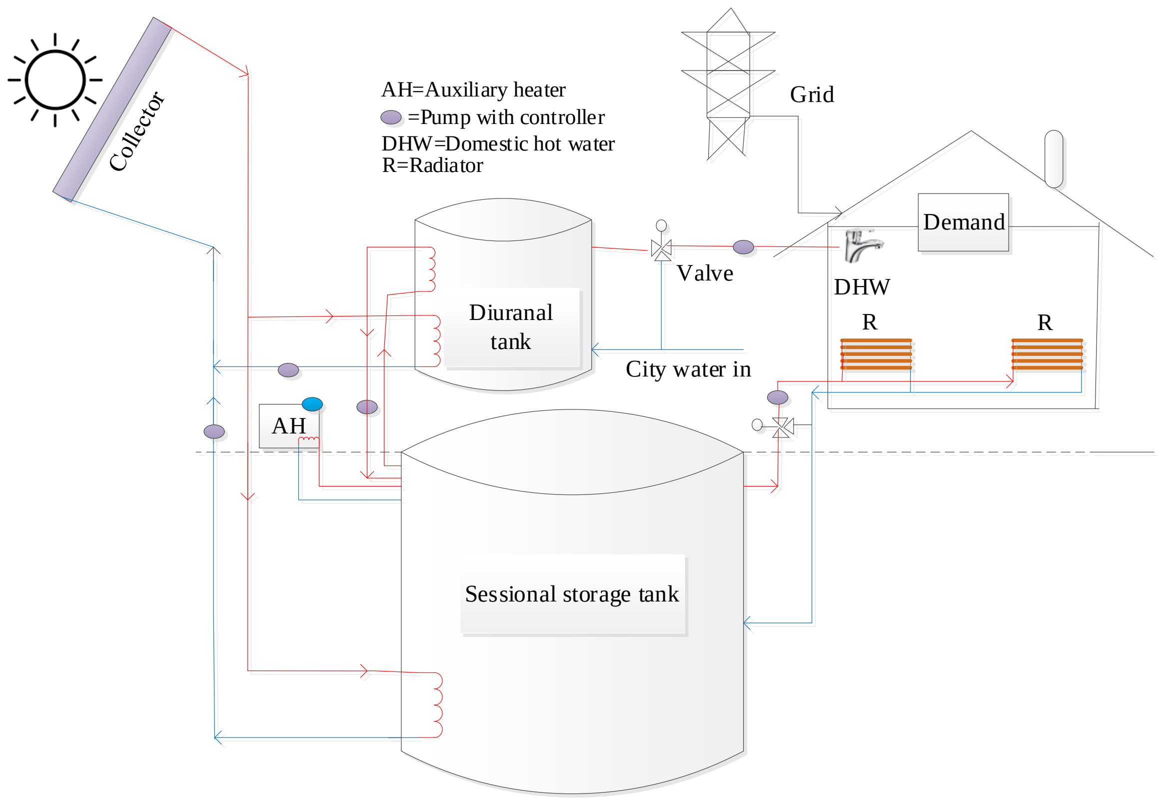

Fig. 2.25 The Seasonal energy storage system configuration

The house energy demand is described in section 5.2, and the Seasonal thermal energy storage system components specification is described in table 2.6 below:

Table 2.6. The SSTES system components and parameter settings.

Name	Component name	Main parameters	Descriptions
Solar collector	Collector	Manufacturer: Viessmann Werke GmbH & Co Model no: Vitosol 100-F Optical efficiency: 81.3% Thermal efficiency: 70% Module absorber area: 2.32 m^2 Module gross area: 2.51 m^2 Thermal capacity: 6.4 KJ/(m^2.k)	The detail description about the collector is given in [42]

		Number of collectors: 7 Number of arrays: 1 Total required absorber area: 16 m^2 Total required gross area: 17.37 m^2 Tank volumes: 30 m^3 Tank height: 2.2 m	
Storage tank	Seasonal storage tank	The thickness of the insulation: 101.6 mm Thickness at the top of the tank: 101.6 mm Manufacturer: Hansan Tank, US	Two well-insulated hot water tank has been considered.
Diurnal tank	Storage tank	Same as Table 2.4	
Pumps	Pump	Same as Table 2.4	

2.8.1 Simulation Result

The system again simulated, and the results are summarized in Fig. 2.26 and Fig. 2.27, where it is found that the house energy demand is mitigated with the lower amount of grid electricity. The annual thermal power production for space heating is 8050 kWh. Whereas the total space heating demand was 7887 kWh, so it can cover 100% of space heating demand as shown in Fig. 2.26. Normally the hot water demand in winter is comparatively higher than the summer. Similarly, the monthly energy production and demand scenario for the domestic hot water (DHW) is shown in Fig. 2.27 and it was 4817 kWh and 4689 kWh respectively which covers 100% of hot water demand as well. The monthly energy production, demand and temperature in hot water and space heating scenario is shown in Fig. 2.28. The temperature scenario in Seasonal tank upper level, solaar collector, buffer tank, diurnal tank, and hot water tank is shown in Fig. 2.29 which represents that the overall optimization of proposed system and demand. The total thermal energy output of the proposed system is 12855 kWh. Among this amount the 61% energy production is from solar collector and rest of the amount, 39% is from auxiliary boiler throughout the year. The number of the switch on time of electric heater is 3586 yearly, and operation time is 3000 hours, total heat loss is 507 kWh/year, and carbon emission is 3556 kg/year. The availability of space heating and hot water demand is 99.99% and 99.99%, respectively. The total system efficiency is found as 92%.

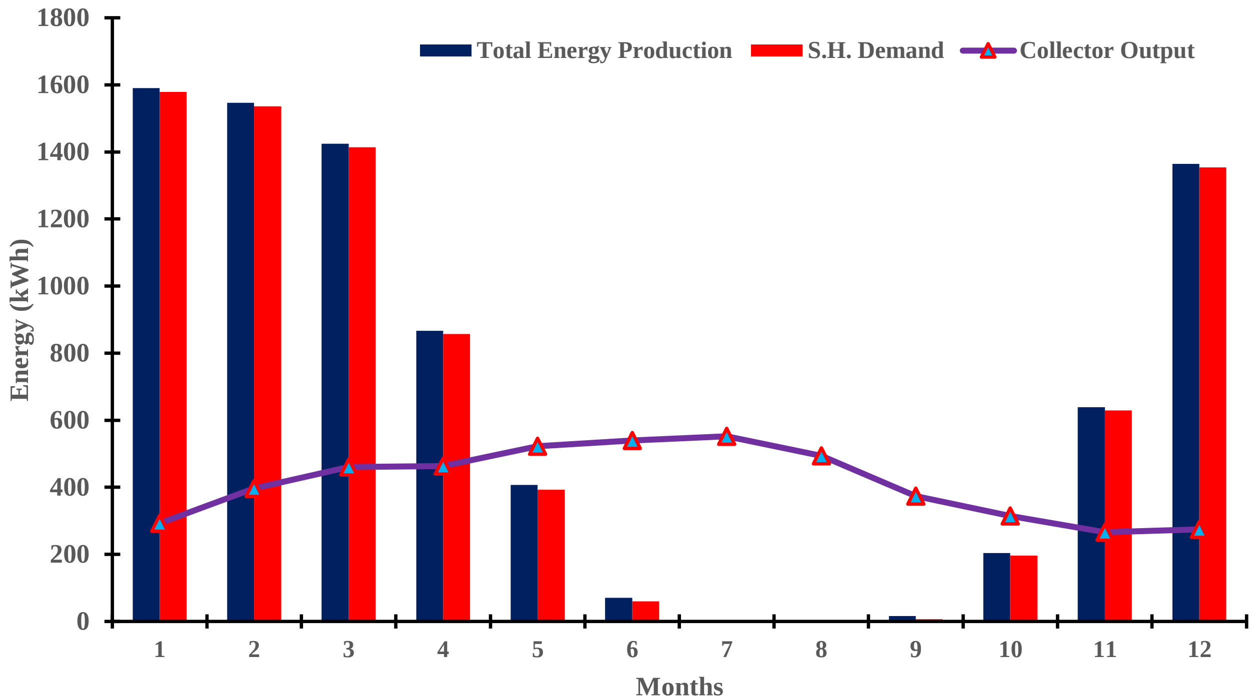

Fig. 2.26 The monthly energy production and consumption scenario for space heating.

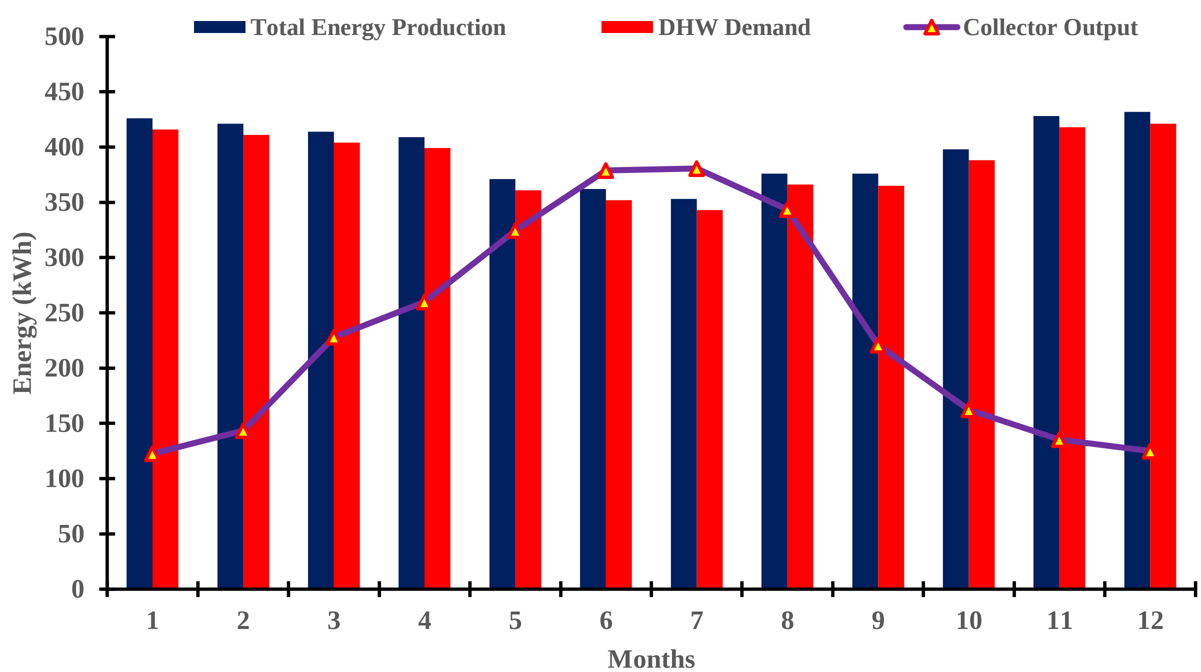

Fig. 2.27 The monthly energy production and consumption scenario for hot water supply

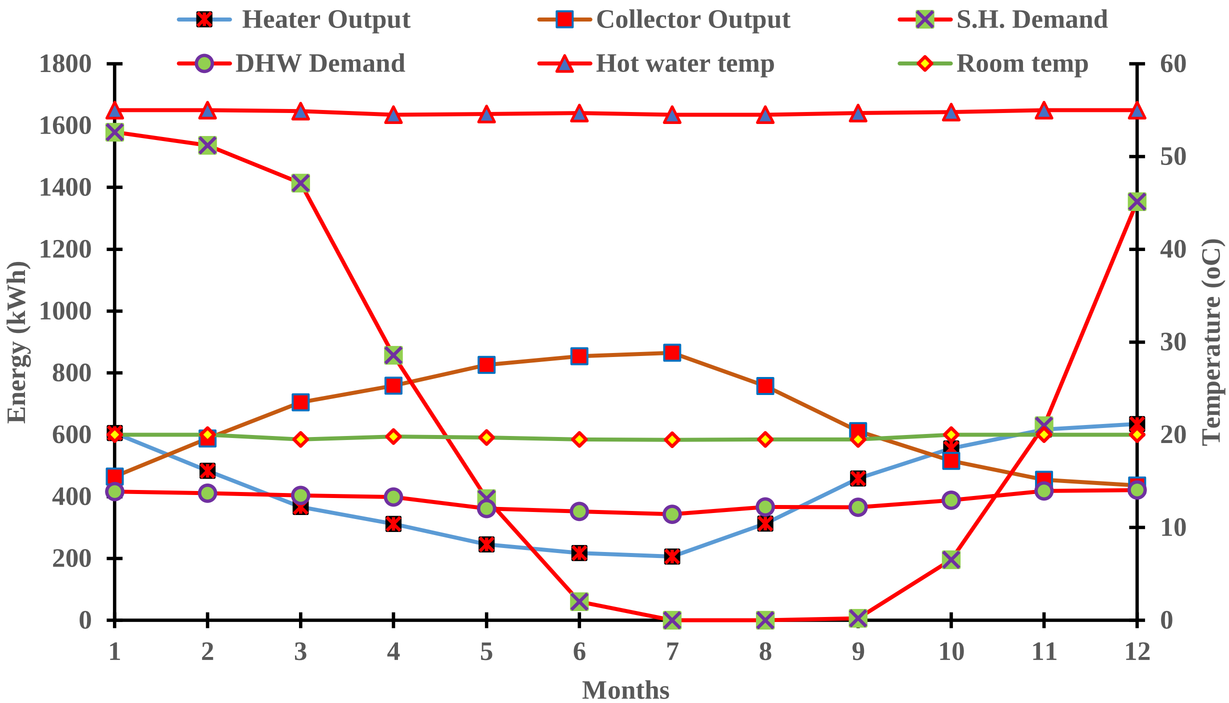

Fig. 2.28 The supply and demand scenario of the Seasonal solar thermal energy storage system

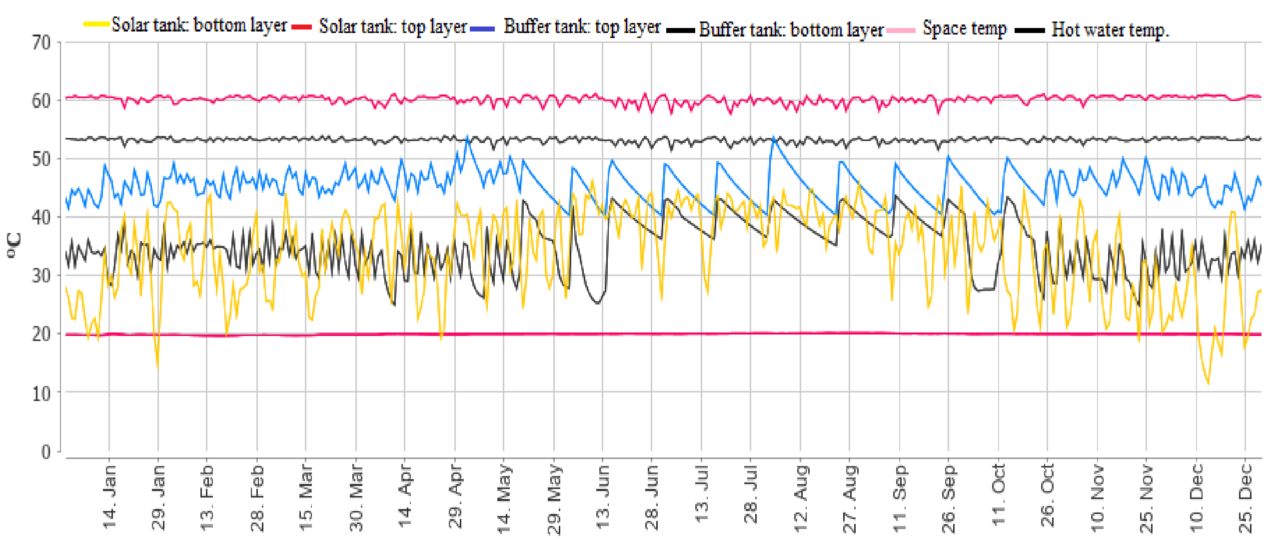

Fig. 2.29 The overall temperature scenario of SSTES systems

2.9. Overall Comparison of Both Systems

The final overview of both configurations is summarized in Table 2.7. The Seasonal solar thermal energy storage systems (SSTES) arrangements are capable of providing the setpoint domestic hot water and space heating as well as the demand for the electric appliances. As there is no renewable source is connected to the existing or reference systems, that's why the grid electricity consumption, Carbone emission is higher. The solar fraction to the hot water and the space heating also varies from configuration to the configuration. In the wintertime, the ambient temperature is mostly negative; that's why the incoming water temperature is too negative, sometimes freezing. To avoid the freezing effect, the incoming water pipe should install in the ground, which is highly recommended in this area. Because of the many advantages like a high solar fraction, lower roof space requirement, lower carbon emission, sustainable and continuous demand mitigation, the Seasonal solar thermal energy storage system (SSTES) is also highly recommended. The energy-saving and all other comparisons are described in table 2.7.

Table 2.7. The overall comparison of PV and collector based systems

particulars	Reference systems (Grid + EH)	SSTES
Total energy demand (kWh)	12873	12573
Space heating temperature (oC)	20	20
Hot water temperature (oC)	55	55
Collector size	N/A	16 m^2
Main tsank size (m^3)	0.189	30
Solar fraction to hot water (%)	0	61
Solar fraction to space heating (%)	0	61
Total thermal energy generation (kWh)	12873	12855
Solar energy production (kWh)	0	7837
Auxiliary heater production (kWh)	12873	5015
CO2 emission (kg)	6224	3556
Electrical energy savings (%)	0	0
Thermal energy savings (%)	0	61%

2.10. Conclusion

In this chapter, a detailed study on the reference house and the Seasonal solar thermal energy storage configurations are conducted through mathematical, numerical, and software analysis. The conventional and SSTES configuration has been tested under the climate condition of St. John's, Newfoundland, Canada. Based on the results obtained, the below conclusions are drawn:

1. It is demonstrated that the change of solar radiation and the ambient temperature are significant for the summer and wintertime for a typical day.
2. A detailed analysis of house energy demand (electrical appliances, domestic hot water, space heating) has been studied.
3. A detailed mathematical model of every component parameters, including the thermal and electrical performance of the reference system and the modified configuration has been developed and analyzed.
4. In the configurations above, solar collector, the auxiliary heater, has been considered as the source of heat and electricity for tank water heating purposes and compared the solar fraction and performance.
5. Finally, the proposed Seasonal solar thermal energy storage (SSTES) system configuration is suitable for the Seasonal energy storage for a single-family residential house in Canadian weather condition because of highest energy savings (100% thermal), lower carbon emission (3556 kg/year), lower rooftop space requirement and other advantages mentioned above. This configuration is very sustainable in supplying domestic hot water and space heating for a residential community as well.

It is also mentioned that if a single-family detached house is modified based on the proposed SSTES configurations, and then the significant portion of the energy demand will be mitigated by using renewable energy. People will see a considerable reduction in electricity bills every month. Besides that, CO_2 emission will be reduced significantly. People need to invest money for the first time as the additional equipment installation cost, but it will return within a few years from the energy saving. The SSTES configurations are practically applicable, profitable, and reliable.

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Chapter 3

Design and Analysis of House Heating System with Storage Using Solar Electric Modules

Preface

An earlier version of this chapter has been published in the IEEE 32nd Canadian Conference on Electrical and Computer Engineering, Edmonton, Alberta, May 5-8, 2019. DOI: https://doi.org/10.1109/CCECE43985.2019.8995175. The extended version of this research has been published in the European Journal of Engineering Research and Science, vol. 4, no. 12, December 2019, DOI: https://doi.org/10.24018/ejers.2019.4.12.1640. In both papers, I am the primary author, and I carried out most of the research work, performed the literature reviews, carried out the system design, and analysis of the results. I also prepared the first draft of the manuscript and subsequently revised the final manuscript based on the feedback from the co-author and the peer review process. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding.

This chapter is a version of -

[1]. H. Rahaman, R. Rasha, and M. T. Iqbal, "Design and analysis of a solar water heating system for a detached house in newfoundland," in 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), May 2019, pp. 1–4, doi: 10.1109/CCECE43985.2019.8995175.

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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.

Keywords: Solar photovoltaic, thermal collector, water heating, space heating, performance, and cost analysis.

3.1. Introduction

Canada has a large landmass and diversified geographical structures which is suitable for many renewable energy resources. 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 photovoltaic (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 6300 MW [4]. There are more than 138 numbers of solar PV farms in Canada with a capacity of at least 1 MW, totaling over 1700 MW, whereas the rest of the energy is produced from the rooftop PV panel. 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 of them. Solar PV and solar collectors can mitigate this energy demand partially or fully.

Solar photovoltaic array (typical efficiency is around 11~16%) can directly convert solar energy into the electric energy, which is directly using for electrical appliances and water heating or space heating. There are some heat losses (around 80~85%) under the panel, and the efficiency is decreased at high or low temperatures [2]. The solar thermal collector (ability is around 60~80%) can convert solar energy directly to heat energy, which is also used for water and space heating, but it is too expensive[3].

The heat energy produced from the solar resources can be sent to the storage tank. The storage tank hot water can directly be used for domestic purposes and space heating purposes. This technology is not new, but recently the researcher found that this is the most economical way to save energy. Similarly, storing solar thermal energy for a long time is not a new technology and has become relatively advanced, and the user can get heat instantaneously[5]. The total available solar radiation is shown in Fig. 2.3, and the hot water and space-heating demand of the selected home is shown in Fig. 2.13 and 2.14, respectively. From those curves, it is found that the demand in winter is higher, but solar radiation is low. The opposite scenario in the summertime, the demand is low, but the radiation is high. That is why for continuous and immediate hot water and space heating supply, the thermal energy storage system with an auxiliary heater is essential. Storing the solar thermal energy for space heating during the peak demand can reduce the overloading of the electric grid that way, the consumer can reduce the monthly electric bill.

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].

3.2. 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 Seasonal energy storage systems. Thus electricity demand will be reduced. For instance, the University of Ontario Institute of Technology built a low-temperature borehole thermal energy storage system (BTES) system in 1990, which had 384 holes, provide the basis for a highly efficient heating and cooling system for eight University buildings [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. Eight hundred solar flat plate panels (2.45 m $\times$ 1.18m) are producing 1.5 MW of thermal power and supply heat to the district heating system. The panels are connected with an underground pipe that carries the heated energy to the community's TES [17].

A large energy-saving building (15000 m^2) was constructed in St. John's, NL, Canada, 25 years ago by East Port Properties. It was the first building in Newfoundland, which to use seawater tides for space heating and cooling with 50% energy efficiency[18]. The Newfoundland government is also focusing on green building energy projects like solar-based thermal energy, storage system design, net-zero energy building, energy efficiency, and many more relating to green energy production [19]. K & P contracting Ltd. first successfully built up a net-zero energy home in St. John's, Newfoundland, in 2013 [20].

Ronald Brakels mentioned that the sun flux company in Australia proposed the newly designed off-grid PV water heat controller that can be manually and automatically controlled from PV or to the grid. Its efficiency is excellent, but this is not suitable for a bulk amount of electricity generation and heating element. Its rating is near 4.00 kW, which is capable of raising the temperature to 3.4^{o}C per hour in a 250-liter water tank [21].

Fudholi et al.[22] analyzed the performance of photovoltaic (PV) and photovoltaic thermal (PVT) and compared the cost, efficiency, and output, he found that the PVT system is efficient than a PV system. However, the problem is that the PVT system cost is much higher than the PV based systems.

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.

3.3. Data Collection and Analysis

3.3.1. 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. In St. John's, NL, the average wind speed is 6.6 m/s. The average daily solar radiation is 3.06 kWh per m^2 per day, which is enough to generate heat or electricity. Based on the HOT2000 software (an energy simulation and design tool), in the selected house location, the annual sum of global irradiation is 1130 kWh/m², and the annual sum of diffuse irradiation is 611 kWh/m². The average minimum and maximum temperature at St. John's NL are the 1°C and 9°C, respectively, as shown in Fig. 3.1.

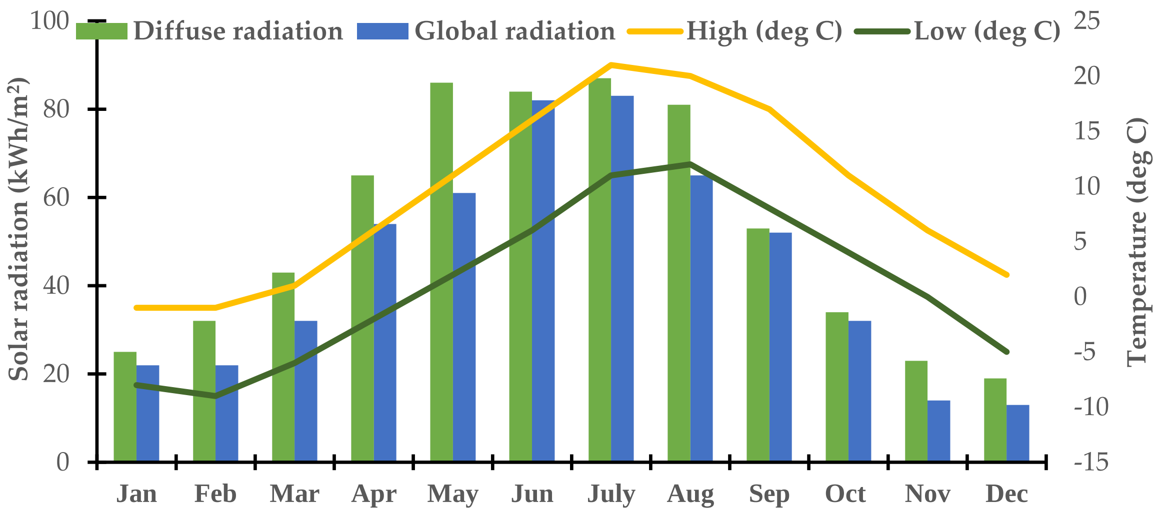

Fig. 3.1. Yearly solar radiation and temperature data

3.3.2 House Analysis

The considered house is a typical single-family house in Canada, and the details of this house are described in Table 3.1. In the tested house, the hot water supplied by an electric boiler and space heating is provided by the grid electricity that is the most common scenario of all Newfoundland single-family houses. Thus the vast grid electricity is required, and consumers are paying a large number of electric bills every year.

Table 3.1. The tested single-family house details

House Particulars	Values
Latitude	47.6
Longitude	-52.7
Facility full size (13.7 m × 9.144 m)	125.27 m^2
Annual energy demand (space heating & domestic hot water)	153.56 KWh/m^2
Hot water temperature	50 ^0C
Space heating setpoint temperature	24^oC
Annual electricity demand (Based on NL power)	19007 kWh
Annual electricity demand (BEopt. analysis)	19511 kWh

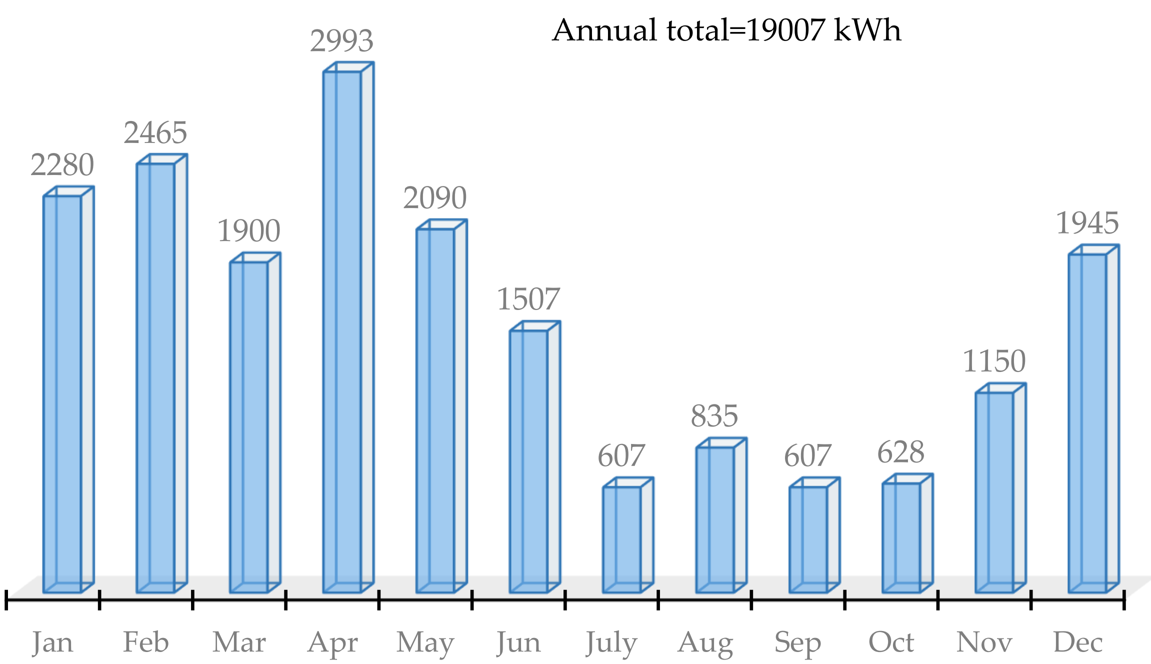

Fig. 3.2. The total actual electricity consumption (kWh), 2017.

