SOLAR WATER HEATING SYSTEMS WITH THERMAL STORAGE FOR APPLICATION IN NEWFOUNDLAND

By

Rabbani Rasha

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Abstract

Solar water heating systems are commonly used in many parts of the world. Some such systems have thermal energy storage option. No such example could be found for Newfoundland. Such renewable energy systems could be designed and implemented for Newfoundland to reduce CO_2 emissions. In this thesis, thermal modeling of a house is presented to design a solar water heating system with thermal storage for residential applications in St. John’s, Newfoundland, Canada. Also, an experimental investigation of a heat recovery ventilator (HRV) unit is done to find out the annual heat loss and power consumption of HRV. Lastly, a dynamic simulation of a space heating system is presented to figure out the transient response of various components of a solar water heating system. Polysun, SHW, MATLAB/Simulink and BEopt are used as the simulation software for this thesis. Some results of this thesis have been published and compared with the existing systems. This thesis presents full details of system modeling, simulation and some experimental results. The thesis is written in a manuscript format based on published papers.

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List of abbreviation

SHWS	Solar water heating system
HTF	Heat transfer fluid
ICS	Integral- collector storage
TES	Thermal energy storage
CEO	Chief executive officer
SHES	Sensible heat energy storage
LHES	Latent heat energy storage
PCM	Phase change material
TCES	Thermochemical energy storage
UTES	Underground thermal energy storage
CSP	Concentrating solar power plants
COP	Coefficient of performance
KSV	Kerava solar village
ECN	Energy Research Centre of the Netherlands
NL	Newfoundland
HVAC	Heating, ventilation and air conditioning
BEopt	Building energy optimization tool
OSB	Oriented strand board
ACH	Air change per hour
HRV	Heat recovery ventilator
PEX	Cross-linked polyethylene
CFL	Compact fluorescent
EF	Energy factor

GHG	Greenhouse gas
STES	Seasonal thermal energy storage
DTES	Diurnal thermal energy storage
ASHRAE	American Society of Heating and Air-conditioning Engineers
SSTES	Seasonal solar thermal energy storage
CSHPSS	Central solar heating plants with seasonal storage
SSHS	Solar space heating system
SH	Space heating
DHW	Domestic hot water
NRC	Natural resource Canada
IEA	International energy agency
BedZED	Beddington zero energy development
SHW	Thermal solar system
MVHR	Mechanical ventilation heat recovery

List of symbols

Q	Amount of heat stored
m	Mass of heat storage material
C_p	Specific heat of storage material
ΔT	Amount of temperature change
ρ	Density
k	Thermal conductivity
a_m	Melting fraction
C_{lp}	Average specific heat between T_f and T_m
C_{sp}	Average specific heat between T_i and T_m
Δh_m	Heat of fusion per unit mas
T_f	Final temperature
T_i	Initial temperature
T_m	Melting temperature
a_r	Extent of the conversion factor
Δh_r	Endothermic heat of reaction
$a1, a2$	Collector area
Q_{demand}	Monthly energy demand
$Q_{solar(1,2,3)}$	Monthly solar radiation
Q_{excess}	Excess energy
η	Collector efficiency
$D = H$	Height and diameter
E	Excess electrical energy
V	Volume
Power1	Power of solar collector loop pump

Power2	Power of another loop pump
Q_{DHW}	Amount of energy to heat the daily hot water demand
C_w	Specific heat capacity of water
V_{cyl}	Minimum volume of tank
Vn	Domestic hot water demand per person/day
P	Number of people
T_h	Temperature of hot water at the outlet
T_c	Temperature of cold water
T_{dhw}	Temperature of stored water
N	Collector number
$\mathrm{A_R}$	Total required collector area
$\mathrm{A_S}$	Selected collector's aperture area
SF	Solar fraction
$\mathrm{V/A}$	Volume to area ratio
Q_v	Flow rate of air
d	Density of air

Chapter 1

Introduction and Literature Review

Introduction

1.1 Solar Water Heating System (SWHS)

The most rewarding application of solar energy is when it replaces electrical energy and non-conventional energy like oil for heating of domestic hot water and space heating application. Solar energy also can be considered as an alternative source of energy that is coming from the sun in the form of solar radiation. This radiation from the sun varies from place to place over time. When an absorbing surface absorbs this radiation, it gets heated, and this heated energy is the prime source of a solar water heater. Owing to increasing demand for power with the massive population growth and the rising cost of fossil fuels like natural gas, oil, and the like, it is becoming a promising source of renewable energy. A solar water heating system is the cheapest, environmentally friendly way to get hot water and consume approximately 20% of the total energy consumption of a family [1]. The solar water heating system is used for converting solar energy to thermal energy through different types of solar thermal collectors to get thermal energy, not electricity. There are many types of solar collectors present in the world; among them, flat plate solar collectors and evacuated tube collectors have been used in the domestic and industrial applications. Notably, domestic demand splits into solar hot water and solar space heating purposes. A solar water heating system is simple and incorporates with working fluid that passes through the solar collector by taking the heat and stored in a storage tank for later use. A typical solar water heating system is as follows,

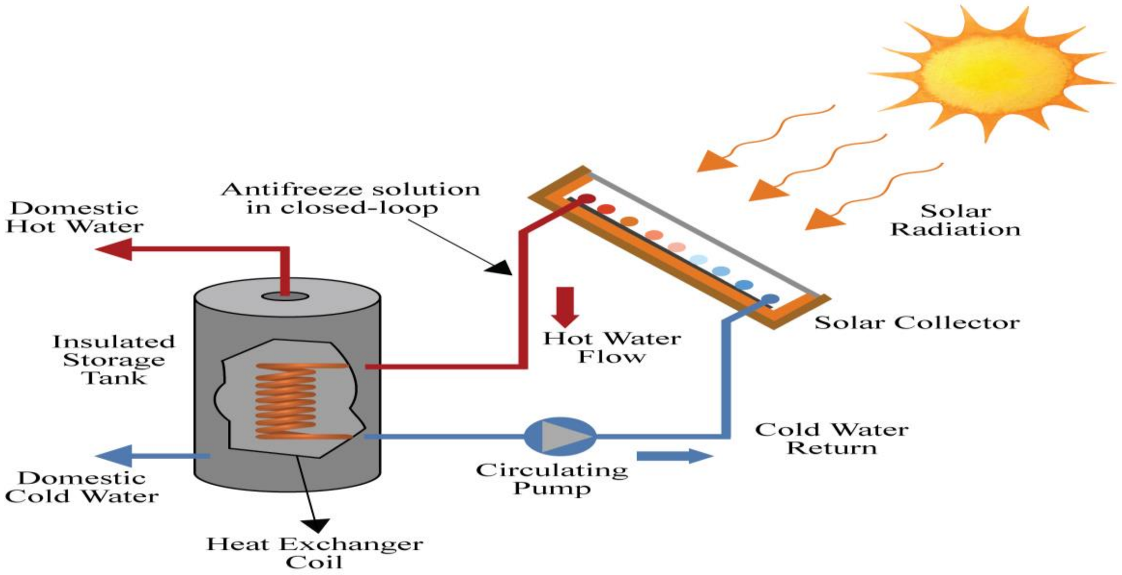


Figure 1.1: Solar water heating system [2]

1.2 Solar water heating system components

1.2.1 Solar collector

A solar collector is one of the crucial parts of a solar water heating system. It can be used as a heat exchanger. They collect the energy in the form of radiations from the sun, convert it into heat, and then transfer that heat to a colder fluid (usually water or air) [3]. This energy can be used for residential or commercial space heating and domestic hot water, solar pool heater, etc. [4]. The selection of suitable solar collectors depends on several factors. In Canada, it is necessary to select a solar collector that can be protected from freezing [5]. There are three types of solar collector available in the market, and these are as follows,

1.2.2 Flat plate collector

Flat plate collector divided into glazed and unglazed. Glazed collectors are made with insulation, copper tubes, and weatherproofed boxes that contain a dark absorber plate and glass cover. On the other hand, an unglazed collector having a dark absorber made of metal or polymer, copper tubes, and without a cover [3]. The typical flat-plate collector is shown by the figure (1.2).

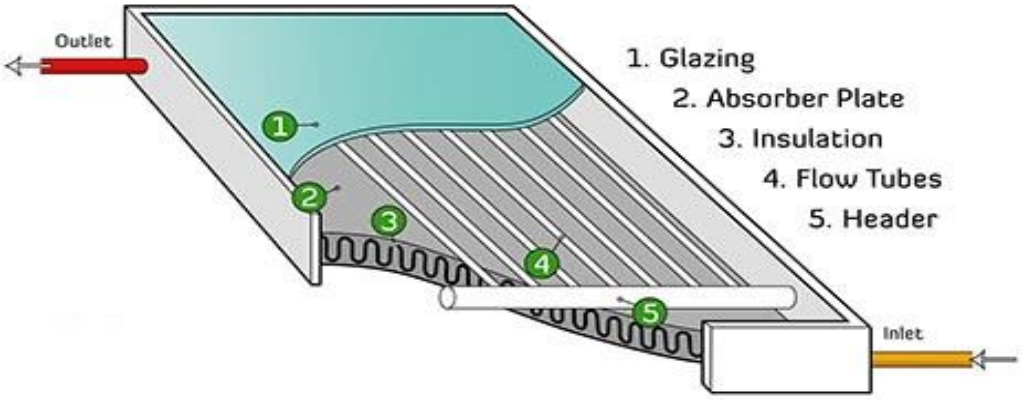


Figure 1.2: Flat plate collector [6]

1.2.3 Evacuated tube collector

This type of collector is more popular nowadays and efficient to collect energy from the sun. The cost of an evacuated tube collector is higher than the flat plate collector. They can work well in temperatures as low as -40°C (-40°F) and in overcast conditions [5]. They feature with parallel rows of transparent glass tubes. Each tube contains an outer glass tube and metal absorber tube that is attached to a fin. The fin’s coating absorbs solar energy but prevents radioactive heat loss [3]. An evacuated tube collector is shown by the figure (1.3),

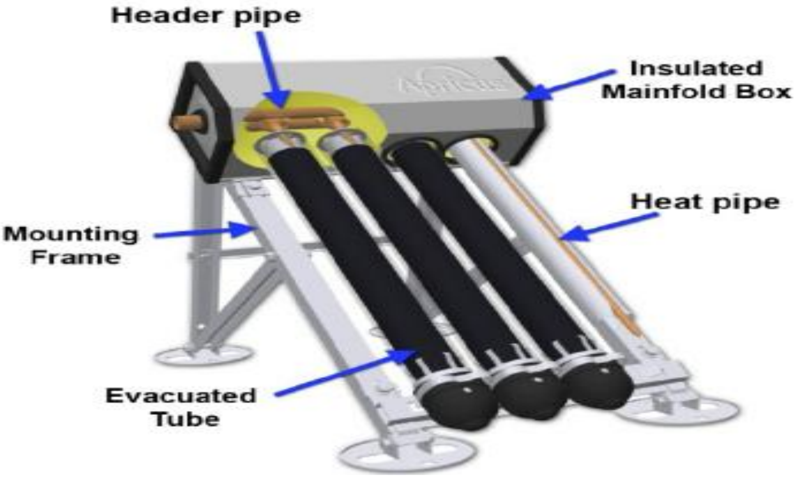


Figure 1.3: Evacuated tube collector [7]

1.2.4 Batch or Integral collector

This type of collector system featured with one or more black tanks or tubes in an insulated and glazed box. The associated system with this collector follows the conventional backup heater. They are not recommended for cold climates because the outside pipe could freeze in severe cold [3] [8]. A batch collector is shown by the figure (1.4),

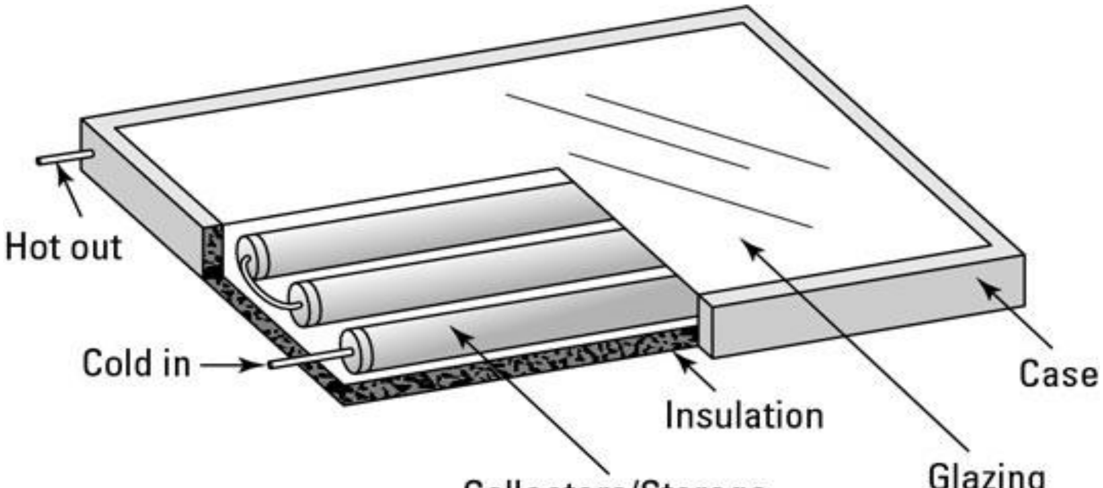


Figure 1.4: Batch or integrated collector [8]

1.3 Storage tank

Storage tanks mainly stored the hot water for later use and made of steel, concrete, plastic fiberglass, and other suitable materials. Among all the materials, steel tank is mostly accessible in the residential and commercial uses because of easiness to maintain and available in many sizes. To avoid corrosion and heat losses, a steel tank should be galvanized and appropriately insulated [3]. More details of a storage tank mentioned in chapter 3.

1.4 Heat exchanger

Solar water heating systems commonly use a heat exchanger to exchange useful heat from collectors to liquid or air for space heating and hot water. Heat exchangers can be made of steel, copper, bronze, stainless steel, aluminum, or cast iron, but the solar heating systems usually use copper because it is an excellent thermal conductor and has a higher resistance to corrosion. There are three types of heat exchangers with liquid to liquid, air to liquid, and liquid to air. They can be designed as a coil in the tank, shell and tube, and tube in tube. Some factors contributed to the proper and efficient design of the heat exchanger and featured with the working fluid, flow rate, inlet, and outlet temperature of all fluids [9] [10].

1.5 Pump

The pump is one of the crucial components of a solar water heating system to circulate the hot water or glycol solution from the collector to the storage tank. In any solar heating system, there are several loops available, and based on the loops, necessity pumps need to be selected. Proper controlling helps to maintain the pump speed as the speed and enough pressure head are prime factors for selecting an appropriate pump. Most of the solar system uses the centrifugal pump, and in our research, a centrifugal type constant speed pump was used. This pump was selected because it was able to meet some crucial features and design criteria like flow rate of the system, the power consumption of the pump, system type, operating temperature, friction losses, and the type of heat transfer fluid [11] [12]. A solar water heating pump is shown by the figure (1.5),

Figure 1.5: Typical pump for a solar heating system [13]

1.6 Pipe

The piping network usually makes way for transporting the hot water and heat transfer fluid in the solar water heating system. The choice of a smart piping system is essential for long term feasibility and easy to install. Owners are looking for a cost-effective and trouble-free piping system in their heating system. Each pipe and fittings have some physical and thermal properties to meet the operating conditions and help to choose the most effective pipes. The selection of the right piping system depends on the pressure and temperature rating, joinability and ease of fabrication, availability, resistance to corrosion, type of application, the lifetime of the material and installation, etc. and it should follow the local codes [12] [14].

1.7 Heat Transfer Fluid (HTF)

Heat transfer fluid extracts typically heat energy from the collector and take this heat in the storage tank either directly or using the external or internal heat exchanger. HTF should have some properties like high specific heat capacity, high thermal conductivity, low viscosity, low thermal expansion coefficient, inexpensive, and anti-corrosive quality. Based on the properties mentioned above and readily available with popularity, the most common type of heat transfer fluid is water, air, ethylene glycol, a mixture of water and ethylene glycol, silicon oils, refrigerant, and hydrocarbon oils. It should be chosen carefully for the places where the temperature drops below zero in winter [15] [16].

Except for the description of the above-mentioned significant components, a solar water heating system featured with different kinds of values, control strategy, temperature and pressure sensor, etc. in order to make the system more efficient and reliable.

1.8 Types of a solar water heating system

Solar water heating systems are divided into “Active” and “Passive” solar water heating system or the combination of both. The active solar water heating system uses mechanical device or circulator that can be used to transfer heat energy into the system and on the other hand, passive system operates without reliance on external devices. Also, the active system needs more maintenance and expensive than the passive system. The main components of an active solar water heating system are solar collectors which can be concentrating or non-concentrating. This device absorbs heat energy from the sun, converting it into heat, and transfers the heat into working fluid (anti-freeze, air, water) following through the collector. This warmed fluid carries the heat directly to the useable hot water or space heating equipment or a storage medium from which can be drawn for use at night and on cloudy days [4].

1.8.1 Active Solar hot water system

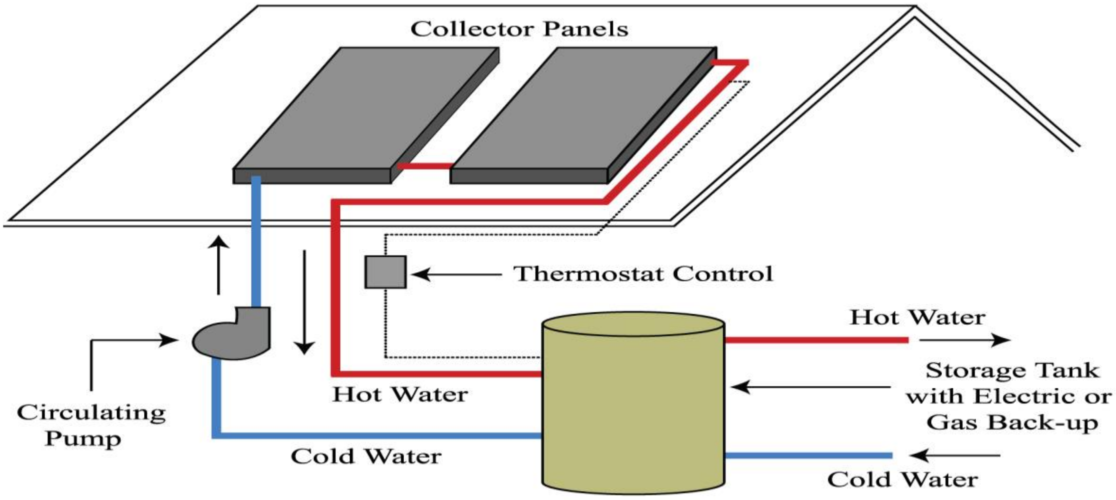


Figure 1.6: Active solar water heating system [2]

In an active solar water heating system, the mechanical device pump is used to circulating the liquid through the whole system as well as to control the system correctly; electrical control devices also needed. It can be categorized by two and shown by the figure (1.6),

1.8.1.1 Direct circulation system (Open-loop system)

This system circulates water from the storage tank up to the solar collector and back it again with the help of a pump. In this method, heat energy from the sun is transferred to circulating potable water directly through the collector and the tank. That is why it is called a direct circulation system or an open-loop system. An anti-freeze can be used in this system. It also uses the various controller to sense the required temperature regarding turn on and turn off the pump when it is needed and has one or more collectors that mounted on the roof and a storage tank located suitably in the building [17].

1.8.1.2 Indirect circulation system (closed-loop system)

This system is suitable for colder countries, where the freezing condition can occur. Working fluid and heat exchangers have required the feature. In this way, heat from the sun is transferred to a working fluid solution and circulates this working fluid from the collector up to the storage tank, and a heat exchanger transfers heat from working fluid to storage tank water before back it again with the help of a pump. Usually, a double-walled heat exchanger is required when it used toxic working fluid. Heat transfer occurs within a closed-loop cycle; that is why it is called an indirect circulation system or closed-loop system. This loop includes the collector, connecting pipe, pump, expansion tank, heat exchanger, and controller. It is remembered that the heat exchanger coil should be placed in the lower half of the storage tank to alter the heat accurately [17].

1.8.2 Passive Solar hot water system

In a passive system, there is no need for an electrical device as it relies on gravity and has the tendency to circulate the water naturally when it is heated. It also has a longer lifespan compared to an active solar water heater, more reliable and very easy to maintain. This type of heaters can be categorized below and shown by the figure (1.7),

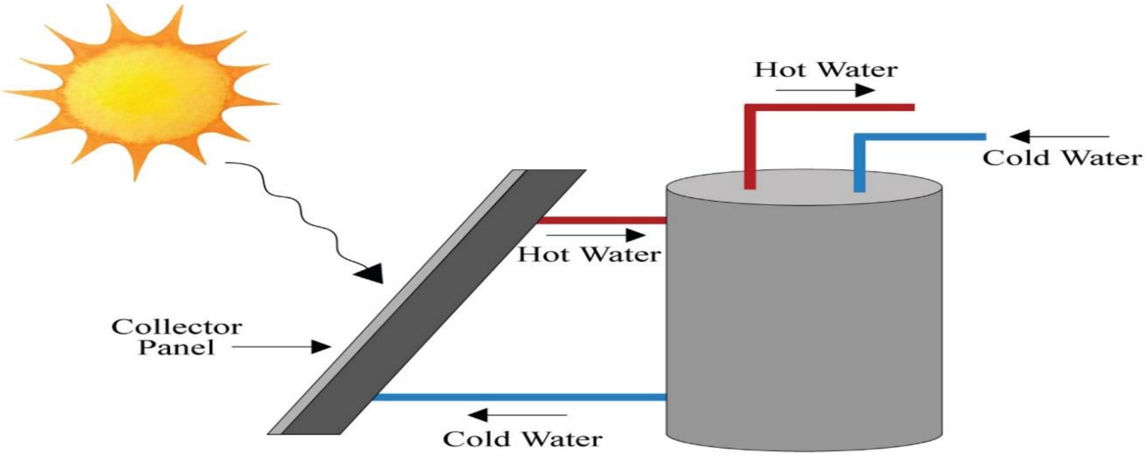


Figure 1.7: Passive solar water heating system [2]

1.8.2.1 Integral- Collector Storage (ICS) system

ICS is one of the most popular kinds of passive solar water heating system. In this system, the collector is considered as a hot water storage system. When the collector is heated by the sun, cold water from outside flows progressively through the collector and gets heated. At last, the hot water from the top is drawn to the storage tank for further use, and at the bottom, replacement water flows continuously. Pumps and controllers are not used in this simple system, but a flush type freeze protection valve is required in the top piping near the collector to protect from freezing.

1.8.2.2 Thermosiphon system

The thermosiphon system is relatively more complicated than an integral collector storage system. In this system, the circulating pump and controller are not used. Potable water flows directly to the tank mounted on the collector, gets heated from the collector, and expands slightly and becomes lighter more than cold water of the tank. Due to gravity and the water mentioned above property, cold water pushes the heated water through the collector outlet and store heated water into the top of the tank. This hot water then flows from the rooftop tank to a backup tank, installed at ground level whenever the hot water demand is needed in the building [17].

1.9 Thermal Energy Storage (TES)

Proper energy conversion system, control, analysis of data, and implementation of it can lead people to attain clean power from renewable energy sources. At present, most of the countries of the world are facing a problem like this; the power supply is less compared to their daily demand. It creates a mismatch between demand and supply. Such a problem occurs due to insufficient energy production, lack of utilization of energy storage systems, no or minimal power balance mechanism, and very minimum expertise on diverse energy sources. That is why it is high time to focus on advanced and efficient energy storage system design and way of collecting solar energy adequately so that it can be integrated with renewable power technologies**.** Ice energy CEO Mike Hopkins expected that the thermal energy would be more significant than battery storage because thermal storage is the larger and do not lend themselves using the electrical storage [18]. The relation between solar radiation and solar collectors are indispensable in the field of solar thermal energy. Solar thermal energy used for domestic water heating purposes as well as seasonal energy storage has attracted growing attention in recent decades because the availability of solar energy is discontinuous, so the heat storage method is a vital element in a building's solar energy-based thermal system [19]. Additionally, the presence of the energy storage unit is a driver for the self-production and self-consumption of energy [20]. Energy storage has special importance because users can separate themselves from current energy use, enabling the decoupling of supply from demand [21].

1.10 Classification and characteristic of the different storage system

Thermal Energy Storage (TES) not only reduces the discrepancy between demand and supply but also improves the performance and thermal reliability of the system. Therefore, designing an efficient and economic TES system is of high preference. TES has many advantages, like increasing the overall efficiency, better economics, less pollution of the environment [22]. Also, the selection of thermal energy storage depends on the required storage duration, economic viability, and the type of energy source and operating conditions. Energy storage technologies are categorized into five and showed in figure (1.8). Also, the main types of thermal energy storage of solar energy are represented in figure (1.9).

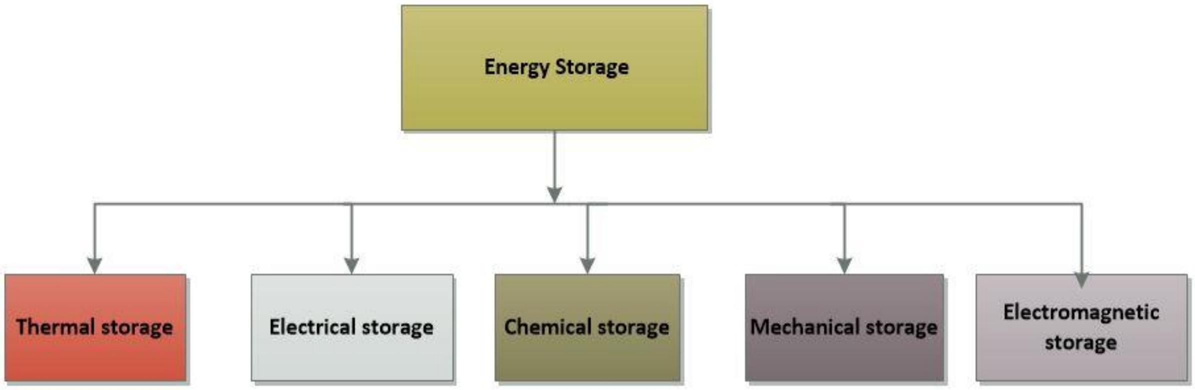


Figure 1.8: Classification of energy storage system [23]

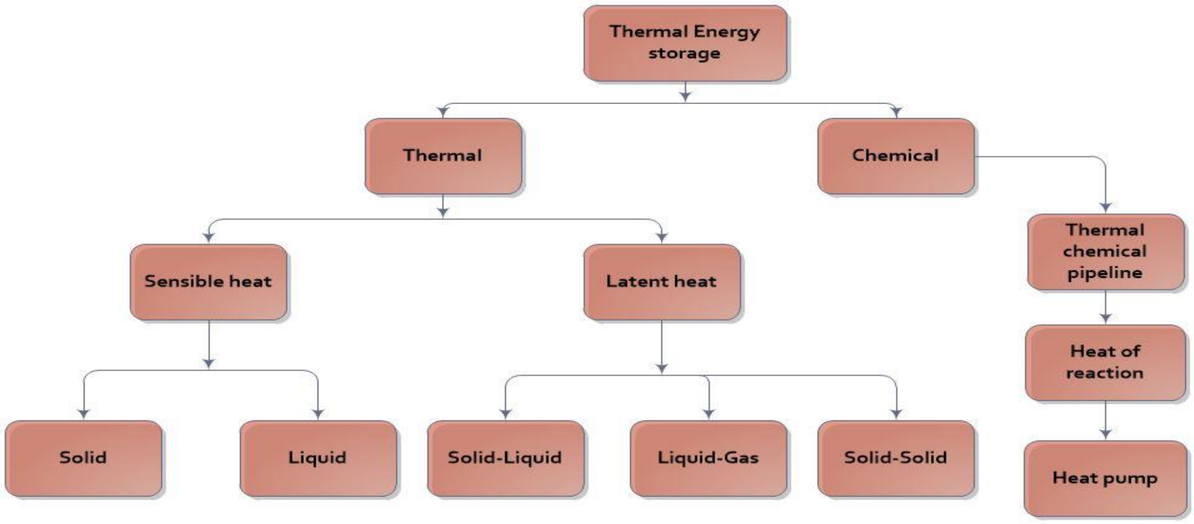


Figure 1.9: Types of thermal energy storage (TES) [24] [25]

1.10.1 Sensible Heat Energy Storage (SHES)

In this system, thermal energy is stored by heating or cooling liquid and solid storage materials. These materials include water, sand, molten salt, rocks, and the like [26]. Hot water storage tanks are one of the best technologies for storing thermal energy because of the low cost and high specific heat of the water compared to phase change materials and Thermo-chemical storage. A storage medium, specific heat, and the increased temperature of the water are the vital factor for sensible heat that needs to be stored [27]. The amount of heat stored relies on the specific heat of the medium, temperature change, the amount of heat storage material, and expressed with the equation (1.1) [28] [29].

$$Q = mC_p\Delta T \tag{1.1}$$

Where Q is the amount of heat stored (J), m is the mass of heat storage material (Kg), C_p is the specific heat of the storage material ($J/Kg.K$) and ΔT is the amount of temperature change (℃). Table (1.1) and (1.2) shows the most used sensible heat storage material with properties and the main characteristics of the most common solid-state heat storage material. A sensible heat storage system needs large volumes due to its low energy density that is 3 and 5 times higher than Phase Change Material (PCM) and Thermochemical Energy Storage (TCES) and needs an accurate and precise design to discharge thermal energy at a steady temperature. These two problems are the main barrier to the sensible heat storage system. Research shows that efficiency can be increased by ensuring an optimal water stratification and highly effective thermal insulation in the tank [30]. Underground Thermal Energy Storage (UTES) is a standard storage technology that is accomplished by different methods using underground as a storage medium, which are Borehole storage, Aquifer storage and Cavern storage [31].In the Borehole storage system, vertical heat exchangers are installed in the underground that ensures the heat transfer to and from the various ground layers (clay, sand, rock). It is a part of the seasonal energy storage system. Although this system extracts low-temperature heat from the underground soil, a combination of ground heat exchangers and heat pumps is usually used to increase the heat transfer rate of this system. Another type of underground storage system is Aquifer storage, whereas as a storage medium, a normal underground water penetrable layer is used. The heat transfer occurs through mass transfer, and the availability of suitable geological formations are the prime conditions for this type of technology. Cavern storage and pit storages are the last storage system of UTES and a more significant underground water reservoir required in the subsoil to do the duty as thermal energy storage. Though these systems are technically feasible, the main problem is high investment costs. It is one of the critical issues of Underground Thermal Energy Storage (UTES) [26].

Table 1.1: Available and selected Solid-Liquid materials for sensible heat storage [32] [24]

Medium	Fluid type	Temperature range (℃)	Density, $\rho\ (Kg/m^3)$	Specific heat, $C_p\ (J/Kg.K)$
Sand	-	20	1555	800
Rock	-	20	2560	879
Brick	-	20	1600	840
Concrete	-	20	2240	880
Granite	-	20	2640	820
Aluminium	-	20	2707	896
Cast Iron	-	20	7900	837
Water	-	0-100	1000	4190
Calorie HT43	Oil	12-260	867	2200
Engine oil	Oil	≤ 160	888	1880
Ethanol	Organic liquid	≤ 78	790	2400
Propane	Organic liquid	≤ 97	800	2500
Butane	Organic liquid	≤ 118	809	2400
Isotone	Organic liquid	≤ 100	808	3000
Isopentane	Organic liquid	≤ 148	831	2200
Octane	Organic liquid	≤ 126	704	2400

Table 1.2: List of solid-state sensible heat storage materials [24] [33]

Storage material	Working temperature (°C)	Density, ρ (Kg/m^3)	Thermal conductivity, k $(W/m.K)$	Specific heat, $C_p\ (KJ/Kg.K)$
Sand-rock minerals	200-300	1700	1.0	1.30
Reinforced concrete	200-400	2200	1.5	0.85
Cast Iron	200-400	7200	37.0	0.56
NaCl	200-500	2160	7.0	0.85
Cast steel	200-700	7800	40.0	0.60
Silica fire bricks	200-700	1820	1.5	1.00
Magnesia fire bricks	200-1200	3000	5.0	1.15

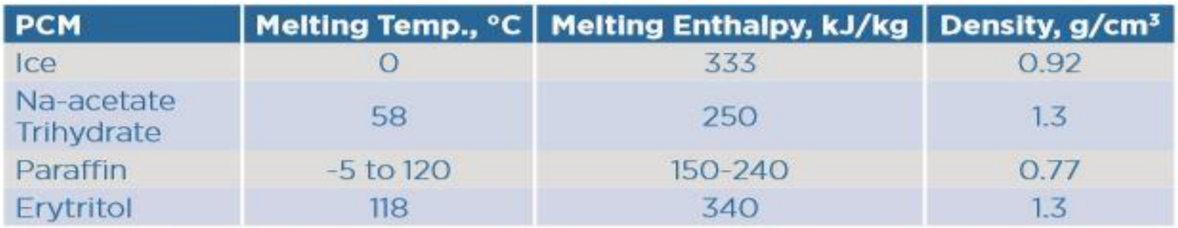
1.10.2 Latent Heat Energy Storage (LHES)

To overcome the drawback of sensible thermal energy storage, a Phase Change Material (PCM) based technology is developed that can be able to provide higher storage capacities as well as target-oriented discharging temperature. This storage system is called a latent heat energy storage system. In this system, heat is absorbed and released through the phase changing properties of a PCMs material at a constant temperature. The storage capacity of the latent heat storage system with a PCMs medium is as follows [33] [34],

$$Q = m[C_{sp}(T_m - T_i) + a_m \Delta h_m + C_{lp}(T_f - T_m)] \qquad (1.2)$$

Where a_m is the melting fraction, C_{lp} is the average specific heat between T_f and T_m $(J/Kg.K)$, C_{sp} is the average specific heat between T_i and T_m $(J/Kg.K)$, Δh_m is the heat of fusion per unit mas (J/Kg), m is the mass of heat storage medium (Kg), Q is the amount of heat stored (J), T_f is the final temperature (°C), T_i is the initial temperature (°C), and T_m is the melting temperature (℃). The phase change can occur within a solid/liquid or a solid/solid process as the liquid/solid needs less volume change. When the temperature of a material is raised above its melting points, then the material takes up energy and starts to melt and complete the phase change process [35]. Significant enthalpy changes and the ability to release and charging of energy lead the materials to phase change. This phase change process associates with three main parts: a heat storage material that experiences phase change, a heat transfer surface and a container that encloses the material [36]. This process can use a lot of techniques and materials and can be used for both short-term (daily) and long-term (seasonal) energy storage. The below table (1.3) shows the most useful and relevant PCMs and their operating temperature ranges, melting temperature, enthalpy, and density.

Table 1.3: Different thermal energy storage PCMs properties [26]



PCM	Melting Temp., °C	Melting Enthalpy, kJ/kg	Density, g/cm³
Ice	0	333	0.92
Na-acetate Trihydrate	58	250	1.3
Paraffin	-5 to 120	150-240	0.77
Erytritol	118	340	1.3

Some renowned PCMs are ice, paraffin waxes, salts, fatty acids, and metals. As water is considered the best thermal storage medium with the high latent heat of fusion, an ice storage system is prevalent in the sector of latent heat energy storage systems.

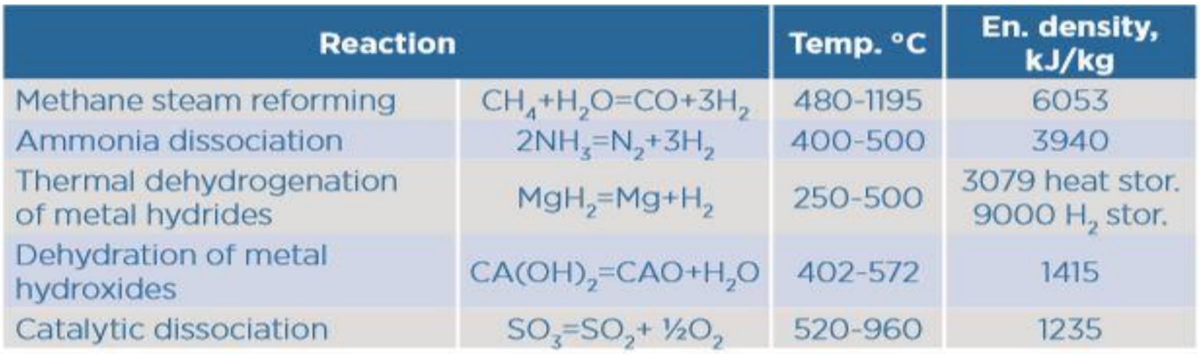
1.10.3 Thermochemical Energy Storage (TCES)

In order to overcome the curbs of the sensible and latent heat storage system, new and emerging technology is introduced called Thermochemical Energy Storage (TCES). High energy density around $300\,KWh/m^3$ can be achieved by chemical reaction [37]. In thermochemical reaction, energy is stored through reversible and irreversible reaction, and the thermal energy stored relies on the amount of storage material, endothermic heat of reaction, and the extent of conversion [17]. The associated equation of it is as follows [25],

$$Q = a_r m \Delta h_r \tag{1.3}$$

Where m is the mass of storage material (Kg), a_r is the extent of the conversion factor, Δh_r is endothermic heat of reaction (J/Kg), and Q is the amount of stored heat (J). In order to release the heat and control the reaction to get a high energy density, this chemical reaction requires a catalyst. Usually, a lot of chemical reactions are used to store thermal energy, and these reactions, temperature and the energy density are as follows,

Table 1.4: Mostly used chemical reaction in TCES [38] [39]



Reaction		Temp. °C	En. density, kJ/kg
Methane steam reforming	$CH_4+H_2O=CO+3H_2$	480-1195	6053
Ammonia dissociation	$2NH_3=N_2+3H_2$	400-500	3940
Thermal dehydrogenation of metal hydrides	$MgH_2=Mg+H_2$	250-500	3079 heat stor. 9000 H_2 stor.
Dehydration of metal hydroxides	$CA(OH)_2=CAO+H_2O$	402-572	1415
Catalytic dissociation	$SO_3=SO_2+½O_2$	520-960	1235

Adsorption and absorption are another type of chemical reaction process, and both are considered as a sorption storage system [40]. Absorption means to enter a liquid and gas into another material and captured its volume. The working principle of the adsorption system is that when an adsorbate (gas or vapor) is captured by the adsorbent (solid or porous material), the adsorbent binds the adsorbate to its surface. After that, once the saturation process is completed with the adsorbate and no more gas or vapor can bind to the adsorbent surface. Then the adsorbent materials need to be regenerated by the assist of the desorption process so that the adsorbent can return to its original form to repeat the adsorption process cyclically [41].

1.11 Literature review

Thermal Energy Storage (TES) is a developing process to store thermal solar energy by heating or cooling a storage material so that stored energy can be used to meet the peak demand as well as later for heating and cooling applications and electricity generation. In Concentrating Solar Power Plants (CSP), the stored solar heat can be used to produce electricity when sunlight is not attainable**.** This system can be used in centralized and distributed ways. Centralized applications included district heating or cooling, large industrial plants, combined heat and power plants, or in renewable power plants like CSP plants and the distributed applications are mostly used in domestic or commercial buildings water and space heating or cooling purposes [26]. A model was established by Yumrutas and Unsal [42] to find out the way of measuring temperature and COP of the heat pump of hot water tank storage system with heat pump for a single-family house. The system consists of 300 m^3 volume storage tank and 20 m^2 solar collectors and depends on mainly ground properties, operations year, storage tank volume, and collector area. After completing 5 years of successful operations, they noticed that the temperature of a well-insulated buried storage tank varied from 14 ℃ to 40 ℃, with the mean annual COP of the heat pump was 6. In addition, to know the thermal performance, this type of system is so imperative.

In Sweden, researchers [43] [27] focused on designing such kind of system that can meet the aggregate demand for space heating and domestic hot water for 55 housing structures. Their system was vast, with 2700 m^2 collector area and 1000 m^3 volume of the storage tank. Their result was not satisfactory (solar fraction 37 %) as it was expected (solar fraction 100 %) due to the thermal loss and high vapor transport between the tank wall and the surrounding ground. This result indicated the importance of buried storage tank's insulation for seasonal storage performance. A similar type of system was constructed in Herlev and considered as the first seasonal thermal energy storage system in Denmark to supply around 74 % of space heating and domestic hot water demand for 92 houses. The result showed that this system met around 35 % of demand because of the high leakage issue was introduced in the first year of operation [44]. In order to get higher system efficiency and make it more cost-effective, a combination of two seasonal energy storage system become widespread to the people. The first large scale combined system was built in Finland, referred to as the Kerava Solar Village (KSV) project, to deliver about 75 % of heating demand for 44 flats. This system was combined with a water pit and borehole seasonal storage system with the help of the heat pump. It consisted of 1100 m^2 collector area, 1500 m^3 water storage, and 11000 m^3 duct storage. The solar output fraction for this system was 26 % due to the heat pump malfunction, lower storage capacity than calculated, and the higher return temperature to the collector that made the lower collector efficiency [45] [46].

Another excellent task of combined two systems was constructed in Attenkirchen, Germany, with the help of 836 m^2 collector area, 500 m^3 hot water tank, and 9350 m^3 duct storage. This system was made for providing heat for 30 single detached families. The result concluded with around 74% of solar fraction, and the connected Coefficient of Performance (COP) for hot water storage and duct storage is 4.4 and 3.9 respectively [47] [48]. Williams et al. [49] worked with a method to determine the optimum thermal insulation for the unground heat storage tank and make the system affordable. The optimum insulation distribution is calculated using various geometries of storage tanks and related properties of thermal insulation. The results made a good agreement between insulation thickness with the cost and storage volume of the buried storage tank. To make successful of the prototype plant goal and monitor different results, a 500 m^3 storage tank was made using reinforced concrete with a flat bottom and a spherical cover and buried to avoid the heat losses. This tank was insulated internally using foam glass and waterproofed with the help of a geomembrane to ensure direct contact with water. After the one-year operation, the experimental results showed a good agreement with numerical results, and the numerical tank heat losses were around 10.4% less than the experimental value. Also, the energy collected value from the simulation result was 6.9% higher than the measured value, and the total energy efficiency numerically obtained was 31.3% against an experimental value of 28.2% [50].