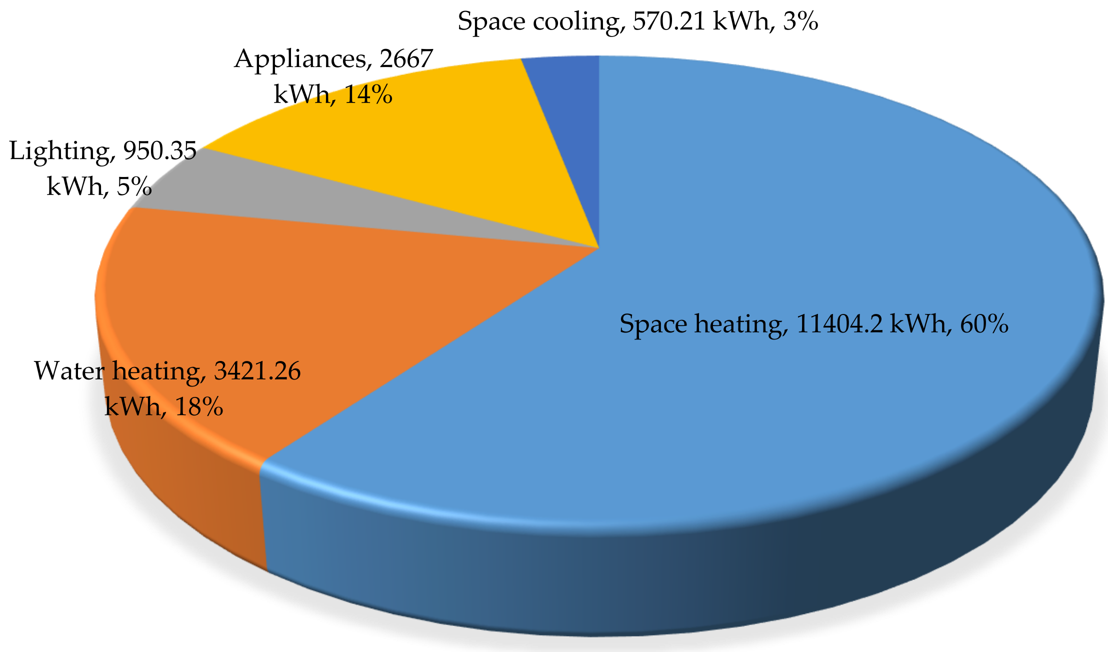

Fig. 3.3. The actual electricity consumption distribution [23]

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. 3.2. The distribution of this consumption shown in Fig. 3.3 where it is shown that the majority of electricity consumed for space heating and DHW.

3.3.2.1 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. 3.4.

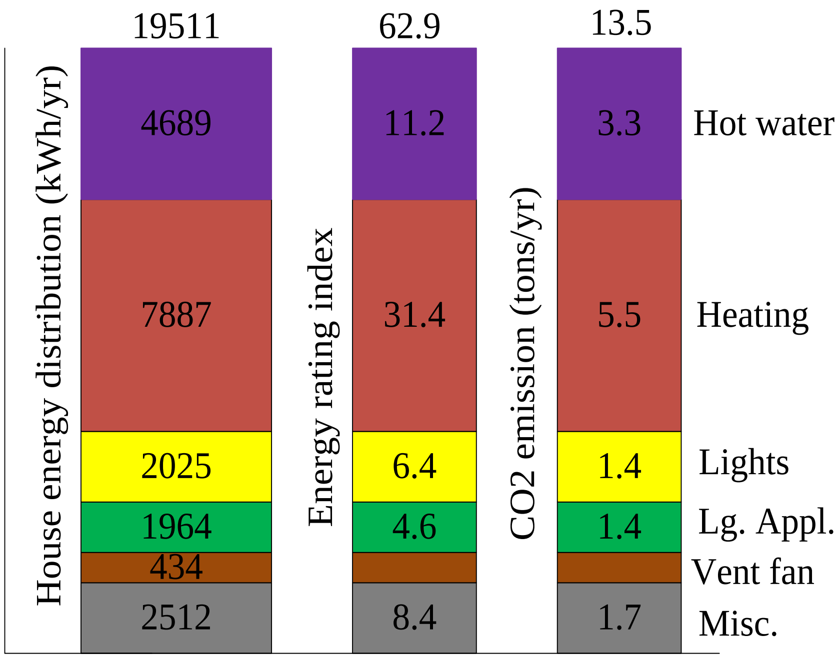

Fig. 3.4. The tested house standard annual energy demand.

It is a result that the actual energy consumption in the house in Fig. 3.2 is almost similar to the electrical and thermal consumption of the house, as shown in Fig. 3.4.

3.4. 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 is connected with two water tanks. As solar energy is always variable, the preheating tank water temperature may not reach the desired value at all times. 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. 3.5.

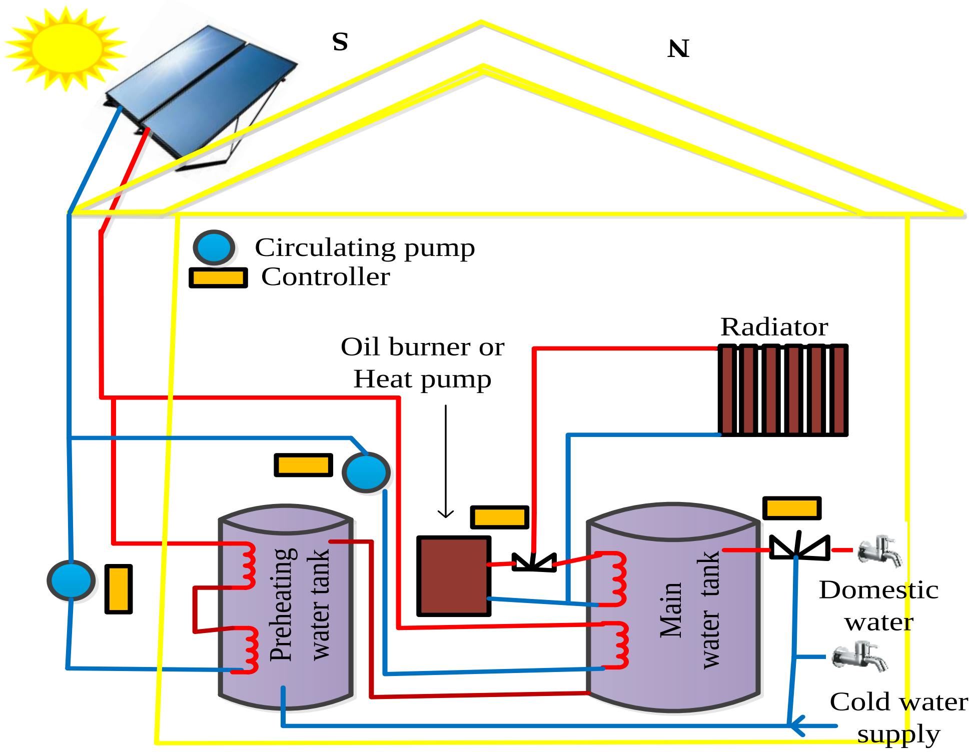

Fig. 3.5. The proposed model for the tested house.

3.4.1 Design of Solar Collector

A solar collector is the primary source of renewable energy in this work. 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). To control the circulating pumps are mandatory for water flow. For enhancing heat transfer, proper design is essential. The DHW distribution scenario is taken for 24 hours, as mentioned in Fig. 3.6. The design calculation for hot water heating is given below [24]:

Beds, B=02 numbers

Occupation, O=200% (considered, four people are living)

Per person hot water demand, DHW= 20 liter/day

Hot water demand in kitchen, HWD_k= 30 liter/day

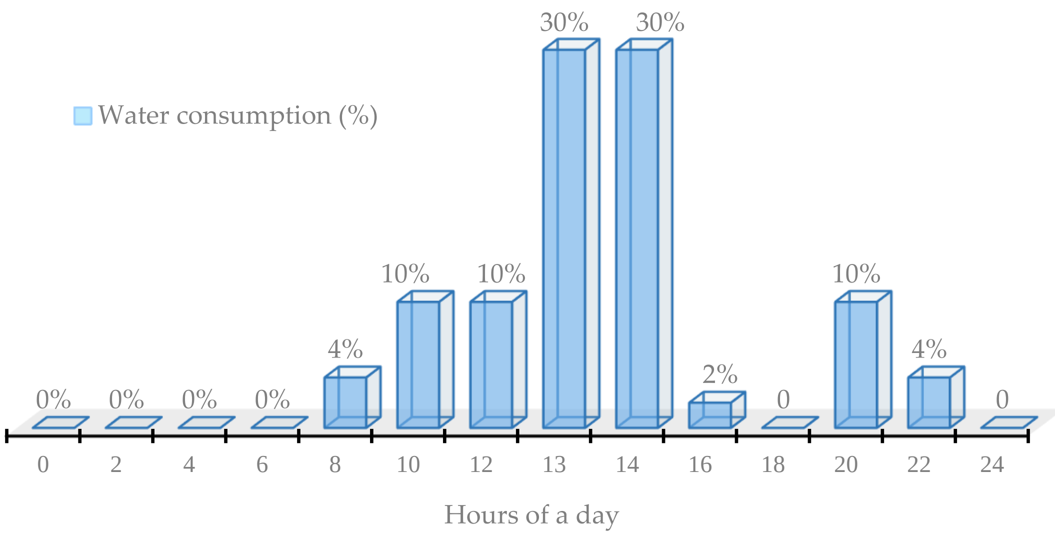

Fig. 3.6. The daily water consumption scenario in the tested house

Coldwater temperature=10 ^{0}C.

Storage hot water temperature= 55 ^{0}C.

Average solar radiation for high solar fractions=3.06 (Kwh/m^2/d).

Storage volume,

$$V_{ST} = [(B \times O \times DHW) + HWD_K] \times 1.2$$

$$= [(02 \times 02 \times 20) + 30] \times 1.2$$

$$= 132 \text{ liter} = 0.132 \text{ m}^3 \tag{3.1}$$

Where B is the number of bedrooms in the house.

O=Percentage of occupation, number of people on average.

DHW= Hot water use per person in the bathroom.

DHW_k= Hot water use by per person in the kitchen.

Energy demand for hot water,

$$Q_S = V_{ST} \times C_p \times \Delta T \tag{3.2}$$

$$= 0.132 \times 1.16 \times 45 = 6.89 \text{ kWh/day}.$$

Where, C_p is the heat capacity of water in kWh/m^{3}K.

ΔT is the temperature difference between hot and cold water.

By using HOT2000 software, the calculated global solar radiation at AM 1.5 for St. John's, NL, Canada and it is $S_r = 2.9$ kWh/day.m^2

Collector yield,

$$C_Y = S_R \times \eta_K \times \eta_{sys} \tag{3.3}$$

$$=2.9\times0.6\times0.8=1.392 \text{ kWh/m}^2.$$

Where $\eta_K$is the collector efficiency and η_{sys} is system efficiency. If 100% solar fraction, the maximum value considered then,

$$\text{Collector array, } C_A = \frac{Q}{C_Y} = \frac{6.89 \text{ kWh}}{1.392\frac{\text{kWh}}{\text{s.m}}} = 4.95 \text{ m}^2 \tag{3.4}$$

The design calculation for space heating given below:

A standard flat plate collector can produce 9085.23 kW/m^2/day [25], and the daily requirement is 202.7 kW/m^2/day

$$\text{The required number of collectors} = \frac{\text{Daily requirement}}{\text{Collecotor output}} = 0.0223 \text{ (m}^2\text{/day)} \tag{3.5}$$

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

The surface area of collector array=No of collectors $\times$ size of each collector in m^2

$$=2.7 \times 1.9 \text{ m}^2 = 5.13 \text{ m}^2 \tag{3.6}$$

AE-21 model solar collector dimension is considered

Total collector area for space heating and DHW=10.08 m^2 $\cong$10 m^2 (eq. 4 and eq. 6).

The collector should be facing the south at an angle of 47^0. As the selected house is on the northern side of the equator, the collector should be placed on the south side of the rooftop [23].

3.4.2 Selection of Water Tanks and Burners

In the existing house, the electric boiler size is smaller because it is supplying the only DHW. The conventional electric heater is supplying space heat. Based on section 4, it is shown that the preheating tank size is 132 L, and the main tank size is 200 L. both models. The solar energy is intermittent, so for maintaining the fixed temperature at the output the auxiliary burner is necessary. There are different types of auxiliary burners available such as a gas burner, heat pump, oil burner, Siemens, hydraulic, air inverter, and air combo. Before selection, the consideration of input and output power of each burner is essential. Among them, the oil burner and the heat pump is popular in NL area. The oil burner efficiency is less compared to the heat pump. The performance of both systems as compared in Table 3.2. The heat pump self-power consumption is also considered a load of the designed house.

3.4.3 Installation Cost Analysis

The setup cost distribution for the solar collector and energy storage system described in Fig.. 3.7.

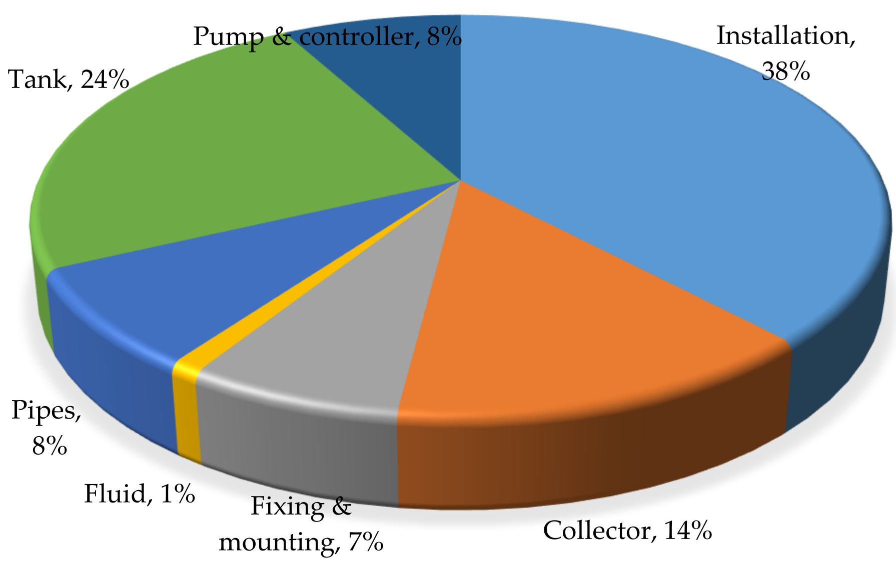

Fig. 3.7. Installation cost distribution by section [26]

The calculation has been done based on the above design and the latest market price according to Amazon.ca

Table 3.2. The cost summary of collector-based systems based on Amazon.ca.

Descriptions	Sizing and prices
The selected collector area (each)	68×48×60 inches=2.1 m^2.
The total area of all solar collector	2.1×5=10.5 m^2.
Tank size (two tanks)	332 Liter
Solar collector cost	5×3000=30000 CAD
Installation costs	30000 × 0.34=10200 CAD
Tank cost	2000×2=4000 CAD
Pipes cost	2400 CAD
Pumps and controllers' cost	2400 CAD
Furnace oil boiler	2200 CAD
Heat pump	3200 CAD
Miscellaneous cost	2400 CAD
Total investment cost with oil burner	53,600 CAD.
Total investment cost with heat pump	54,600 CAD.

3.4.4 Simulation Result

The modified single-family house, as shown in Fig. 3.5 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, such as tank size, types, and house energy demand (DHW and space heating).

The simulation was done carefully for every month of a year. It is compared that the model 2 solar fraction and collector output are always higher compared to model 1. The collector output is available around the year, as shown in Fig. 3.8.

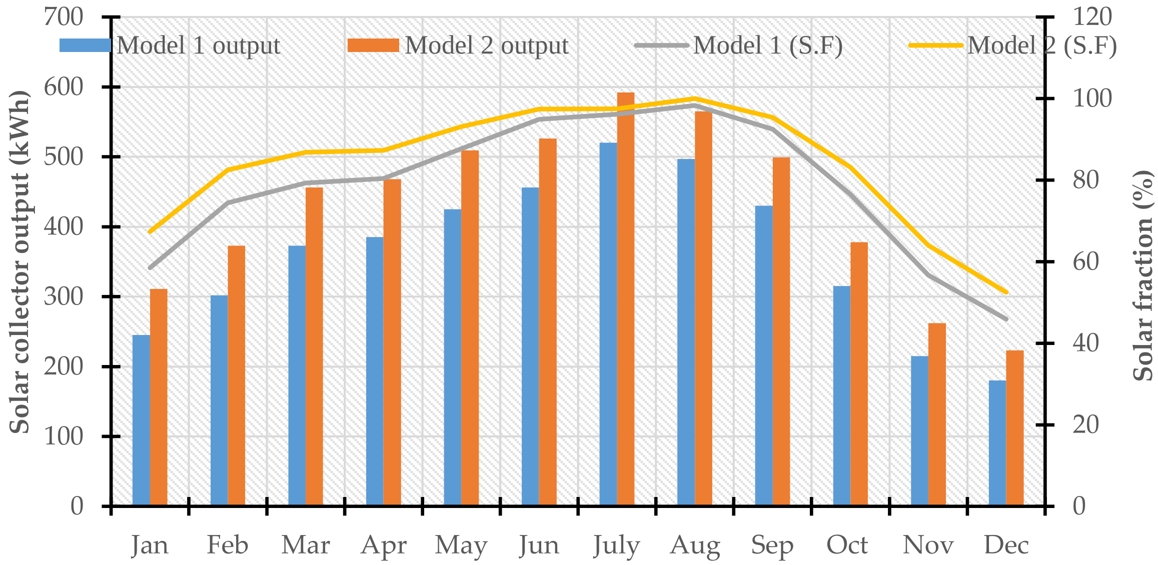

Fig. 3.8. Solar collector and fraction comparison.

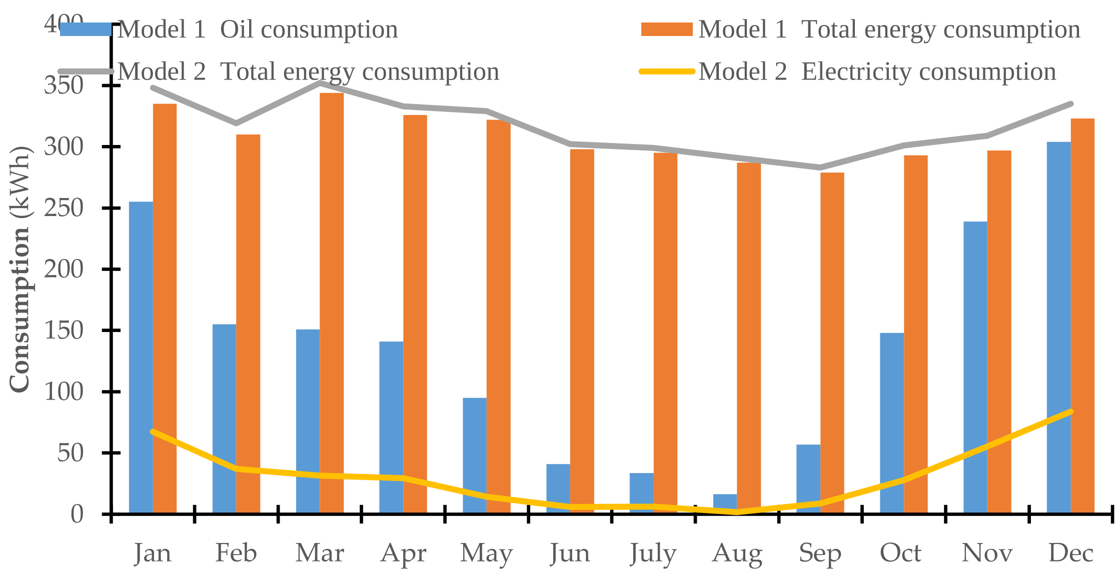

Fig. 3.9. Burners and hot water energy demand

The total system energy consumption is higher with a heat pump than the oil burner. 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. 3.9. Here the total energy consumption means electrical and thermal energy.

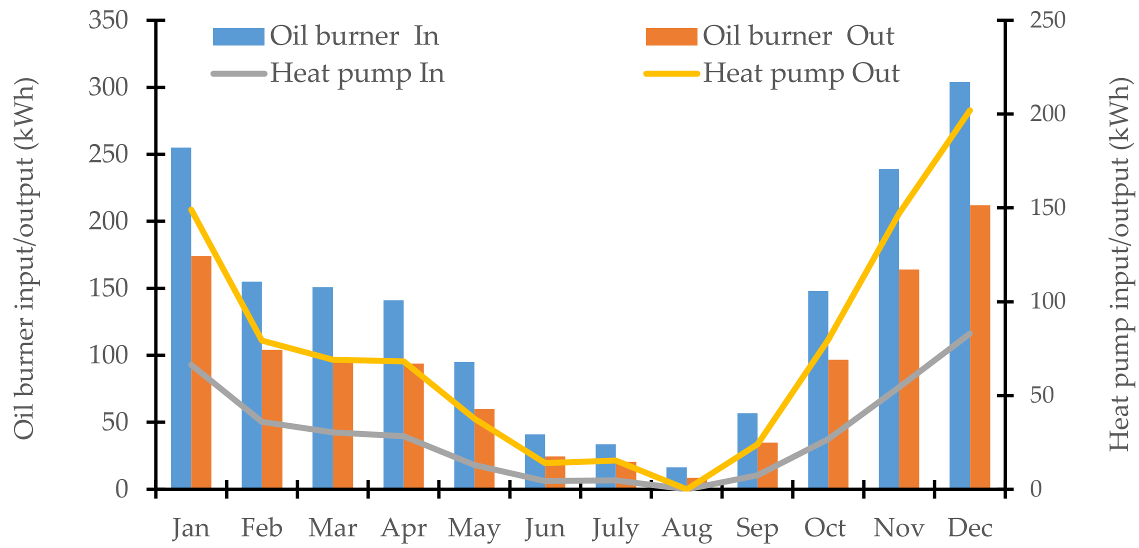

Fig. 3.10. Burner's efficiency comparison.

The input/output data of an oil burner and heat pump is compared in Fig. 3.10. It is compared that the output is much higher to input for the heat pump than the oil burner curve.

The existing house has been modified in two possible ways, such as model 1 and model 2. The performance of both systems is compared in Table 3.3. 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.

Table 3.3. Performance comparison of two models

Basic sections	Particulars	Existing/ reference system	Model 1 (Oil Burner)	Model 2 (Heat pump)
Solar collector	Type	N/A	Flat plate	Flat plate
	Number of collectors	N/A	05 (No tracking)	05 (No tracking)
	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
	Functions	DHW only	DHW and space heating	DHW and space heating

Auxiliary burner	Type, capacity	Electric resistance (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%

Annual output (collector & heat pump system) = 5161 kWh (without tracking)

Annual saving=2090.77×0.387=809.127 CAD.

3.4.5 Performance Analysis

In this research, it is mentioned that if a single-family detached house is modified based on the proposed model 2 (with heat pump), then some portion of the energy demand will be mitigated by using renewable energy. People will see a considerable reduction in electricity bills every month. Besides that, CO_2 emission will be reduced significantly. People need to invest money for the first time as the additional equipment installation cost, but it will return within a few years from energy saving. The proposed system (model 2) is practically applicable, profitable, and reliable.

3.5. Solar Photovoltaic Based System

The central systems in Fig. 3.5 is considered again with the solar PV module instead of solar thermal collector, and the design steps are given below [27]:

3.5.1 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 area of PV panel=0.93 × 0.675 m^2= 0.6277 m^2/per panel

The total area of PV panel= 11.3 m^2

3.5.2 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 area of PV panel=0.93 × 0.675 m^2= 0.6277 m^2/per panel

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.

3.5.3 Sizing of Inverter and the MPPT

For safety purposes, the inverter must be 20-25% bigger size then demand. The detail specification of the PV module described in section 5.4. The maximum power point tracking (MPPT) is optional in this research.

3.5.4 Specifications of Selected PV Panel

There are many companies that are manufacturing the PV module. The detail descriptions of the selected 150 W PV Polycrystalline module is given here: Item Size: 930×675×3 mm, maximum power (Pmax): 150W, the voltage at Pmax (Vmp): 18.2V, current at Pmax (Imp): 8.34A, open-circuit voltage (Voc): 21.6V, short-circuit current (Isc): 9.17A [28].

3.5.5 Control and Monitoring Systems

The description of each PV module has been described in section 5.4. The complete system is shown in Fig. 3.11, and the controller operating principle is described in Fig. 3.12. During the day time, when the sunshine is available, the three-position switch transfers the AC power to the water tank. The temperature of the water reaches the desired temperature (50 ^{0}C) within two hours. 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, when solar energy is not available, it is difficult to maintain the set temperature; consequently, based on the temperature sensor reading, 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 then valve two opens until the tank fills up. The controller will do everything, as shown in Fig. 3.11.

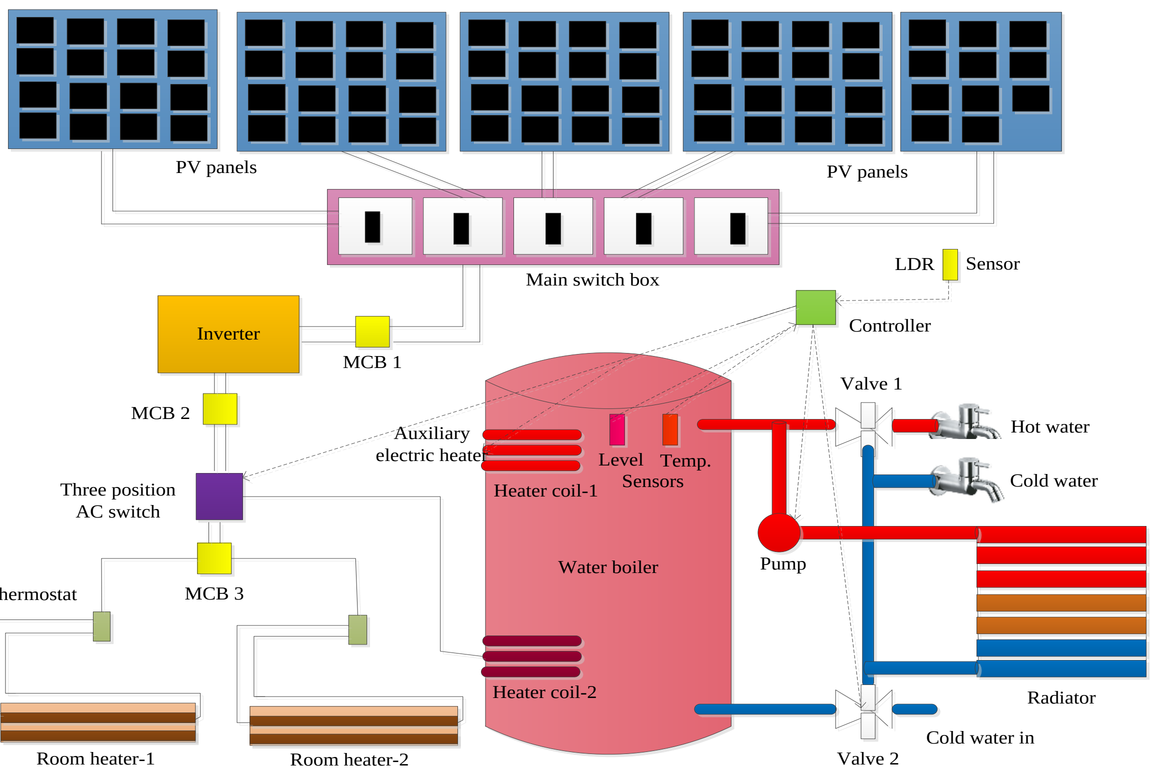

Fig. 3.11. Solar PV based residential water heating and space heating system

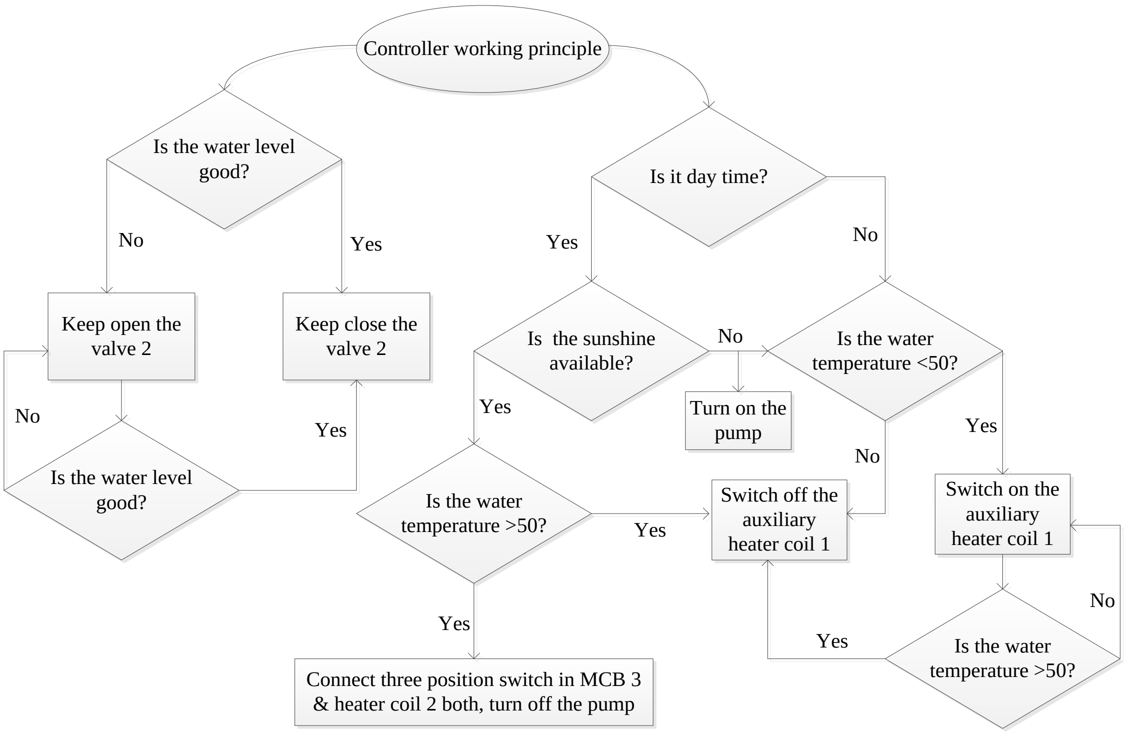

Fig. 3.12. The operating principle of the controller

3.5.6 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..13.