Melíß and Späte et al. [51] discussed a seasonal storage system to facilitate the solar district heating system for low energy building in Germany, the Solar- Campus working group at the Aachen University of Applied Sciences. A reverse pyramidal storage tank, storage volume of 2500 m^3 with steel, or polypropylene liner to guarantee water tightness was considered to make this tank. The top part and the whole tank were well insulated to reduce heat loss. This system was made for meeting around 50% of heating demand, but the expected result was not reasonable as the energy price was higher than the regular price. The large hot water storage tank can be used as seasonal storage in combination with a small district heating system. A solar district heating system named “Am Ackermann-Bogen” was built in Munich, Germany to provide space heating and domestic hot water for 320 apartments. This system was designed with 2761 m^2 of flat plate solar collector, 6000 m^3 underground seasonal hot water storage tank to cover around 50% demand of this area. An absorption heat pump was used for additional heating sources and operated at a supply temperature 60 ℃ with a return temperature of 30 ℃. After a one-year operation, the solar fraction was found approximately 45% and could reach this value above 50% in the following year [52]. Regarding biological energy storage, an investigation was conducted by Lee. et al. [53]. On the energy storage mechanism of Flavin’s, organic compounds produced in the mitochondria chloroplasts have high energies stored in their chemical bonds. The outcome of this research found that to improve energy storage performance and the proper function of the energy storage medium like batteries, it is inevitable need to modify the Flavin molecule. This research also proved that natural living systems could give a chance to design a sustainable energy storage process. Although this kind of system is a promising field for energy storage technologies, it has some drawbacks.

To overcome the flaws of a sensible heat energy storage system, a Latent heat energy storage system was introduced where heat is absorbed and released through the state change of materials at a stable temperature, like the phase change from gaseous to liquid, liquid to solid and vice versa. There are mainly three possible parts of the latent heat energy storage system, such as (a) a heat storage material with phase change property (b) surface with heat opposing ability (3) and a container that can encircle the material [36]. An extensive study was carried out by researchers and research centers or various organizations to find out the suitable phase change material with high energy densities relying on temperature and chemical structure. The Energy Research Centre of the Netherlands (ECN) is one of them. They investigated around ninety potential latent heat storage materials for Thermal Energy Storage (TES) purposes in 2004. They found the most promising material was magnesium sulfate heptahydrate ($MgSO_4.7H_2O$) that can provide a theoretical energy density of $778\ Kwh/m^3$ for the seasonal solar energy storage system [54]. According to Finck et al. many optimization studies have been performed to show the use of a phase change material tank for thermal energy storage in office building applications. As a result, energy can be saved up to 12.5% using a phase change material tank and make the system economically feasible and sustainable [55].

1.12 Findings of Literature review

From the above literature search, among the three primary thermal energy storage process, Thermochemical storage (TCES) provides the highest amount of energy density. It helps to get more seasonal thermal energy storage energy for heating and cooling applications in the residential and commercial sectors. However, the main challenges of this type of method are adsorbent instabilities, system variabilities, high cost, etc. Researchers are focusing more on adsorbent sizes, constant output, charging and discharging process temperature, development of various new methods to reduce the cost of TCES. Besides, the latent heat energy storage system can provide less amount of energy density compared to TCES but higher than the sensible heat energy storage system. As though the cost is moderate, research shows that numerous problems can associate with the latent heat energy storage system such as unstable, still outraging of manufacturers, and can not guarantee the best possible longer storage period. At present, many organizations and companies are trying to get high-temperature PCMs through different experiments.

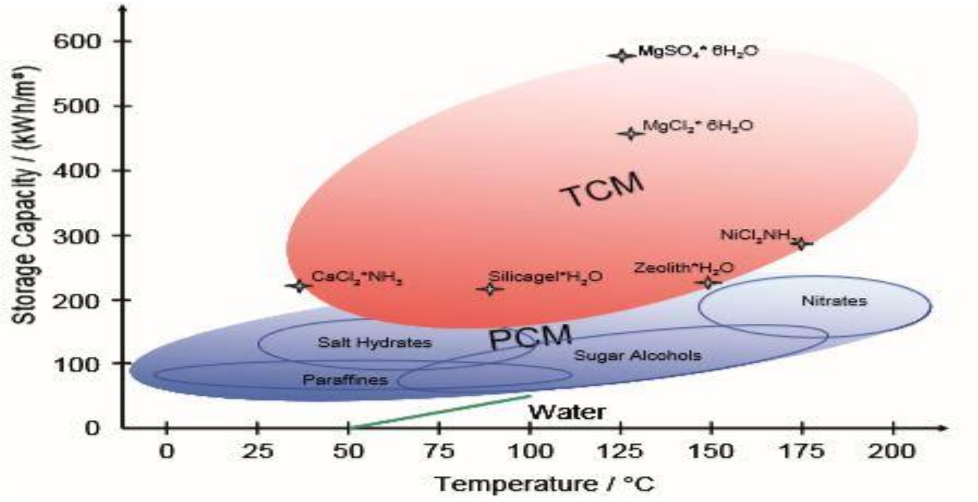


Figure 1.10: storage capacity with temperature for sensible, latent and thermo-chemical TES [56]

Besides, the sensible heat energy storage system is perfect and convenient for diurnal storage and suitable for seasonal thermal energy storage. Though it can provide less amount of energy density compared to latent and thermochemical energy storage and needs a larger volume of a storage tank with proper stratification and insulation but in terms of the availability of storage medium (waster), abundant free resource of solar energy, less maintenance, easy to install makes sensible heat storage system more viable and effective way to get hot water for residential and commercial space heating and domestic hot water preparation. The above figure

(1.10) shows that among these three thermal energy storage systems, the thermochemical energy storage method sustains the best storage capacity with the temperature profile.

1.13 Objective of the research

- To do extensive literature review on solar water heating system with thermal energy storage for collecting proper data and get to know their various types and methods.
- To figure out the annual electrical energy consumption of different loads of a house using thermal modeling of the house with thermal simulation software.
- To meet the annual demand, a solar seasonal energy storage system for space heating, design, and analyze for a single house in St. John’s, NL, Canada.
- To meet the domestic hot water and space heating demand, a solar water heating system design and analyze for residential applications with thermal storage.
- Yearly heat loss of a heat recovery ventilator unit needs to calculate and analyze for a single-family house.
- Finally, a dynamic simulation using MATLAB/Simulink was done to find out the transient response of a typical solar water heating system.

1.14 Research outline

- Chapter 1 discuss the introduction and literature review of this research work.
- Chapter 2 will be concluded to do the thermal modeling of a typical detached house.
- Chapter 3 will present a solar seasonal energy storage system for space heating.
- Chapter 4 will reveal a solar water heating system design for residential applications like space heating and domestic hot water preparation.
- Chapter 5 will show a yearly heat loss calculation approach for a heat recovery ventilator unit.

- Chapter 6 will discuss a dynamic simulation of a typical solar water heating system.
- Chapter 7 will merge the above outline with the conclusion, discussion, and future scope part.

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Chapter 2

Thermal modeling of the house in St. John’s, Newfoundland

2.1 Introduction

Thermal modeling, simulation with energy consumption analysis of modern houses is a vital aspect of making the houses more energy efficient. Thermal modeling assists to know the yearly electrical consumption of the house that makes the consumer to focus on using more energy-efficient appliances in the house. This type of thermal analysis not only studies the human behavior impact on the house’s annual load profile but also uses to design renewable energy system, especially solar water heating system. In this chapter, a house in St. John’s, NL, is modeled and simulated using thermal simulation software. Here the hourly value was considered to analyze output results. The output result from the thermal model is compared with the monthly electricity bill that showed a good agreement to know the annual load consumption of all the appliances of the house.

2.2 Literature review

Thermal modeling and optimization of the house using different techniques and software is essential. These options can work both for existing and new houses. The annual house loads depend on many factors like house size, house materials for insulation, and the number of occupants living in the house. The thermal analysis of a house shows the yearly energy demand of various loads on a monthly basis. Several software and techniques have been available in the literature to make the thermal analysis of the house. Dimoudi and Tompa et al. [1] mentioned that building construction plays a vital role in the environment, and it indirectly emits greenhouse gases as waste. They concluded that to make the house more efficient, it is necessary to reduce the energy demand during operations. Christopher et al. [2] studied the thermal analysis to find out the annual energy demand of an old house in Thessaloniki, Greece, using HOT2000 software. After comparing the electricity bills with actual utility bills, they concluded that climate conditions and the existing house materials have a significant effect on the energy efficiency of the single-family house. Yohanis et al. [3] discussed the electricity consumption profile in dwellings in Northern Ireland. The author founds some factors that are responsible for increasing electricity consumption. These factors are dwelling type, floor area, number of occupants and bedrooms, tenure, occupant age, and household income. Among these, the electricity consumption profile is mostly influenced by the floor size in the house.

Shimoda et al. [4] studied and modeled the hourly residential electricity consumption based on various house characteristics in Osaka city, Japan. The result revealed that occupant’s time use, indoor temperature, efficiencies of the household appliances, and dwelling thermal features are contributed greatly to change the daily electricity consumption. Papadopoulos et al. [5] modeled and analyzed two multifamily domestic building energy use using simulation software EnergyPlus to find out the optimal economic and environmental performance of house space heating. They mainly discussed and compared three types of systems. Among them, the electrically driven heat pump and gas-fired space heating system showed the rival characteristics in some instances and found heat pump system is a best and suitable option for domestic space heating. Peeters et al. [6] worked with the overall heating efficiency of the house, employing building insulation quality and the emitter's control strategy. Though the result showed that building heating efficiency and insulation quality improvement are inversely proportional to each other, but they recommended to use a modulating boiler, an outdoor air temperature compensation, and a thermostatic radiator valve. Florides et al. [7] demonstrated the house space heating and cooling load variation in Cyprus using simulation software TRNSYS. They emphasized to put the better roof insulation in the house as this property of the house can minimize the heating load up to 75 % and cooling load up to 45.5 %. El Fouih et al.

[8] studied the low energy building and the ventilation system to analyze the energy performance of the house. The result concluded that humidity-controlled ventilation is suitable for the moderate and warm climate, and for cold climates. A heat recovery ventilation system can be more efficient if it has low power consumption and high heat exchanger efficiency.

Kapsalaki et al. [9] have introduced a methodology and calculation approach for making the cost-effective design for net-zero energy building in a residential application. Their study ended that the net zero energy building becomes so expensive in terms of initial cost than life cycle cost. Also, they found that the optimal design solution can be lower in mild-winter climates than cold-winter climates as the local climate and economic conditions influence it. Sun et al. [10] discussed the design parameters of net-zero energy building in terms of sizing the HVAC system, renewable energy technologies, and energy storage systems. From their studies, it can be said that building system size and the overall initial investment cost are responsible to control the indoor temperature set points. They also added that the system's efficiency and Co-efficient of Performance (COP) are noticeable and significant with medium impacts of wall thickness and window to wall ratios. Moreover, the infiltration rate and losses have very fewer impacts, while the PV efficiency has different effects, relies on the system sizes and the cost. Kalogirou et al. [11] studied and simulated four-zone featured buildings, adding dense concrete wall as the thermal mass in the south façade. They compared the result having thermal mass and without the thermal mass and finally recommended that the optimal thickness of 25 cm thermal mass can be suitable to diminish the heating loads around 47 % and increase the cooling loads by approximately 4.5 %. Fay et al. [12] evaluated the Australian residential building and its insulation materials with all properties. They concluded that after adding the better insulation material in building the total embodied and operational energy can be saved about 6 % over a 100-year lifespan. For cold climate zones, they also mentioned that not only the additional insulation but also some efficient strategies could be beneficial for saving more energy. Pikas et al. [13] studied the energy efficient building and the optimal design for the building components. They figured out a few factors that are mainly contributed to select the possible optimal solution. These factors are a small window to wall ratio based transparent triple glazed argon filled windows and 20 cm thick insulation of the house wall. The findings mentioned above become further verified by Thalfeldt et al. [14]. From their outcome, it is recommended that window to wall ratio can be increased to (40-60) % if the heat transfer coefficient or U-value of the window would become the range of (0.21 -0.32) W/m^2K.

Goia et al. [15] deliberated about the optimal window to wall ratio for various low energy office building in Frankfurt, having different HVAC system efficiency. They demonstrated that the optimal window to wall ratio is between 35 % and 45 % with different orientations of the building. Vanhoutteghem at al. [16] studied the net zero energy house, taking some features like the effect of size, orientation, and the glazing properties of the window. The result exposed that high g value and large window to wall ratio for south oriented house is less useful to reduce the space heating demand of the house. On the other hand, for the north-facing houses, high g value, low U value, and large window to wall ratio are suggested to uphold the space heating demand within the end-user's range. Besides, Li et al. [17] figured out the design of zero energy building, measuring energy efficiency, and the various renewable energy technologies. They included that thermal insulation, thermal mass, glazing, and daylighting are the significant factors that have a high impact on building energy use with measuring energy efficiency. Ihara et al. [18] mentioned the façade properties of the office building in Tokyo. The result determined that the lessening of solar heat gain coefficient, U value of the windows, and increasing the solar reflectance is the best way to reduce the annual energy demand, but in case of opaque parts of the high rise buildings, the annual energy demand increased with reducing the U value.

After analyzing the literature, it is obvious to say that before taking any decision or implementing the solar thermal systems with energy storage, thermal modeling of the house becomes inevitable to know the annual electrical demand of the individual loads. It also helps to select the best house materials and appliances in order to make the balance between energy demand and supply. As the low energy building and energy-saving matters rely on the house properties and the ventilation system, so the thermal modeling and simulation are effective ways to get the idea of these parameters. The simulation results and necessary graphs are discussed below in the latter section.

2.3 Modeling of the house

2.3.1 Site selection

To model and analyze any house in colder countries, it is necessary to select a proper site for the house. Many available data are required in order to get an accurate output, and the proper place where the house should be located ensures these accessible data efficiently for the designer. The selected house was in St. John’s, NL, Canada, latitude (47.56 ºN) and longitude (52.71 °W). The selected house is in climate zone 6.

2.3.2 Physical model and BE opt design of the house

The physical model and BE opt designed of the selected house are shown by the figure (2.1) and figure (2.2). The dimensions of the house length: 45 feet and width: 30 feet was given as an input of the design and analysis software. It has two floors, contains four rooms with two washrooms on the first floor, and four rooms with a half washroom on the ground floor. Moreover, correct values mentioned in table (2.1) of all outside walls, windows, doors, roof, orientation, location, all major electrical appliances, and their types were given as inputs into BE opt.

Figure 2.1: Physical view of the designed house

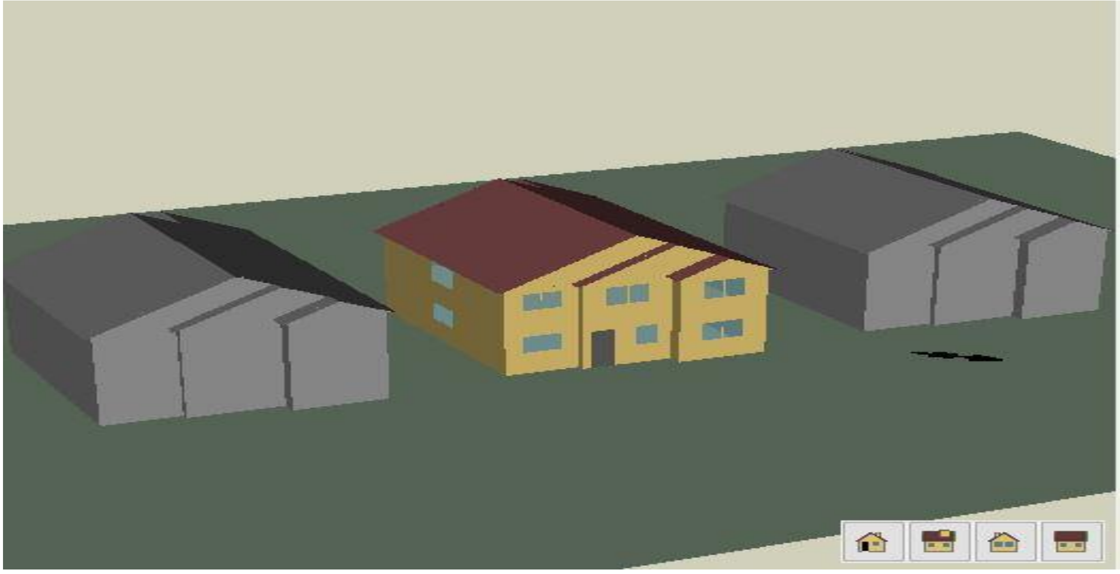


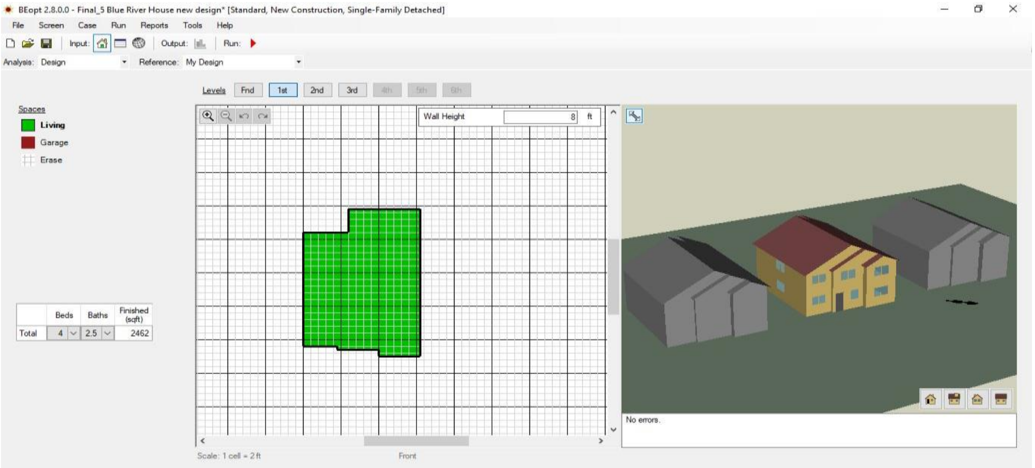
Figure 2.2: BE opt designed for the selected house

2.3.3 Modeling software

The thermal model and analysis were done by using BE opt (Building Energy Optimization tool) software. National Renewable Energy Laboratory has developed this software by the support of the U.S Department of Energy to meet the Building America program goal of market-ready energy solutions for new and existing houses. It can simulate and evaluate the residential building's energy consumption by calculating the maximum energy saving case or minimum cost case according to the end user’s requirement [19].

2.3.4 Inputs to the software

This software interface consists of a total of three screens for designing purposes. The first screen is named as a geometry screen, which can be used to draw the house according to the user dimensions and other physical parameters of the house. The geometry screen of this software is shown in figure (2.3).



Analysis: Design
Reference: My Design

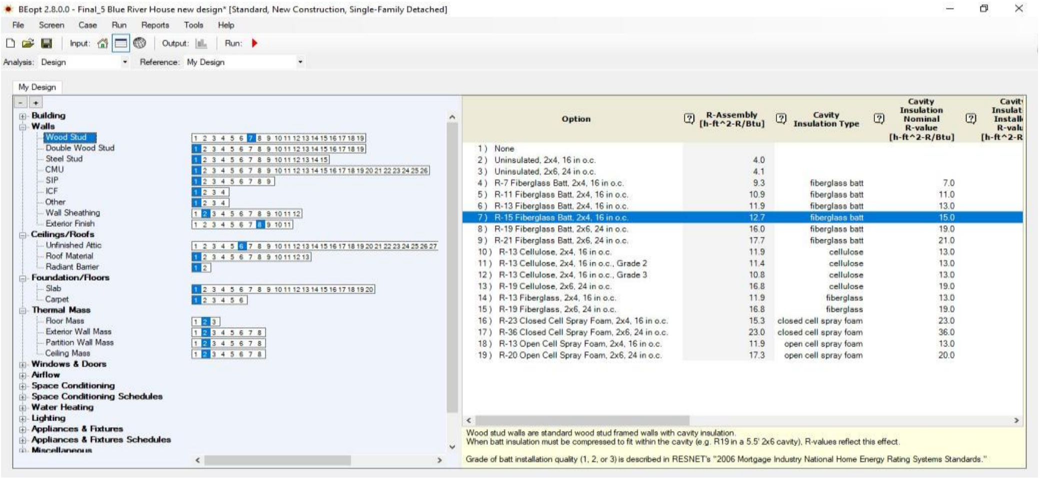
Wall Height 8 ft

	Beds	Baths	Finished (sqft)
Total	4	2.5	2462

No errors.

Figure 2.3: Geometry screen of the software

The second screen is referred to as an input screen where all the input parameters are inserted for taking the preparation for simulation. The input screen and the values are shown by the figure (2.4) and table (2.1), respectively.



Option	R-Assembly [h-ft^2-R/Btu]	Cavity Insulation Type	Cavity Insulation Nominal R-value [h-ft^2-R/Btu]
1) None			
2) Uninsulated, 2x4, 16 in o.c.	4.0		
3) Uninsulated, 2x6, 24 in o.c.	4.1		
4) R-7 Fiberglass Batt, 2x4, 16 in o.c.	9.3	fiberglass batt	7.0
5) R-11 Fiberglass Batt, 2x4, 16 in o.c.	10.9	fiberglass batt	11.0
6) R-13 Fiberglass Batt, 2x4, 16 in o.c.	11.9	fiberglass batt	13.0
7) R-15 Fiberglass Batt, 2x4, 16 in o.c.	12.7	fiberglass batt	15.0
8) R-19 Fiberglass Batt, 2x6, 24 in o.c.	16.0	fiberglass batt	19.0
9) R-21 Fiberglass Batt, 2x6, 24 in o.c.	17.7	fiberglass batt	21.0
10) R-13 Cellulose, 2x4, 16 in o.c.	11.9	cellulose	13.0
11) R-13 Cellulose, 2x4, 16 in o.c., Grade 2	11.4	cellulose	13.0
12) R-13 Cellulose, 2x4, 16 in o.c., Grade 3	10.8	cellulose	13.0
13) R-19 Cellulose, 2x6, 24 in o.c.	16.8	cellulose	19.0
14) R-13 Fiberglass, 2x4, 16 in o.c.	11.9	fiberglass	13.0
15) R-19 Fiberglass, 2x6, 24 in o.c.	16.8	fiberglass	19.0
16) R-23 Closed Cell Spray Foam, 2x4, 16 in o.c.	15.3	closed cell spray foam	23.0
17) R-36 Closed Cell Spray Foam, 2x6, 24 in o.c.	23.0	closed cell spray foam	36.0
18) R-13 Open Cell Spray Foam, 2x4, 16 in o.c.	11.9	open cell spray foam	13.0
19) R-20 Open Cell Spray Foam, 2x6, 24 in o.c.	17.3	open cell spray foam	20.0

Wood stud walls are standard wood stud framed walls with cavity insulation.
When batt insulation must be compressed to fit within the cavity (e.g. R19 in a 5.5' 2x6 cavity), R-values reflect this effect.

Grade of batt installation quality (1, 2, or 3) is described in RESNET's "2006 Mortgage Industry National Home Energy Rating Systems Standards."

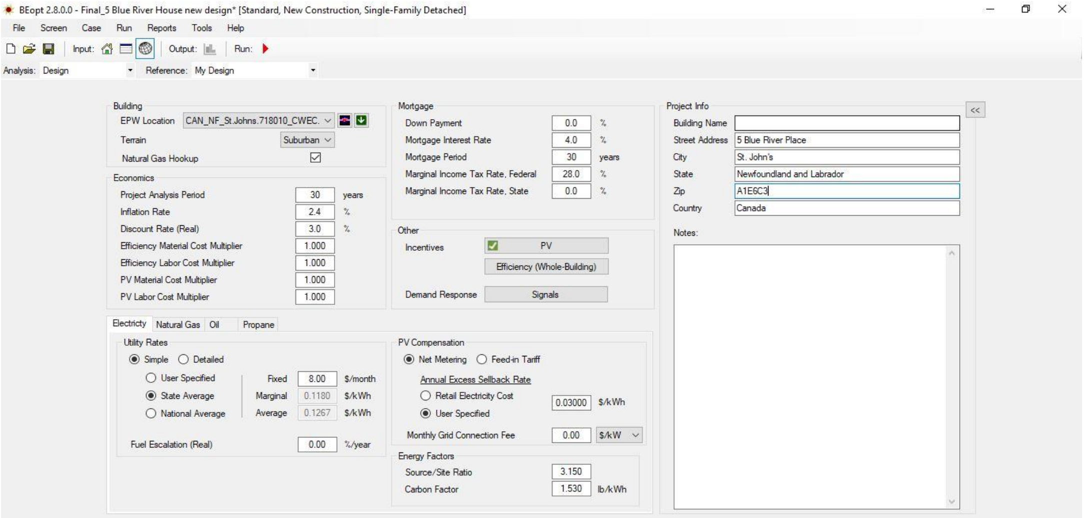
Figure 2.4: Input screen of the software

Table 2.1: Input parameters for the input screen of this software

SL. No	Particulars	Inputs
1	Building	
	Orientation	Northeast
2	Wall	
	Wood stud	R- 15 Fiberglass Batt, 2*4, 16 in o.c
	Wall sheathing	OSB
	Exterior finish	Vinyl, light
3	Ceilings/Roofs	
	Unfinished attic	Ceiling R-38 Fiberglass, Vented
	Roof material	Asphalt Shingles, Dark
4	Foundation/Floors	
	Slab	Uninsulated
	Carpet	0 % Carpet
5	Thermal mass	
	Floor mass	Wood Surface
	Exterior wall mass	½ in. Drywall
	Partition wall mass	½ in. Drywall
	Ceiling wall mass	½ in. Drywall

6	Windows & Doors	
	Window areas	New input of window areas has been inserted
	Windows	Clear, Double, Non-metal, Air
	Door Area	20 ft^2
	Doors	Wood
	Eaves	1 ft.
7	Airflow	
	Air leakage	4 ACH50
	Mechanical ventilation	2010, HRV, 70%
	Natural Ventilation	Cooling months only, 7 days/week
8	Space conditioning	
	Electric baseboard	100% Efficiency
	Ducts	15 % Leakage, Uninsulated
9	Space conditioning schedules	
	Heating set point	60 F
10	Water Heating	
	Water heater	Electric Standard
	Distribution	Uninsulated, Home Run, PEX
11	Lighting	
	Lighting	34 % CFL Hardwired, 34 % CFL plugin
12	Appliances and fixtures	
	Refrigerator	Top freezer, EF= 21.9
	Cooking range	Electric
	Dishwasher	290 Rated kWh, 80 % usage
	Clothes washer	Energy star cold only
	Clothes dryer	Electric
13	Miscellaneous	
	Plug Loads	1.00

The final screen is called a site screen where the location of the building, economics, utility rate, and mortgage are mentioned properly as these parameters are the prime concern before going to the simulation. The site screen of this software is shown by the figure (2.5).



BEopt 2.8.0.0 - Final_5 Blue River House new design* [Standard, New Construction, Single-Family Detached]

Analysis: Design
Reference: My Design

EPW Location: CAN_NF_St.Johns.718010_CWEC.
Terrain: Suburban
Natural Gas Hookup: ☑

Project Analysis Period: 30 years
Inflation Rate: 2.4 %
Discount Rate (Real): 3.0 %
Efficiency Material Cost Multiplier: 1.000
Efficiency Labor Cost Multiplier: 1.000
PV Material Cost Multiplier: 1.000
PV Labor Cost Multiplier: 1.000

Down Payment: 0.0 %
Mortgage Interest Rate: 4.0 %
Mortgage Period: 30 years
Marginal Income Tax Rate, Federal: 28.0 %
Marginal Income Tax Rate, State: 0.0 %

Incentives: ☑ PV
Demand Response

Building Name:
Street Address: 5 Blue River Place
City: St. John's
State: Newfoundland and Labrador
Zip: A1E6C3
Country: Canada
Notes:

● Simple ○ Detailed
○ User Specified
● State Average
○ National Average
Fixed: 8.00 $/month
Marginal: 0.1180 $/kWh
Average: 0.1267 $/kWh
Fuel Escalation (Real): 0.00 %/year

● Net Metering ○ Feed-in Tariff
Annual Excess Sellback Rate
○ Retail Electricity Cost
● User Specified
0.03000 $/kWh
Monthly Grid Connection Fee: 0.00 $/kW

Source/Site Ratio: 3.150
Carbon Factor: 1.530 lb/kWh

Figure 2.5: Site screen of the software

2.4 Simulation result

To accomplish the output results accurately and precisely, some selected input parameters regarding the house location, properties of making house materials, and all major home appliances rated value were used as an input of thermal modeling and analysis software. After simulating and analyzing the one-year hourly value, it was found that the total electrical energy consumption of the designed house is 19511 kWh/yr. Among these, the hot water consumption was 4689 kWh/yr., Space heating 7887 kWh/yr., Lights 2025 kWh/yr., Lg. Appl. 1964 kWh/yr., Miscellaneous 2512 kWh/yr., and Vent. fan 433 kWh/yr. The total demand of electricity for one year of the house is shown by the figure (2.6).

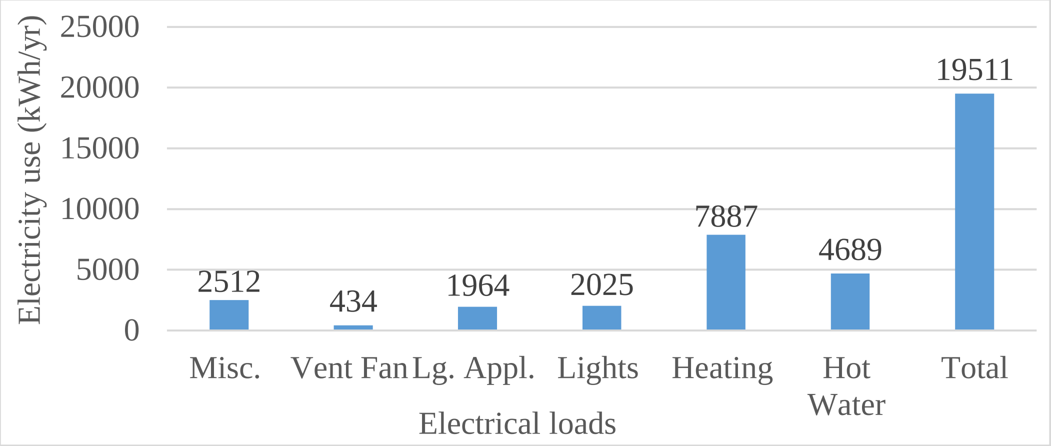


Figure 2.6: Electricity consumption of designed house for one year

The electricity consumption from BE opt analysis, and Newfoundland power is mentioned in figure (2.7). From the result, it can be said that the pattern of electricity consumption for both look identical except in March, where NL power is showing a little bit higher than the BE opt. This happened because one guest came to visit us in March that made the total number of occupants five, and the other months four people were living in the house. The amount of electricity consumption from BE opt, and NL power is 19500 kWh and 18494 kWh individually.

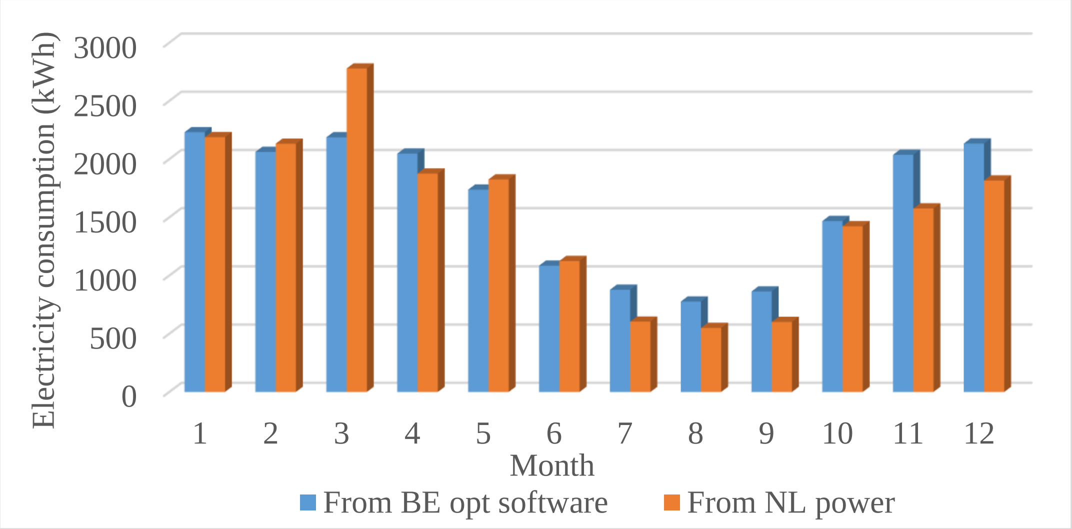


Figure 2.7: Electricity consumption from BE opt and NL power for one year

Figure (2.8) shows the CO_2 Emissions from the existing electrical loads of the house for one year. Among these loads, the heating load releases the highest portion of CO_2 Emissions. Hot water is followed by it. The value of CO_2 Emissions for heating and hot water loads is 5.5 and 3.3 metric tons/year. The total value of CO_2 emissions from electrical loads from the house is around 13.5 metric tons/year.

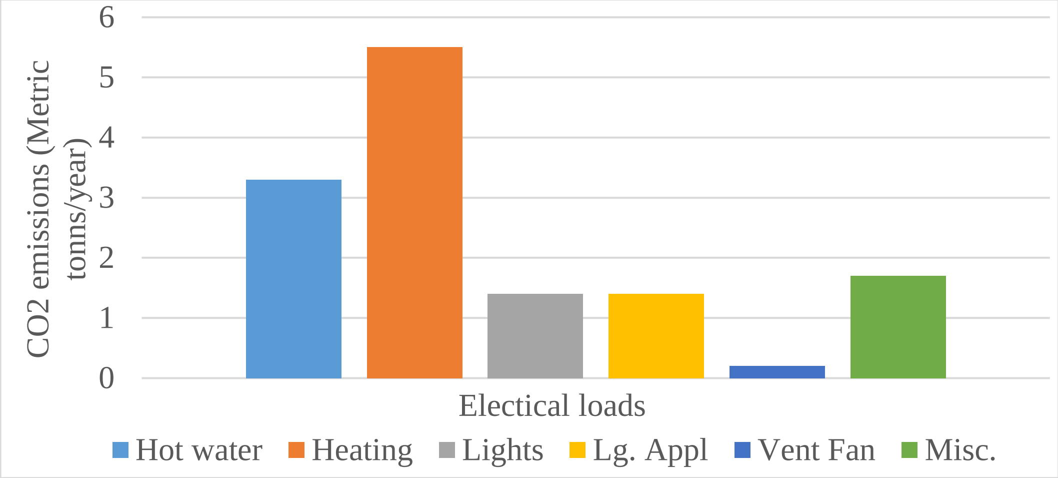


Figure 2.8: CO_2 emissions from electrical loads of the house for one year

Figure (2.9) displays the hourly total energy of the house for one year. The figure indicates that the overall consumption profile is comparatively less in summer than in winter. The average hourly value of the total load is 2.22 kW, and the demand for the total energy of the house from the BE opt data viewer is 19511 kWh per year.

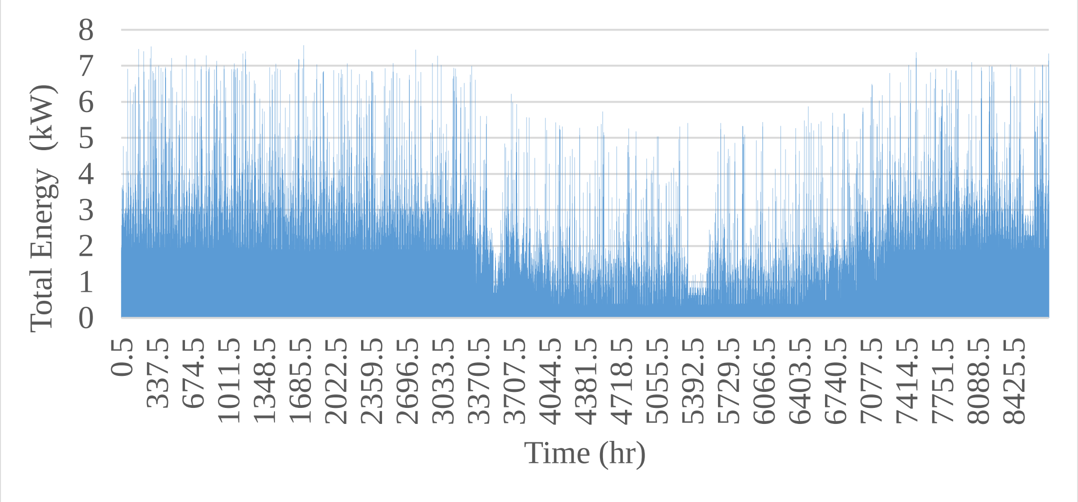


Figure 2.9: Hourly total energy profile of the house for one year

Hourly space heating energy consumption for one year is shown by the figure (2.10). It is noticeable that the demand for space heating energy is more in winter months and reached almost zero in the summer months. The average hourly space heating demand is around 0.90 kW, and the yearly space heating demand from BE opt data viewer is 7887 kWh.

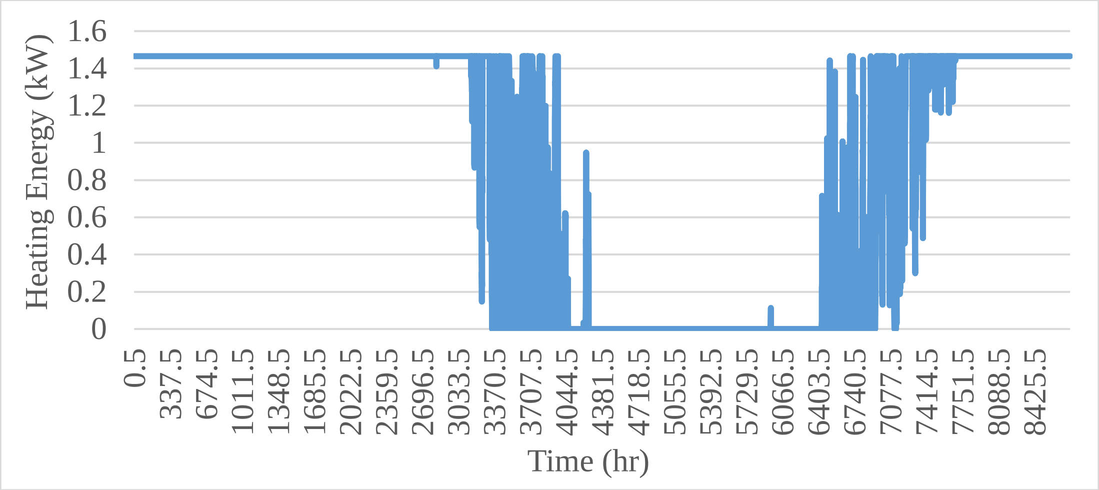


Figure 2.10: Hourly space heating demand profile of the house for one year

Figure (2.11) mentions the hourly hot water demand of the house. From the result, it is noteworthy that the use of hot water throughout the whole year is almost constant. The average hourly and the total yearly consumption of hot water is about 0.54 kW and 4689 kWh, respectively.

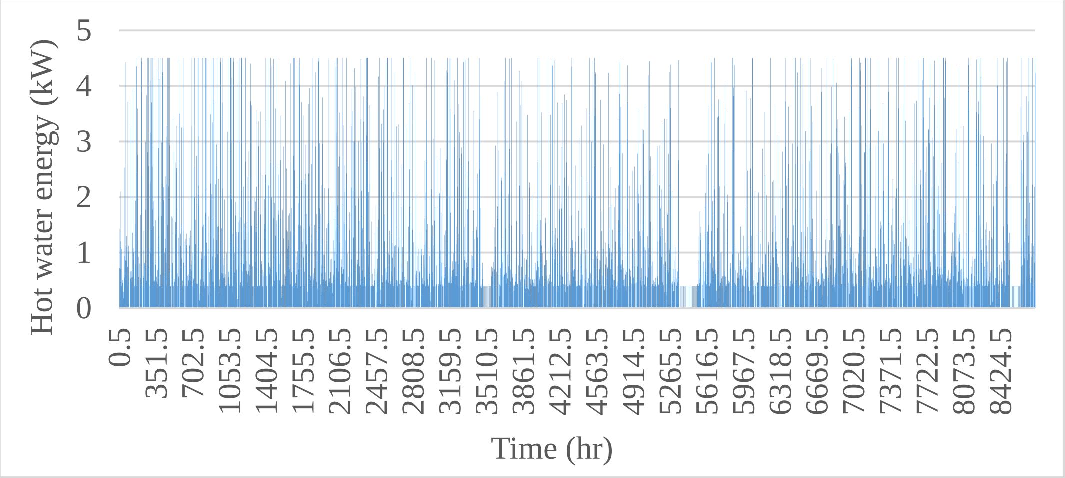


Figure 2.11: Hourly hot water demand profile of the house for one year

Figure (2.12) illustrates the total hourly horizontal solar radiation value of the selected area where the house is located. The solar radiation is comparatively higher in summer months than in colder months. The average solar radiation value is found around 0.13 kW/m^2. It indicates that this location has a reasonable prospect of installing the solar system.