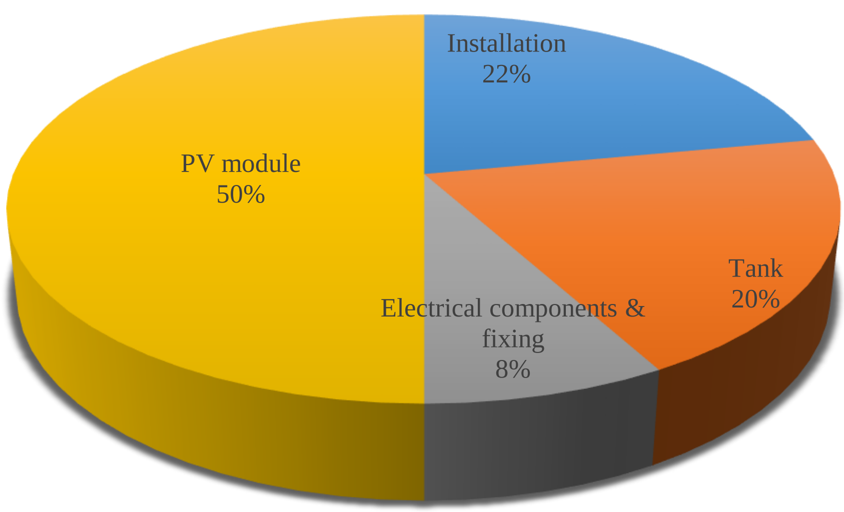

Fig. 3.13. The cost distribution of solar PV based system [22]

The calculation and the total installation cost have been done based on the above design and the latest market price according to Amazon.ca.

Table 3.4. The cost analysis of solar PV based system based on Amazon.ca.

Descriptions	Sizing and Prices
PV Panel cost	150$×70 no's=10500 CAD.
Installation cost	10500×34%=2310 CAD.
450 L of Electric Water Tank with high insulation cost	3000 CAD
Combiner box (6 String, 250 V AC, 10 A each)	12×225 = 2700 CAD
MPPT installation	optional
Inverter cost (12000 W)	3000 CAD
Electrical components and fixing	10500×8%=840 CAD.
The total investment cost	22350 CAD

Time to reach the set temperature (2^{o}C to 50^{o}C)

Thermal power requirement, $Q=(4.2\times332\times(50\text{-}2))/3600=18.60$ kW.

If the two heating element is used with 12.0 kW each, then the time needed to reach this temperature is 18.60/12=1.55 hours.

3.5.7 Simulation Result

The total solar PV based space and water heating system is described in Fig. 3.11. This complete system has been designed and simulated in the PolySun software environment. The total output of all PV modules shown in Fig. 3.14.

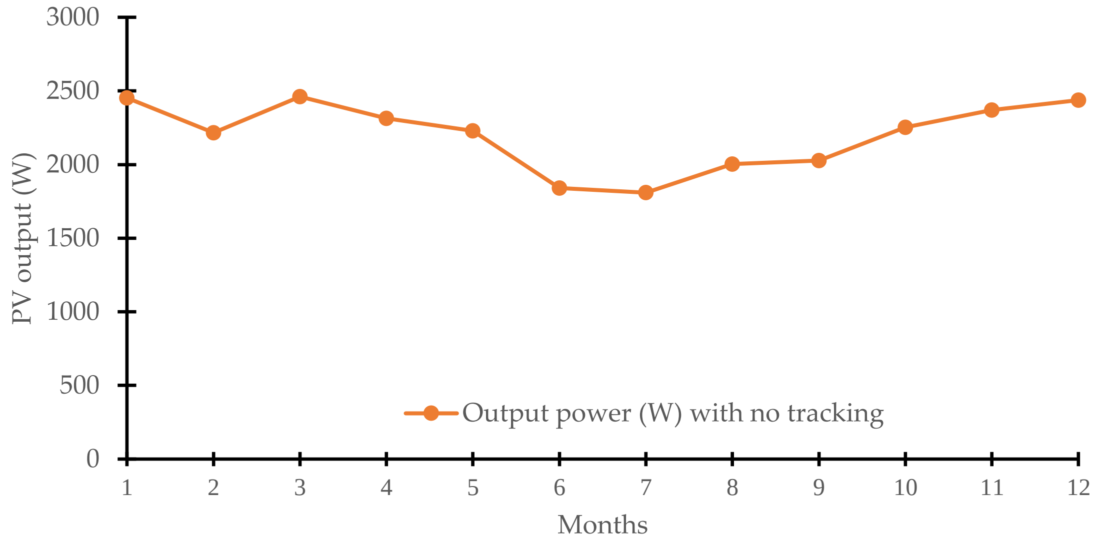

Fig. 3.14. The output power of designed PV panels

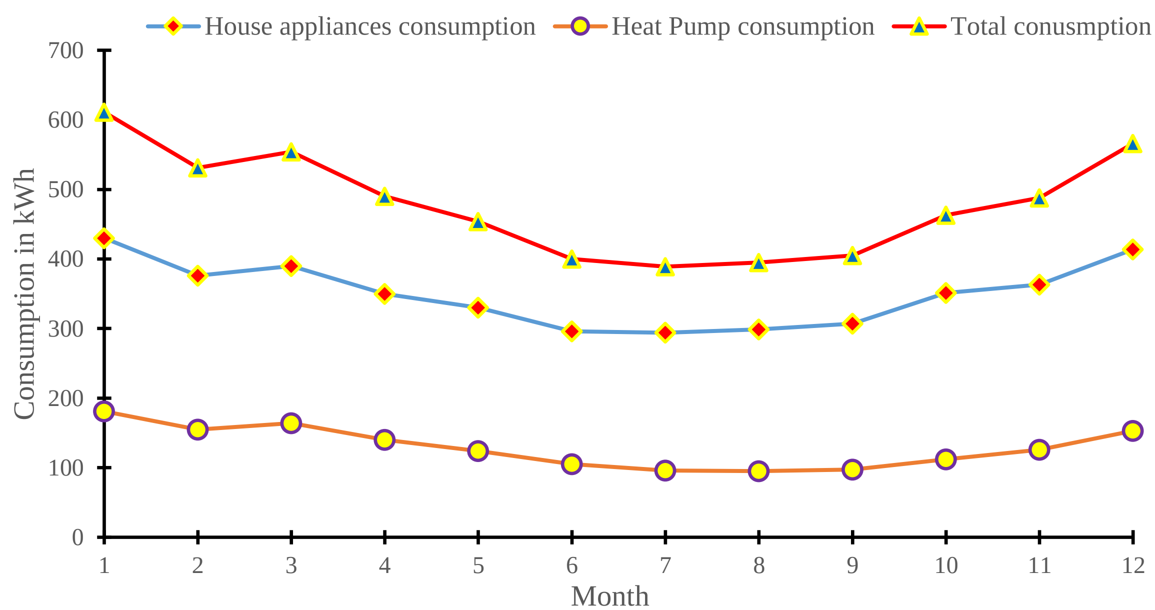

Fig. 3.15. Selected house electrical consumption profile.

The electrical power consumption is given in Fig. 3.15. 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. The whole system has been simulated again with the MPPT and a 12 kW DC battery bank with an on-grid power system network for storing energy for residential appliances..

3.6. Overall Comparison of the 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 3.5.

Every year, the depreciation cost has been considered as 5% of the investment and calculated the total annual savings up to 30 years because the lifetime of the system has been considered as 30 years, as shown in Fig. 3.16. It is concluded that the PV based system is more efficient and economical.

Table 3.5. Overall comparison of PV and collector based 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%)

Although the general efficiency of the solar PV module is around 15~20% and the efficiency of solar collectors is around 60~80% but the summation of 30 years annual savings in the PV based system is much higher than the solar collector based system. The PV based system is much cheaper than solar thermal collectors based systems. The PV based system needs lower maintenance as well.

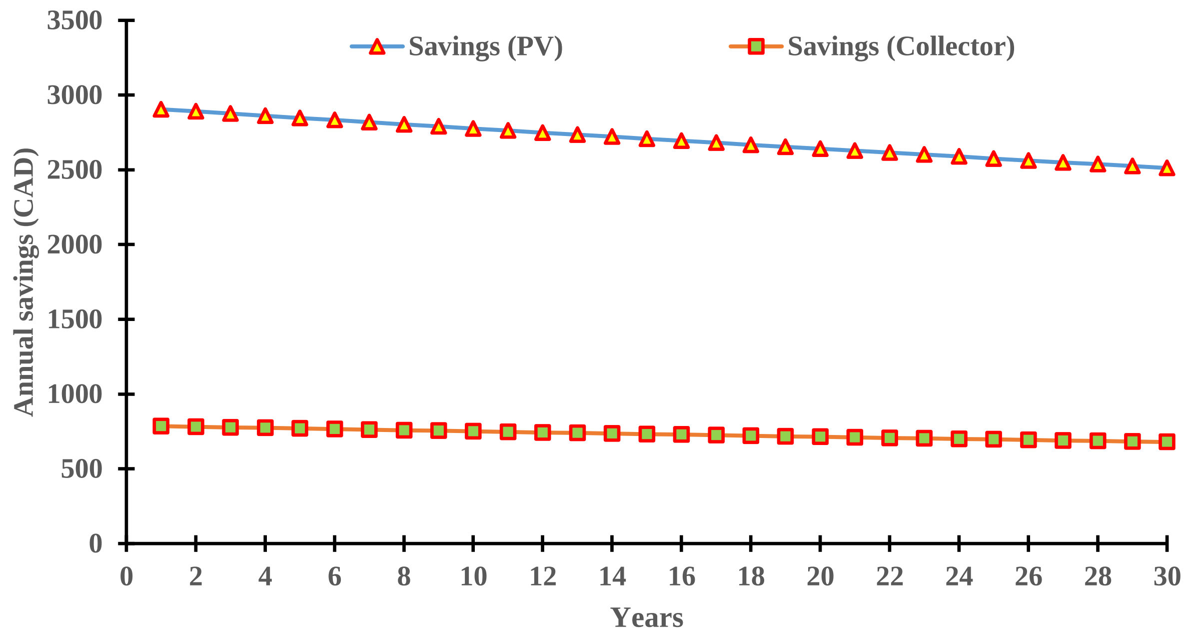

Fig. 3.16. The annual savings comparison of both systems.

3.7. Conclusion

In Canada, 13% of total electricity is consumed by the residential sector, where 81% of electricity is consumed for space heating and water heating purposes. By implementing the solar collector based thermal energy storage system, it is possible to save 50% of electricity. By implementing the 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. Recently the cost of PV panels is reduced significantly. This system is also suitable for other house appliances as well. However, it needs more space for PV panel setup. 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.

Data Availability

The meteorological data used to support the findings of this study are included in the article.

Conflict of Interest

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

Acknowledgment

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Chapter 4

Mathematical Modeling and Simulation of Solar Water Heating Systems.

Abstract

The majority of the electricity consumption in Canadian single-family house is for space heating and water heating. In some cities in Canada, the wintertime is more extended with the worst temperature. Currently, all residential home in Canada using the conventional grid electricity for heating purposes. In this research, two solar thermal energy storage systems have been studied, such as solar collector based and solar photovoltaic (PVT) based. The mathematical modeling, sizing, designing, and simulation has been conducted in MATLAB and PolySun software and determined their thermal and electrical performance of a house consists of four persons in the Canadian climate environment. The detailed working principle and mathematical formulation of each STES system component have been developed. To validate the feasibility and numerical studies of the developed STES systems, the configurations have been simulated in a professional thermal simulation software named PolySun and Matlab/Simulink environment. The STES systems have been tested using the solar radiation data of St. John's city/NL, Canada.

Keywords: Hybrid solar photovoltaic, thermal systems, domestic hot water, solar collector, electric load, auxiliary heater, MATLAB, PolySun.

4.1. Introduction

The renewable energy-based hybrid systems have been recently developed to penetrate renewable generation, reduce greenhouse gas emissions, and flexibly balance the supply-demand requirements.

The total contribution of solar photovoltaic energy in Canada is around 1%, and the installed capacity is approximately 6300 MW[1]. Solar energy is free and a promising technology alternative to fossil fuels to provide electricity or heating for the building. Solar PV and solar collectors can play a significant role in generating electricity and heat, respectively, from renewable resources. Solar photovoltaic (PV) module typical efficiency is around 11~16%; this efficiency can increase by approximately 30% more with introducing tracking systems, although there are some power consumption and cost. The efficiency is lower because of some heat losses in the bottom plate of the solar PV module. There are some heat losses (around 80~85%) under the panel, and the efficiency is decreased at high or low temperatures[2].

Similarly, the efficiency of the solar thermal collector is around 60~80% depending on the manufacturer. Although its effectiveness is higher, but it's too heavy and expensive compared to the solar PV module. There are so many working fluids are available. Among them, the water is considered in this research. The sunlight falls at the collector surface, which will make the circulating water hot, which will be available at the output hot water. This water will flow to the collector to the storage tank loop and will store it at the storage tank through the circulating pump. The storage water will be directly using for electric water heating or space heating.

On the other hand, in chapter 3, we designed a PV based thermal energy storage systems were the large space is required to install PV panels. The large area is needed to install separate PV and thermal collectors to generate electricity and heat, which is not wise; that is why the hybrid photovoltaic thermal (PVT) systems can be a good idea to generate the heat and electricity both[3]. This technology consists of a solar PV panel, coupled with a solar thermal collector installed on the back of the PV panel to preheat the domestic hot water. PVT collector and flat plate collector with thermal energy storage systems can be used together in a system to improve the system efficiency and performance.

The heat energy produced from the solar resources can be sent to the storage tank. The storage tank hot water can directly be used for domestic purposes and space heating purposes. This technology is not new, but recently the researcher found that this is the most economical way to save energy. Similarly, storing solar thermal energy for a long time is not a new technology and has become relatively advanced, and the user can get heat instantaneously[3]. The total available solar radiation is shown in chapter 2, and the hot water and space-heating demand of the selected home are shown in section 5.2.1. From those curves, it is found that the demand in winter is higher, but solar radiation is low. In the opposite scenario, in the summertime, the demand is small, but the radiation is high. That is why for continuous and immediate hot water and space heating supply, the thermal energy storage system with an auxiliary heater is essential. Storing the solar thermal energy for space heating during the peak demand can reduce the overloading of the electric grid that way, the consumer can reduce the monthly electric bill.

Proper design is essential to increase the overall efficiency of a thermal energy storage system (TES). TES system can be designed by considering heating demand, climate conditions, availability of sunlight, storage temperature limit, energy efficiency, and many more. Authors in [4] proved that the effectiveness of the system depends on the heat source, solar thermal panels, transmission loss, standby loss. To maximize efficiency, optimum system design, capital, and maintenance cost consideration is essential. The energy inside of a storage system can be balanced by selecting the solar radiation rate, convective and conductive heat transfer rate, ventilation loss, the specific heat of air, density of air, existing temperature of the storage system, and losses due to heat transfer in various modes [5]. The solar radiation rate again depends on the wall surface area. The insulation of storage roof, solar collectors, and each wall is important in design consideration. The surface insulation again depends on location, orientation, slope, and time and atmosphere transmittance. If the house is not insulated correctly, then a large amount of heat will be lost; thus, efficiency will be decreased. In this case, to know about financial and technical assumptions and power to energy ratio is essential. A superinsulated house with multiple heating strategies is seen in some cold climate zone, as described by [6]. The key design factors are high thermal energy storage capacity, high efficiency, excellent chemical and mechanical stability, reversibility of a large number of charging and discharging cycles, low thermal losses, and ease of control, cost-effectiveness, optimum sizing, and maximum loadability and so on.

The objective of this research is to design a TES system in Matlab/Simulink environment, mathematical formulation and simulation to look into how much renewable power can cover the space heating and domestic water heating. Also, to design a PVT based TES system in PolySun software. To minimize fuel consumption and regular electric boiler consumption, to maximize the energy savings, to reduce carbon dioxide emissions.

In this chapter, two solar thermal energy storage system configurations and possibilities have been introduced for domestic water and space heating purposes for a single-family residential house in St. John's, NL, Canada. The whole systems have been analyzed in many different ways and compared their performances. The numerical analysis, simulation, and results have been presented.

The chapter is organized as follows. In Section 2, the problem description and TES system assumptions and constant has been described in detail. In section 3, the popular software used for TES system simulation have been discussed. The mathematical formulation of all TES components has been described in section 4. The weather data and house energy demand have been analyzed in section 5 and in chapter 2 (section 5.2). The MATLAB/Simulink design and modeling of Solar collector-based system has been shown in section 6. The simulation and result analysis have also descried there. In section 7, the PVT based TES system modeling, simulation and result analysis have been conducted. Both system performances, energy production and demand mitigation are discussed in section 6 and 7 respectively. Finally, the conclusion is drawn in section 8.

4.2. Problem Description and Assumptions

In this study, only solar thermal energy storage systems have been considered. A residential house has been selected as an example, and the schematic diagram of the physical problem has been shown in chapter 2. Currently, the hot water and space heating is coming from an electric heater and an electric hot water tank. The majority of electric bill and energy consumption is for space heating (60%) and hot water (18%). In our previous study, we designed three solar thermal energy storage systems and verified which system will be more energy-saving i) solar collector [7] or ii) solar photovoltaic (PV) [8] based and Seasonal solar TES system in chapter 2. It was concluded that the solar PV based proposed system is cheaper and more energy-saving, but it will not work at the off-grid system, and the designed total PV arrays area were extensive (43 m^2). The solar collector-based system and Seasonal solar TES system performance were excellent, but those are very expensive. Now the same house and TES system have been redesigned with Matlab/Simulink software environment to see the performance difference.

Similarly, another design with a hybrid photovoltaic thermal (PVT) water-based collector, external auxiliary heater, storage tank, pumps short term thermal energy storage with the necessary control systems has been presented. Based on the weather condition, only the renewable energy source may not be enough to mitigate the electrical appliances demand, hot water demand, space heating demand for 24 hours around the year. That's why the external auxiliary heater has been considered. It is the objective the TES system will mitigate the house energy demand, will keep the room temperature as consumer desired, will reduce the monthly bill and CO_2 emission. TES configurations will work on the same weather data (solar radiation, wind speed, and ambient temperature) located at 5, Blue, River Place, St. John's, NL, Canada.

The thermal energy storage systems have been developed in the present studies is based on the following assumptions[9]:

1. The water flow has been considered under steady-state conditions.
2. The tube flow has been assumed fully developed flow.
3. The PVT and collectors layer temperature has been neglected.
4. All other parameters have been assumed; temperature independent.
5. There is no heat gain (or loss) when the water through the pumps and pipes.
6. It is assumed that there is no shading and dust on the PVT and collector panel.

4.3. TES System Simulation

The complete system can be designed at various simulation and optimization software such as TRNSYS, ESP-r, POLYSUN, TRNSOL, MINSUN, SOLCHIPS, MATLAB, DYOMLA, SmartStore, EnergyPlus, eQuest, HVACSIM+, GeoStar, GetSolar (GR), Fortran. Among them, TRNSYS, MATLAB, POLYSUN, KALKENER, TRANSOL are also very useful software to design, calculation, optimization, and simulation of solar-based TES systems. To work with some software, commercial and numerical calculation codes may be used, such as TRNSYS, MINSUN. TRANSIT with ESP-r software has been applied in Canada Drake Landing System. SOLCHIPS has some own building function that is predesigned, and the existing system cannot simulate. For a single-family detached size residential building, Visual Basic may be used for simulation to analyze the performance and design of ground heat pump and UTES system.

The control system can be designed by the embedded system, DSP board, Texas instrument C2000 microcontroller, and many more. To develop a robust remote control system is also possible. Authors in [10] suggested a predictive optimal controller, which is also efficient and cost-effective. This controller works in discrete time steps so that the load and weather information can be known easily. CanmetENERGY's is the most important thermal research and development software for sizing the system for getting the maximum solar contribution based on the French research center CSTB report. The detail description of some potential software's is given below:

TRNSYS: This software is developed by thermal energy system specialists, LLC, USA. It is a flexible, graphically based software environment that is used to simulate the transient systems. It has two parts; the first part is called the kernel, which read and process the input file, solves the problems, and plot the system variables. It determined the thermos physical properties. The second part is called the library, which includes more than 150 models/components present such as pumps, wind turbines, electrolyzes, weather data processors, and basic HVAC equipment, and so on.

TRNSOL: TRNSOL is developed by Aiguasol and the French research center CSTB in 2004. It is a solar thermal energy-based software which is used to design, calculation and optimization of solar thermal systems. It is very user-friendly, and it does a dynamic simulation like the TRNSIS engine.

POLYSUN: POLYSUN is a professional solar thermal energy-based software which is mostly used in designing and sizing. It has extensive components library databases such as collectors, tanks, and pumps, and so on. It is a powerful software platform for the simulation-based planning, designing, and optimizing of comprehensive energy systems for buildings and district heating systems. Thermal energy storage system design, components sizing, simulation, report generation, system comparison, control structure, and techno-economic analysis can be conducted.

4.4. Mathematical Formulation

In this section, the mathematical model should be developed for the basic components like solar photovoltaic thermal, solar collector, storage tank, heat pump. Based on the mathematical model, the total electrical energy output, thermal energy output, energy consumption, electrical and thermal efficiency, and storage tank temperature have been estimated and tried to compare with the total energy demand for a single-family residential house considering four people living in St. John's, Newfoundland, Canada. The mathematical model of each system component has been developed below.

4.4.1 Solar Collector Based Systems

In literature, lots of research can be found about design and sizing, but very few of them discussed to design of the efficient controller. To improve the efficiency of TES, proper, and optimize controller is mandatory. Authors in [10] invested that three main parameters may be considered mainly such water temperature control, auxiliary burner control to keep reference temperature with hysteresis control, and water pump control to control the circulation of water. To serve this purpose, a central monitoring and control can be developed which will monitor all sensor temperatures and will control the circulating pumps, valve relays and thermostat locally and/or remotely. The controller can be designed by power electronics such as dc-dc converters, inverter-based drives, and other existing hardware. The other function of controllers is that it takes monthly solar radiation data and optimize the off and on-peak periods of electric heating. The control system automatically adjusts the collector temperature and set the desired temperature. TES system has three temperature limits such as low, medium, and high. Solar collector always sends temperature, when the temperature of TES goes to the minimum, it starts charging, and when it crosses the maximum temperature, it cannot be charged. The rest of the energy goes to the electrical grid. If the sunlight is not available for a few days, then some heat may be supplied to the TES system through an auxiliary burner. The whole system can be controlled by the predefined command of the central controller [11]

The performance of various collectors has been compared in [12], and among all of them, a flat plate collector is popular, cheap, and considered in this research.

The well-known equation of the collector [13] is given below:

$$\frac{\mathbf{dT_{co}}}{\mathbf{dt}} = \frac{\mathbf{A_c \eta_o}}{\mathbf{C}}\mathbf{I_c} - \frac{\mathbf{U_L A_c}}{\mathbf{C}}(\mathbf{T_{av}} - \mathbf{T_{ca}}) + \frac{\mathbf{\dot{v}_c}}{\mathbf{V_c}}(\mathbf{T_{ci}} - \mathbf{T_{co}}) \tag{4.1}$$

Where, T_{ci} is the temperature of entering fluid, T_{co} is the temperature of leaving fluid, T_{ca} is the temperature of ambient fluid, A_c is the collector surface area, I_c is the irradiance, U_L is the overall heat loss coefficient (7 W$\mathbf{m^{-2}K^{-1}}$), $\boldsymbol{\eta_o}$is the collector optical efficiency (80% considered), C=$\boldsymbol{\rho_c v_c c_c}$ is the overall heat capacity where $\boldsymbol{\rho_c}$ is the fluid density, $\boldsymbol{c_c}$ is the specific heat capacity, $\boldsymbol{v_c}$ is the collector volume. Again, T_{ci}, T_{ca}, $\boldsymbol{v_c}$ are the input parameters, T_{co} is the output variable.

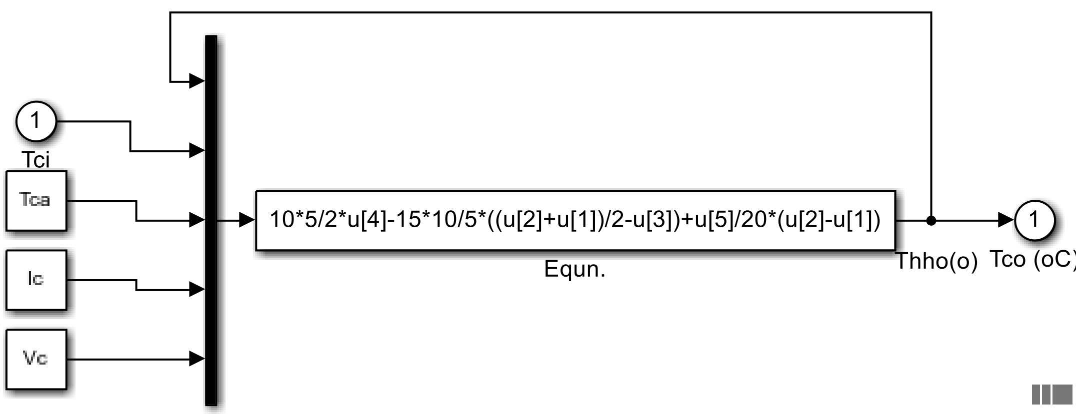

Fig. 4.1 The solar collector modeling

4.4.2 The Heat Exchanger

A heat exchanger is used in almost all thermal energy storage systems which is used to transfer the energy collected in the heat transfer fluid from the solar collector to the storage tank (it can be placed either externally or internally). Heat exchanger functions are to transfer heat in between two or more mediums, in cooling and heating purposes. There are several types of the heat exchanger available such as tub pipe, shell-in-tube, coil-in-tank, wraparound-tube and wraparound-plate, sidearm design, plate type, double pipe type, parallel flow heat exchanger, counterflow, adiabatic wheel, plate fine, pillow plate, fluid type, dynamic scraped surface, phase change, direct contact, microchannel, micro-scale, micro-structured, helical-coil, spiral type and so on.

Fluid circulates through the inner tube while the other fluid moves in a different direction in the space between inner and outer tubes, then heat transfer occurs. A TES system with a heat exchanger can experience a 10~20% loss in total efficiency. However, these losses can be minimized with economic savings and introducing fail-safe freeze protection systems. To reduce the galvanic corrosion effect, copper, brass, or similar alloys types materials can be used as the heat exchange materials.

For geothermal heating, normally plate type heat exchanger is preferred because of easier maintenance, and its heat transfer coefficient is three to four times than shell and plate tube units. It consists of some separate plates with a large surface area [14]. For small to large scale industries, the double pipe heat exchanger is used because of simple, cheap for design and maintenance. Shell and tube consist of a series of tunnels where hot water flows through the one side tube, and cold-water flows through the other side so that they can exchange heat. These types of exchanges are typically used in high pressure (more than 30 bar) and high temperature (more than 260^{o}C) applications. There are several factors in designing this exchanger, such as optimum tube diameter, thickness, length, pitch, corrugation, layout, baffle design [15]. By tracking the overall heat transfer coefficient, the online monitoring of heat exchangers can be done. The value of the overall heat transfer coefficient can be declined due to the fouling effect (the rate of particle deposition). The value of this coefficient can be calculated periodically by considering the exchanger's flow rates and temperatures. If it is lower than the exchanger should be cleaned for better performance. To achieve optimum process operations, among many types, it is essential to select a suitable heat exchanger for a specific site. It's size ultimately depends on the TES system sizes and heat transfer capabilities, flow rates, and the fluid incoming and outgoing temperature. For a certified system, normally, manufacturers have seized the heat exchanger so that its performance will be matched with the system. However, the undersized heat exchanger may affect the overall system performance.

Heat exchangers have a variety of apparatus. Heat exchangers are available in a wide range such as plate surface area from 0.04 to 0.56 m^2, heat exchanger area from 0.16 to 2750 m^2, diameter range from 32 to 200 mm, temperature range up to 180 ^{0}C, Airflow rates from 500 to 100 000 m^3/h and heat load capacity from 0.02 to 16 Gcal/hr. Water to water heat exchanger heat load capacity up to 16 Gcal/hr and steam to water capacity is 13 Gcal/hr [15]. In a small single-family detached house commonly plate type heat exchanger is used because its thermal efficiency is more than 80%, low cost, low energy consumption, low environment hazard, lightweight, easy installation, and easy maintenance. For minimizing rigidity and leakage, the plates are sealed with a double sheet metal fold. Recirculating box based exchanger may choose for more cost savings. The tested single-family detached house area is 13.716 m$\times$ 9.144 m= 125.42 m^2=1350 ft^2. By using this area, the heat exchanger can be designed.