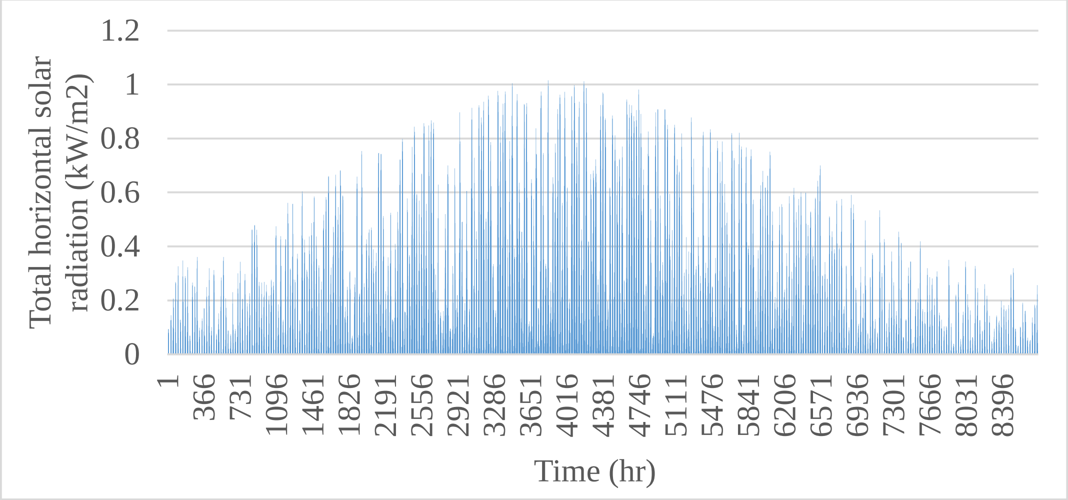


Figure 2.12: Total horizontal solar radiation in the selected area

The groundwater temperature of the selected area is discussed in figure (2.13). As solar radiation is higher in summer, so the highest ground temperature is found in summer. The water heater inlet temperature mainly depends on the ground temperature. The more ground temperature helps to keep the inlet water heater temperature stable and suitable for the boiler input. The average ground temperature of the selected location is 5.05 °C.

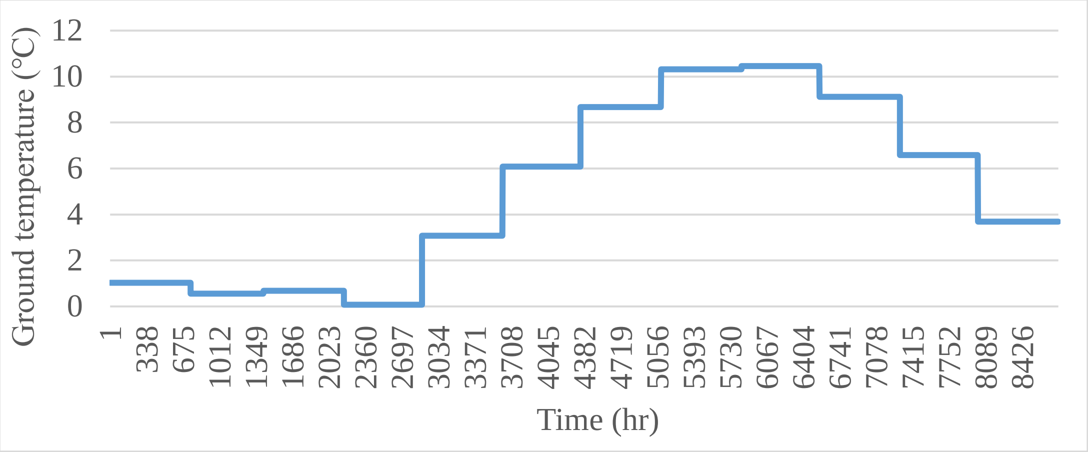


Figure 2.13: Ground temperature of the selected area

Figure (2.14) reveals the water heater inlet temperature for one year. The inlet temperature in summer is higher than in winter. In summer, the temperature is reached at the highest around 12 ℃ and reached nearly 4 ℃ in winter. This happens because the outside temperature and ground temperature drops drastically and tends to zero in winter, and in summer, the location of the selected house gets the highest total horizontal solar radiation. The average water heater inlet temperature is found approximately 8 ℃.

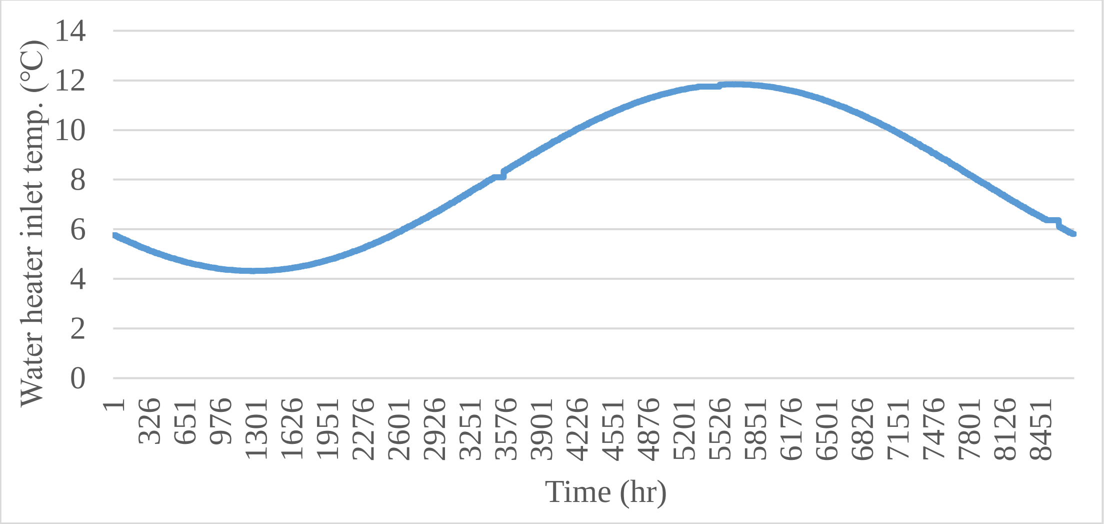


Figure 2.14: Water heater inlet temperature profile of the house for one year

Figure (2.15) shows the water heater outlet temperature. The boiler is used as the central water heater of the existing house. The result indicates that the delivered hot water temperature maintains at around 50 ℃ throughout the year as the end-user required to use the hot water daily. The average delivered hot water temperature is 50.45 ℃.

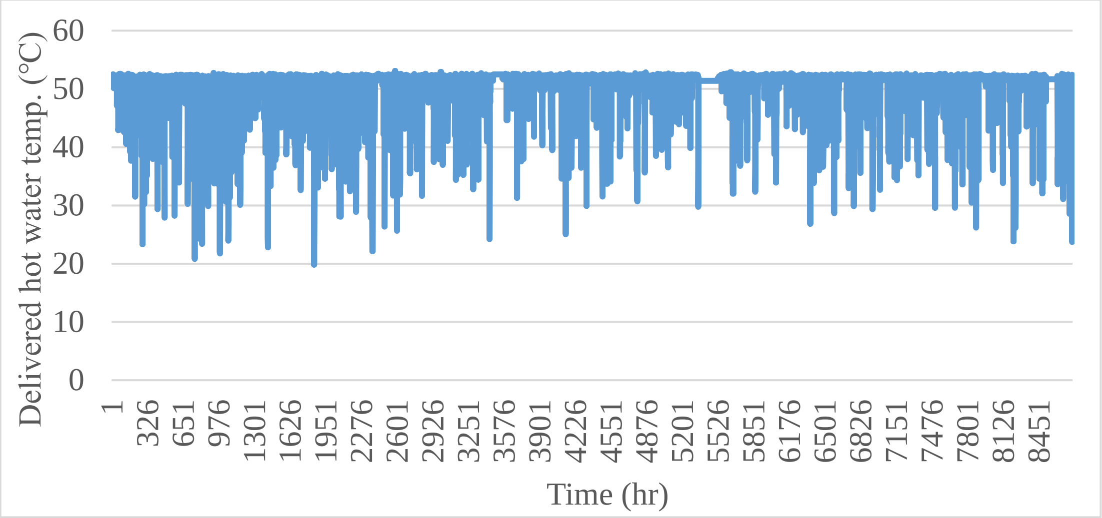


Figure 2.15: Delivered hot water temperature of the water heater for one year

Figure (2.16) shows the hourly indoor relative humidity of the house. It is necessary to maintain air quality and thermal comfort at the maximum level. A heat recovery ventilator (HRV) assists in making the air quality better to fulfill the requirements of the occupants. It is recommended to keep the relative humidity comfort zone range (30-60) % [20]. It is noticeable that the humidity level should not be set below 30 % to avoid the dryness in the air. The relative humidity is higher in summer months than in winter months and maintains within the comfort zone level in winter months from January to April and October to December.

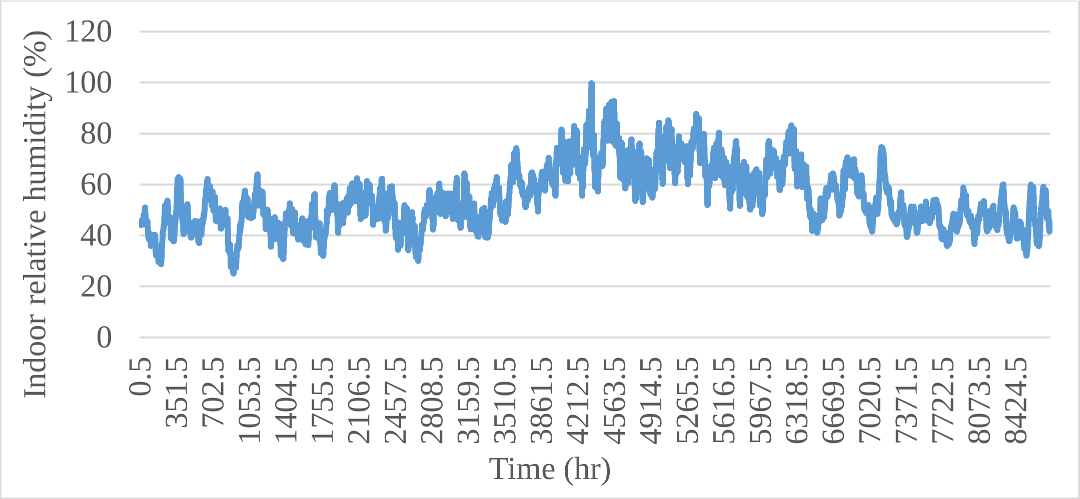


Figure 2.16: Indoor relative humidity of the house for one year

Figure (2.17) indicates the individual monthly total energy consumption profile. The total energy demand in winter is higher than in summer because, in colder countries, the heating energy demand always stays high in winter months and becomes almost zero in summer. From the figure, it is evident that in winter months the total demand for energy reached over 3.5 kW, but in summer this value is dropped at 2 kW.

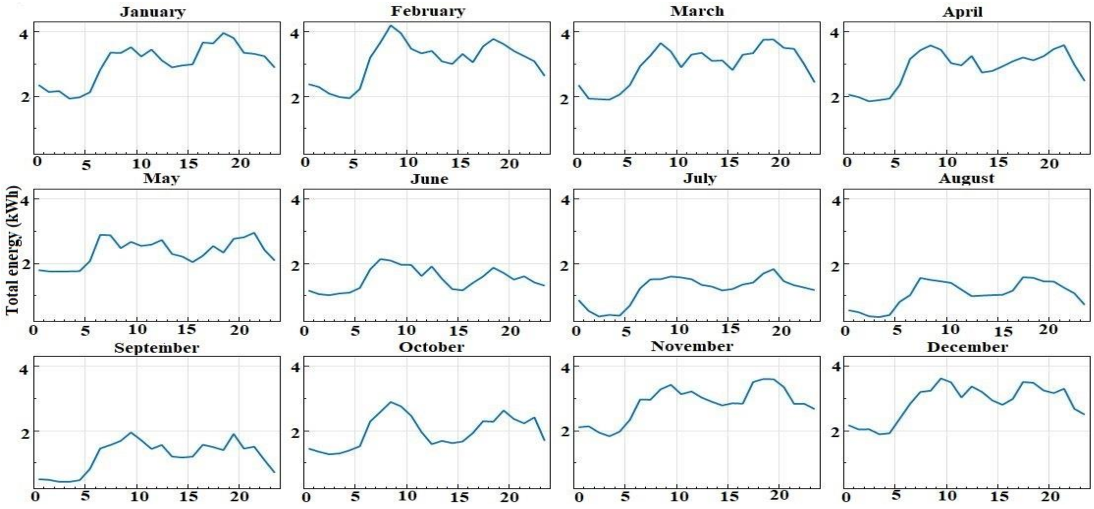


Figure 2.17: Total energy demand of the house for one year

From the BE opt result, we got the total energy demand of the house. Among them, space heating and domestic hot water demand are essential as we mainly designed the solar water heating system that can supply and contribute that space heating and hot water demand according to the end-user demand. Figure (2.18) demonstrates the individual monthly space heating and hot water energy consumption profile. From the result, it can be said that the hot water demand curve fluctuates over the whole year. The highest hot water demand is 485 kWh in January, and the lowest demand becomes 271 kWh in August. On the other hand, in summer, the space heating demand of the house becomes zero, and in winter it becomes mostly constant with 1.5 kW. The highest value of space heating demand is 1116 kWh both in January and December.

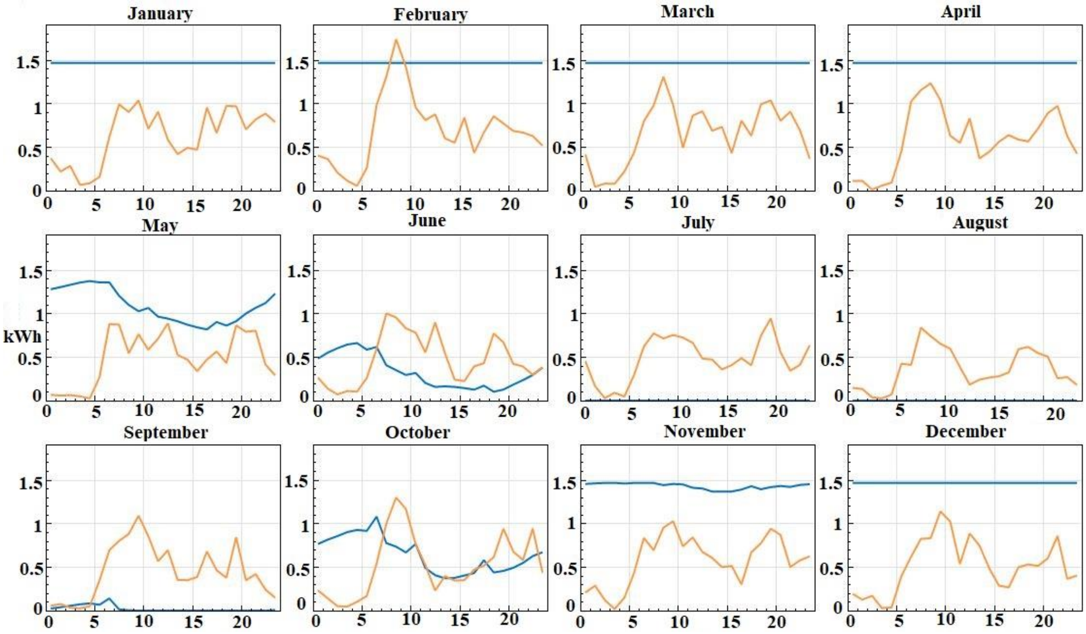


Figure 2.18: Space heating and hot water demand profile of the house for one year

2.5 Conclusion

After analyzing the result presented above, it is obvious to say that thermal modeling of the house is an indispensable way to know the thermal characteristics of the house as well as to get a clear idea of the annual electrical loads. These loads contribute to the design and modeling of an energy-efficient renewable energy system. This analysis also helps to attain the knowledge of house materials, insulation properties, estimates the yearly loads, and the electricity consumption of the various home appliances, etc. These aspects assist in taking action to reduce the annual electricity loads, make more energy-efficient and energy-saving houses. Nowadays, energy-efficient houses are an attraction to the people. This tends to have less electricity bill. From the thermal analysis of the house, the total electrical energy demand is found around 19511 kWh. Among them, the prime energy loads are space heating and domestic hot water with consuming 7887 kWh and 4689 kWh, respectively.

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Chapter 3

Sizing, modeling and analysis of a solar seasonal energy storage system for space heating in Newfoundland

Rabbani Rasha, Md. Habibur Rahaman & M. Tariq Iqbal

Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada

A version of this chapter has been presented and published in the conference proceedings of Canadian Society for Mechanical Engineering (CSME 2019), held between 2-5 June,2019 at the Western University, London, Canada. Rabbani Rasha developed this work under the supervision of Dr. M. Tariq Iqbal. Rabbani Rasha performed the literature review for necessary background information, did the simulation, analyzed the result and finally wrote the paper. Also, Md. Habibur Rahaman gave some important notes during the writing periods.

Dr. M. Tariq Iqbal provided the technical guidance with support, checked the results, reviewed the manuscript, modified the final version of this work and provided the valuable suggestions to accomplish the work.

Abstract—This paper presents the thermal modeling of a house and design of a solar space heating system with seasonal storage to meet the annual heating demand for residential applications. Load estimation is an essential part of designing an energy system in any house. In addition, the sizing of various components of the thermal system is a complicated procedure requiring demand and local climate data to obtain the desired solar fraction and seems to be one of the biggest challenges of this research. In this paper, thermal modeling is done by BE opt software, and a simple calculation approach is used to find design parameters of various components of the system. A simulation software, Polysun, was used to acquire the optimal energy output of the proposed system. Design, simulation results, and detailed analysis of this research are included in this paper.

Keywords- Thermal modeling; BE opt; solar water heating; seasonal energy storage; Polysun simulation software

3.1 Introduction

The global energy demand, as well as the use of conventional energy production, has been increasing rapidly and can affect the environment in the form of global warming, wildfires, etc. Reducing Greenhouse Gas (GHG) emissions and increasing the use of renewable energy are the major challenges nowadays that can lead to a better environment. According to Natural Resources Canada (2015), in the residential sector, space heating consumed around 62% of total energy, whereas consumption of space heating is about 55% in commercial use. It is noticeable that space heating consumed the highest energy in both cases. Also, in Newfoundland, the consumption of space heating energy is higher and uses approximately 70.9%. Greenhouse gases included space heating, produces 91.8% [1] [2]. Researchers and energy companies around the world have emphasized the need to find a solution that can be used to produce and store thermal energy from solar energy during the summer and be used during the winter as it is free energy, but it is not readily available. To overcome these flaws, seasonal solar thermal energy systems with more extended storage periods can be an effective way for colder countries throughout the world to utilize the abundant resource of solar energy feasibly. System performance is one of the crucial factors for end-users and relies on various system configurations like solar collectors, low-temperature storage water tanks, auxiliary heaters, and heat pumps [3].

Extensive research has been going on to obtain the best and most feasible options to store thermal energy seasonally that can mitigate the mismatch between supply and demand. Out of them, the sensible heat storage system is one of the suitable choices because of its cost-effectiveness, longer lifespan, and easiness to maintain. Antoniadis and Martinopoulos [4] designed a solar thermal system with seasonal thermal energy storage and simulated, the energy use of a single-family detached house in Thessaloniki, Greece, using TRNSYS software. They found that the STES system covered only 52.3 % of the space heating demand, but that was able to fulfill the hot water load over the whole year. A seasonal solar thermal energy storage system using TRNSYS simulation software made for a student housing project at Virginia Commonwealth University followed the American Society of Heating and Air-conditioning Engineers (ASHRAE) specifications. Due to the availability and cost, sand was used as the storage medium. Simulations were done for five years to make the sand-based system reach a steady and concluded that an effective and efficient SSTES system could meet up to 91% of the heating energy demand of the building [5]. A solar-assisted heat pump system's performance was simulated by Lie et al. [6] with the help of TRNSYS software for covering the space heating and domestic hot water demand with seasonal storage. Water was used as a storage medium of their system, as well as an air-to-water heat pump unit, while a water-to-water heat pump unit with other necessary components was used for making the simulation model. After completing a one-year simulation period and comparing the findings to conventional space heating systems, it was noticeable that the domestic hot water solar fraction and the energy-saving ratio was around 68.1% and 52% respectively every month.

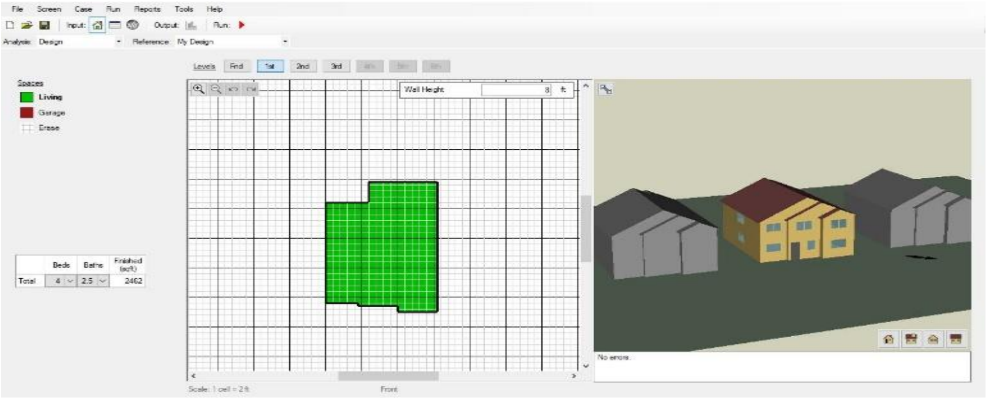
On the other hand, the annual seasonal storage tank's energy storage efficiency was about 64% for space heating. A loss-free thermal energy storage system was built by researchers in Germany using a small size Fraunhofer's zeolite, which can store heat up to four times more effective than water for indefinite periods [7]. A water tank based system was designed and simulated by Lund [8] for Central Solar Heating Plants with Seasonal Storage (CSHPSS) and concluded that about 35% to 60% of solar fractions for this type of system was increased using a stratified storage tank rather than the thoroughly mixed tank. Wills et al. [9] designed and simulated a solar thermal system with seasonal storage as a part of the C-RISE project at Carleton University. A domestic hot water tank and a buried concrete tank were used to provide hot water and space heating demand for the selected house. A co-simulation tool was used to do the different parametric and sensitivity analysis and found that the system at the C-RISE house met about 89.2 % of space heating and domestic hot water demand. A study showed that renewable energy has been contributing to meet around 17% of primary energy demand in Canada, which will lead them to lessen GHG emissions by 30% of 2005 levels by 2030 [10].

From the literature search, it found that renewable energy-based systems and projects should be implemented in the residential sector to reduce greenhouse gas emissions and provide a better and more livable environment. The best option to utilize this solar energy in residential and industrial uses through proper design, sizing, and control to make the system economically viable and more practical. If this happens, then the proposed solar space heating system will be useful to supply thermal energy in the houses of Canadians.

In this work, section 2 will present thermal modeling and analysis. Section 3 will show the proposed system and methodologies. Sizing of proposed system components and results with discussion will be discussed respectively, and the paper will end with a conclusion.

3.2 Thermal modeling and analysis of a house

To design a solar system, the total amount of space heating load per year is required. A thermal model of the house was developed using BEopt (Building Energy Optimization) software to get that load. The house has two floors, contains four rooms with two washrooms on the first floor, and four rooms with a half washroom on the ground floor. Overall dimensions (length: 45 feet and width: 30 feet) were given as an input in Geometry screen, and correct values for all outside walls, windows, doors, roof, orientation, location, all major electrical appliances, and their types were given as inputs into BEopt. The geometry screen of this software is shown in figure (3.1).



Analysis: Design
Reference: My Design

Wall Height 8 ft

	Beds	Baths	Finished (sqft)
Total	4	2.5	2462

Figure 3.1: Geometry screen of a designed house (input)

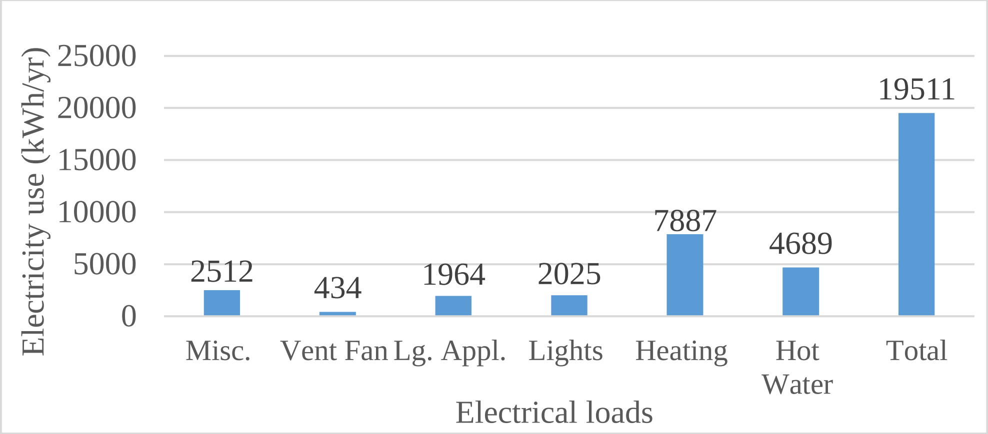


Figure 3.2: Electricity consumption of designed house for one year

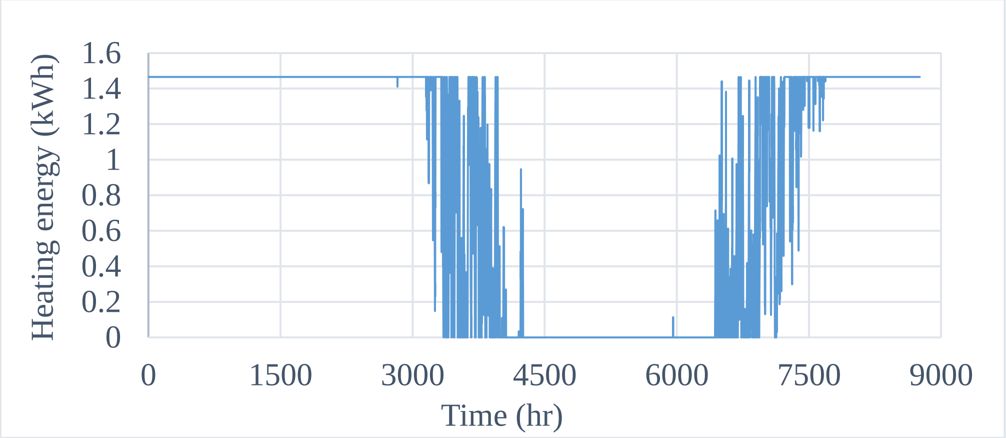


Figure 3.3: Hourly space heating consumption profile from BEopt data viewer

From BEopt, the hourly space heating consumption data was found, and it shows the average hourly space heating demand to be around 0.90 kWh. Figure (3.3), above, represents the data. To attain output results accurately and precisely, some selected input parameters regarding the house location, properties of making house materials, and all major home appliances were used as an input of thermal modeling and analysis software.

After analyzing the result, it was found that the total electrical energy consumption of the designed house is 19511 kWh/yr. mentioned in the above figure (3.2). Among these, the hot water consumption was 4689 kWh/yr., Space heating 7887 kWh/yr., Lights 2025 kWh/yr., Lg. Appl. 1964 kWh/yr., Miscellaneous 2512 kWh/yr., and Vent. Pump 433 kWh/yr. Therefore, our primary concern is to design a solar heating system that can replace the electric space heating energy consumption of 7887 kWh/yr. and reduce the overall electricity bill with seasonal energy storage. A list of these properties is given below in table 3.1.

Table 3.1: selected input parameters of a house for options screen

House parameters	Particulars	Descriptions
Building	Orientation	Northeast
Wall	Wood Stud	R-15 fiberglass batt 2*4, 16 in o.c
Ceilings/ Roofs	Unfinished attic	Ceiling R-38 fiberglass, vented
Windows & Doors	Window areas	New input of window areas has inserted with clear, double, non-metal, air
Space conditioning	Electric baseboard	100 % efficiency
	Ducts	7.5 % leakage, uninsulated
Airflow	Air leakage	4 ACH50
	Mechanical ventilation	2010, HRV, 70%
Water Heating	Water heater	Electric standard
	Distribution	Uninsulated, HomeRun, PEX

Lighting	Lighting	34% CFL hardwired, 34 % CFL plugin
Appliances and fixtures	Refrigerator	Top freezer, EF= 21.9
	Cooking range	Electric
	Dishwasher	290 rated kWh, 80% usage
	Clothes washer	Energy star cold only
	Clothes dryer	Electric

3.3 Proposed system and methodologies

According to our literature search and the geographical features, one of the suitable options for our selected area in St. John’s, NL, Canada, latitude (47.56 ºN) and longitude (52.71 °W), is an active closed-loop solar heating system that can produce required space heating energy with seasonal storage. Since the outside temperature of this area drops below zero, its easiness to maintain, its reliability, its longer lifespan, and its cost-effectiveness are the primary reasons to choose this type of system. The proposed Solar Space Heating System (SSHS) is as follows,

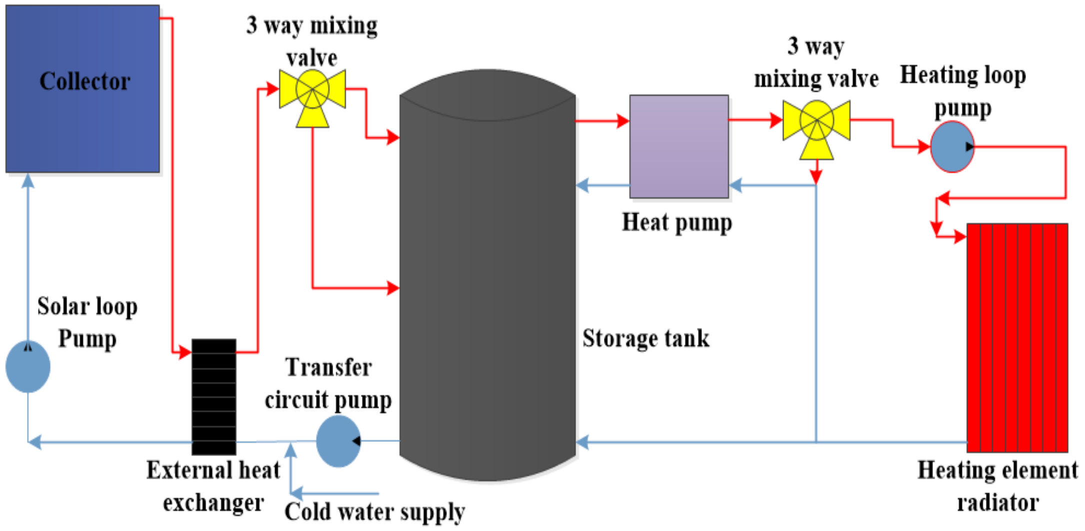


Figure 3.4: Proposed space heating system with components

The proposed system consists of a solar collector, storage tank, external heat exchanger, pump, heat pump, three-way mixing valve, and heating element radiator with necessary control devices. In this proposed work, all control strategies are neglected. The working principle of this system is like the active closed-loop water heating system where solar energy transferred directly to working fluid and circulates this working fluid from the collector up to the storage tank. An external heat exchanger transfers heat from working fluid to storage tank water before transferring it back again with the help of a pump. Here, the water tank worked as a seasonal storage tank for space heating purposes during the heating periods. A heat pump is used to keep and supply the desired temperature of the system throughout the year. Thus, the hot water is passed through the radiator heating element of the building and finally stored in the seasonal storage tank. Various components' designs with detailed parameters according to research criteria are discussed in the next section.

3.4 sizing and selection of proposed system components

3.4.1 Solar collector

System performance and efficiency depend on the perfect sizing of the components of any system. In our system, the main components are mainly the solar collector and storage tank. To design the solar collector size correctly, different equations were used from the literature we reviewed that can meet the space heating demand of the house in the heating period. The calculation method for getting the solar collector area is as follows:

$$Collector\ area, a1 = Q_{demand}/Q_{solar1} \tag{3.1}$$

Here, Q_{demand}=Monthly energy demand of the house from BE opt and Q_{solar1}=Monthly solar radiation of the selected area from RET Screen (3.06 KWh/m^2/day). The initial collector area, a1, was calculated by using (3.1), and using this collector area, the new Q_{solar2} was calculated from (3.2) and determined the minimum excess energy from (3.3).

$$Q_{solar2} = a1 * Q_{solar1} \tag{3.2}$$

$$Q_{excess} = Q_{solar2} - Q_{demand} \tag{3.3}$$

After that, some assumptions have been taken from literature like collector efficiency η=50%, standby loss of insulated storage tank=0.05 kWh/hr., and circulation loss through insulated pipes=5%. Using the below equation, Q_{solar3} was found.

$$Q_{solar3} = \eta * Q_{solar2} - \eta * Q_{solar2} * 0.05 - 0.05 \tag{3.4}$$

$$Collector\ area, a2 = Q_{demand}/Q_{solar3} \tag{3.5}$$

Finally, using (3.5) we found the new collector area, which is larger than the previous one. By following the same procedure, our desired solar collector area with other parameters like the final collector area, a_2= 16 m^2, and excess energy amount: 0.150 kWh were found. For our proposed system, a flat plate collector was chosen, and the selected collector model is the Honeycomb collector HC1-A, manufacturer: TIGI Ltd., test standard: North America, data source: SRCC. In addition, a total number of collectors and arrays were used, 9 and 8, respectively. The collector tilt angle and orientation were 47° and 0°. These types of collectors are available in the market at an affordable cost.

3.4.2 Storage water tank

Based on our proposed system, a storage tank, commonly referred to as a seasonal storage tank, was designed without using any sizing software. The storage tank plays a vital role in holding the hot water at the desired temperature. The amount of solar energy available in the summer months of the selected area, St. John's, NL, Canada, was used to determine the tank's volume. May to September is considered the summer period in this research.

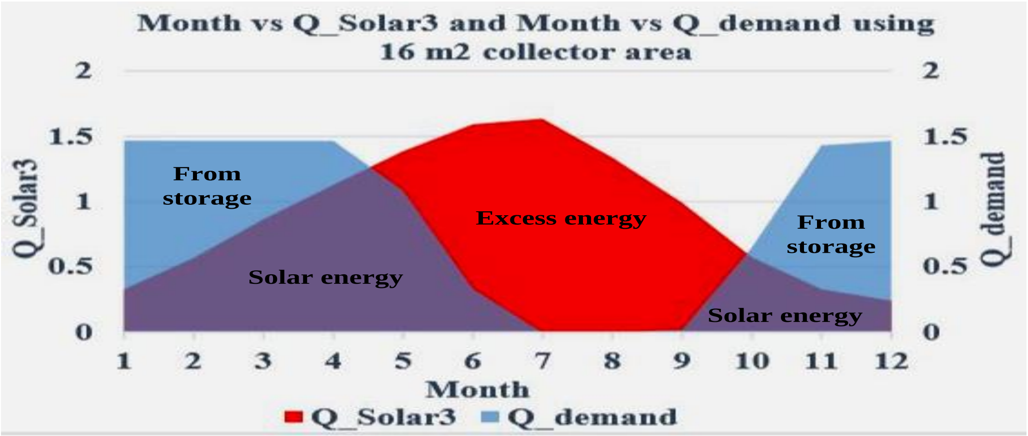


Figure 3. 5: Month vs. Q_{solar3} and Month vs. Q_{demand} for storage tank design

The above figure (3.5) shows that the demand for space heating in the summer months is less than the colder months. The difference between available solar energy and energy demand from the summer months is considered as the excess energy and is demonstrated by the red. The total amount of excess electrical energy, E=4100 kWh, from the summer month needs to be stored in the storage tank for winter use. Several equations have been used to find out the storage water tank's diameter and height, and these are as follows,

$$Excess\ electrical\ energy, E = m * C_p * \Delta T \tag{3.6}$$

$$Mass\ of\ water, m = E/(C_p * \Delta T) \tag{3.7}$$

$$Volume\ of\ water\ tank, V = m/\rho \tag{3.8}$$

$$Volume, V = (\pi * D^2 * H)/4 \tag{3.9}$$

Here, D=H=Height and the respective diameter of the tank (m), ΔT= temperature difference (75 °C), C_p= specific heat of water (4.2 KJ/Kg°C), and ρ =water density (1000 Kg/m^3). After the calculation, we found the following values of the water storage tank: the mass of water, m= 47000 liters, the volume of the water tank, V= 47 m^3, and D=H= 3.91 m. The assumed storage tank height to diameter ratio, H/D: 1 and several vital parameters were considered in order to design the storage tank more accurately and ideally from the default value of the Polysun software, such as the material of the tank: enameled steel, and the insulation material: flexible polyurethane foam with a thickness 101 mm. The thickness of the top and base of the tank were 100 mm and 76 mm, respectively.

It is noticeable that the volume of the designed water tank is larger because if we take one-day solar irradiance, it will not provide the required energy to make the desired hot water. Therefore, back up stored hot water was inevitable for space heating purposes during winter. This type of storage-oriented water tank is available in the market and can incorporate our proposed solar system design.

3.4.3 Pump

The pump, commonly referred to as circulators, plays a vital role in circulating the hot water in the system. In the proposed system, there are three types of loops available. These are the solar loop pump, transfer circuit pump, and heating loop pump. Several parameters should be taken into accounts, such as flow rate, electricity consumption, pressure drop, and pump speed. In this proposed system, the variable speed pump was used. Some simple equations can be used to define the power consumption of these pumps. According to the International energy agency-solar heating and cooling program Task 26 [11]**,** the below equation can find the power consumption of the solar collector loop pump,

$$Power1 = [44.6 * \exp\,(0.0181 * a_2)] \tag{3.10}$$

Also, for the other loops, the power consumption can be found by the below equation,

$$Power2 = [78.3 * \exp(0.0156 * a_2)] - power1 \tag{3.11}$$

Using the above equations, it was found that the power requirement of a solar loop pump is 59.54 W, and the other two loop pumps require around 40.91 W each.

3.4.4 Heat pump

In this research, a heat pump is used to transfer thermal energy from the heat source. It mainly absorbs the heat from the storage tank and releases it into the radiator inlet water. Though the installation cost is higher than the electric heater, it is more efficient and can provide three to four times more energy depending upon weather conditions [12]. A coefficient of performance, the seasonal coefficient of performance, and seasonal performance factors are the crucial parameters for selecting the most efficient heat pump for typical space heating applications. For this research, the selected model was the Belaria 5 KW, water to water heat pump. The COP and the performance factor of this heat pump are 3.5 and 2.96, respectively, with a variable flow rate. Simulation results with necessary graphs are discussed in the results section.

3.4.5 External heat exchanger

A heat exchanger is a device that can be used to transfer thermal energy (enthalpy) between two or more fluids, such as between cold water and hot water. There are many types of heat exchangers available in the market. Different heat exchangers have different flow patterns, and these are divided into the parallel flow, counter flow, multi-pass, and crossflow. In this proposed system, an external heat exchanger was used with the heat transfer capacity 5000W/K, and the number of heat exchanger plates was 20.

3.4.6 Working fluid

The working fluid is one of the vital features where freezing conditions can occur in colder countries. Therefore, the selection of a suitable working fluid depends on many factors. The working fluid will be more efficient when it extracts the maximum amount of thermal energy from the collector field. A propylene mixture was used as a working fluid, with a fluid concentration of around 33.3 %, in this proposed system.

3.4.7 Radiator

A radiator is one type of heat exchanger that can be used to transfer thermal energy from one medium to another for space heating. It mainly follows the convection heat process where hot water circulates through the pipes with extended surface area, or what one often called fins [13]. In this proposed system, a 2.5 m^2 area-based radiator was used with a power of 1000 W per heating element under standard conditions. Moreover, the selected nominal inlet and return temperature of the radiator were 45°C and 35°C, respectively.

3.5 Simulation results and discussion

After sizing the significant components of the proposed system, the full system was simulated for one year using professional Polysun design software, from Switzerland. Version 11 of this simulation software was used to identify various components output as well as the system's overall performance along with various conditions. In addition, the software assumes different parameters to associate with individual components that of different components were suitable and more convenient to obtain an accurate and appropriate result. Figure (3. 6) demonstrates the overall production of and demand for electrical energy for a given year of this selected house. From this figure, it can be said that the proposed system met the demand for space heating entirely, and the overall production of electrical energy is higher than the demand not only in the winter months but also for the whole year. The heating period considered from October to April and the total demand for these months was 6337 kWh, and the production during this period was 6932 kWh. On the other hand, the total annual demand of this house was 7887 kWh, and the total production was 12751 kWh, including the losses of system components and the loss to an indoor room.

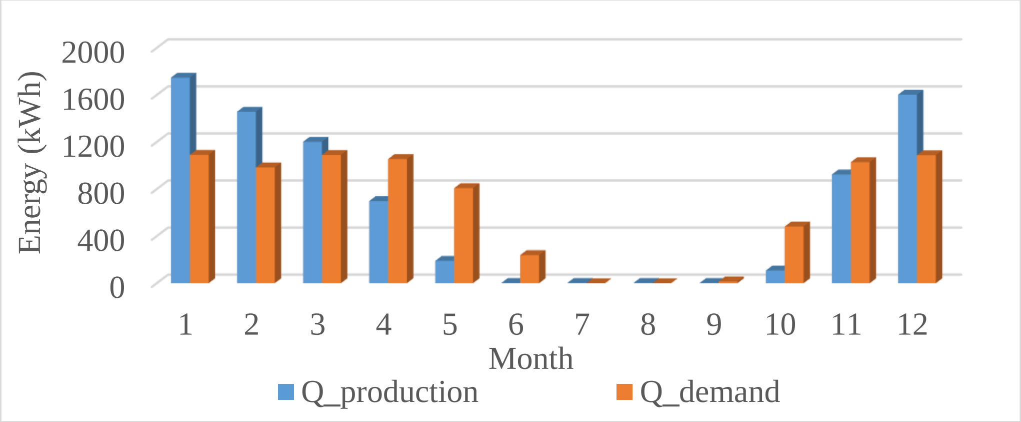


Figure 3.6: Annual demand and production of the proposed system

Figure (3.7) demonstrates the various layer temperatures of the storage tank. The storage tank was divided into ten layers; the top layer has the highest temperature compared with the bottom layer. In the summer months, all three layers were higher than in the winter months. The heating set point temperature was 17 ºC. From the figure below, it is concluded that this setting temperature was maintained in the storage tank through the whole year and, the average top layer temperature was around 43.9 °C and the bottom layer 33.2 ºC.