The collector hot fluid, T_{hho} is flowing to the heat exchanger and oppositely the cold fluid, T_{hhi} is flowing to the collector. Similarly, the cold side parameters are $T_{hci,}$ the fluid return temperature from the tank to heat exchanger, and T_{hco} is the fluid return temperature from the heat exchanger to the tank. The schematic diagram of the heat exchanger is shown in Fig. 4.2

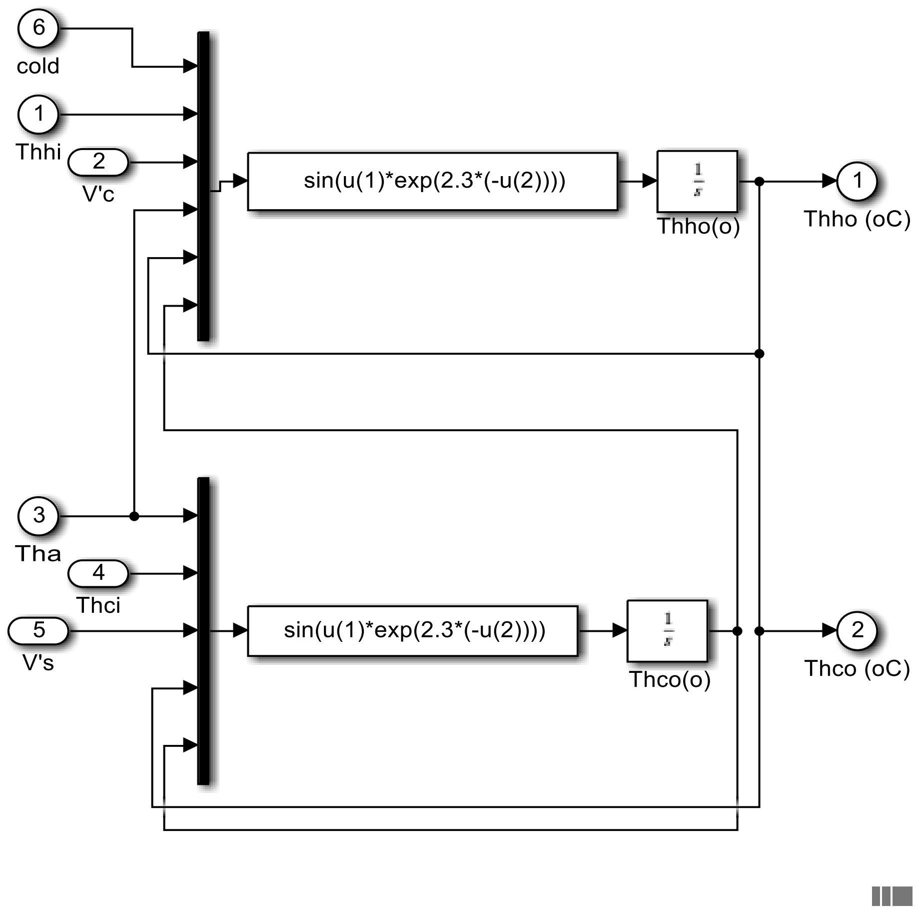

Fig. 4.2 The Simulink model of the heat exchanger.

4.4.3 The Storage Tank

The storage tank is an important part of thermal energy storage systems. In a direct system, the freshwater circulates from the storage tank to the collector again back to the storage tank; this is called a solar collector loop. So, no heat exchanger is needed in this type of system. The water is used as a fluid in the designed systems, and this type of system is called the latent heat TES systems. In the indirect system, where the heat exchanger is necessary. The fluid circulates from the collector to the heat exchanger loop, and heat is transferred to the water tank from the heat exchanger to tank water. The multilayer water-based storage tank has been considered in this research where the two inlets are considered one is for cold water, and another one is hot water inlet from the heat exchanger. The energy flow of the water tank is affected by the two flows, one side is the collector loop and the other side is the demanding loop. There are two outlets has been considered in the demanding loop, one is for hot water supply, and another one is for space heating purpose. In this research, the various combinations have been performed with the storage tank like the circulating pump, heat exchanger, and radiator. Sizing of the water tank depends on water consumption. Since the solar radiation and the water consumption are in the various schedule as mention in Chapter 2, the time difference needs to be bridged, that's why the storage tank size and water volume should be larger then the conventional storage tank and an auxiliary heater (heat pump or electric heater) are needed [16]. However, the large storage tank needs more energy to reach the water temperature to the setpoint temperature, and the energy loss is more too. The size, capital cost and loss must be optimized. The aperture area and the volume of the storage tank are calculated using a trial and error approach to meet a desired solar fraction. Conventionally, a 0.2 m^3 water tank is installed in the house premises but in this research, for a single-family with four people houses, to mitigate the demand, 0.189 m^3 water tank is considered in this research and simulation. The MATLAB/Simulink design and connection of the water tank and heat exchanger are shown in Fig. 4.3, 4.4 and 4.5 respectively.

The output parameters of the considered system are T_s is the water temperature, and the input parameters: T_{sa} is the storage tank ambient temperature, T_d is the cold water supply to the tank, V_s is the tank volume. The detail description of the governing equation for storage tank can be found in [13] which is given below:

$$\frac{dT_s}{dt} = \frac{\dot{v}_l}{V_s}(T_d - T_s) + \frac{\dot{v}_l}{V_s}(T_{hco} - T_s) - \frac{A_s k_s}{\rho_s c_s V_s}(T_s - T_{sa}) \qquad (4.2)$$

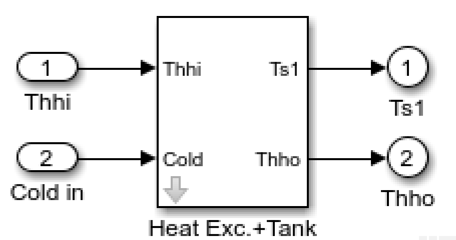

Fig. 4.3 The block diagram of the heat exchanger with a storage tank (indirect system)

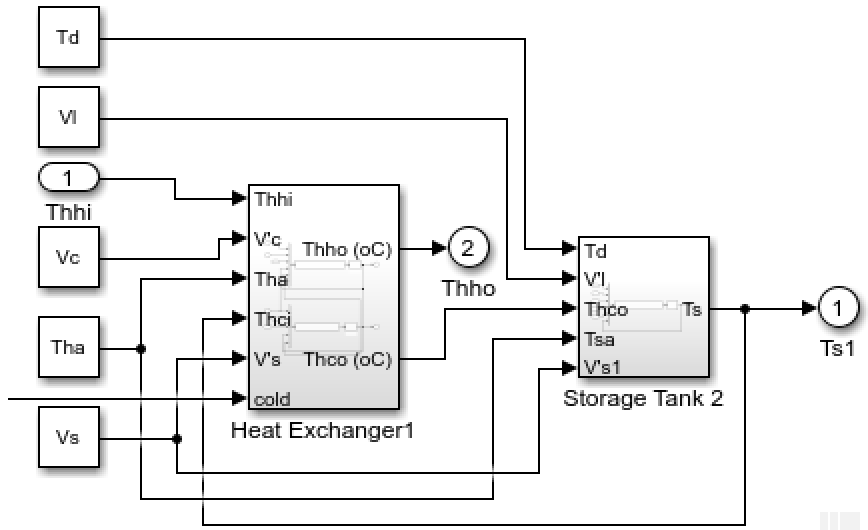

Fig. 4.4 The details connection between the heat exchanger and storage tank.

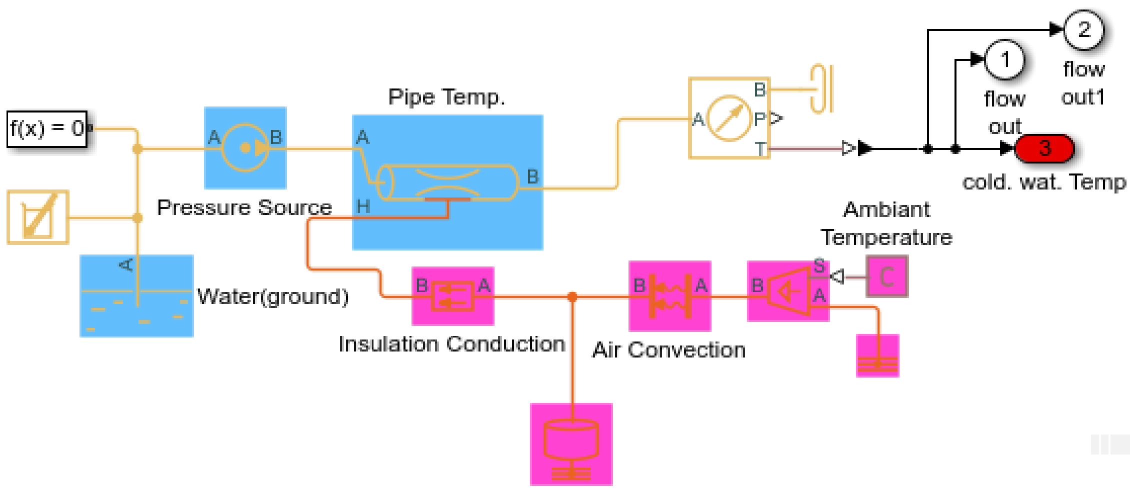

Fig. 4.5 The Simulink diagram of city cold water supply to the tank.

4.4.4 The Circulating Pump

The circulating pump transfer the fluid from the solar collector to the tank and from the tank to solar collector and radiator, as shown in Fig. 4.6 [17]. If the pump is in operation mode, then the heat exchanger hot side outlet temperature, T_{hho} is equal to the collector inlet temperature, T_{ci} otherwise $T_{ci} = T_{ca}$.

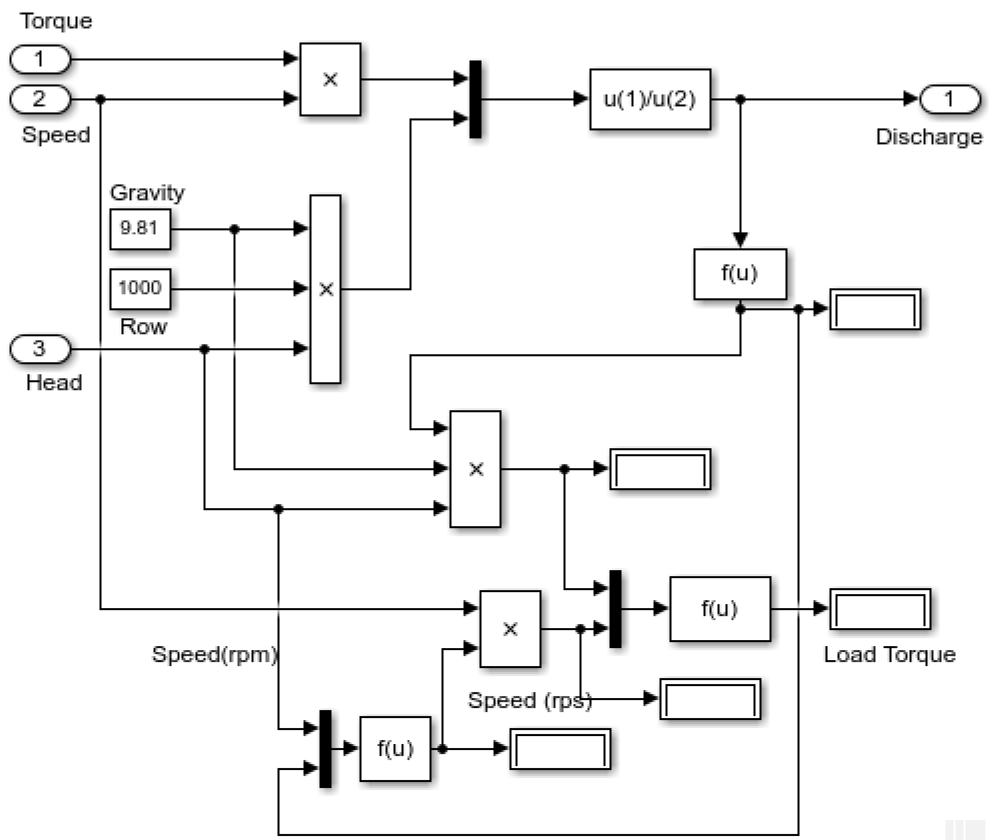

Fig. 4.6 The modeling of circulating pump.

In this research, the pump On/Off control was used. The upper and lower band temperature is 3 °C. The fluid flow rate is given below:

The flow rate in the collector to storage tank loop[13]:

$$\dot{v}_c = \begin{cases} 2.9 \times 10^{-5}\ \mathrm{m^3\ S^{-1}} & \text{when } T_{co} \geq T_s + 3 \\ 0 \quad \mathrm{m^3\ S^{-1}} & \text{when } T_{co} \leq T_s + 3 \end{cases} \tag{4.3}$$

The Simulink model of this flow rate loop is shown in Fig. 4.7 (a)

The flow rate in the storage tank to the radiator loop:

$$\dot{v}_c = \begin{cases} 5.9 \times 10^{-5}\ \mathrm{m^3\ S^{-1}} & \text{when } T_{co} \geq T_s + 3 \\ 0 \quad \mathrm{m^3\ S^{-1}} & \text{when } T_{co} \leq T_s + 3 \end{cases} \tag{4.4}$$

The Simulink model of this flow rate loop is shown in Fig. 4.7(b) The complete system overview is shown in Fig. 4.14 where the meteorological and ambient parameters and the other operational parameters of the system has been taken from the Table 4.1.

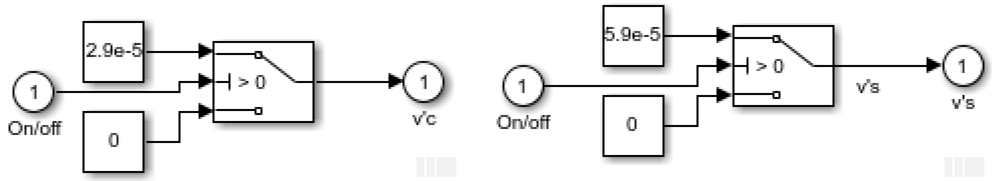

Fig. 4.7 The flow rate controller modeling

4.4.5 The Auxiliary Electric Heater

The main function of the auxiliary heater is to provide the instant heat supply to the tank when needed. In chapter 2, section 5.2.1, we know that the consumer needs the space heating and water heating at around 24 hours, but the solar radiation varies over time. The solar radiation in the summertime is normally available in the daytime, but at the wintertime, even day time, it is not available; the sky becomes cloudy. That's why for continuous heat supply, an auxiliary heater is necessary. It will automatically begin to function as soon as a certain temperature level is not sensed by the solar thermal portion of the systems. The auxiliary heater can be many types such as electric, oil burner, gas burner, heat pump. Among them, the electric heater [18] is considered in this study and it's Simulink model is shown in Fig. 4.8.

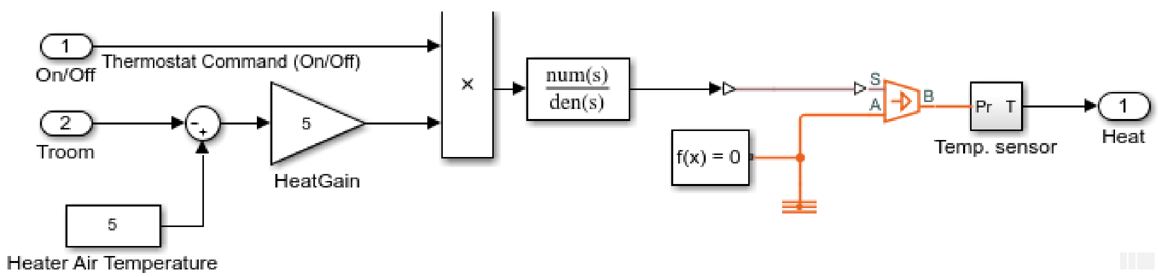

Fig. 4.8 The Simulink model of an electric heater.

4.4.6 The Controlled Valve

The valves are used to protect and control the TES system from overflow, overheating. When it is turned on, then hot water will flow from the storage tank to the radiator, and if the consumer sets the thermostat in such a way that they do not need any space heating, then the controller controls the valve to close it and vise versa. Similarly, the tank water level is always monitoring by using a level sensor; if the level goes below the threshold, then the incoming water valve is opened, and city water will enter into the storage tank. When the water level goes to the upper level, then the controller will close the valve, and the city water flow will stop. The Simulink diagram of the valve is shown in Fig. 4.9.

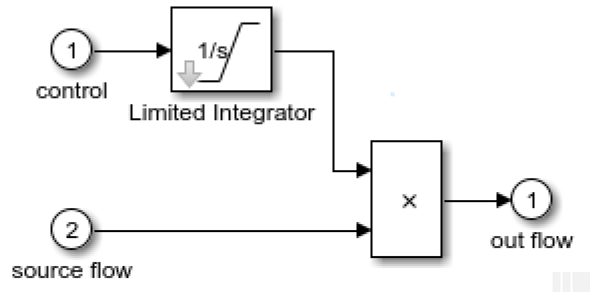

Fig. 4.9 The Simulink model of controlled valve.

4.4.7 Radiator System Design

Three basic parts of the heating and storing systems are the radiator, heat exchanger, and storage system (TES). The radiator is used for room heating. The radiator sizes depend on heat load requirements and space available for insulation. The manufactures catalog mentioned the dimensions and power output for the given logarithmic temperature differences -between room and radiator. If the required energy is known that the calculation of the total heat load of the system becomes easy. Understanding the quality factor is important to determine the total heat load. The quality factor means the maximum energy that is converted into the work (heat). To calculate the energy load, to know about the indoor and outdoor temperature is mandatory. The proposed small single-family detached house front and back side wall are considered windward and left, and the right-side wall is upwind type. The overall heat transfer coefficient for a single-family detached size house [19] is given below:

Table 4.1: The house thermal parameters

The front side wall (wind side)	3.1 W/m^{2}K (assumed)
Backside wall (wind side)	3.1 W/m^{2}K
The left side wall (upwind)	2.8 W/m^{2}K
The right side wall (upwind)	2.8 W/m^{2}K
Glass	6.1 W/m^{2}K
Doors (04 numbers)	1.7×4=6.8 W/m^{2}K
Roof	4.1 W/m^{2}K
Floor	0.56 W/m^{2}K
Total heat load required	29.36 W/m^{2}K

Considering this parameter, the radiator Simulink model is shown in Fig. 4.10 which can be designed with the house thermal network model components choosing the ambient temperature is -15^{o}C and room temperature is 20^{o}C.

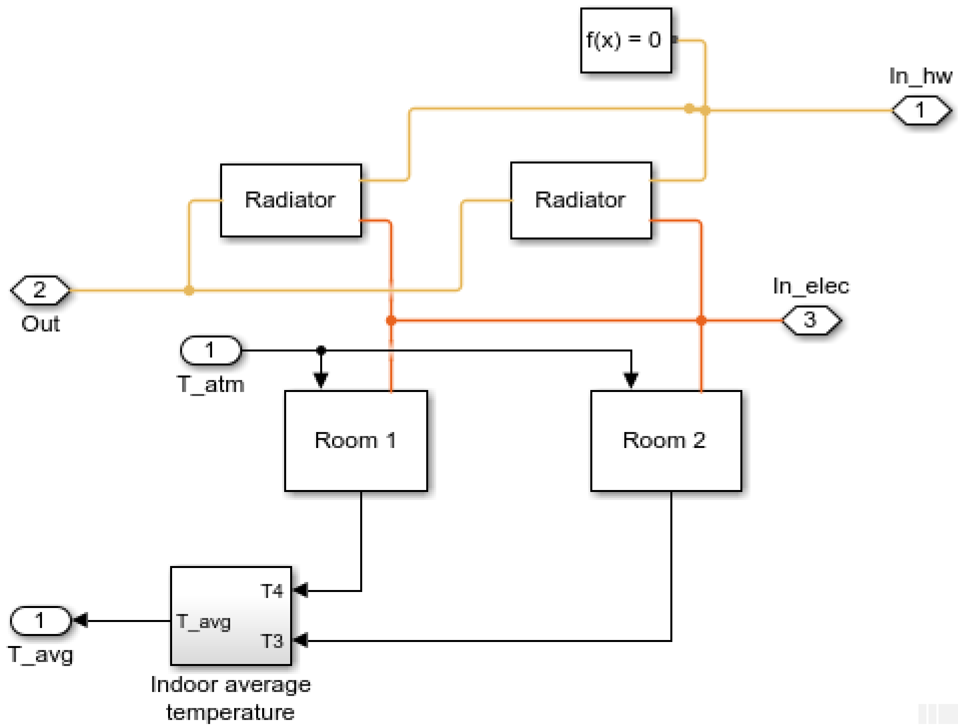

Fig. 4.10 The Simulink model of the house thermal network and radiator.

4.4.8 Thermostat

A thermostat turns on the burner or electric heating element to maintain the water temperature and room temperature in the storage tank. It is a TES component that senses the ambient and room temperature of the selected single-family house and performs an action to maintain a system temperature as the customer desired. In literature, it can be classified as thermostatically controlled loads. It operates as a closed-loop control device, as it seeks to reduce the error between the desired and measured temperatures. It can be automatic and manual control. A thermostat can often be the central control unit for a heating or cooling system, in applications ranging from ambient air control to automotive coolant control. Previously analog and mechanical types thermostat have been used, but nowadays, the digital thermostats, which have no moving parts, have a touch screen where the temperatures have been displayed and the control channels exist.

The basic algorithm of a thermostat is shown in Fig. 4.11.

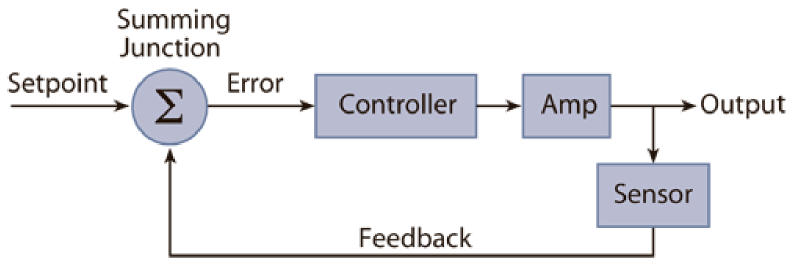

Fig. 4.11 The basic operating principle of a Thermostat.

4.4.9 Heat Pump and Pipe Insulation

Heat pump and piping design is also an important factor to improve efficiency. The heat pump is also an auxiliary heater that is available inside of a storage tank or separately. There is so many TES system available practically and in literature where heat pump has been used. It depends on the heat demand, mechanical, and economic aspects. The head loss of a heat pump may be calculated by using Bernoulli's equation [20]. The characters of pipe material must be high heat conductivity, low cost, high durability, low corrosive and hazardous, withstand high temperature and pressure such as steel, polyvinyl, polybutylene, polyethylene, and fiberglass. To reduce the heat loss, a pipe may be insulated in different ways to sustain temperature for long times for short distance only because 50% of the distribution expenses have been done by such insulation. If the flow rate is increased in uninsulated areas, then heat loss may also be reduced, but things should be optimized[19].

4.4.10 PVT Collector Sizing

Typically, the PV module generates electrical energy, and the thermal collector produces heat, but the photovoltaic thermal (PVT) is capable of generating both heat and electrical energy; thus, it is more efficient and needs lower rooftop space. The classification and working of the PVT collector [21] are shown in Fig. 4.12.

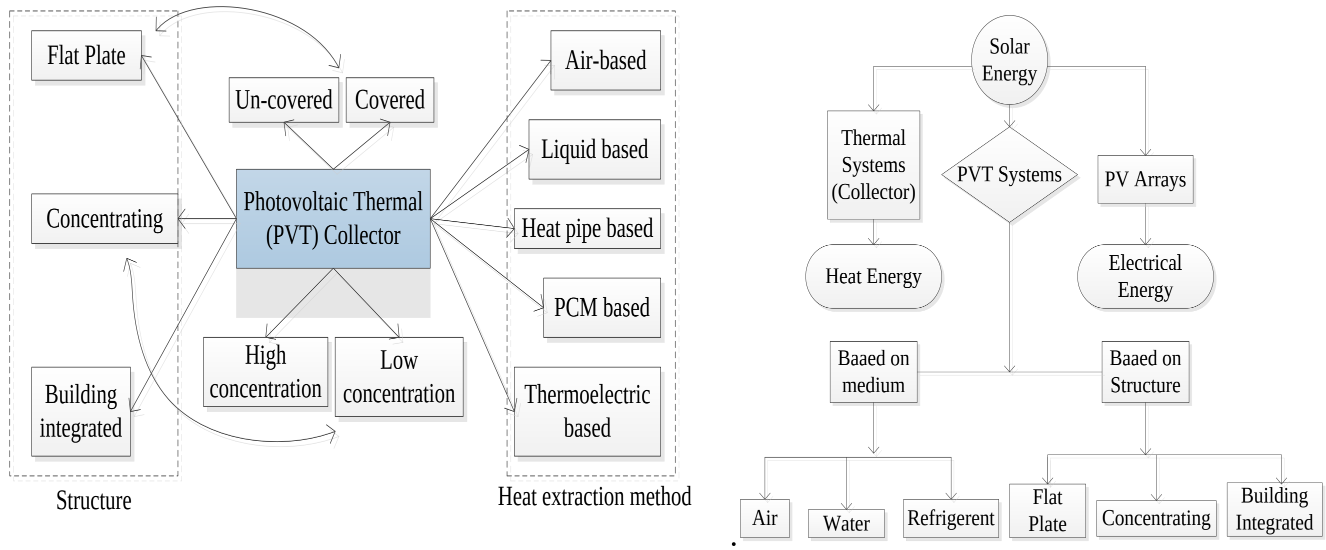

Fig. 4.12 The basic types and function of PVT collector

For this study, the PVT system has been considered as conventional water-based flat plate solar collector, then its thermal efficiency[9] can be calculated as

$$\eta_{thermal} = \frac{Q_{useful-heat}}{I_x \times A_{collector}} \tag{4.5}$$

The useful heat $\mathbf{Q_{useful-heat}}$ can be evaluated. $Q_{useful-heat} = \dot{m} C_p \Delta T$

Where $\dot{\mathbf{m}}$ is the working fluid(water) mass flow rate (90 kg/s), $\mathbf{C_p}$ is the water-specific heat (4.18 kj/kg^{o}C), the average solar radiation (I_x) in St. John's, NL is 3.06 kWh/m^2, $A_{collector}$ is the collector absorber area which is 16 m^2 and $\mathbf{\Delta T}$ is the water temperature difference between the inlet and outlet are considered as 10 ^{o}C and 55 ^{o}C respectively.

The equation (5) can be rewritten as

$$\eta_{thermal} = \eta_o - \alpha_1 \frac{\Delta T}{I_x} \tag{4.6}$$

Where the thermal efficiency ($\boldsymbol{\eta_o}$) for glazed and unglazed PVT at zero reduced temperature is 0.51 and 0.45 respectively and the loss coefficients ($\boldsymbol{\alpha_1}$) are -5.36 W/m^2 and -10.15 W/m^2 respectively. Based on the equation (10), it is calculated that the thermal efficiency of a glazed and unglazed PVT collector is about 48% and 35%, respectively.

The electrical efficiency is calculated in standard form as:

$$Q_{electrical} = \frac{I_m \times V_m}{I_s \times A_{collector}} \tag{4.7}$$

Where I_m and V_m are the operating current and voltage of the PV module operating at the maximum power. I_s is the solar radiation intensity in W/m^2, $A_{collector}$ is the PV panel area which is the same as the collector absorber area, 16 m^2. The electrical efficiency[22] of glazed and unglazed PVT collector can be expressed as follows:

$$\eta_{electrical} = \eta_o - \alpha_1 \frac{\Delta T}{I_x} \tag{4.8}$$

Where electrical efficiency ($\boldsymbol{\eta_o}$) for glazed and unglazed PVT at zero reduced temperature is 0.108 and 0.123 respectively and the loss coefficients ($\boldsymbol{\alpha_1}$) are -0.15 W/m^2 and -0.22 W/m^2 respectively. Based on the equation (8) and table 4.2, It is calculated that the electrical efficiency of a glazed and unglazed PVT collector is about 11.5 and 13.4%, respectively.

The total efficiency of PVT collectors is used to evaluate the performance of the overall system.

$$\eta_{total} = \eta_{electrical} + \eta_{thermal} \tag{4.9}$$

So, the total efficiency of glazed and unglazed PVT collectors is 59.5% and 48.4%, respectively. The PV system can produce electrical energy in kWh, which is calculated by

$$E_{PV} = A_{PV} \times I_x \times \eta_{module} \times \eta_{inv} \times \eta_{wire} \tag{4.10}$$

Where A_{pv} is the PV array area in m^2, I_x is daily solar radiation which is 3.06 kWh/m^2, and η_{module}, η_{inv} and η_{wire} are the efficiencies of the PV module and wires are 14%, 90%, and 95%, respectively.

4.5. Data Collection and House Analysis

The tested house location is 5, Blue River Place, St. John's, NL, Canada. There is a vast temperature difference between the ambient and the ground temperature. It is found that the environment temperature range is from -10 ^oC to 15 ^oC, and the ground temperature range is from 3 ^oC to 4 ^oC at a depth of up to 5 meters, as shown in Fig. 4.3. The average daily solar radiation is 3.06 kWh per m^2 per day, as shown in Fig. 4.4, which is enough to generate heat or electricity. The environment Canada is recording the hourly solar radiation data every year, which is shown in Fig. 4.5, and it is found that solar radiation is available every month, and the recorded radiation range is from 0.1 to 0.95 kWh/m^2. The detail of weather data, house parameters, and energy demand in the selected location is described in chapter 2.

4.6. Solar Collector Based STES System

The existing house energy demand is the same, and it has been redesigned with a water-based solar collector. Two tanks have been considered one is 0.151 m^3 called preheating tank, and the other one is 0.189 m^3 called the main tank. As the collector output temperature is not always high enough, that's why a preheating tank has been introduced. The preheated water will go through the main tank, and the temperature will rise further from the output heat of the auxiliary heater. The thermal efficiency of the heat pump is higher compared to the oil burner; that's why the heat pump is chosen in this research. The pump and auxiliary heater controller have collected the temperature form the collector output, the tank water, and turned on only to keep the tank water temperature constant. The solar flat plate collector has been chosen in this research, but still, there is some grid electricity consumption because of the intermittent nature of solar energy. The schematic diagram of the solar collector-based energy storage system is shown in Fig. 4.13 which is also similar to the collector based system as discussed in chapter 3.

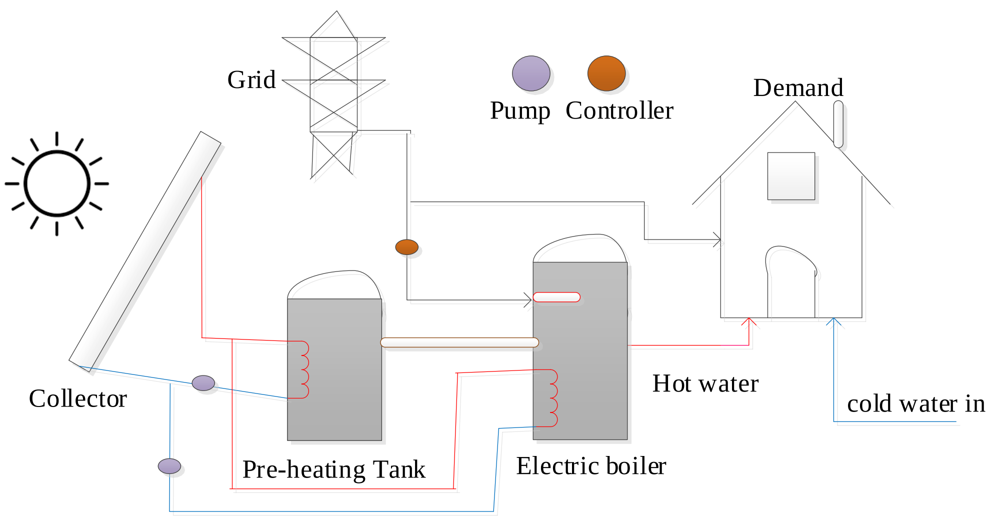

Fig. 4.13 The solar collector based energy storage systems

The house energy demand is described in chapter 2, and the solar collector based energy storage system components specification is described in table 4.2. The mathematical formulation, TES components design description, design steps and individual Simulink model is described in section 4. The complete solar collector-based TES system has been designed in MATLAB/Simulink environment, which is shown in Fig. 4.14.

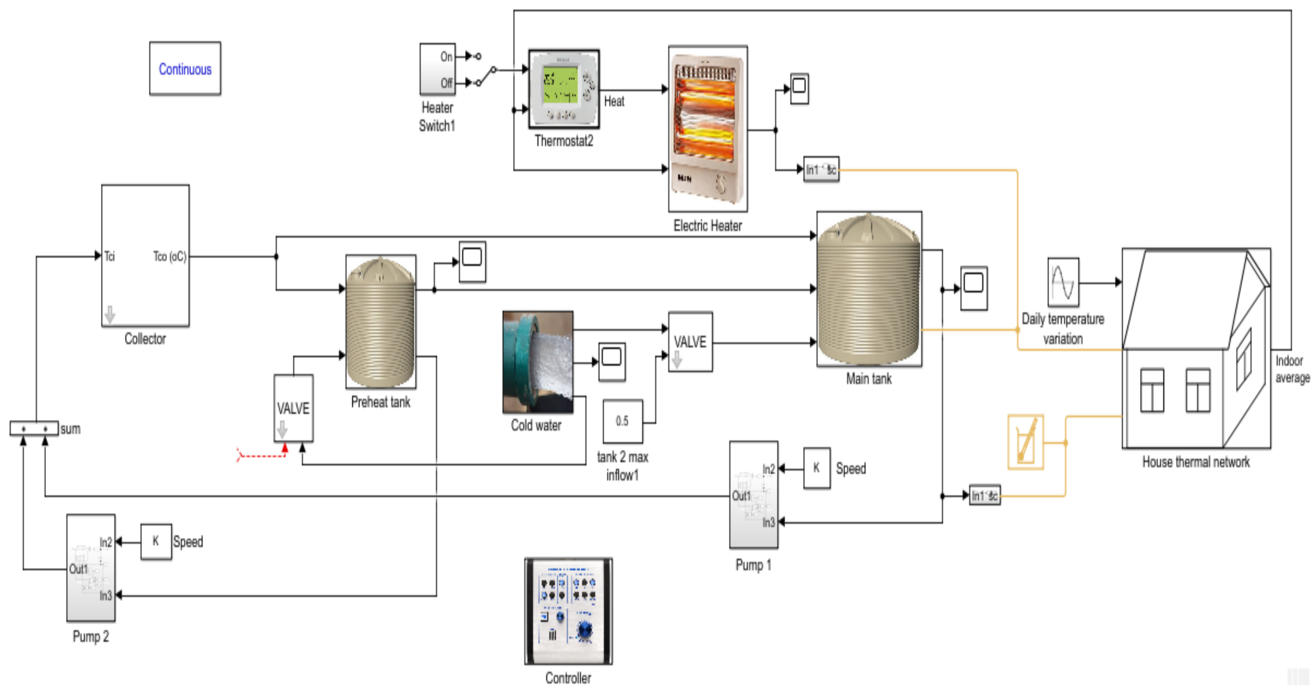

Fig. 4.14 The complete solar collector based thermal energy storage systems.

Table 4.2. The system components and parameter.

Name	Main parameters	Descriptions
Solar collector	Optical efficiency: 81.3% Thermal efficiency: 70% Module absorber area: 2.32 m^2 Module gross area: 2.51 m^2 Thermal capacity: 6.4 KJ/(m^2.k) Number of collectors: 7 Number of arrays: 1 Total required absorber area: 10 m^2 Total required gross area: 17.37 m^2	The detail description of the collector is given in [13]
Preheating tank	Tank volume: 0.151 m^3	
Main tank	Tank volume: 0.189 m^3	
Radiators	Number of radiators: 02	The detail description is given in Table 4.1
House description	Total area: 125 m^2	Mentioned in Chapter 2.

4.6.1 Simulation Result

The designed system has been simulated in Matlab/Simulink environment. It is found that the house energy demand is mitigated with a lower amount of grid electricity. The annual thermal energy production is 5172 kWh from 17.37 m^2 of the collector array with seven solar flat plate collectors, as shown in Fig. 4.19; the number of switch-on time of auxiliary electric heater is 3119, and operation time is 900 hours, as shown in Fig. 4.15. The room inside temperature sensor reading is shown in Fig. 4.16, which is around 20~23 ^oC. The ambient and room temperature variation is shown in Fig. 4.18. The availability of space heating and hot water demand is 95.8% and 100%, respectively.

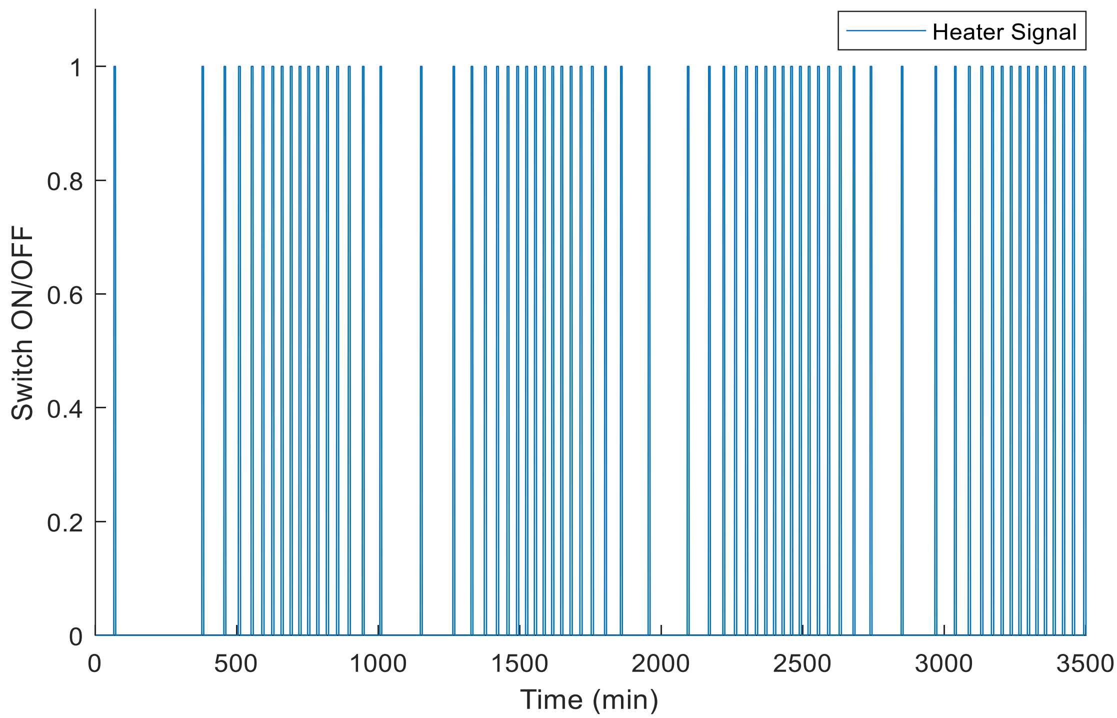

Fig. 4.15 The auxiliary heater was switching ON/OFF time.

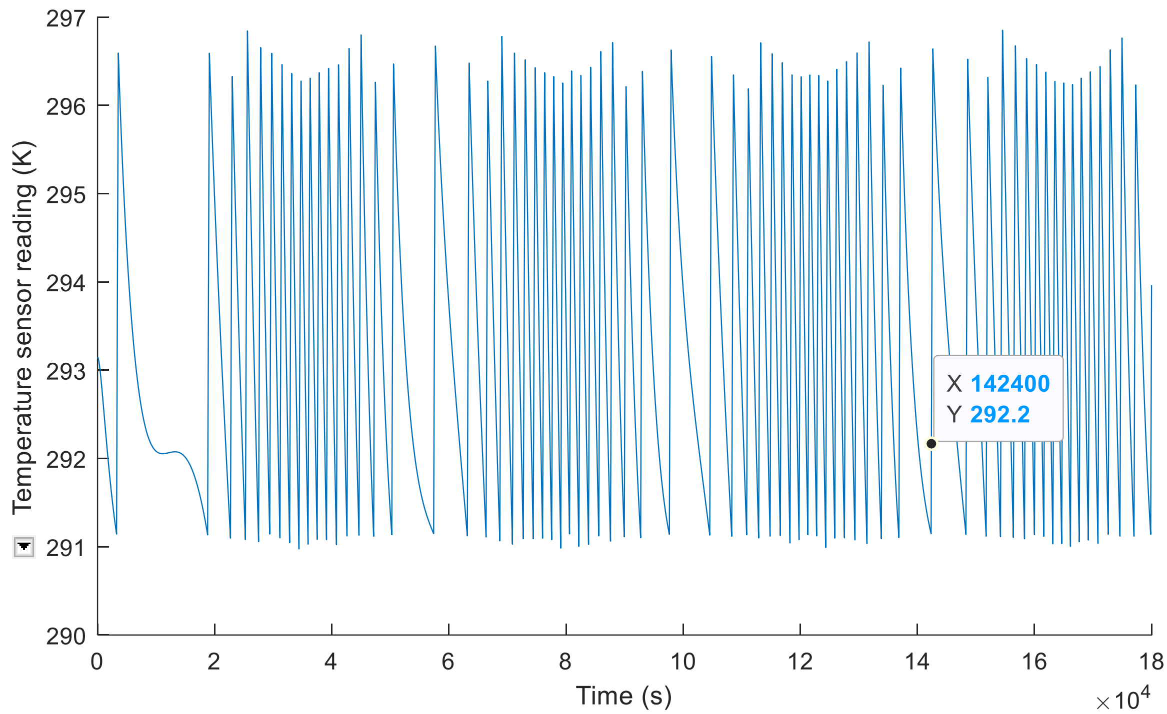

Fig. 4.16 The sensor reading temperature at the room inside.

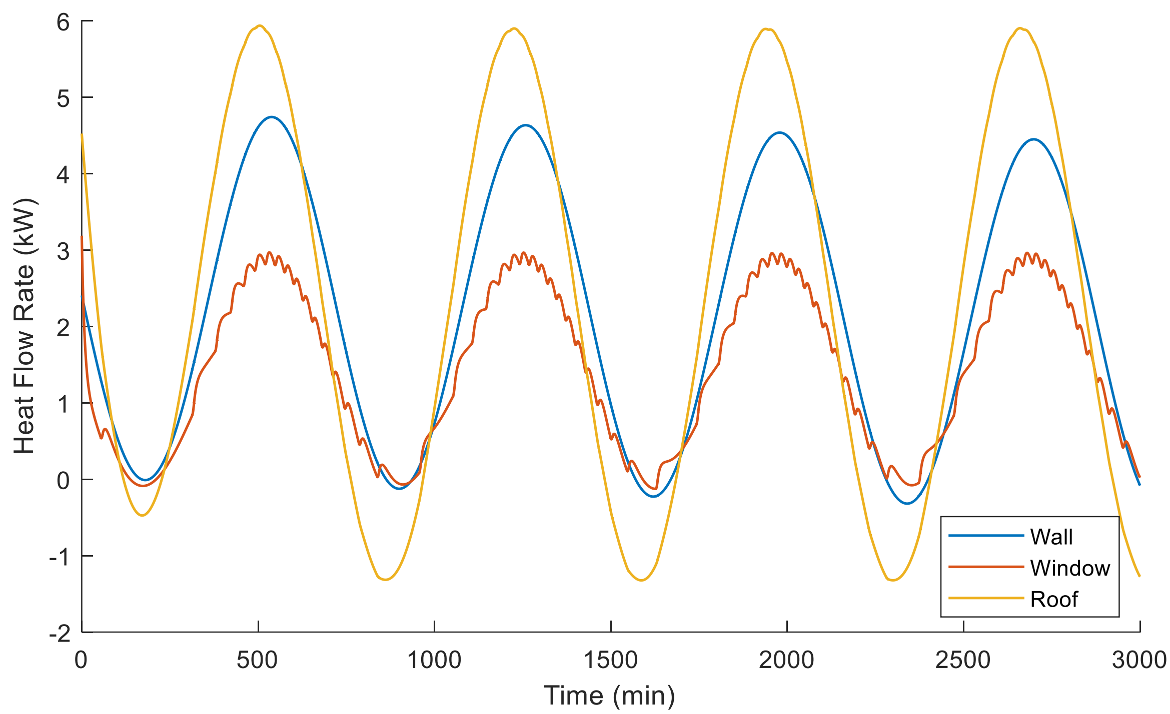

Fig. 4.17 The heat flow rate of a house thermal network

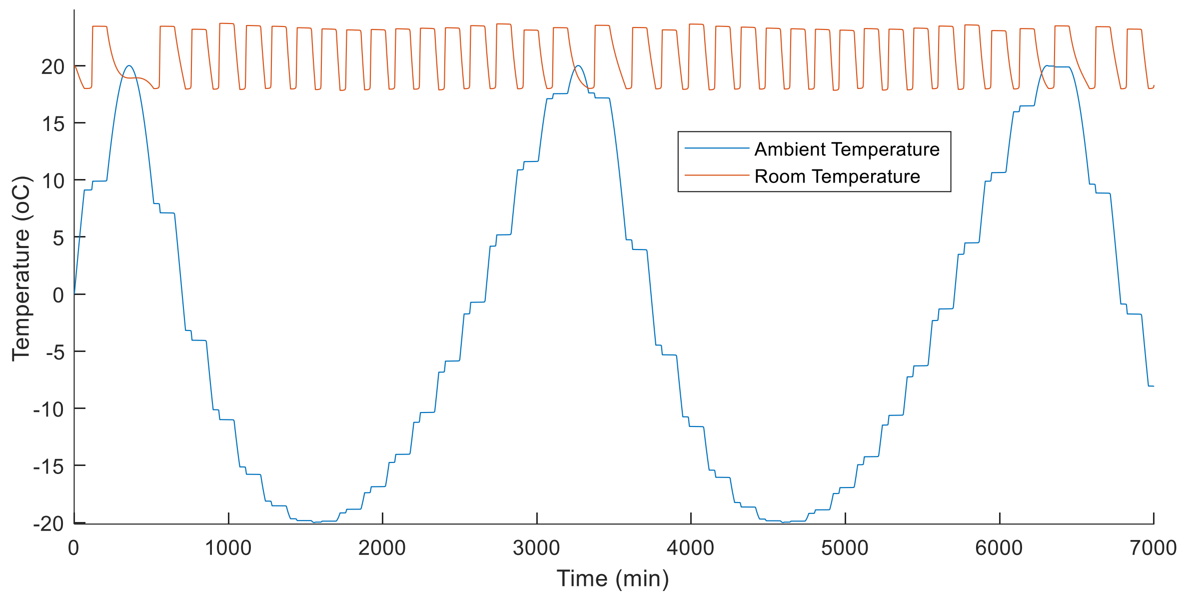

Fig. 4.18 The ambient and room temperature.

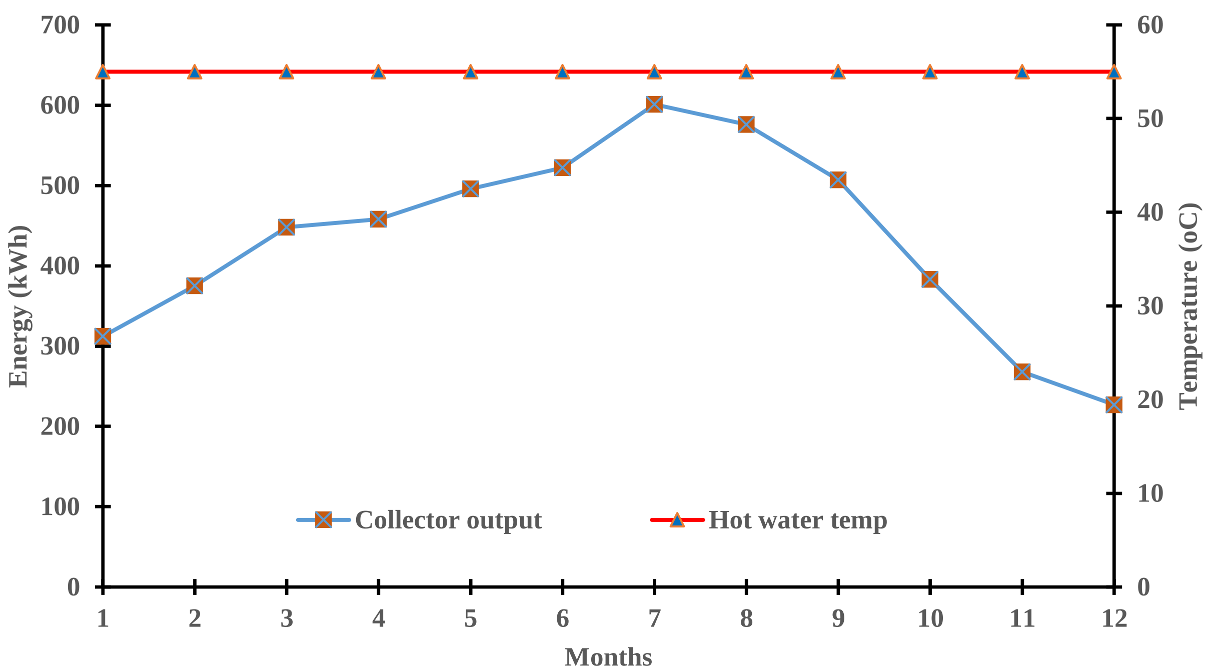

Fig. 4.19 The solar collector annual output and water tank (upper layer) temperature.

4.7. PVT with Electric Heater Based STES System

The existing house energy demand is the same, and it has been redesigning with the solar photovoltaic thermal (PVT) collector. We talked the details about the PVT collector in section 4.10. The PVT collector loss is very lower because it can generate the electrical and the thermal power both simultaneously. The photovoltaic panel has some heat that goes to the heat exchanger. The heat exchanger transfers the PV heat to the tank water, and thus the tank water temperature is increased. Based on solar radiation and PVT output, the water temperature is increased. The controller monitored the PVT output, tank temperature. If it is lower then the set temperature, then the controller turned on the auxiliary electric heater, and the water temperature increased to the set point. In this configuration, one 0.189 m^3 water tank has been considered. There is some grid electricity consumption because of the intermittent nature of solar energy. The schematic diagram of PVT based energy storage system is shown in Fig. 4.20.

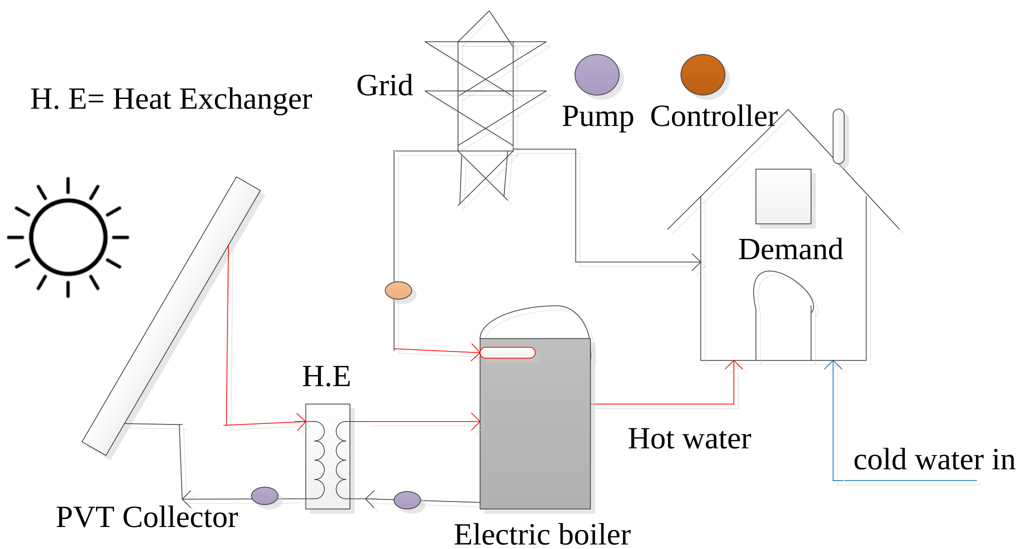

Fig. 4.20 The solar photovoltaic thermal (PVT) collector-based energy storage systems

The house energy demand is described in chapter 2 (section 5.2.1), and the PVT based energy storage system components specification is described in table 4.3 below:

Table 4.3. The system components and parameters setting.

Name	Main parameters	Descriptions
PVT collector	Model: SolarOne, 290 W Type: Monocrystalline, Flat plate Electrical power rating: 265 W Output voltage: 31 V Output current: 8.6 A Standard electrical efficiency: 15.5% Thermal power rating: 825 W Modules aperture area: 1.575 m^2 Total nominal power: 3 kW Total gross area: 17.4 m^2 Total aperture area: 16 m^2 Standard thermal efficiency: 49.5% Total number of modules: 12 Number of strings: 3 Modules per string: 4	The details about the module are given in [23].
Storage tank	Same as Fig. 4.13	
Pump 1-5	Same as Fig. 4.13	

4.7.1 Simulation Result

The system again simulated in PolySun software, and the results are summarized as Fig. 4.21 where it is found that the house energy demand is mitigated with the lower amount of grid electricity. The annual electrical and thermal power production is 5891 kWh and 1894 kWh, respectively, from 3 kW PVT collector array; thus, the grid electricity consumption is reduced to 11729 kWh/year. The number of switches on time of electric heater is 2564, and operation time is 750 hours, total heat loss is 977 kWh/year, and carbon emission is 7833 kg/year. The availability of space heating and hot water demand is 99.6% and 100%, respectively. The electrical and thermal efficiency has been found as 14.3% and 48.4%, respectively, which is almost close to the calculation, as mentioned in section 4.10.

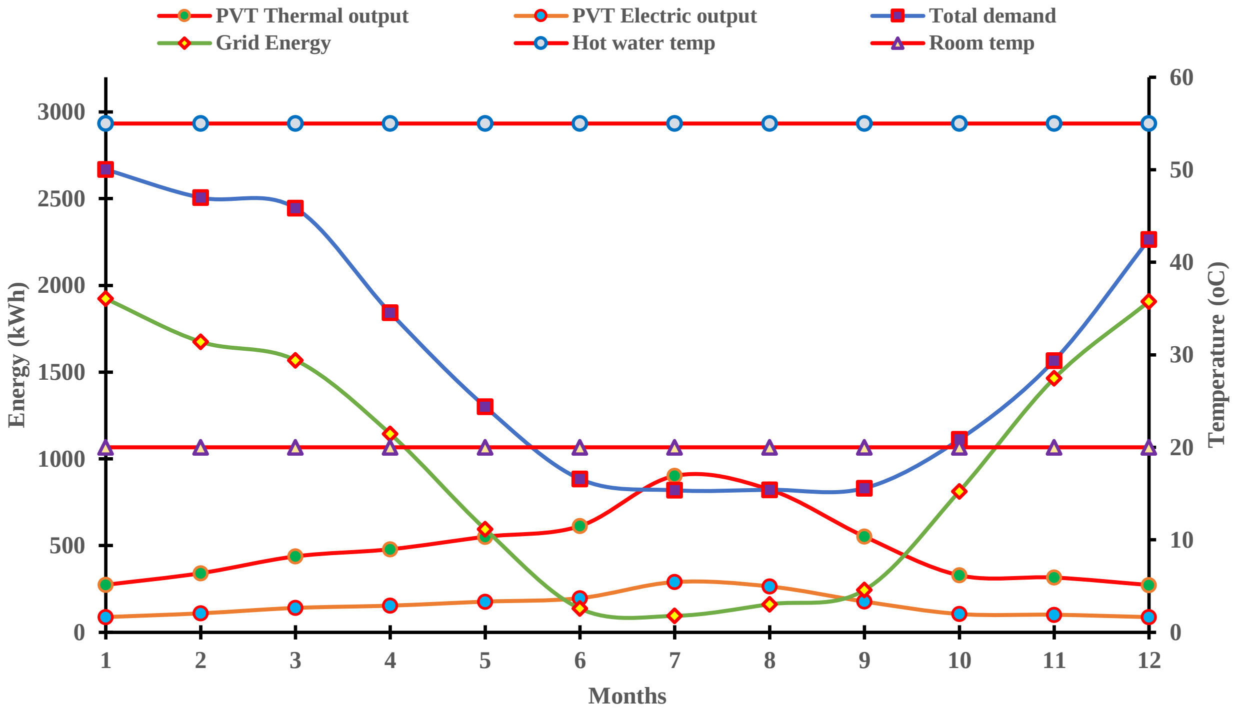

Fig. 4.21 The supply and demand scenario of the PVT and electric heater-based energy storage system

4.8. Conclusion

The thermal energy system (TES) is a simple, inexpensive way to store energy for peak period demand. Among both of the energy storage systems, solar collector-based TES systems, PVT based hybrid energy storage is very highly efficient and smaller storage is required to store large amounts of energy. If the required solar collector is placed in the rooftop with the TES system with an efficient controller than the overloaded energy demand can be mitigated. A large amount of energy will be saved as well as GHG emission will also be reduced. The monthly electric bill will be reduced as almost 70~80% energy is consumed for space heating and hot water supply and this will mitigate from stored energy. The TES system is still suffering some limitations like optimization and intermittency. Development of advanced and more adaptive control system these limitations can resolve with efficiency. If this system is developed successfully in all over Canada, then the GHG emission and the use of fossil fuel will be reduced, and people may mitigate their electricity demand most cheaply. In this research, details mathematical modeling and simulation of solar collector-based TES system and PVT based TES system sizing have been studied. The TES system controller has been implemented in chapter 5, where the local and remote, manual, and automatic control and monitoring system have been implemented practically. Finally, owing to the high grid electricity demand in Canada for space heating and water heating, it is possible to advantage the solar energy by using such configurations as a successful alternative and a sustainable solution for the low heat applications such as energy demand in a single-family house in Canada. This part of the research can be further improved to design another type of robust controller or to connect this Matlab simulation with the hardware to control the stimulation parameters from a remote place.

Conflict of Interest

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

Acknowledgment

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Chapter 5

Remote control of house thermal energy storage system

Preface

A version of this chapter has been submitted and is in under review in the Int'l Journal of Renewable Energy and Research. I am the primary author, and I carried out most of the research work, performed the literature reviews, carried out the system design, analysis of the results and experimental setup and hardware implementation. I also prepared the first draft of the manuscript and the final manuscript. The Co-author, Dr. M. Tariq Iqbal, supervised the research, acquired and made available the research funding.

This chapter is a version of -

[1]. H. Rahaman, M. T. Iqbal, "A Remote Thermostat Control and Temperature Monitoring System of a Single-Family House using openHAB and MQTT ," in European Journal of Engineering Research and Science (Accepted)

Abstract

In this research, an open-source IoT platform named openHAB smart home automation is used as a home server, an ESP32 Thing microcontroller board is used to design a remote-control system for a thermal energy storage system. It consists of temperature sensors for real-time temperature monitoring, ESP32 Thing board is used for data receiving, processing and sending it to the MQTT broker, openHAB software installed in the personal computer is used as a home server for creating dashboard panel, MQTT broker is used to establishing the communication in between openHAB home server and ESP32 Thing board, Wi-Fi router is used to create the communication channel, a battery-powered remote-controlled heater with a digital thermostat is used as a testing device where user can set the desired temperature for house heating. The main objectives of this work are to design a low-cost monitoring and control system for thermal energy storage systems, to monitor the real-time temperature data, to design a control system for thermostat settings with the following features such as manual/automatic operations, local/remote control options. The user can access the dashboards locally via any computer and remotely via openHAB Cloud console from anywhere in the world. The proposed system in this work will help residence to manage their heating systems smartly in a cost-effective way, which will be the replacement of the conventional thermostat settings. The utility provider company can also use this system to control the thermostat settings from centrally, wirelessly, and remotely.

Keywords: openHAB home automation, MQTT, IoT, Sparkfun ESP32 Thing, Remote control, Remote Monitoring.