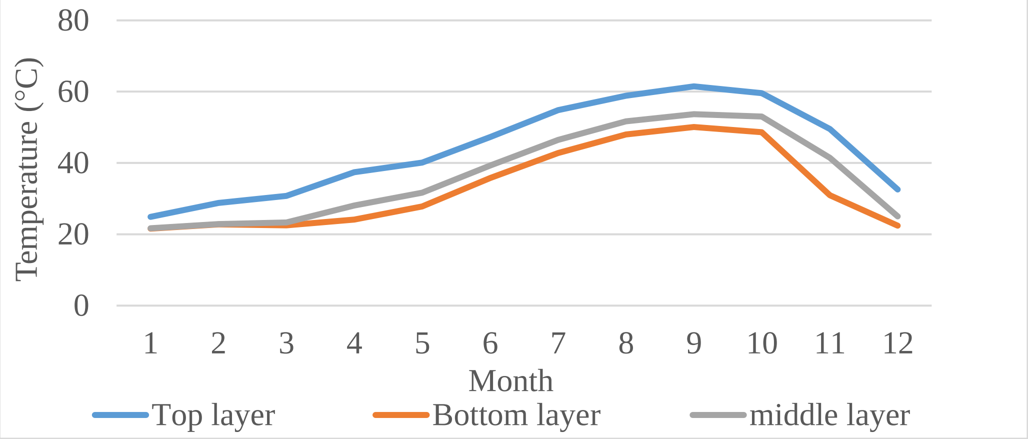


Figure 3. 7: Different layer temperatures of the storage tank

Figure (3.8) reveals the daily top layer temperature of the storage tank. The highest layer temperature was 61.5 °C in September and lowered 24.9 ºC in the freezing month of January. January 1 was set as the reference day for hourly analysis in this research. In the daily profile, the temperature started to rise after 8 AM and reached its highest point between 1 PM and 4 PM. After 4 PM, this value remains almost constant. During both summer and winter, the hourly temperature difference was small, and the temperature remained in the range of (21 to 23.5) °C.

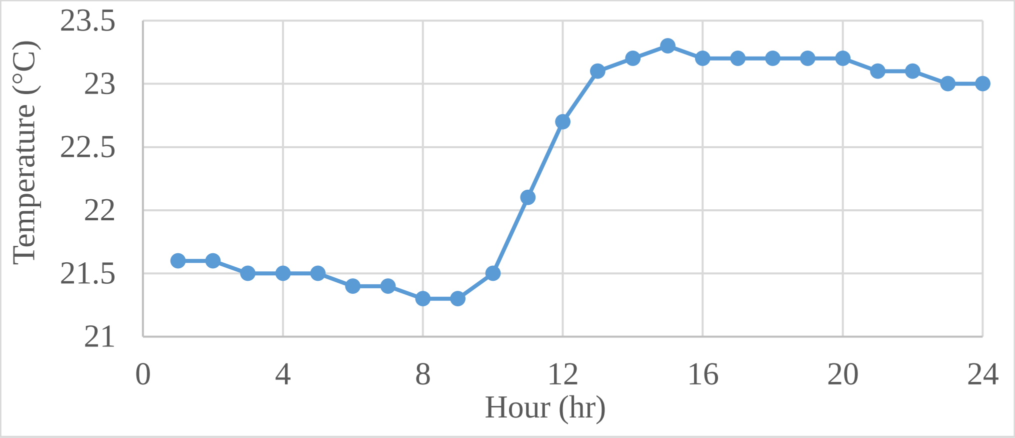


Figure 3. 8: Daily top layer temperature of the storage tank

Figure (3.9) shows the operational and mean temperature of the solar collector field at a constant flow rate. The operational temperature started at 28 °C and ended above 25 °C. Similarly, the mean temperature started and ended at 5 °C. Though the temperature range is different for both, the temperature pattern was identical. In summer, the operational and mean temperatures were more because of the lower amount of heat loss and the higher amount of irradiation on the collector field.

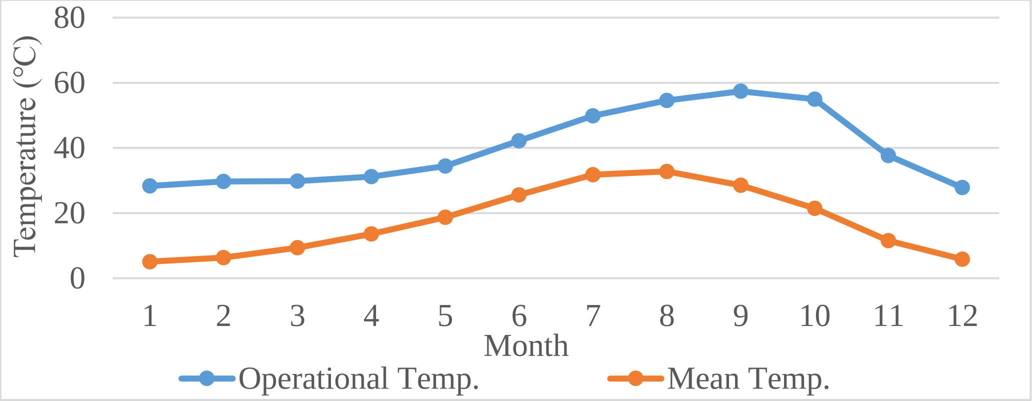


Figure 3.9: Operational and mean temperature of the solar collector

Solar irradiation on the collector and the collector field yield are presented in the below figure (3. 10). From the graph, it is noteworthy that solar irradiation on the collector field was higher than the collector field production. Due to the loss of heat in the collector area throughout the year, the yield rate of the useful solar collector field becomes as follows.

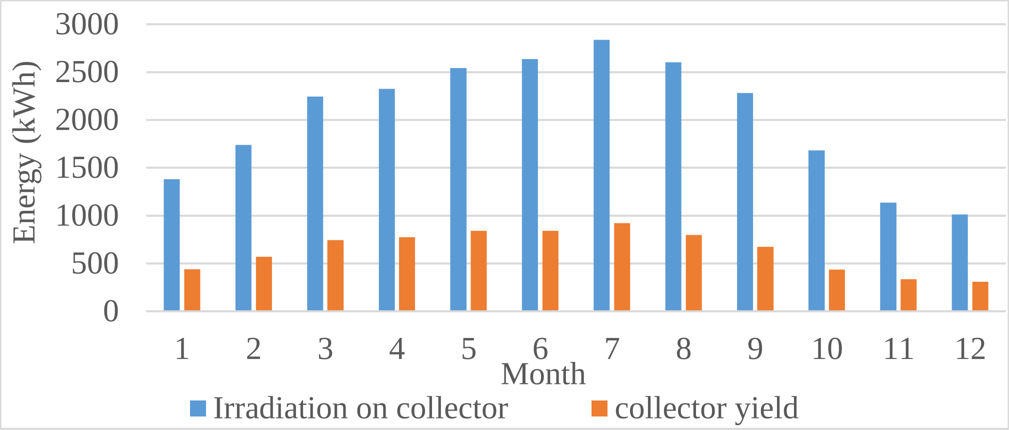


Figure 3. 10: Irradiation on collector and collector field yield of the proposed system

Figure (3.11) shows the heat pump’s electricity consumption and the total production for one year. A heat pump was used to provide additional energy to the system in only the winter months. A water-source heat pump was used that took heat from the storage tank water to increase the water temperature up to the desired level for space heating. The electricity production was three times more than consumption. The COP of the heat pump was 3.5. Also, the production and consumption of the heat pump were 4812 kWh and 1623 kWh, respectively. The temperature of the heat pump’s thermal energy was higher in colder months and firmly constant in the summer months.

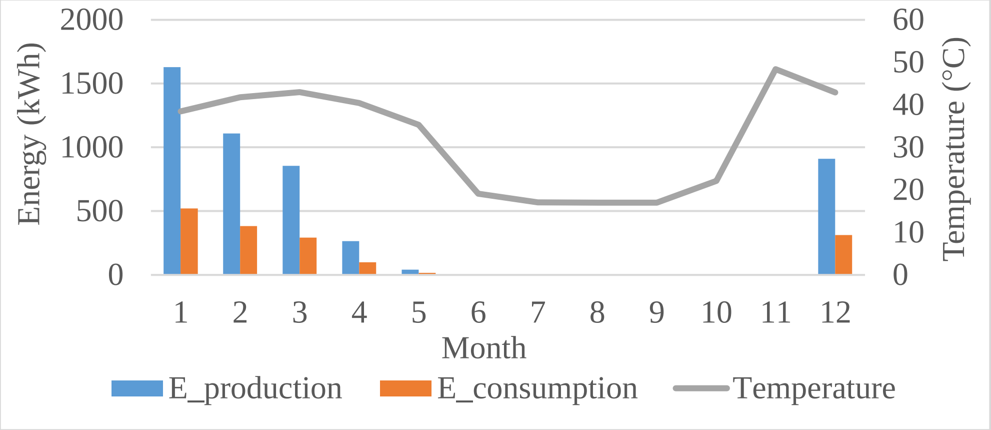


Figure 3.11: Electricity consumption and production with the temperature of heat pump

Figure (3.12) presents the temperature profile of the heating element radiator. The actual inlet and the outlet temperatures of the radiator showed a similar character. The inlet temperature was comparatively higher than the outlet temperature. Both started with a temperature range of 20°C to 25 ºC and ended with a similar range. After the heating periods, the graphs started to rise because, in summer, there was an extra thermal energy needed. Also, the demand for space heating was lower, and the flow rate was constant.

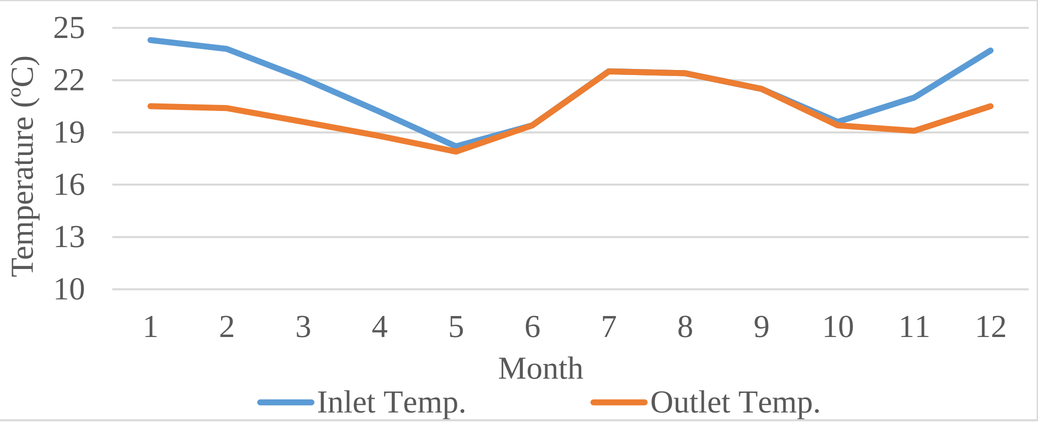


Figure 3.12: Inlet and outlet temperature profile of heating element radiator

Figure (3.13) offerings the external heat exchanger supply and demand temperature with transfer efficiency. The result showed that the temperature difference between the supply side and the demand side was very low though, in summer months, both the temperatures were higher than in the colder months. The transfer efficiency of heat was constant throughout the winter months, and this value decreased by only 1 % in the summer months.

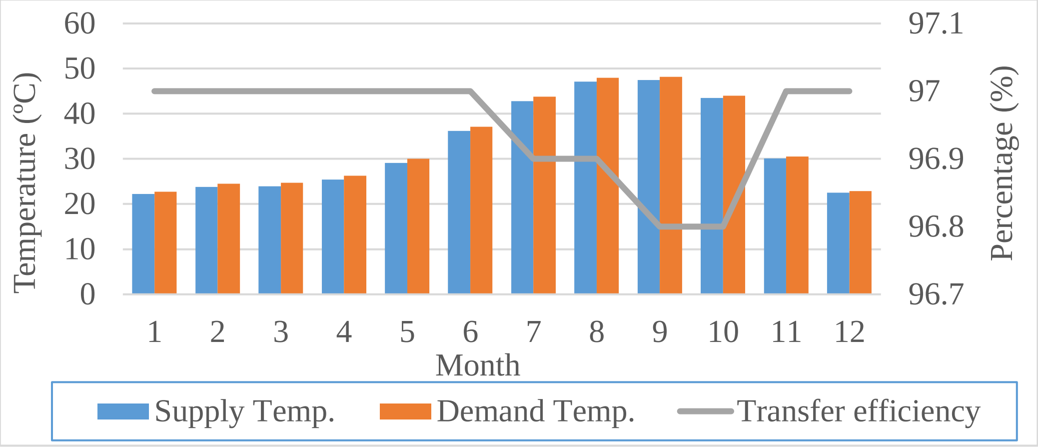


Figure 3.13: Temperature and transfer efficiency of the external heat exchanger

Figure (3.14) demonstrates the daily pump solar loop temperature. In the proposed system, three different pump loops were used, as mentioned earlier. After analyzing the daily loop temperatures, it was evident that the solar pump loop and the transfer circuit loop have similar temperature patterns. The temperature started to rise after 9 AM and reached its highest point at noon. Then the temperature started to decrease in value because the solar collector received the highest level of solar radiation at that time. On the other hand, the pump heating loop showed a slightly different profile with a low-temperature difference. However, in cases of yearly loop temperatures, pump solar loop and transfer circuit loop possessed the highest temperatures in summer while the pump heating loop achieved the highest temperature in winter.

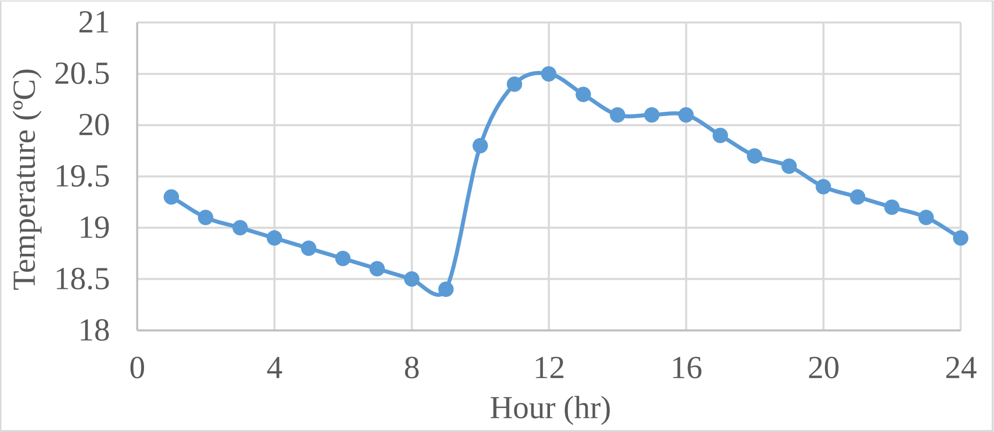


Figure 3.14: Daily pump solar loop temperature

Figure (3.15) determines the supplied heating energy and the room temperature of the building for the designed system. The room temperature was near or above 17 ºC during the heating periods as it was the set temperature for the building, but in summer months, it went higher and reached 22.5°C because of the comparatively lower space heating consumption mentioned in the earlier section. Moreover, the supplied heating energy was enough to meet the space heating demand.

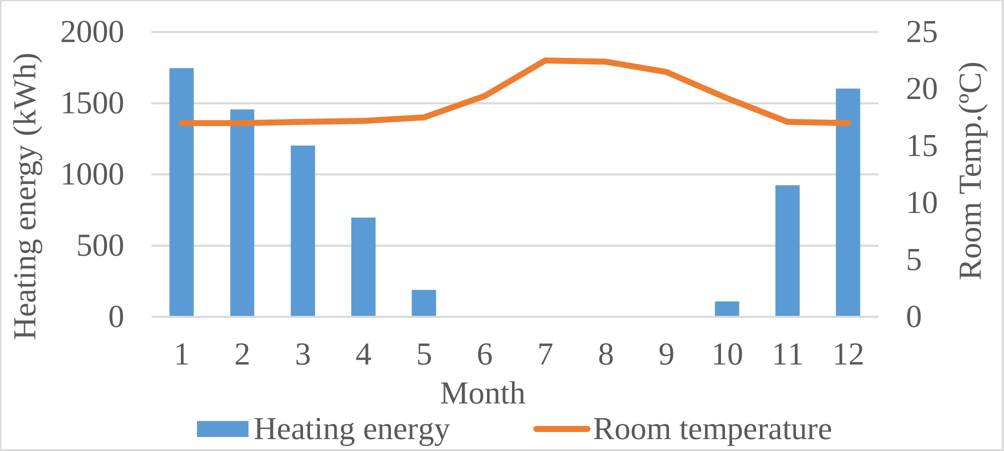


Figure 3.15: Supplied heating energy and room temperature of the building

Figure (3.16) shows the overall solar fraction and irradiation fraction of the proposed system. From the results, it can be said that the overall solar fraction was 61.4 %, but in the summer months, the percentage was 100. On the other hand, the overall solar irradiation on the collector was 93.8%, but during the summer months, the percentage was 100. Due to the various losses and inefficient collectors cause higher space heating demand in winter months.

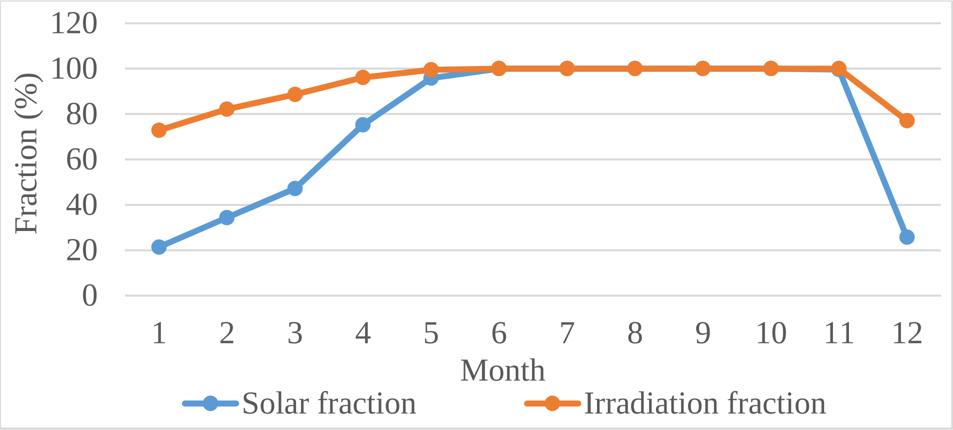


Figure 3.16: Solar and irradiation fraction of the collector of the proposed system

Different losses from the system are shown in figure (3.17). Four significant losses through the system discussed in this research. These losses occur in tank, building, ventilation, and infiltration. Among these, the building was the primary source of loss. In our next phase of research, minimizing the overall losses of the system will be the prime target.

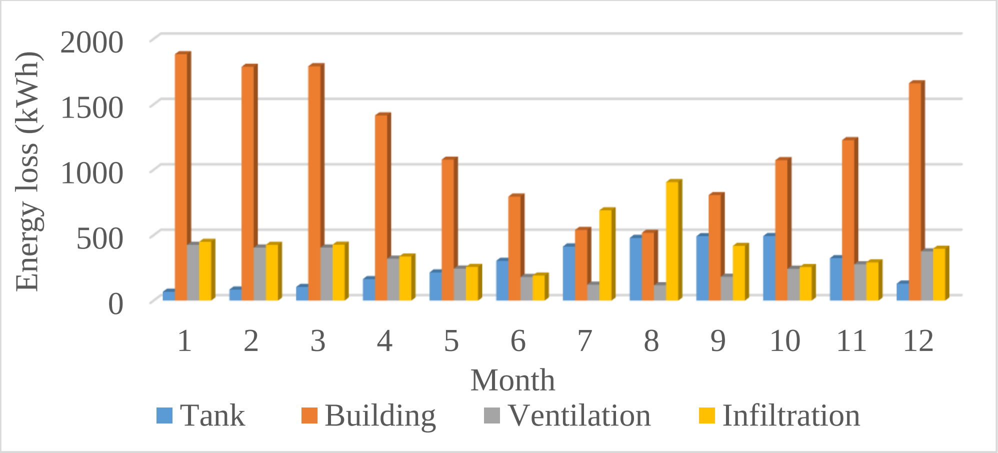


Figure 3.17: Different losses throughout the proposed system

3.6 Conclusion

In this study, a solar space heating system was designed and simulated with professional Polysun software to fulfill the annual space heating demand with seasonal energy storage of a single-family house. The simulation results depend on the actual sizing of the system components and the other values given as inputs for the simulation environment. After demonstrating the output, it can be said that the proposed system was more practical, profitable, and efficient in colder countries with more considerable seasonal differences. It was concluded that the proposed system should consist of 16 m^2 flat plate collector area, 47 m^3 proper insulated storage tank with a height and diameter of 3.91 m and a 5-kW heat pump. Then, this system will meet the space heating demand in the heating periods of the selected house. A heat pump was used to boost up the backup heat to this system for the heating months, as discussed earlier. This system can be further modified by controlling the individual components and the cost analysis of the full system to make it more affordable and reliable.

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Chapter 4

Design and analysis of a solar water heating system with thermal storage for residential applications

Rabbani Rasha, & Dr. M. Tariq Iqbal

Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada

A version of this chapter has been accepted and published at the Journal of Sustainable Energy, (ISSN: 2067-5534 & Vol. 10-Nr. 2), 2019. This journal was published by the Department of Power Engineering, University of Oradea, Romania. Rabbani Rasha developed this work under the supervision of Dr. M. Tariq Iqbal. Rabbani Rasha performed the literature review for necessary background information, did the simulation, analyzed the result and finally wrote the paper.

Dr. M. Tariq Iqbal provided the technical guidance with support, checked the results, reviewed the manuscript, modified the final version of this work and provided the valuable suggestions to accomplish the work.