5.1. Introduction

The space heating system and domestic water heating system is prevalent and used in every house in Canada. Conventionally, the wood, gas, and oil-based heating system have been used, and even nowadays, in some regions, these are being used. In a typical single-family house, the standard electric heating components are a small water tank integrated with the electric heating element, electric heating resistance elements, sensors, a small control system to turn on and off the auxiliary heater. House demand-side management is essential to supply continuous space heating and domestic water heating in various weather scenarios. In cold climate countries like Canada, people are paying high electricity bills monthly. But the electric-based thermal energy storage systems consume a lot of grid electricity; thus, grid energy saving and greenhouse gas (GHG) reduction are the primary concern in Canada [1].

In our previous research [1][2], we proposed the solar photovoltaic and solar thermal collector based short term and long term (Seasonal) thermal energy storage systems. There is some one-time investment cost for system modification and solar photovoltaic or thermal collector installation. Still, the rate of return was acceptable (5~7 years), and the system saves grid electricity and GHG.

The system components sizing has been conducted considering the housing demand and weather. The necessary control system has also been proposed and simulated. Without proper control, these losses can not be minimized to apply the effective operation with proper monitoring and control systems.

To address this effective and robust controller, we developed a monitoring system with some sensors to monitor the sensing parameters such as ambient temperature, indoor house temperature, tank water temperature. Similarly, based on the sensor value, a control system has been developed with a low-cost open-source IoT platform named openHAB home automation, which can control the thermostat settings, to turn on/off of auxiliary heater. A demonstration has been presented in this research. The paper organized as follows: In section 3, the details literature review and the latest IoT based automation, control projects have been presented. We presented the problem statement, and how this the proposed system is practically meaningful. In section 3, we presented the latest IoT thermostat control technology and highly popular thermostat which is available in the market. Their market price, operating principle, pros and cons have also mentioned shortly. In section 4, the proposed system architecture, system development approach, the system requirement and specifications have been listed. In section 6, the details description of the proposed system components, their ratings, connection procedure and requirements, short working principle have been presented. The step by step openHAB IoT setup in a personal computer windows, configuration, connection with MQTT broker have been conducted in section 6. The JAVA programming methodologies and details development have been presented there based on the practice experience. In section 7, the proposed system experimental setup, component connection, testing and validation, how to monitor the sensor values and control the thermostat have been presented. In section 8, the proposed system performance, cost and power consumption analysis have been conducted and compared with the existing technology. The strength and highlighted features of the proposed system has been presented. The conclusion and future work have been drawn at the end.

5.2. Literature Review

There are several published works on solar thermal energy storage system design and control to ensure an efficient system and reliable control. The system components monitoring, and control can reduce system losses and improve system efficiency. Authors in [3] developed an optimal control system of integrated heating and cooling systems that are capable of reducing 5-11% electricity cost depending on the electricity price, weather, and size of the storage tanks. Still, the details system cost calculation is absent. A model predictive control (MPC) has been applied to an on-grid photovoltaic (PV) based heating and cooling energy storage systems in [30], where the authors monitored the operations for 24 hours and achieved 58% energy savings.

Similarly, in [4], the authors proposed another MPC control system incorporated with the artificial neural network and saved 29% operating cost but presented only 1-hour data and did not present the monthly and Seasonal. An optimal control algorithm has been applied in borehole thermal energy storage systems in various weather scenarios to supply continuous heat and cold [4]. Authors in[5] presented a fuzzy logic-based control system considering weather information and heating demand. Basically, in that research, they did energy management. Similarly, there is more similar simulation-based research available; however, very few researches available in hardware applications. The energy storage system can be monitored and controlled by using open source Internet of Things (IoT) such as Thinger.io, ThingsSpeak, openHAB home automation, Home Assistant platforms, and so on. Similar to software simulation, there are several types of research available with the application of single-family residential house apparatus control and monitoring. For instance, authors in [6] [7], designed an IoT based system with Raspberry Pi device with the integration of openHAB platform with integration of hypertext transfer protocol (HTTP) networks, which can monitor the system components remotely, but the system is not customer friendly. Another research[8] presented the design and implementation of the wireless module with openHAB GPIO binding, Raspberry Pi, Arduino, NodeMCU, which is also capable of monitoring the sensor values and controlling the household supporting devices. Other studies in [9] proposed a single-family house demand-side management systems with openHAB platform with various communication protocols such as HTTP and use datagram protocol (UDP) and energy sharing based algorithm. The research conclusion was to monitor and control of house devices, but they did calculate the total device energy consumption and cost. Similar to the above research, some sensors, MQTT protocol, Raspberry Pi, IoT based home assistant, and openHAB platform has been used for home devices automation[10]. Finally, the authors concluded the remote controllability, and which one would be better in between home assistant or openHAB? In a Germany based openHAB conference, the authors in [11] fully automated the most significant public Building using the openHAB platform. Paper[12] [13] also highlighted the security concern of openHAB and open-source IoT based systems.

In 2018, the University of Tartu published a master's thesis [14] about the security concern of openHAB, such as authentication and authorization. Another latest research published in 2019[15], where the authors proposed a home device control system with ESP32, openHAB, MQTT protocol, that's the almost similar research like me, but the did not mention the system energy consumption, energy management systems and system cost.

There are also other similar works[16], device control using mobile phone or web through Arduino, Bylink, relay, MQTT, and so on. Another application of IoT is the monitoring of refrigerated temperature is mentioned in[16]. Similarly, authors in[17] [18] [19]proposed a web-based control system and an intelligent thermostat using IoT, MQTT, Arduino, but they did not work with open source cloud control capabilities.

In this paper, the authors proposed a low-cost open-source IoT based remote monitoring and control system for a thermal energy storage system. Where a thermostat has been controlled from locally and remotely, and the energy storage systems temperature has been monitored by using the openHAB home server dashboard, MQTT establishes the connection in between openHAB home server and Sprukfun ESP32 Thing microcontroller. The authentication and system security has also been ensured and also worked with the open-source cloud development.

5.3. Available Technology in the Market

Several products on the market are working as the same functions, such as Google Nest thermostat, Honeywell thermostat, ecobee thermostat, Sinop thermostat, Lux Kono thermostat, Johnson controls the thermostat, ThermoPro digital hygrometer thermometer, Mysa smart thermostat and so on. Among all of them, Google nest thermostat is highly popular.

5.3.1 Google Nest thermostat:

It first developed in 2011 form Google bought nest labs, and now the 3rd generation is available in the market, which one brilliant way to control the heating and to cool simply. The compact hardware packages wiring is simple as well, the common point is C, and 24-volt wires can be connected with the other. This smart thermostat can support multi-stage, heat pump, and multi-zone HVAC systems, but it does not like geofencing and expensive, $329 market price [20].

5.3.2 Honeywell thermostat:

This allows local and remote control options through a computer, tablet, or smartphone. In the digital screen, the humidity, temperature, and thermostat settings options are available. But the worst Thing is that it does not include the wall plate for installation, wiring is too complicated, which can cause expensive equipment damage, it is a non-programmable device as well, and its price is around $149[20].

5.3.3 ecobee thermostat:

It is compatible with temperature and humidity sensors, and in the automatic mode, it is estimated that around 23% annual savings are possible in heating and cooling. Similar to another thermostat, the house components can be controlled locally and remotely using a laptop and mobile phone, and its cost is in between the above two thermostats, which is around $229[20]. The main issue with that is it has only one temperature sensor and two occupancy sensors build in at Ecobee4 systems.

These are the most popular available smart and Wi-Fi thermostat, which is used commonly in the single-family house for room heating and cooling application. However, there are other manufacturer's smart thermostats available at different prices.

5.4. System Description

5.4.1 System Architecture

Lots of wireless smart thermostats are available in the market that already discussed in section 2 what market price is high, and some thermostat wirings are not so simple.

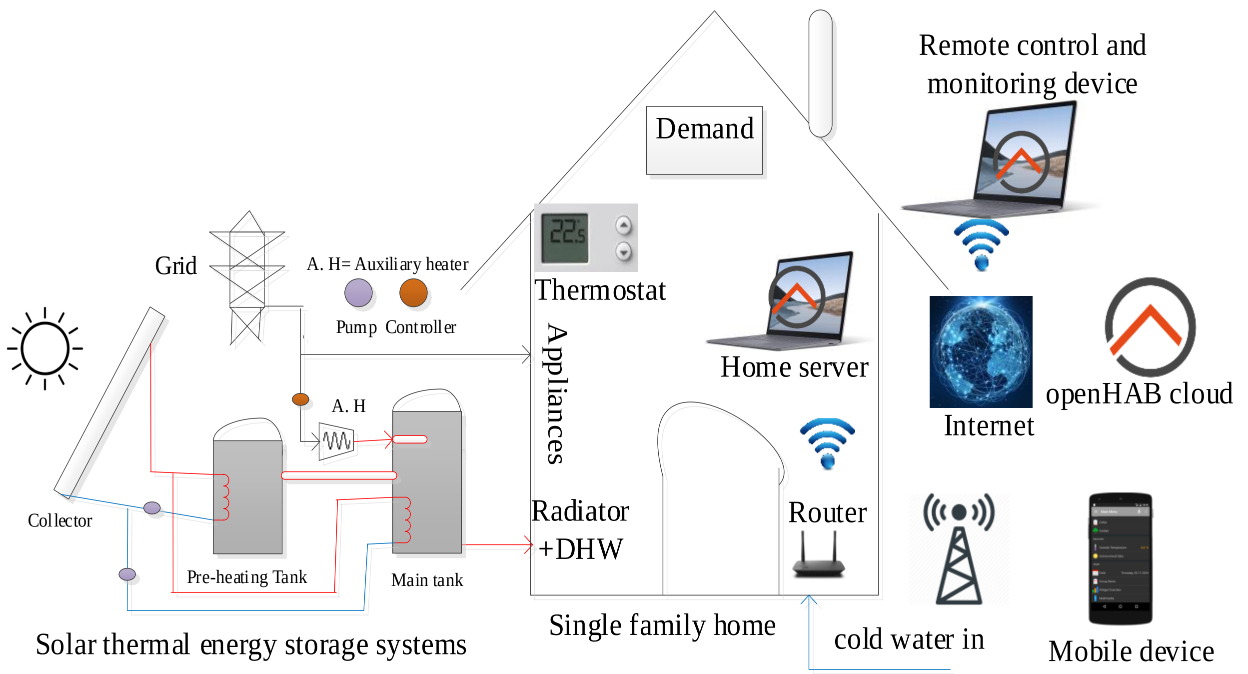

Fig. 5.1 The system architecture

Some other PLC applications are also available what require particular installation, and the majority of circuit elements, sensors, and relay are connected with other integrating technologies. Those technologies are also useful; however, in this study, we are proposing a smart way, cost-effective structure of house heating and cooling applications, temperature measurement, and monitoring[8]. The openHAB home assistant open-source IoT platform is a highly popular and designer choice IoT platform. It is free and easy to install and easy to integrate with an electronic microcontroller such as Arduino, Sprukfun ESP32 Thing, ESP8266, and so on. Similarly, it is so simple to connect solid state relay and DHT11 temperature and humidity sensors and other analog temperature sensors with those devices. The working system architecture is shown in Fig. 5.1 below: The proposed system architecture is designed to reduce the complexity and cost of implementation. No expensive and complicated components have been used in this research such personal computer, mobile devices, Wi-Fi router, which is available in every single-family house in Canada.

The system is designed as user-friendly, low power consumption, low cost, allowing users to use a traditional thermostat, to monitor the room, ambient temperature, and to control the thermostat settings locally and remotely. The users can monitor temperatures and can manage the thermostat settings using their laptops or mobile devices through the local available Wi-Fi network. Through the portable device uses communication services such as GSM, with access to the internet, a user can have access to the home server using openHAB apps or openHAB Cloud and can do the same. The other family member can also have access to the home server using their laptops and monitor and control the thermostat settings. The system architecture has a flexible user interface that can be customized based on user requirements, such as indoor room temperature settings. As the server has no SIM card or separate IP address, so the users do not need to memorize. The system components setup flow is shown in Fig. 5.2.

5.4.2 System Development Approach

The openHAB home automation is a very user-friendly open-source IoT platform software that is easy to set up at Windows, RaspbberyPi, Linux, Windows, macOS, openHABian, PINE A64, Armbian, Docker and so on. But in this work, we installed openHAB in a laptop with Windows operating systems. It is using the same process of the computer, no need to buy RaspberyPi and pay an extra dollar or RaspberyPi software version is available freely, which is also same as the hardware RaspberyPi. The performance of openHAB with windows installation is excellent as the home server, and there is no need for any extra third party software or hardware. Arduino or ESP23 board is also another microprocessor where the sensors are connected, which is made with the reply, temperature sensors. The temperature sensors measure the environment temperature and sent it to the microcontroller, the ESP32, or the Arduino microcontroller. The microcontroller is connected with the Wi-Fi network [9], so it embedded the data and sent it to the openHAB windows home server. Similarly, the thermostat control signal came from the openHAB windows home server to the Arduino microcontroller through the Wi-Fi network; thus, the solid-state reply controlled, and thermostat settings controlled. The detailed system block diagram is given below in Fig. 5.3.

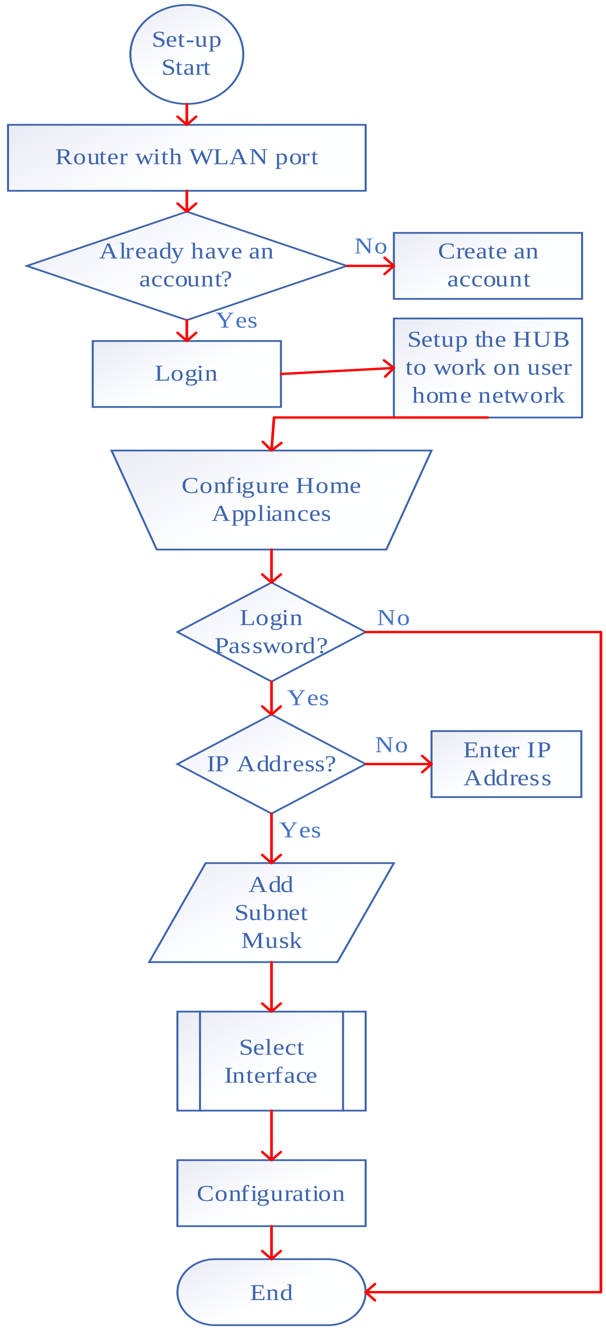

Fig. 5.2 The Wi-Fi setup and other components setup.

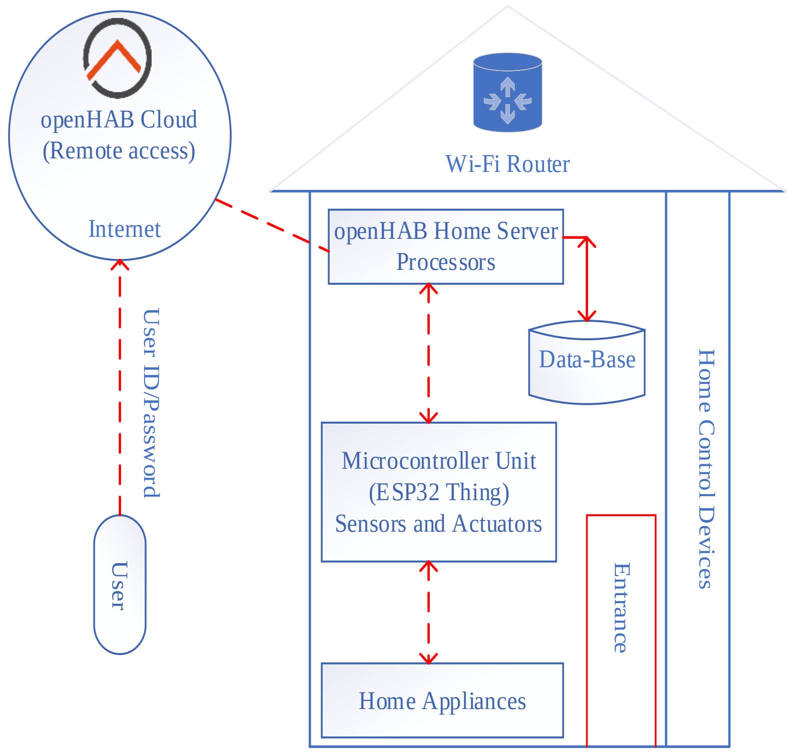

Fig. 5.3 The overview of system development

5.4.3 System Specifications and Requirements

The proposed monitoring and control systems have some requirements which are given below:

- ✓ All sensors, microcontroller devices must be low power consumption, energy-efficient, low cost, smaller sizes.
- ✓ The home server should be easily accessible from locally or remotely. There is no need to memorize the computer or network IP address or SIM number to access the home server.
- ✓ The system must be secured enough to ensure that there will be no third-party intrusion and the safety of the householder.
- ✓ For security and safety operations, just a user login and credential and password will be well enough to access and control the whole systems.
- ✓ The systems should be controllable from anywhere in the world.
- ✓ The system architecture should be simple so that every illiterate user can use these systems.
- ✓ Limit the amount of power an appliance can consume.
- ✓ Update the user on the state of appliances, either running or not.

5.5 Components Description

The proposed control and monitoring system are made up of sensors, ESP32 Thing board, relay, digital thermostat, and so on. The temperature sensors have been used for data accusation. Similarly, SparkFun ESP32 Thing micro-controller is a primary device used for data receiving, processing, and transmitting to other hardware. A solid-state relay is used to turn on/off the heater, and a heater with digital thermostat used a plant which is capable of indicating the status of room temperature. To create Wi-FI Router for local Wi-Fi network creation (communication channel), and openHAB home automation server is a local IoT server with a graphical user interface (dashboards) for monitoring the sensor's data and controlling the thermostat locally and remotely. The details description of every component are given below:

5.5.1 openHAB Home Automation Local Server IoT Platform

openHAB home automation software is an open-source powerful and user-friendly software for the Internet of Thing (IoT), which can be installed in RaspberyPi, windows, Linux, and so on. It supports the Representational State Transfer (REST) Application Programming Interface (API) which enables controlling and reading of smart devices. REST uses Hypertext Transfer Protocol (HTTP) for communication, and it is an architecture based on the standard of the web. This protocol enables the different machines on the network by considering every component as a resource. The unique features of the HTTP protocol which can connect and manage IoT devices using the automatic discovery of API. openHAB IoT platform is fully supported by GitHub (the highly popular and world-leading open-source development platform). openHAB open-source home automation IoT platform is fully supported with the other software such as MQTT broker and other hardware. openHAB is integrating with Arduino IDE compatible. The following boards which are worked with Arduino IDE, such as Arduino, Arduino+Ethernet Sheild, Arduino+WIfi Sheild, ESP32/8266/13, NodeMCU, TC CC320, and so on. It can operate in Windows and Linux powered devices such as Raspberry Pi (both version), Intel, and any other personal computers working with Windows, Linux running with Ubuntu, or macOS.

In this research, the openHAB software IoT platform has been installed in computer windows, so there is no component associated with it. It can perform well and can communicate well as a home server with all other external microcontrollers at Wi-Fi networks such as Arduino, Sparkfun Esp32 Thing. In this project, openHAB smart home automation software has been installed in C drive of personal computer windows, and openHAB worked as a home server in the Wi-Fi environment, and it will be fully able to communicate with other microcontroller development board. Home server (openHAB) specifications will be the same as the personal computer specifications such as RAM capacity, Processor capacity, HDMI port, Memory capacity, and so on. In this section 8, the authors presented the detailed description of low-cost and low power consumption hardware and software components used in the realization of the proposed openHAB IoT based remote monitoring and control systems design. The ESP32 Thing microcontroller is configured with the MQTT Client to process and publish the sensor data to openHAB and similarly sent the thermostat settings value to the ESP32 microcontroller through MQTT subscribe/publish protocol which is also configured as the MQTT broker as shown in Fig. 5.15. Finally, a Wi-Fi router is used for creating the TCP/IP Wi-Fi connection for the MQTT protocol implementation. The external hardware components associated with this project are described below:

5.5.2 DHT11 Digital Temperature Sensors

The DHT11 is a temperature and humidity sensors, it has a dedicated NTC to measure the environment temperature, and an 8-bit microcontroller inside that can generate the output in the values of temperature as a serial data. The serial pin is connected with one of the digital PIN in ESP32 microcontroller. This is cheap and available anywhere. It can measure temperature from 0 ^{o}C to 50 ^{o}C with an accuracy of ±1°C. It's a small device with a length of 16 mm, and the width is 12.9 mm. DHT11 is available in two different pin configurations, and it may contain 4 pins or 3 pins. The PIN diagram of both DHT11 sensors is shown in Fig. 5.4.

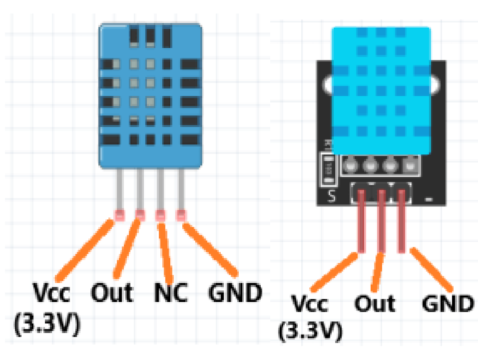

Fig. 5.4 The pin diagram of DHT11 temperature sensors.

The out (data) pin is connected with an I/O pin of the ESP32 microcontroller digital input pin (pin 34 and 35). Typically, 5 voltage is available in ESP32 think device and power supply board, but DHT11 needs 3.3 V power supply: that's why a 5k pull-up resistor is needed. The out pin (pin 34 and 35) value is a serial data contains temperature and humidity. The library file for DHT11 is available, which has been uploaded to the ESP32 library for successful operation. ESP32 sensors have 3.3 V pin, so the VDD pin of DHT11 is connected to the 3.3 V pin of ESP32. Similarly, the ground of ESP32 and ground of DHT11 are connected. The connection of DHT11 sensors with ESP32 microcontroller is shown in Fig. 5.5.

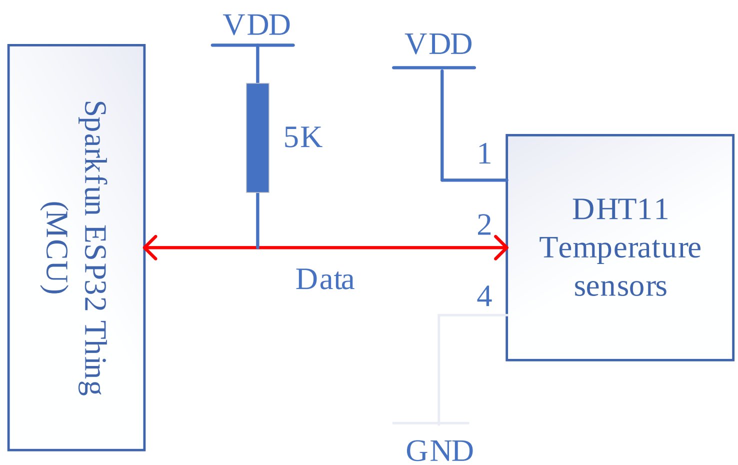

Fig. 5.5 The connection diagram of ESP32 and DHT11.

The specifications of DHT11 sensors are given below:

- Operating Voltage: 3.5V.
- Operating current: 0.3mA (measuring) 60uA (standby)
- Output: Serial data
- Temperature tolerable range: 0°C to 50°C.
- Humidity detect range: 20% to 90%.
- Resolution: Temperature and Humidity both are 16-bit
- Accuracy: ±1°C and ±1%

5.5.3 Sparkfun ESP32 Thing Micro-Controller (RTU)

The Sparkfun ESP32 Thing microcontroller board, manufactured and supplied by the Sparkfun Electronics, is a micro-controller unit that is almost similar to an Arduino development board. It is a Wi-Fi compatible micro-controller with around 30 Input/output pins, and it supports off Wi-Fi line Bluetooth low-energy such as BLE, BT4.0, Bluetooth Smart. Based on the manufacture report (datasheet), the reason of its name "Thing" is that it is mainly manufactured for the Internet of Things software so that the user can implement and do lots of projects, for example, wireless monitoring and control system development for local or remote control through Wi-Fi network. Compare to all other available IoT supported microcontroller development boards, it has unique characteristics that it has low power consumption (around 0.5W), low cost (about CA$ 20) [21]. There are two ways to supply power to this board with either a 5 V USB power supply cable or with a small lithium-polymer (Lipo) battery. It's operating signal voltage range is 2.2 V to 3.6 V, although the I/O pins of ESP32 Thing board van tolerate 3.3 V. A single Sparkfun ESP32 Thing development board is shown in Fig. 5.6.

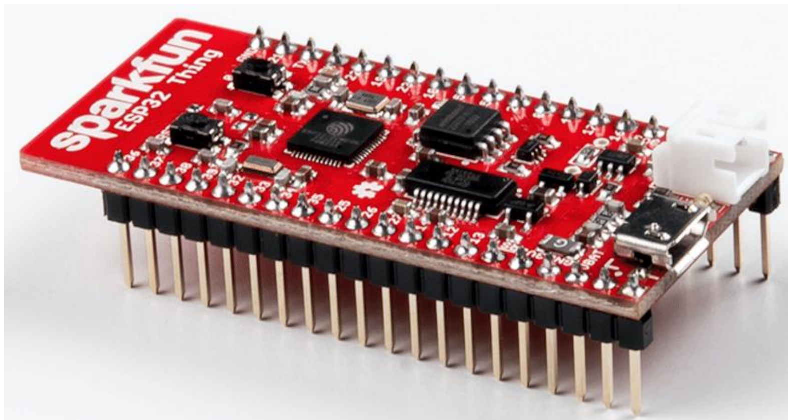

Fig. 5.6 The picture of Sparkfun ESP32 Thing.

It can be programmed with the Arduino integrated development board (IDE) tools. If the ESP32 board is connected with a personal computer with a USB cable, any program written in Arduino IDE can be uploaded directly to ESP32 micro-controller by selecting the board types and port type. The common name of the Arduino program is Sketches, and typically, it's C/C++ functions. To implement this project, the ESP32 thing microcontroller has been hooked up in a breadboard, and the temperature sensors and solid relay are connected. There two temperature sensors have been used; one is to measure the room temperature, and the other one is to measure the ambient temperature—the C++ program written in Arduino IDE in degree centigrade format and uploaded to the board. The ESP32 thing board has been powered with 5 V USB power cable. The measured and calculated temperatures are displayed in the IDE serial monitor by selecting the specific Baud Rate. Both temperatures will show as a digital form at the user monitoring panel. The Input/output and analog/digital pin, ground, VCC pins, reset pin, USB connected power supply pin configuration, and details structure of the Sparkfun ESP32 Thing development board are shown in Fig. 5.7.

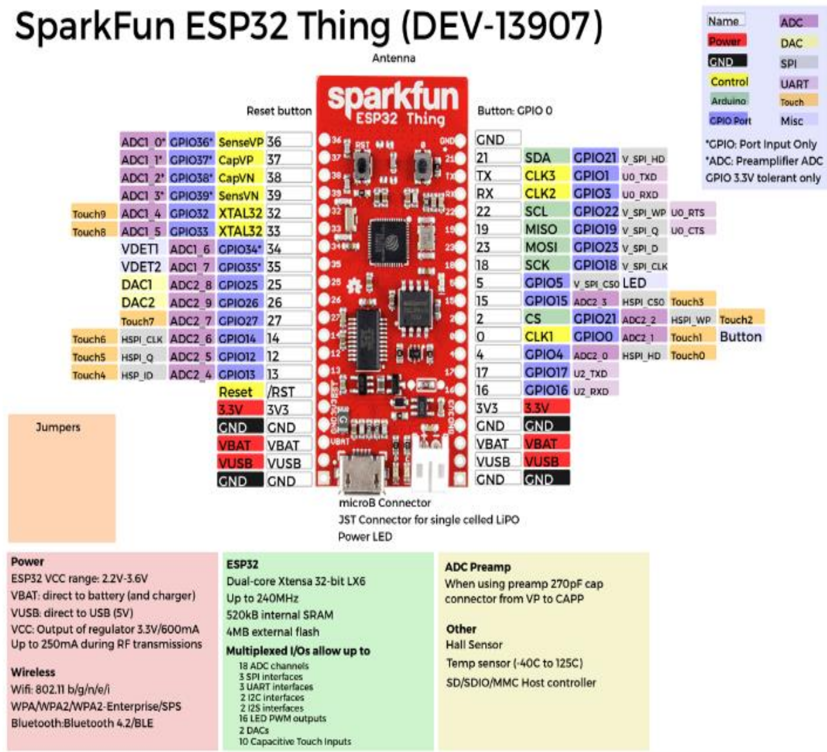

Fig. 5.7 The detailed architecture of the ESP32 Thing board.

5.5.4 Wi-Fi Router (Communication Channel)

In this monitoring and control system work, the local Wi-Fi serves as the communication channel between the ESP32 Thing (RTU) and the openHAB IoT home server. The high-speed Bell-Aliant Router (Model number Home HUB 3000) has been used to create the local WI-FI network. Its data transfer rate is 1 Gbps, 802.11b/g wireless protocol, and it is IEEE 802.11 standards-compliant. The Router operating frequency is 2.4 GHz, and it has one WAN power and four LAN ports. According to the datasheet of ESP23 Thing (MCU), it can implement TCP/IP full 802.11b/g/e/i WLAN MAC protocol and Wi-Fi direct, so it matched. A local WLAN Ethernet cable has been connected to the LAN port of Router. The Router has been configured to set up the needed local Wi-Fi network. After that, the communication established in between openHAB home IoT server and ESP32 Thing using the server IP address to identify the platform. To ensure the network security, the Wi-Fi Router user credentials (network name SSID and the password has been assigned.

5.5.5 Digital Thermostat and Heater

The project is related to temperature monitoring and thermostat control, so these components are the output components where the openHAB thermostat control topology has been applied. It has a digital thermostat, which indicated the running room temperature in degree centigrade in digital format. We selected one digital output port of ESP32 and connected the solid-state relay to turn on and off the heater. The other two digital output pin has been selected in ESP32 Thing are for thermostat control and for setting the thermostat value. In this work, a comfort zone brand heater has been chosen, which has a large easy to read digital display thermostat as well as a remote power by two 1.5 V dry-cell battery. It is a built-in electronic circuit. It is a 23 in black oscillating ceramic tower heater with 1500 watts ratings. It has three temperature settings, lower (800 W), medium (1000 W), and high (1500 W). The connection of heater thermostat and ESP32 Thing is shown in Fig. 5.8.

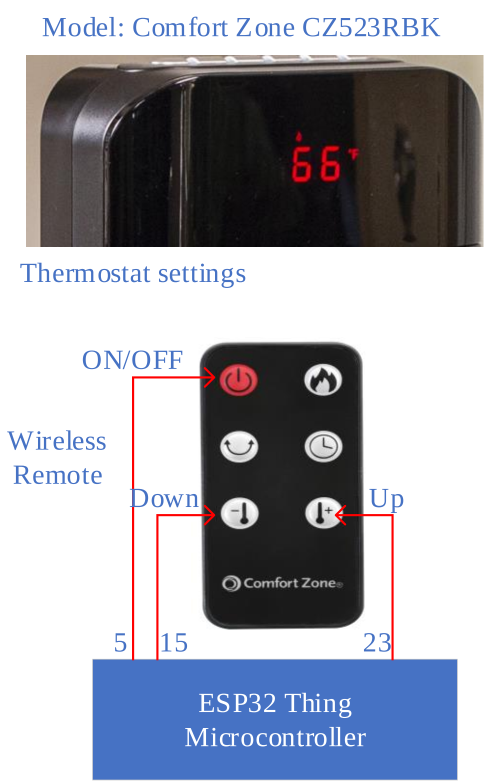

Fig. 5.8 The connection diagram of remote and ESP32 Thing for thermostat settings

The remote has two buttons one is used to up the thermostat settings (connected with Pin 15 and 23), and the other one is used to down the thermostat settings. According to the user demand, the user can press these two buttons in remote and wirelessly; the thermostat settings have been changed. These two buttons in remote are connected with the digital output pins of ESP32 Thing to control the thermostat settings from ESP32.

5.6. openHAB Setup and JAVA Programming

Open Home Automation Bus (openHAB) is an open-source IoT platform that is working with the JAVA programming language [22]. There is so many open-source IoT based software available like Thinger.io, ThingSpeak.com, Ubidots, ThingsBoard, Zetta, Node-RED, Flutter, Kaa, and so on. Among all of them, it has some strength such as it is capable of working with Linux, Windows, macOS, Unix, and Solaris operating systems, and it can integrate with other devices and systems, it can provide a uniform user interface and a common approach to automation rules across the entire system, it is more flexible. openHAB first developed in 2010, which is fully customizable and was capable to connects devices and services from various vendors. Now in the 2019 update, it has 300 bindings as OSGI modules, and multiple control options are available such as controlling the lights, relays, and the manual, and automatic controls are also possible in the user interface by triggering the rule developed by JAVA language.

openHAB works on Java virtual machine (JVM), which enables a computer to run Java programs. If the programs are written in other languages that also compiled to Java bytecode, all openHAB Bindings have a separate function. Whatever we need, we need to install that at runtime via OSGi. For storing and querying the sensors data, including relation and time series database, it also supports several persistence backends.

The openHAB IoT platform has a cloud console with an attractive designed front end where a user can monitor and control the connected devices and visualize the connected devices from another computer on the same server or another computer anywhere in the world. To ensure security, a user must log in to the cloud console using his user authentication ID and a protected password to avoid the misuse.

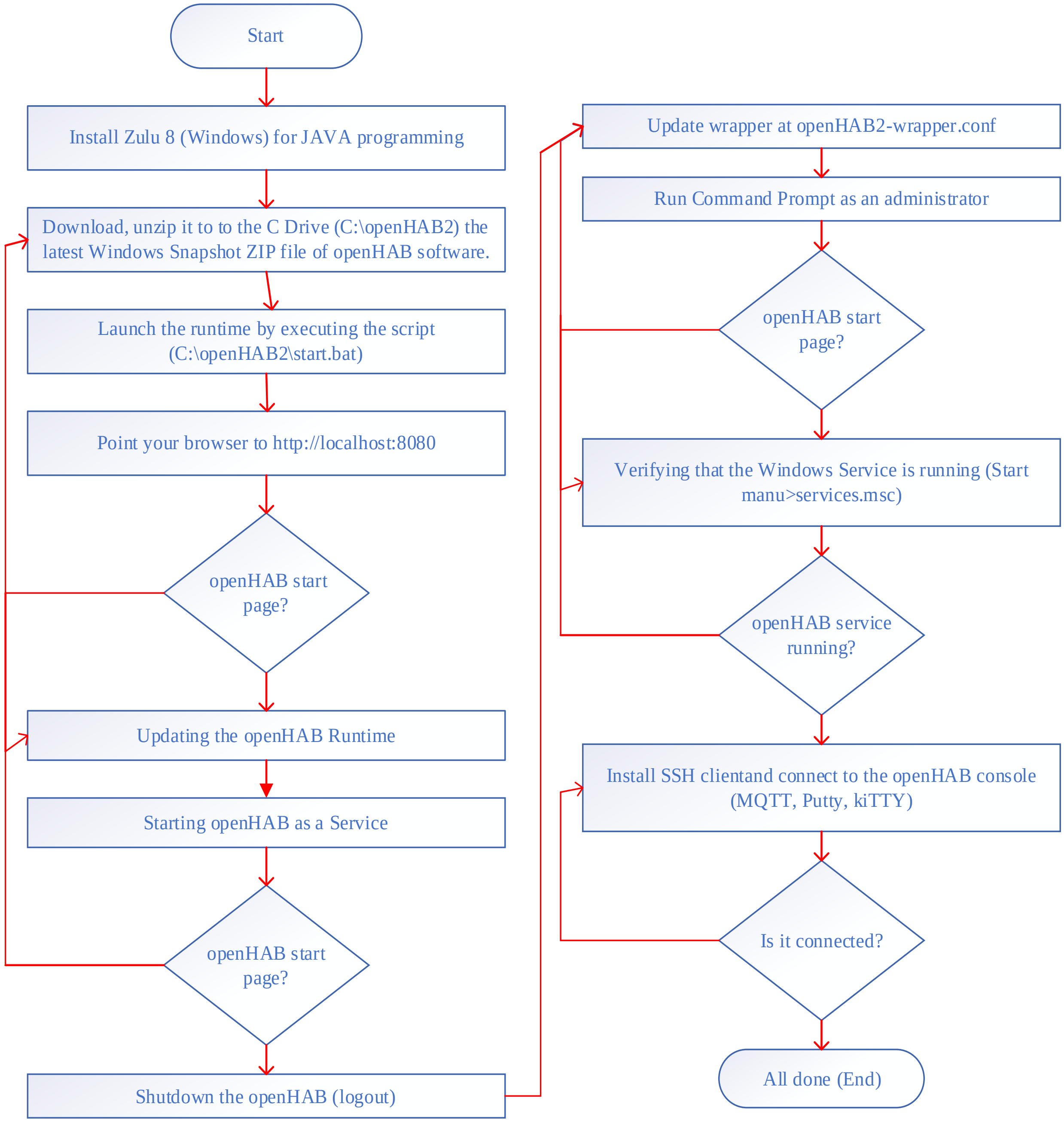

Fig. 5.9 openHAB installation steps in Windows.

To work with openHAB IoT platform, the first step should be to choose the operating system where to install it, such as Windows, Linux, macOS, Raspberry Pi, Docker, PINE A64.

To start with openHAB platform, the first step is to visit its official webpage and download the openHAB windows software latest version, in this project, the latest release version is Stable 2.5.5 and Snapshot 2.5.6-SNAPSHOT, it is better to download Snapshot latest version.

The openHAB is working with JAVA open source development platform, and there are several versions of JAVA platforms available. Among all of them, Zulu 8 is correctly working with openHAB. Then the user should follow the installation steps mentioned in Fig. 5.9.

5.6.1 openHAB Configuration

openHAB is the smartest IoT platform among all of them where the Configuration is also s user friendly, which is capable of connecting all devices available under the Wi-Fi network. Every device is logically and functionally different connected to openHAB. The openHAB-MQTT channel definition is shown in Fig. 5.10. To represent all of these, openHAB defines the following base components:

Table 5.1: Description of openHAB components.

openHAB components	Short descriptions
Add-ons	To communicate with connected devices
Things	Device representation in openHAB
Items	Things properties and capabilities
Groups	Items collections and categories
Sitemaps	User-defined interface to arrange groups, items, and so on.
Transformations	Functions to transform user data.
Persistence	Store updated data service
Rules	It is used to automate the systems.
Javascript	Define rule and other runtime objects using Java programming.

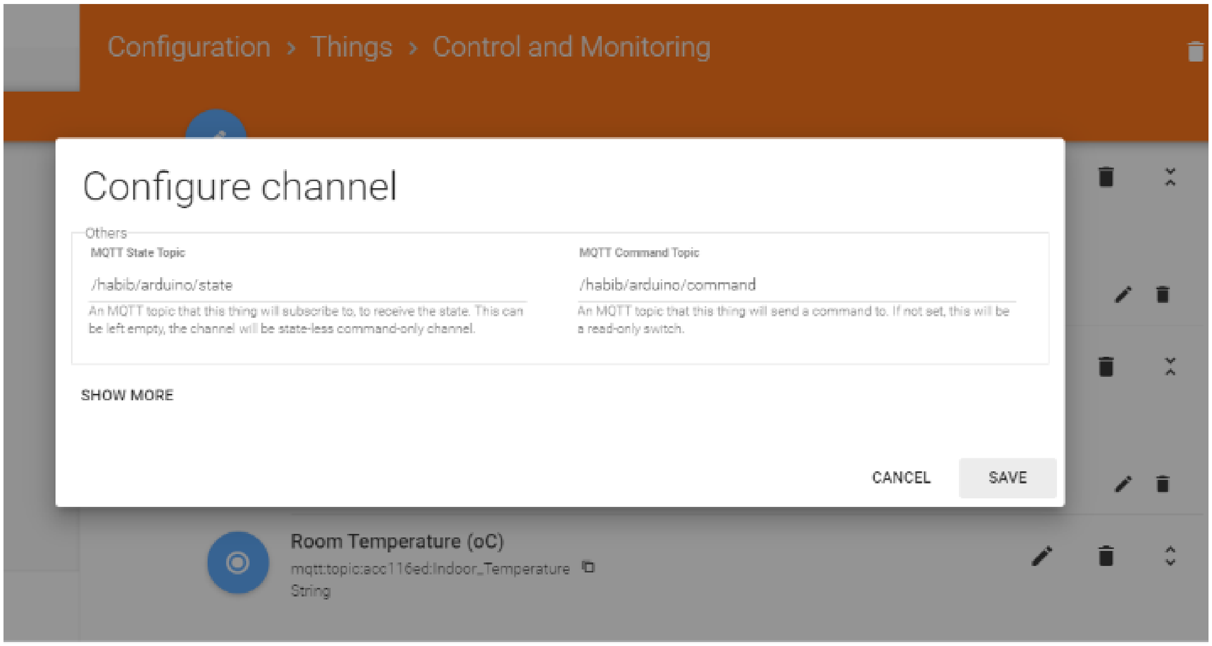

Fig. 5.10 openHAB and MQTT Configuration

5.6.2 Communication Mechanism

openHAB can communicate electronically with smart and not so smart devices, can perform user-defined actions, and can provide a webpage with user-defined information as well as user-defined tools for interaction with all devices.

It has some specific segments, functions, and operations. The main components of openHAB are described below:

Channels: The user can find the channel under the openHAB>PaperUI>Configuration. It is a logical link between a Thing and an Items. The primary function of channels are communication; it originates from Things and communicates with Items or vice versa. During the Thing definition, the user will create channels where items will be lined. Every item has a unique identification number, which we put to the JAVA programming to establish external communication as well with MQTT. Thus the connection has been established between Things and Items. Figure 11 represents the relation between Things and Items and the confirmation of communication establishment in between openHAB and MQTT broker is shown in Fig. 5.12.

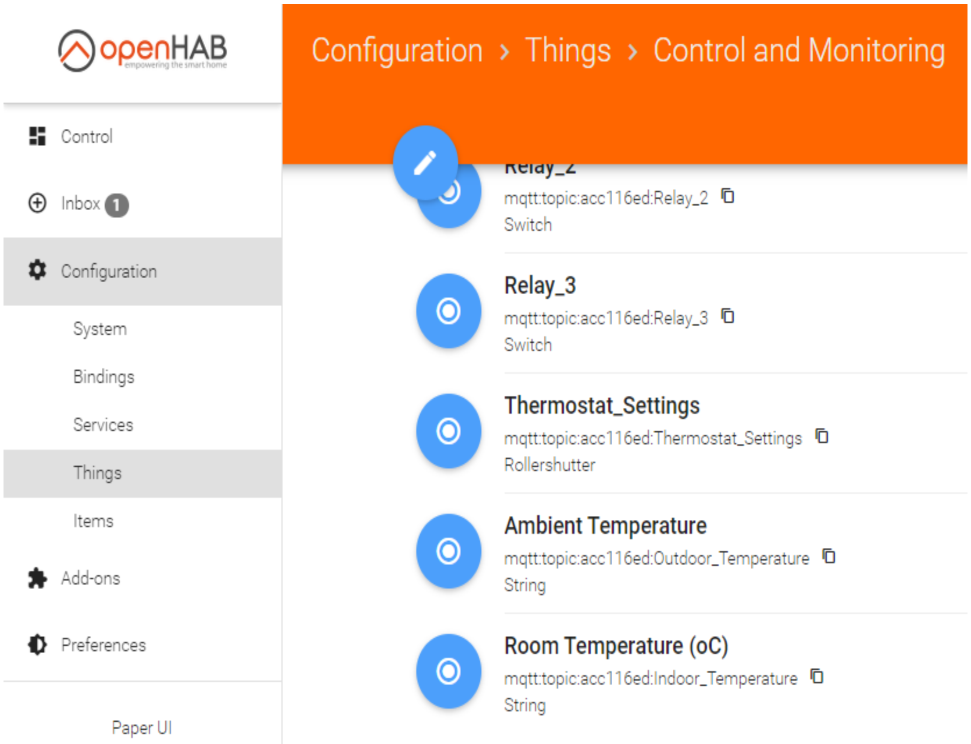

Fig. 5.11 The relation between Things and Items.

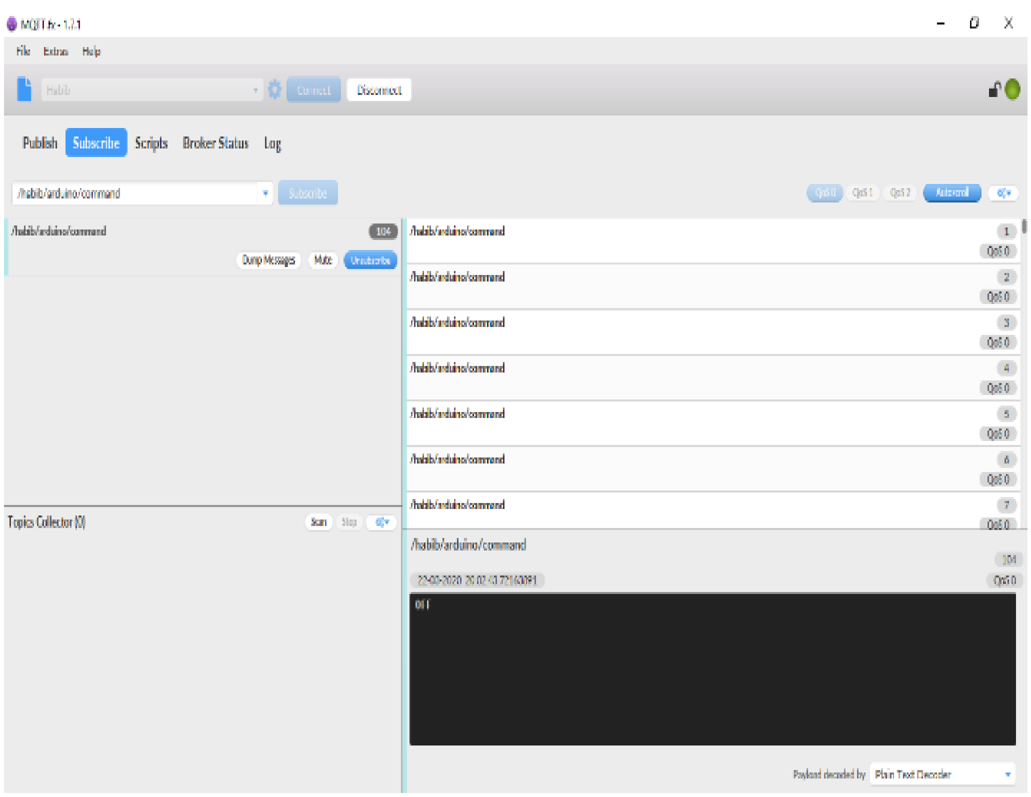

Fig. 5.12 openHAB home server and ESP32 Thing communication via MQTT broker

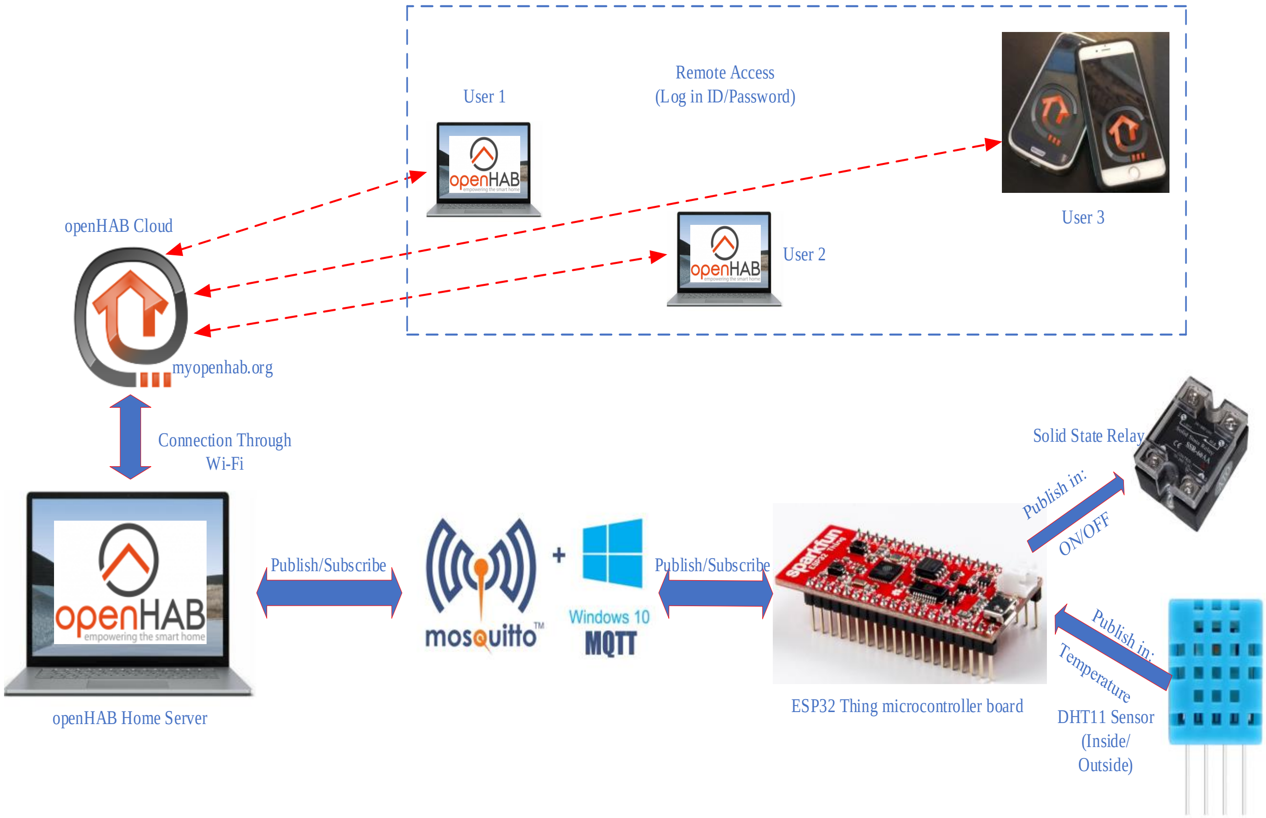

Fig. 5.13 The communication mechanism

5.7. Experimental Setup

This research mainly focuses on the thermal energy storage system monitoring and control, as mentioned in Fig. 5.1. The prototype consists of indoor and outdoor temperature sensor data monitoring and thermostat settings control using Sprukfun ESP32 Thing device and openHAB smart home automation open-source IoT platform. Analog (TMP35) and digital (DHT11) temperature sensors have been used to monitor indoor room and ambient temperature. Similarly, a remote control electric heater with a digital temperature display has been considering as a thermostat settings device. openHAB home server is used for remote monitoring and supervisory control. Here one set of sensors and thermostat control systems is used for testing purposes.

5.7.1 Implementation Methodologies

The primary implementation methodologies are to design a low cost, low power consumption open-source IoT remote monitoring and control system. The analog and digital temperature sensors are connected to the analog and digital input pins of Sparkfun ESP32 Things, respectively. One temperature is placed on the outside, and another one has been placed in the room. These sensors collected temperature data form room and outside environment and sent it to the ESP32 microcontroller through the serial port. The microcontroller is programmed with Arduino IDE to receive these sensor data, displayed them in a serial monitor, and then sent it to the local Wi-Fi network to the MQTT broker. The MQTT broker sent these data to the openHAB home server via the local WI-FI network to display at the openHAB control panel. On the openHAB cloud console, the user can visualize the sensor data by merely putting the user credentials and password, no need to remember the IP/TCP address. The implementation methodology is shown in Table 5.2 below, and the appearance of the received data on MQTT broker and openHAB home server, which is described earlier, is shown in Fig. 5.18.

Table 5.2: The implementation methodologies.

Initialization:

1. Read sensor values on digital pin 34 and 35.
2. Display the sensor values on Arduino IDE serial monitor
3. Connect to the local Wi-Fi network with Wi-Fi Name and password.
4. Connect to the MQTT broker with local WI-Fi.
5. Display the sensor values on the MQTT broker.
6. Connect to the openHAB home server by writing localhost:8080 at the browser URL.
7. Go the BasicUI>Sitemaps>Control and monitoring panels to display the sensor values.
8. Go to the PaperUI>Control to display the sensor values.
9. Change the value of relay and thermostat settings on openHAB control panel.
10. Display the user control response in the MQTT broker.
11. Monitor the output of ESP32 digital output pins to visualize the relay and thermostat display change.

While openHAB home server and MQTT broker Acknowledge data receipt do

12. Display sensor data on openHAB Cloud, and
13. Display "Ok" on Arduino IDE serial monitor.

    If No data receipt acknowledge form openHAB home server then

14. Display Debug/Error message on Arduino IDE serial monitor and MQTT broker.

    else

15. Go to step 1

    end

    end

The user will be confirmed that this algorithm is working perfectly when he/she will see the MQTT broker output, as mentioned in Fig. 5.12, and the sensors post the data as like Fig. 5.18.

Prototype design: The hardware components and the operational principles for every element discussed above have been used to design and to implement the low-cost monitoring and control systems, as shown in Fig. 5.15. The sensors, resistor arrangement, and the ESP32 Thing microcontroller are connected following the correct pin configuration on a breadboard. The ESP32 ADC pins require 3.3 V, but the power supply is 5 V because the ESP32 has been powered with a USB power supply. That's why pull-down resistors are needed. The Wi-Fi router has been turned on; thus, ESP32 is connected to the MQTT broker and openHAB home server installed in the personal computer.

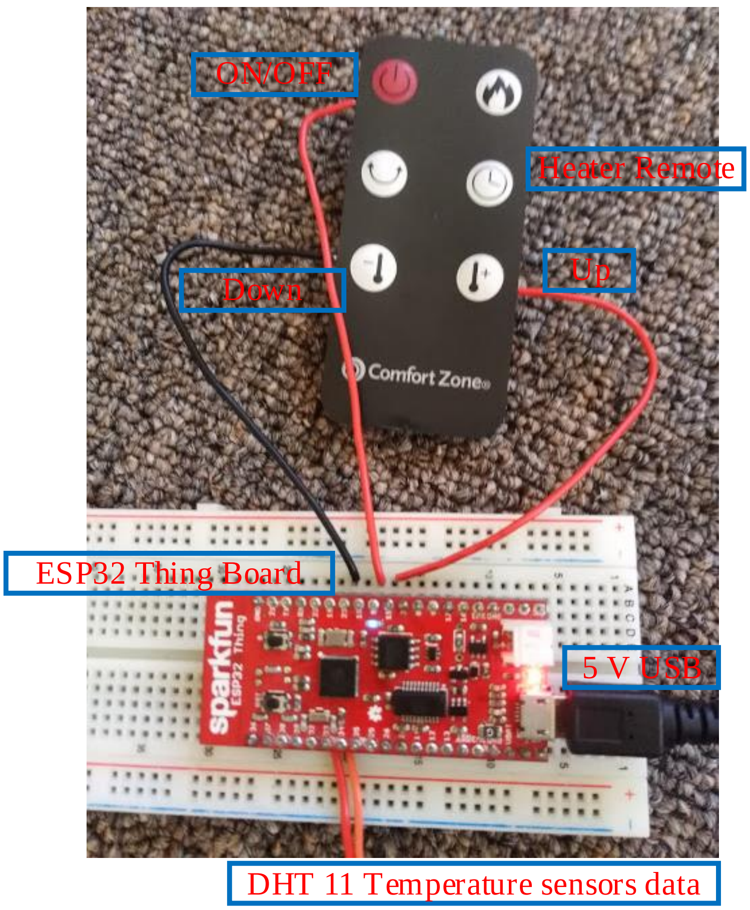

Fig. 5.14 Hardware connection of the proposed monitoring and control systems.

The proposed monitoring and control system project have been implemented at the author's residential house as shown in Fig. 5.14 and Fig. 5.15. Two temperature sensors have been connected, one is in the outside, and another one is in the room inside to measure the ambient and room temperature, respectively.

The rest of the components, Wi-Fi- routers, personal computer integrated with openHAB home server, MQTT broker have been set up in the place inside, as shown in Fig. 5.15. The heater remote and thermostat have been connected with the ESP32 Things. The communication happened bi-directional ways, as shown in Fig. 5.13. The complete experimental setup is shown in Fig. 5.15.

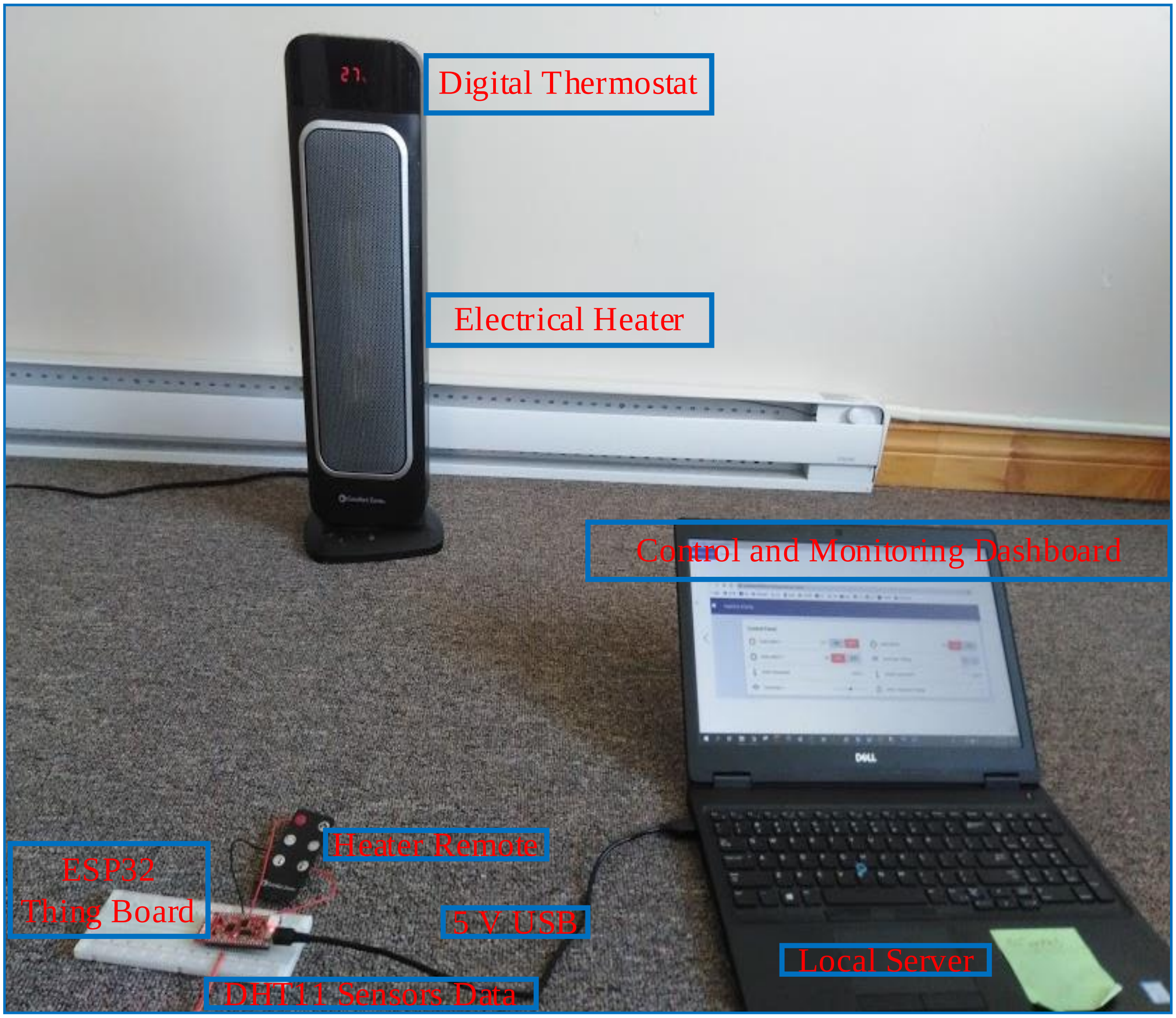

Fig. 5.15 Experimental Setup of proposed systems.

5.7.2 System Testing

The components have been set up at one of the author's residential homes to implement the proposed monitoring and control system. The overview and flow chart of the data acquisition, processing, visualization, and supervisory control process from the sensors to the openHAB home server IoT platform is shown in Fig. 5.16.

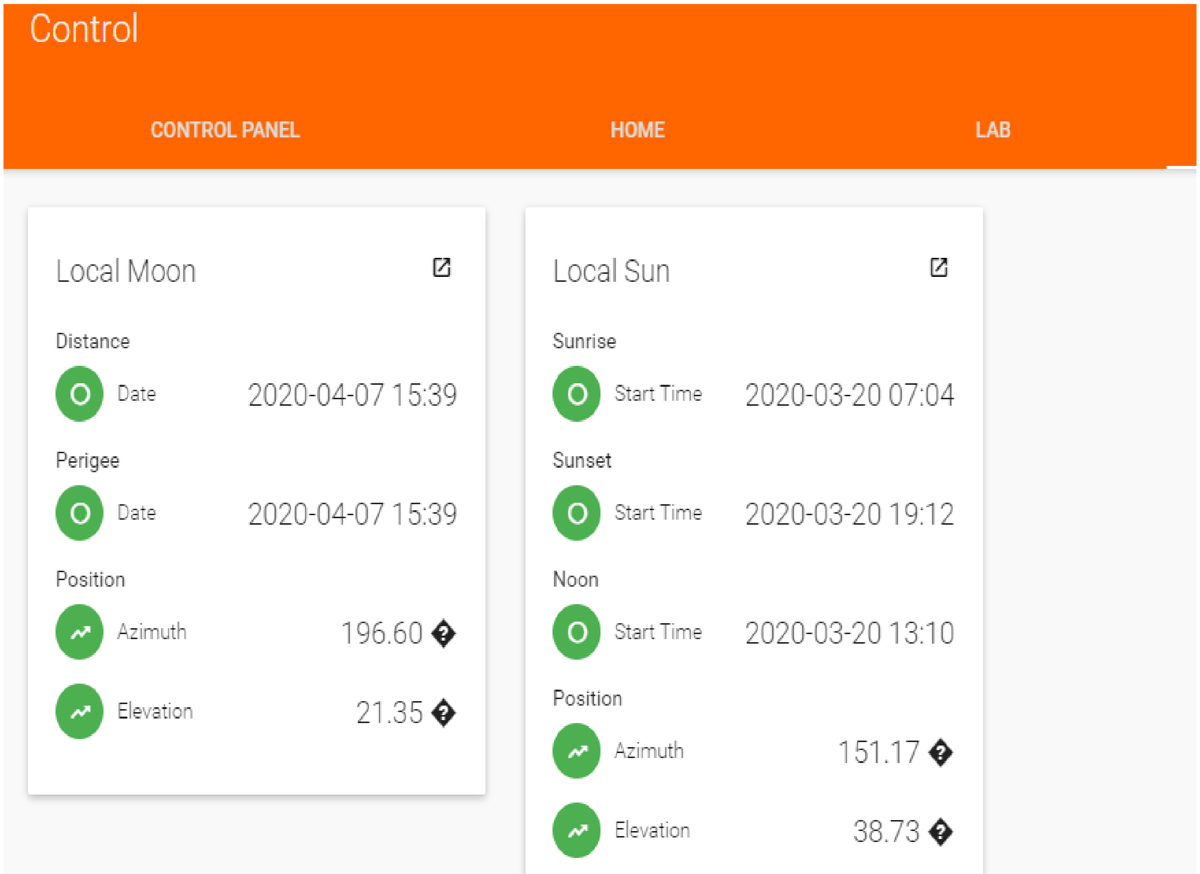

Fig. 5.16 The sensor data is in the openHAB server

The experimental trouble shooting, and data verification has been conducted based on the flowchart in Fig. 5.17.

5.7.3 Experimental Results

The openHAB local server IoT platform was configured in the personal computer following the steps shown in Fig. 5.9, configured the MQTT broker to the personal computer as well, and the necessary library files (MQTT, DHT11 sensor) uploaded to the Arduino IDE to configure and establish the connection among the openHAB home server, MQTT broker and ESP32 Thing.

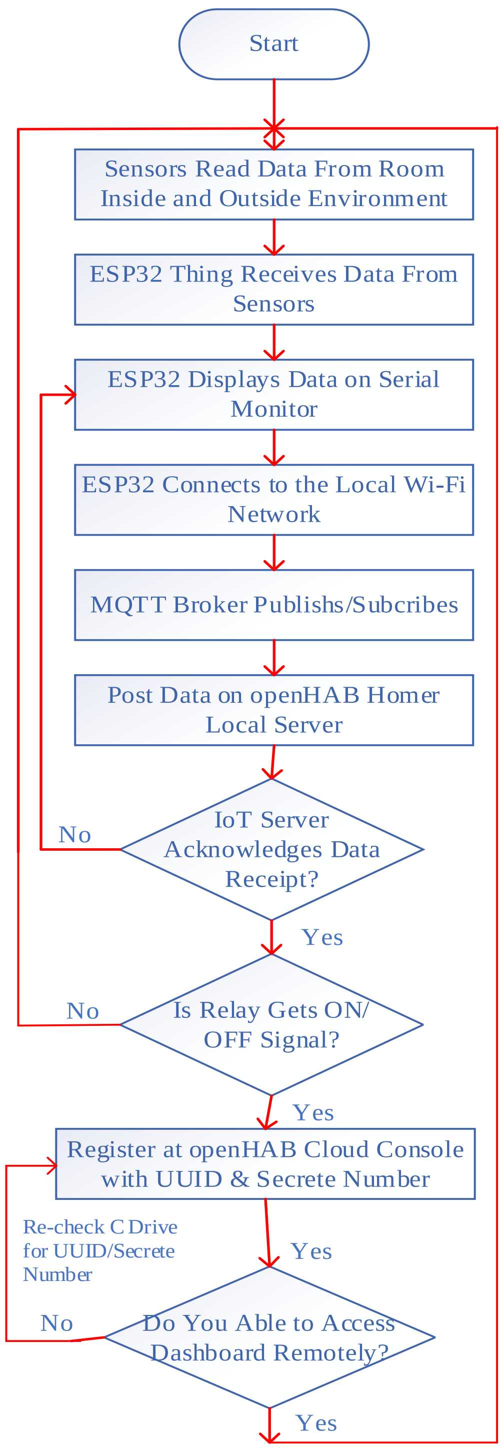

Fig. 5.17 Flow chart of the proposed system.

The sensor's data were posted on the openHAB local monitoring and control system dashboard and Cloud console for remote monitoring and control using a mobile phone and any other computer devices. The openHAB server control panel and main user control panel from Sitemap are shown in Fig. 5.18 and Fig. 5.19 respectively.

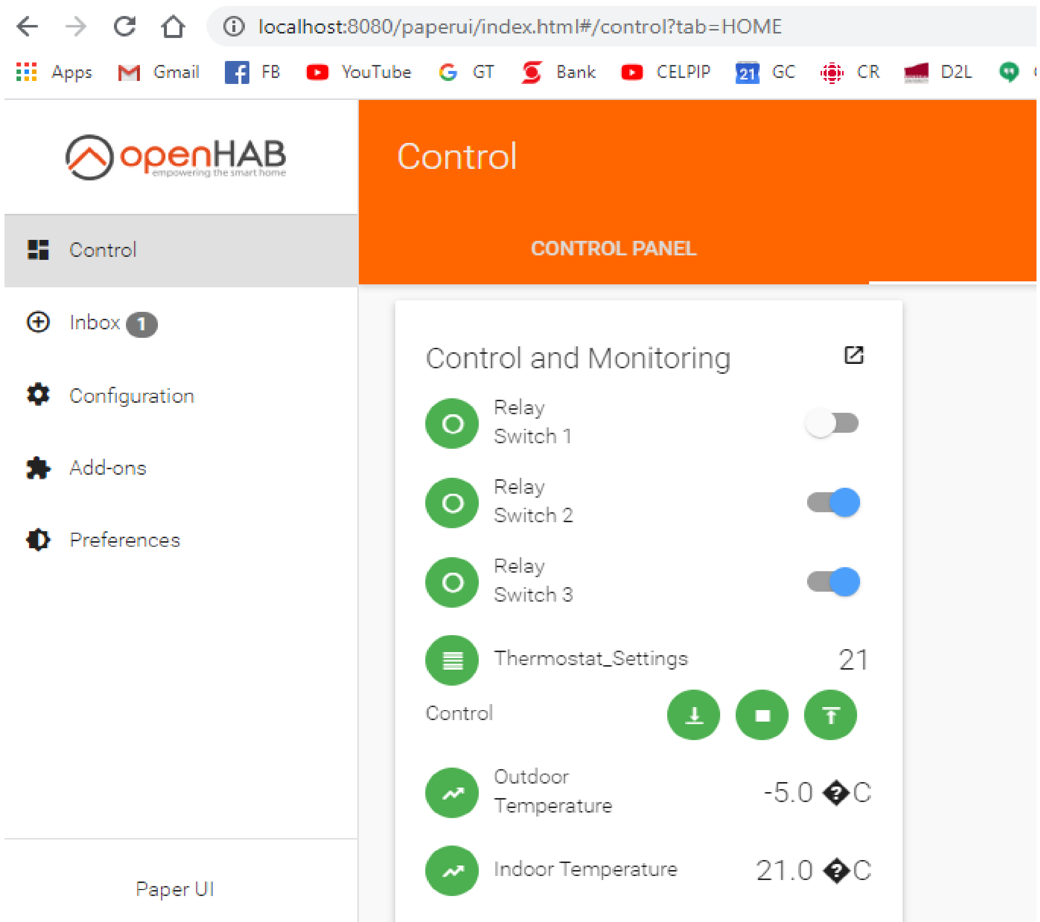

Fig. 5.18 The openHAB home server control panel

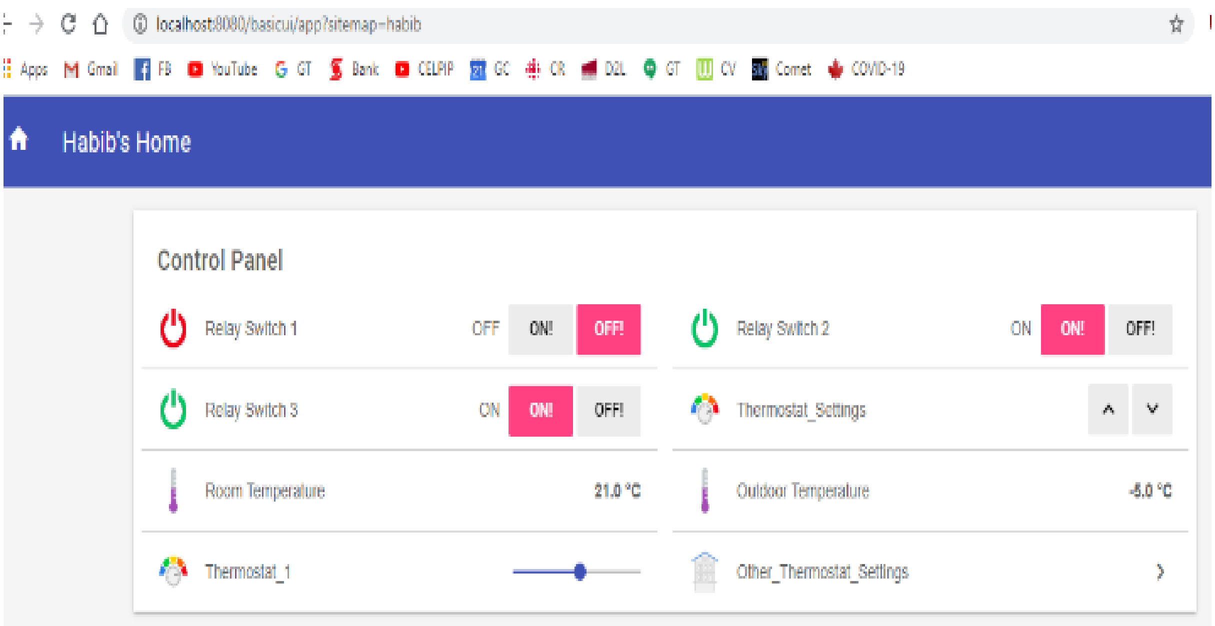

Fig. 5.19 Main control and monitoring dashboards

5.7.4 Remote Control and Monitoring

openHAB Cloud is a smart service that allows users to quickly put the user credentials and explore the dashboard using any computer, laptop, tablets or mobile devices from anywhere in the world. During the setup and Configuration, remote access option was allowed. Similarly, in Fig. 5.9, it is mentioned that how to registrar at openHAB Cloud and where to get the UUID and secrete code for registration. Now, for remote access, the user need to browse the openHAB Cloud console by visiting https://myopenhab.org/login and simple put the user credentials as shown in Fig. 5.20.

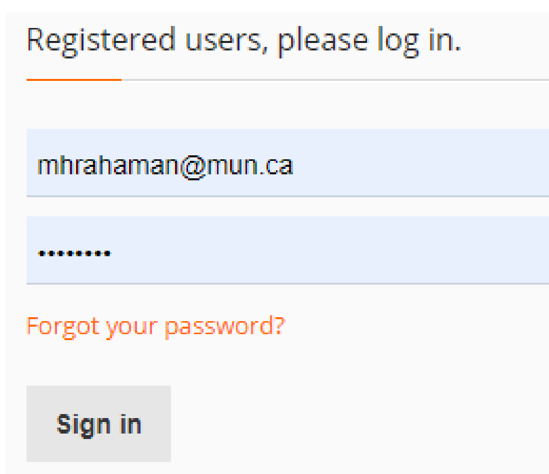

Fig. 5.20 User credential for remote access

User no need to memorize the IP/TCP address or any other credentials. Rather than, users will be simply able to access the monitoring and control dashboard from anywhere in the world, as shown in Fig. 5.21.

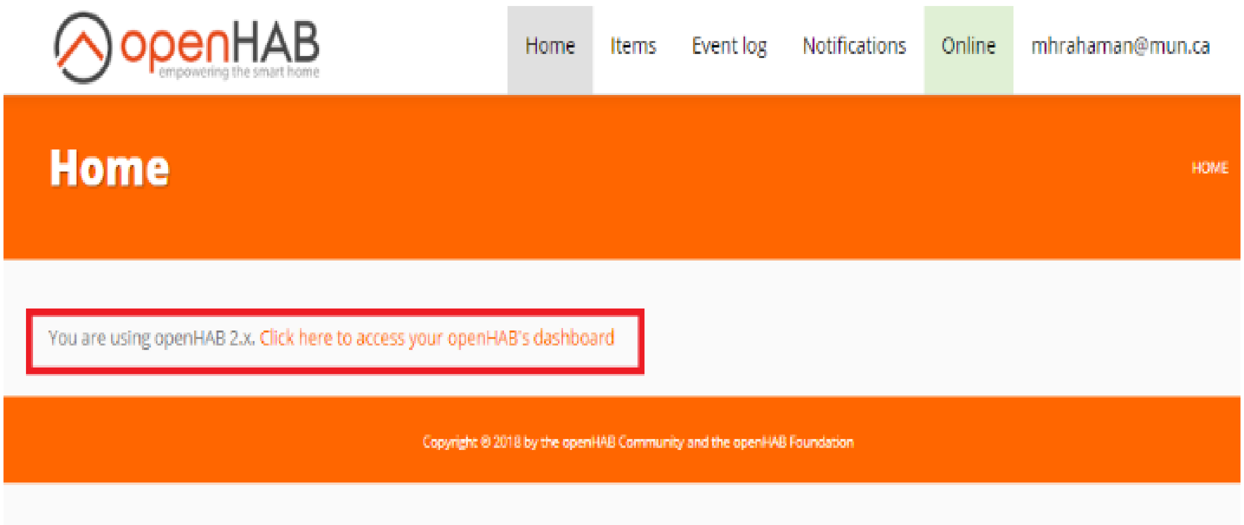

Fig. 5.21 The openHAB Cloud console for remote access

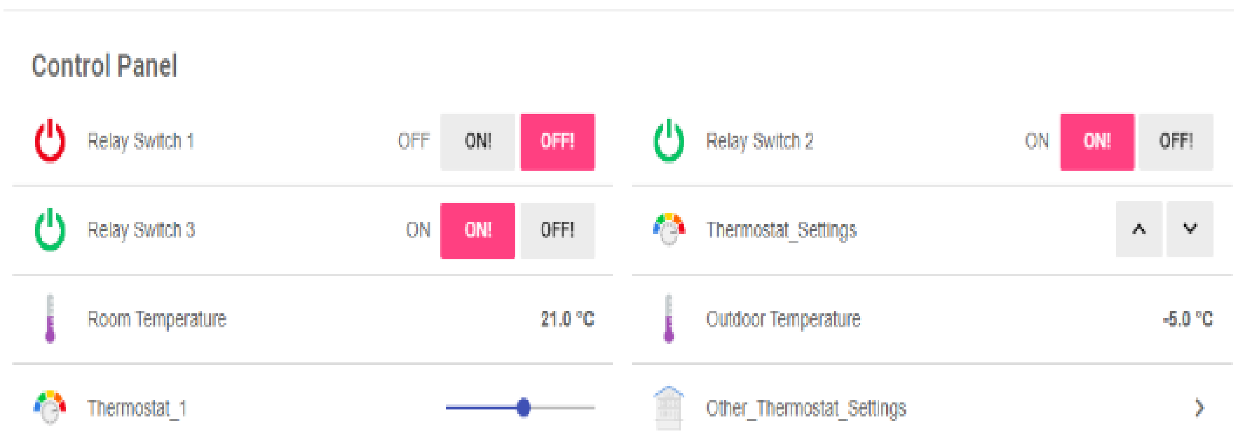

Fig. 5.22 The access of the dashboard from a remote place.

5.8. Discussion

Some of the highlighted features of the proposed low-cost, open-source smart monitoring and control systems are discussed below:

- ✓ IoT based system: The proposed system is based on the Internet of Thing (IoT) which have four basic parts such as the heater with a digital thermostat is used as the facilities (plant) to be managed; sensors are the field instrumentation devices used as a data collection and acquisition, the ESP32 Thing microcontroller device is used as a Master Terminal Unit (MTU) as it has data handling, processing, and human-machine interactions capabilities. The wireless Wi-Fi router is created a communication channel between the openHAB home server and MTU.

- ✓ Low-cost and open-source: All the components discussed above are pretty cheap and readily available everywhere around the world (nearby local store and online). It is the customer's choice to buy the components from their own, which is the key feature of open-source systems. It is assumed that the thermostat and Wi-Fi router are available in every house, so those components cost have been excluded in the cost calculation. The cost of induvial components and over the system is summarized in Table 5.1. As seen, the overall system costs are just around \$50 CAD (Table 5.3). So, it is proved that the proposed systems are a low-cost system compared to the other available technology in the market.

Table 5.3: Project cost calculation

S/N	Name of the components	QTY	Price (CA$)
1	ESP32 Thing	1	31.90
2	TMP35 temperature sensors	2	2
3	DHT11 Temperature sensor	2	2
4	Miscellaneous (Breadboard, Resistors, Wires, Boxes, etc.)	1	10
	Grad total:		45.9

- ✓ Low power: The components described above in Table 5.1 consume very negligible power around (W) in total, which is very low. The power consumption of all components have been measured during the operation and summarized in Table 5.4.

Table 5.4: Project components power calculation

S/N	Hardware	Power (W)
1	ESP32 Thing	0.5
2	Breadboard (with Sensors, ESP32, Resistors, etc. connected)	3.3
	Total:	3.8 W

- ✓ Monitoring: The openHAB home server system has a dashboard for data monitoring and thermostat control. These dashboards are accessible to the user in so many ways, such as the server personal computer, other personal computers and remote computer or mobile devices through openHAB mobile App.

- ✓ Supervisory control: The system allows the user to access the home server via a personal computer to monitor and control. Similarly, the user can log in to the openHAB cloud console by merely putting their user credential and password and can monitor and control the devices anywhere in the world.

5.9. Conclusion

In the most residential house in Canada uses a large amount of electricity for space heating and water heating. To do that, there are huge monthly electricity bills every residence needs to pay, and the grid became overload sometimes. Due to the mismanagement of the electrical heater, radiator, the consumption would be more as well. To ensure the optimum management of heating elements, to monitor the status of room temperature and ambient temperature from locally and remotely, to reduce the system supervisory system cost and power consumption, the proposed system would be highly useful for real application. This system ensured the reliable, flexible, cost-effective, lower power requirement, and sophisticated, coordinated monitoring and control of measurement of temperature and heater/radiator thermostat settings. Although there is some similar system existing in the market which is described in the introduction section, these systems have several drawbacks, such as there is no way to develop the system because the supply industry controls it. There are some limitations in several device integrations, and those systems are costly. Rather than the proposed method is cost-effective, simple, the user can add the Bindings, channels and can add as much as a device he needs to connect for the whole operations. The utility company, such as Newfoundland power, can also use these systems for controlling the thermostat settings in a large area centrally. For example, the utility company will monitor the power generation and demand, as they know that around 60% consumptions are for space heating. Approximately 20% consumptions are for water heating, if they set the thermostat settings as a specific temperature for all house by using the openHAB Cloud console from their office (remotely), then the residence cannot increase the heating temperature beyond this settings, thus grid overloading will be resolved, and mismanagement issue will be resolved.

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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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Chapter 6

Conclusions and Future Work.

6.1 Conclusions

Due to the long and worst winter in Canada, the people are struggling to pay the high electricity bills in every month. All buildings need to supply space heating and water heating for approximately eight months in a year. They are mainly depending on the grid electricity to mitigate this high energy requirements. But that has some problems such as grid overloading, green house emission, high electricity bill and so on. To overcome the greenhouse problem and to ensure the safe and healthy environment, whole world is trying to move into the renewable or green energy solutions such as microgrid, smart grid, grid integration and so on. This research focus on to work with a single-family residential house to analyze the house energy demand and to redesign the space heating and domestic water heating systems to incorporate with the renewable energy coming from solar collector, solar photovoltaic array, hybrid type solar photovoltaic thermal array. As everybody knows that the solar energy emission is not constant and not available in all day and night. However, the consumer needs space heating and hot water continuously in full wintertime and on demand in summertime. That's why the auxiliary heater is considered in every proposed thermal energy storage design. In the wintertime, there is no sun in even a couple of months, then if we use a short time and small storage tank, then the auxiliary heater will be the only source of thermal energy as there is no renewable power generation in these months. To solve this issue, a Seasonal solar thermal energy storage system has been proposed, mathematically designed, simulated and analyzed the result and compared with the annual energy demand and annual energy production. It was concluded that the proposed sizing and instrumentation were perfect and optimum.

There are several temperature sensors are connected with every TES component and sent the reading in the controller. If the temperature in the water tank goes below the threshold, then controller is turned in the auxiliary heater to supply additional heat to the storage tank. Normally, in every system, the insulated water tank, radiator and hot water tank have been used. The hot water move with the insulated pipe to the radiator and hot water tank when consumer needs. The mathematical modeling, proper sizing, analysis, system design, system simulation and simulation result analysis have been conducted in this research. The objectives of the proposed TES systems in second, third and fourth chapter is to compare their thermal and electrical performance and to find out the suitable and sustainable TES systems with a minimum investment.

The monitoring and control of TES system is also a major challenge. There are several companies are offering some digital thermostat but they have some limitation and disadvantages such as expensive, need Wi-Fi service from both side, only few numbers of sensors and devices can be connected, there is no way to develop further from user side because it is the company control. In this research, TES monitoring and control system have been developed which is capable to overcome all of the issues such as it is pretty cheap and around four times lower price (CA $49) compared to the available products, the power consumption is lower (only 3.8 W), around ten times more devices can be connected and user always able to develop the system. The connection diagram is also so simple, and the user can monitor and control their TES system from locally or remotely anywhere in the world, it may be manual control or automatic control.

6.2 Future Research

The research and development in solar thermal energy storage system (short term and Seasonal) is not new, there are so research has already done by many researchers around the world including Canada. Some of the relevant works are mentioned in the various chapter in reference sections. The proposed TES systems are designed, solved high level of mathematical complexity and simulated by the author and the same design with Canadian weather has not been done before, that is the novelty. But the research and development of this branch will continue forever as well. However, several knowledge gaps and scope of work could be further addressed and there are several possibilities to develop the proposed system further are listed below:

- ✓ The proposed system TES systems can be redesign for any other weather environment and any other building size (residential, commercial or industrial) whatever the designed needs.
- ✓ There are several parameters assumed constant or ignored such as flow rate, temperature drop, pipe loss, wind effect, and dust in the collector surface, the same system can be re-designed considering those effect.
- ✓ The research can be done by working with the modeling, sizing and simulation to improve the thermal and electrical efficiency and panel output or to improve the overall system efficiency.
- ✓ The further research can be conducted to work with designing robust controller for the TES systems that could monitor the TES parameters and could control more smart way and accurately.
- ✓ The space heating and water heating for a residential community can be analyzed and can be designed optimum solar thermal energy storage systems for clod climate zones.

- ✓ Detailed reliability of the proposed IoT based remote monitoring and control systems can be analysis in future.
- ✓ The ESP32 Thing board has been chosen, the prototype can be designed with other types of microcontroller unit to reduce the cost and power consumption further.
- ✓ For increased security in implemented control system, data encryption can be implemented on the communication channels of each of the systems.
- ✓ In the future, different open source IoT/ SCADA systems can be developed for data transfer so as to compare their performance with the MQTT API.

6.3 List of Publications

Refereed journal Articles

[1]. M. H. Rahaman and T. Iqbal, "A Comparison of Solar Photovoltaic and Solar Thermal Collector for Residential Water Heating and Space Heating System," European Journal of Engineering Research and Science, vol. 4, no. 12, pp. 41–47, Dec. 2019, doi: 10.24018/ejers.2019.4.12.1640.

[2]. H. Rahaman, M. T. Iqbal, "A Remote Thermostat Control and Temperature Monitoring System of a Single-Family House using openHAB and MQTT," in European Journal of Engineering Research and Science (Accepted)

Refereed Conference Publications

[1]. H. Rahaman, R. Rasha, and M. T. Iqbal, "Design and analysis of a solar water heating system for a detached house in newfoundland," in 2019 IEEE Canadian Conference of Electrical and Computer Engineering (CCECE), May 2019, pp. 1–4, doi: 10.1109/CCECE43985.2019.8995175.

[2]. Rabbani Rasha, Habibur Rahaman, Tariq Iqbal, Sizing, modeling and analysis of a solar seasonal energy storage for space heating in Newfoundland, presented at CSME-CFDSC 2019, London, ON, Canada.

Regional Conference Publication

- ✓ Habibur Rahaman, M. Tariq Iqbal, Load analysis of RUET, ECE building and design of a rooftop PV system to meet all its energy needs, presented at the 28th Annual IEEE NECEC conference, St. John's, November 19th, 2019.

Research Presentations

- ✓ Md Habibur Rahaman and M. Tariq Iqbal, "Design a Low-Cost Remote Monitoring and Control Systems for Thermal Energy Storage System," Presented at the 3 MT thesis competition, 2019 held at the Memorial University of Newfoundland, St. john's, NL, Canada. June 1, 2019 (Awarded 3rd Prize).

- ✓ Md Habibur Rahaman and M. Tariq Iqbal, "Design, Analysis and SCADA Interface for Energy Storage Systems," Presented during the poster session at the NESTNet 5th and Final Annual Technical Conference, Ryerson University, Toronto, ON, Canada. June 16 - 17, 2020 (Virtual).