Abstract - This paper represents a design and analysis of a solar domestic hot water and space heating system with thermal storage for a single-family house. To meet the energy demand of the residential sector like a house, one of the best options is a solar water heating system that can be integrated with space heating (SH) and domestic hot water (DHW). This type of system performance and efficiency relies on the proper design method, the actual size of the components, characteristics, and the behavior of selected heat transfer fluid and the accurate analysis with the appropriate software. In this paper, a complete solar thermal based heating system is introduced that meets the overall energy demand of a house. The designed collector area 18 m^2, the storage tank 31 m^3 is chosen with the volume to area ratio 1.72. It is also noticeable that the percentage of solar coverage for space heating and hot water is 32 and 59, respectively, with average collector efficiency 51 %. Moreover, the overall hot water and space heating coverage using the designed system is 100 % that makes an excellent agreement with the literature. Design, simulation results, and detailed analysis of this research are included in this paper.

Keywords: modeling, space heating, domestic hot water, thermal simulation, SHW software.

4.1 Introduction

Solar energy use is the blessings of modern technology in order to obtain electricity and heat. Electricity production is an indirect process where a photovoltaic cell is used to generate electricity. On the other hand, heat generation is a direct energy conversion process where different collectors are used to producing heat. Thus, the direct system is better than the indirect system in terms of efficiency, cost, lifetime, and so on. The demand for using this heat energy in terms of space heating and hot water production is increasing to mitigate the mismatch between energy and demand in the world's energy sector. Researchers have focused around the world not only to produce thermal energy but also to find a way to store this energy seasonally, referred to as Thermal Energy Storage, due to its use. This energy can be stored through various heat storage technologies such as sensible heat, latent heat, thermochemical heat storage using different mediums like water, sand, air, and so forth.

A solar water heating system is the cheapest, easy to maintain, and a non-pollutant way to get hot water that consumes approximately 20% of the total energy consumption of a typical family [1]. According to Natural Resource Canada (NRC), in 2015, Natural gas and Electricity are the highest energy provider around 48% as an energy source in Canada's secondary energy use, and the total secondary energy is accounted for 17 % by the end-users in Canadian's residential segment. Out of the 62%, energy is used for space heating, and 19% energy is used for domestic hot water preparation. Natural gas is Canadian's primary energy source for around 66% space heating and 74% domestic hot water systems and considered the most significant contributor for GHG emissions by 29% as the energy source [2] [3]. Also, in Newfoundland and Labrador, Electricity and wood are the highest energy sources of approximately 87% as an energy source in Canada's secondary energy use, but in residential sector consumption of space heating and water heating energy are accounted for 70.9% and 12% respectively. As an end-user, space heating and water heating are responsible for primary GHG emissions in this province [4] [5]. Thus, it is perceptible that for both cases, space heating and water heating consumed the highest energy as well as contribute a more substantial portion of GHG emissions in the environment.

Edwards et al. [6] evaluated the performance of single and double tank combi-systems in the residential application. This system consists of the radiator for space heating, 48 m^2 flat plate collector, and the volume of the diurnal tank up to 2000 L. This research concluded that solar fraction is not achieved by more than 50% with this size of the diurnal tank. Edwards et al. added that radiant floor for space heating and used low-temperature hot water as an input and suggested evacuated tube solar collectors may increase the overall required solar fractions. Hugo et al. [7] demonstrated the performance of a solar combi-system based on financial payback with thermal energy storage in Montreal using solar simulation software TRNSYS. This result concluded that there are some factors like high initial capital cost, long payback periods, and lower electricity rates, mostly responsible for making the barriers to set up this kind of system. The Canada Mortgage and Housing Corporation built a solar combi-system project called the Riverdale NetZero under the national $EQuilibrium^{TM}$ Sustainable Housing Demonstration Initiative in Edmonton, Alberta. This system consists of a vertically mounted 21 m^2 flat plate collector, a 17 m^3 seasonal thermal energy storage tank, a 300 L diurnal thermal energy storage tank with a 7 KW heat pump. According to the Canada Mortgage and Housing Corporation, around 83% of domestic hot water and 21% space heating demand was met by this system [8].

An existing 215 m^2 passive house was retrofit in Galway Ireland with the help of 22 m^3 buried water-based seasonal thermal energy storage tank and 300 L diurnal thermal energy storage tank. Firstly, this 300 L DTES tank is heated by the 10.8 m^2 evacuated tube solar collector to 65 ℃ before charging the STES tank. The result showed that domestic hot water and space heating solar fractions are 93% and 56%, respectively. It also recommended that this type of combi-systems is more feasible and profitable for energy-efficient single-family detached houses in Ireland [9]. A single-family residential house was modeled using TRNSYS in Richmond, Virginia. A soil-based STES system was selected due to its cost-effectiveness to other mediums. Six homes were simulated with the range of area from 800 to 2400 ft^2 with an airtightness of 1.0 air changes per hour and the collector size ranging from 39 to 99 m^2. They established around 15 m^3 of STES volume as optimal for the selected case [10].

The first solar house built in MIT (Massachusetts Institute of Technology) in 1939 was considered as the first application of seasonal storage for a single-family detached house. The solar collector of that house was 136 m^2, a cylindrical steel storage tank was 68 m^3, insulated and buried under the house as the temperature reached 90 °C and thus, the performance of the system suffered from condensation which creates a barrier to collect solar energy in summer. As a result, in winter, the collectors cannot produce more than 55 °C, which is not enough for single-family houses [11] [12]. In Canada, many seasonal storage systems implemented. Hooper mentioned about one such house built in Toronto in 1976, whose storage tank size was 277 m^3. Though it was expected, the system could not provide enough temperature due to the higher storage losses. The soil surrounded the tank, and most of the heat from the tank was transferred to soil was the main reason for the losses [13].

According to International Energy Agency (IEA) SHC-task 13, a house called 'zero-heating energy' was built in Berlin, Germany, with 20 m^3 vertical and well-insulated storage tank, 54 m^2 high-efficiency solar collectors. To adapt the active and passive solar strategies for this kind of house, it is made with a higher insulated envelope and airtight to reduce the transmission losses. The result revealed that seasonal water storage in the tank transfers the excess solar energy in summer to heat the house entirely in winter months without using conventional energy throughout the year [14]. Based on the simulation result from DEROB-LTH program, Smeds and wall [15] showed that the heating loads of a typical conventional house can be minimized by up to 83% in cold climate zones, and the total energy demand including space heating, DHW and other loads can be decreased up to 92% for a single-family house. A remarkable project called Beddington Zero Energy Development (BedZED) was constructed with 100 eco-homes and workspaces in Hack bridge, London, England. This project aimed to feature the houses with high insulation levels, high-efficiency windows, active and passive solar design strategies, and combined heat and power plant fuelled by woodchips from waste timber. After the one-year simulation, the result indicated that space heating and DHW demand could be reduced using the features mentioned above in the house. The reduction of space heating and DHW energy demand was around 88% and 57% compared to conventional houses where the percentage was 90 and 33, respectively [16].

From the literature search, it is found that renewable energy-based systems and projects have ethical aspects in terms of providing thermal energy for space heating and domestic hot water in the Canadian residential sector. It does not only help to reduce the greenhouse gas emissions to make the environment better and liveable but also contribute to pay the less electricity bill. However, before thinking above these advantages, the proper method of utilizing solar energy with appropriate control strategy, sizing of the system's components, exact energy demand calculation, cost analysis is the necessary task for this type of system. If this happens, then the proposed solar space heating and DHW system will be viable to supply thermal energy in the houses of Canadians. No such study has been done for Newfoundland, Canada.

In this research, section 2 will present methodology and system design. Section 3 will show the sizing of the collector and storage tank for both space heating and DHW. Various components control, simulation results with discussion will be discussed, respectively and the paper will end with a conclusion.

4.2 Methodology and system design

According to our literature search and the geographical features, one of the suitable options for our selected area in St. John's, NL, Canada with latitude (47.56 °N) and longitude (52.71 °W) [17] is active solar water heating system for producing thermal energy that can meet the annual space and domestic hot water demand in a typical single-family detached house. Figure (4.1) represents the full system where we sized the essential components like collector and storage tank for both space heating and domestic hot water and gave some vital parameters as an input of the other components. At the beginning of the cycle, the collector is heated by the sun, heat transfer fluid, ethylene glycol, with properties like density 1111.6 Kg/m^3 and thermal capacity 3400 $J/Kg.K$ flows progressively through the collector and gets heated.

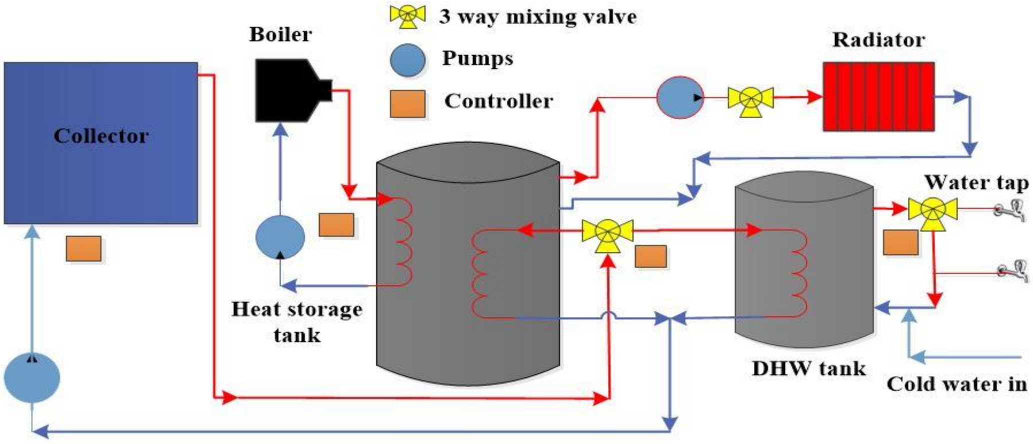

Figure 4.1: Space and domestic hot water system for residential application

After that, this heated HTF circulated through the heat exchanger that is connected in the DHW tank and heat storage tank with releasing enough heat. System was controlled in a way that 70% heat can be released in the heat storage tank and 30% in the DHW tank with the help of control valves. Collector mass flow at DHW and heat storage tank was considered as 0.150 Kg/s. A 3KW e- cartridge or electric heater was placed in the DHW tank as the key energy source of reheating domestic hot water. Moreover, a propane gas based boiler was connected to the heat storage tank that can supply the additional heat for space heating and helps to maintain the constant temperature of the demand side supply annually. On the other hand, according to the heat demand and the house configuration, we assumed some parameters of the building to find out the total amount of energy needed for space heating. These assumptions are the heating load of the house 3.15 KW, Room temperature 20 ℃, night setback temperature 20 ℃, flow temperature in the house radiator 35 ℃, return temperature 30 ℃, design temperature or outside average temperature -10 ℃. The heating temperature starts at 12 ℃. Also, it has some important parameters that need to be considered for getting the exact heat energy demand for space heating. The house has two floors, contains four rooms with two washrooms on the first floor, and four rooms with a half washroom on the ground floor. Overall dimensions (length: 45 feet and width: 30 feet). It has several windows, and the window parameters of the house are shown in table 1. These values were given as input of the simulation part. Necessary graphs and detailed analysis of this research are included in the result section.

Table 4.1: window parameters of the house

Window	window (right)	Window (left)	Window (front)	Window (back)
Gross area (m^2)	7.8	2.8	3.6	2
Inclination (°)	90	90	90	90
Azimuth (°)	0	90	180	270
g-value	0.70	0.70	0.70	0.70

4.3 Sizing of collector and storage tank for DHW

Domestic hot water tank, commonly known as the diurnal tank, is essential for every combi-systems. This tank volume mainly relies on the daily consumption of hot water. To determine an appropriate diurnal tank volume, daily hot water consumption throughout the whole year, as well as the peak month demand, are important parameters. From the literature, several recommendations were found in order to get the best sizing options for the DHW tank. Evarts and Swan noted a rule-of-thumb value of 60 l/day-person for domestic hot water consumption where four or more people are living, and below this number of people, this assumed value might not be perfect [18].In solar applications, Heimrath et al. [19] found that for 200 liters per day consumption of hot water, the diurnal tank should not be smaller than 200 liters. Based on the above literature search, a simple calculation technique is used to find out the geometry of the tank, and these are as follows.

Firstly, the amount of energy to heat the daily hot water demand (Q_{DHW}) is calculated using the formula (4.1) [20],

$$Q_{DHW} = volume\ of\ daily\ DHW * C_w * \Delta T \tag{4.1}$$

Here, $C_w =$ specific heat capacity of water (1.16 $Wh/Kg.K$)

ΔT= Temperature difference between cold water and desired water temperature (°C)

Using equation (4.1), the amount of energy for daily hot water

demand, Q_{DHW}=240*1.16*(50-5) Wh/day

Q_{DHW}= 12.52 KWh/day

Secondly, the volume of storage tank for domestic solar systems can be found by below equation,

$$V_{cyl} = \frac{2*Vn*P*(T_h-T_c)}{(T_{dhw}-T_c)} \tag{4.2}$$

Here, V_{cyl}= Minimum volume of the tank (L)

$Vn =$ Domestic hot water demand per person/day (60 L)

$P =$ Number of people (4)

$T_h =$ Temperature of hot water at the outlet (45°C)

T_c =Temperature of cold water (5°C in wintertime)

T_{dhw} =Temperature of stored water (50 °C)

After putting all values in equation (4.2), the minimum volume of the tank, $V_{cyl} = \frac{2*60*4*(45-5)}{(50-5)}$

$V_{cyl} = 426$ L

Finally, the collector area to meet the daily hot water demand is calculated using the below equation,

$$Collector\ area, A = \frac{No.of\ days * solar\ fraction * Q_{DHW}}{Daily\ solar\ irradiation * Average\ system\ efficiency} \qquad (4.3)$$

Here, No. of days=1

Solar fraction= 50%

Solar irradiation in St. John's= 3.06 $KWh/m^2 . day$

and the average system efficiency= 70%

After putting all values in equation (4.3), the required collector area, $A = \frac{1*0.5*12.52}{3.06*0.7}$

A =2.92 m^2

For sizing the DHW tank, few equations were assumed, and these are as follows,

$$\text{Height to diameter ratio,} \quad H/D = 2 \qquad (4.4)$$

Here, the selected height, H=1.60 m, so, putting this value in equation (4.4), a diameter of the DHW tank was found around 0.80 m. Now the ratio of height and diameter, H/D =1.60/0.80=2.

4.4 Sizing of collector and storage tank for space heating

System performance and efficiency of this seasonal space heating system depend on the perfect sizing of the components of the system. In our system, the main components are mainly the solar collector and storage tank. To design the solar collector size correctly, different equations were used from the literature we reviewed that can meet the space heating demand of the house in the heating period. The calculation method for getting the solar collector area is as follows,

$$Collector\ area, a1 = Q_{demand}/Q_{solar1} \tag{4.5}$$

Here, Q_{demand}=Monthly energy demand of the house from BE opt and Q_{solar1}=Monthly solar radiation of the selected area from RET Screen. The initial collector area, $a1$ was calculated by using (4.5) and considering the average collector area, the new Q_{solar2} was calculated from (4.6) and determined the excess energy from (4.7),

$$Q_{solar2} = a1 * Q_{solar1} \tag{4.6}$$

$$Q_{excess} = Q_{solar2} - Q_{demand} \tag{4.7}$$

After that, some assumptions have been taken from literature like collector efficiency η=55%, standby loss of insulated storage tank=0.05 kWh⁄hr., and circulation loss through insulated pipes=8% to get the minimum excess energy with appropriate collector area to meet the space heating demand. Using the below equation (4.8), Q_{solar3} was found.

$$Q_{solar3} = \eta * Q_{solar2} - \eta * Q_{solar2} * 0.05 - 0.08 \tag{4.8}$$

$$Collector\ area, a2 = Q_{demand}/Q_{solar3} \tag{4.9}$$

Finally, using (4.9), we found the new collector area. By following the same procedure, our desired solar collector area, a_2= 15 m^2, and minimum excess energy amount: 0.150 kWh were found. Based on the efficiency, life expectancy, and cost, the selected collector model is the

COBRALINO AK 2.2 V, manufacturer: SOLTOP Schuppisser AG, test standard: North America. It is a flat plate solar collector with conversion efficiency 85% and dimensions (length:1.897 m, width: 1.166 m, total aperture area: 1.957 m^2). It also has the angle factor of 0.95 for both longitudinal and transversal [21]. Using this parameter as mentioned earlier, the total number of solar collectors can be found by below correlation [22],

$$\text{Collector number, N}=A_R/A_S \tag{4.10}$$

Here,

$A_R =$ Total required collector area (15 m^2)

$A_S =$ Selected collector's aperture area (1.957 m^2)

Putting all in equation (4.10), the total number of collectors, N=7.66$\cong$ 8

Apart from the solar collector, the storage tank plays a vital role in all solar seasonal storage systems. It can hold the hot water at the desired temperature for more extended periods. A seasonal storage tank is the most important parameter to supply solar energy to meet the annual energy demand. It is necessary to size this component adequately to reduce the energy loss through the year and obtain the energy with the affordable tank construction and maintenance cost because the tank construction cost per cubic meter increases typically with smaller dimensions. Different researchers have taken various steps to design the storage tank like storage volume to collector area (V/A) ratio, storage volume to collector area with solar fraction, storage volume to collector area with collector area to heat demand ratio, and total collector energy output that can be stored in summer for winter use. In our research, storage volume to collector area with collector area to heat demand ratio option is taken into consideration for selecting the appropriate and perfect size of the seasonal storage tank. According to the literature review, a typical storage tank volume to solar collector area ratio 2

m^3/m^2 is found as a suitable option [23]. They also mentioned that solar fractions up to 90% could be achievable with V/A and A/heat demand ratio range. These ranges are 1.2- 4.2 m^3/m^2 and 1-2.5 m^2/MWh, respectively. An identical but slightly changed value was suggested in Ref.[24], they indicated 2-3 m^3/m^2 as V/A ratio and 1.5 -2.5 m^2/MWh as A/heat demand ratio for getting the solar fraction SF> 0.4. In Ref. [25], A/ (heat demand) $\approx$ 2.4 m^2/MWh, and V/A $\approx$ 3 m^3/m^2 was put forward for 0.7<SF<0.8. Also, some pilot project has done in Germany, following the above storage tank design criteria. A size selection review was done based on the tank volume to collector area ratio. They also took five scenarios to obtain the required dimensions of the solar collector and storage tank. These scenarios were different from each other. The result showed that the optimal volume to area ratio was 2 m^3/m^2 in order to get the 70% solar fraction. Also, there was storage tank height and funding limitations and made them choose different V/A ratio [26].

So, after taking all the considerations and design criteria, the total required collector area for domestic hot water and space heating is (2.92+15) =17.92 $m^2 \cong$ 18 m^2. The domestic hot water tank is 0.45 m^3, and the space heating tank is found 2*15=30 m^3 as we took tank volume to collector area ratio, V/A=2.

During the simulation, we gave 3 m height of the storage tank as an input, so we need to find out the diameter of the tank. From the literature, we followed several recommendations in order to obtain the best sizing options for storage tank diameter and used the sample equation to obtain the diameter of the tank. The equation is as follows,

$$\text{Volume, } V = (\pi * D^2 * H)/4 \tag{4.11}$$

Here, Height, H=3 m, and the volume, V= 30 m^3. Using equation (4.11), we got the diameter, D= 3.36. So, H/D=3/3.36 =0.89. It showed a good agreement with literature to design the cylindrical storage tank diameter.

4.5 Heat source of the proposed system

The heat source is one of the crucial components that help to maintain the thermal balance of the full solar seasonal storage system. It is mandatory to keep the temperature of the storage tank constant for the heating periods. So, a good relationship between heat source output temperature and the required heating temperature of the house decides the maximum efficiency of the solar system. In our proposed system, a fixed temperature-based boiler is used as the prime heat source. It is a mechanical device that can produce hot water or steam by burning conventional fuels. This hot water or vaporized fluid can be used in different processes such as water heating, central heating, boiler-based electricity generation, and so on. In our work, a propane gas-based boiler is considered. Also, we took some other parameters for the smooth operation of this system. These are the power of the boiler: 4 KW, Boiler outlet temperature: 30 ℃, Mass flow at charge DHW storage: 0.200 Kg/s, Mass flow at charge heating storage: 0.150 Kg/s and mass fraction to DHW storage 30%. However, our recommendation is to use an electric boiler in this selected area due to the availability.

4.6 Control of the proposed system

Control of this type of solar system is very significant to obtain the highest energy output with minimum loss from the system's components. Without controlling the system, it is impossible to obtain the maximum energy output that is the main requirement of this type of combined system. In this proposed system, a controlling process is used to control the energy supply of different energy source to the collector, DHW storage, and heat storage.

4.6.1 Collector

The required temperature difference between the collector and the hot water storage tank was 7 ℃ for the beginning of the solar energy supply. Also, 4 ℃ temperature difference was selected between the collector and heat storage tank sensor for exchanging the maximum solar heat energy at the beginning of the solar energy supply. So, the associated sensors for both are located at the collector output section with the maximum collector temperature 100 ℃ is required to run the pump to avoid the stagnation in the collector.

4.6.2 DHW storage

In terms of DHW storage, the maximum allowable storage temperature by supplying solar energy is 60 ℃ with hysteresis for maximum storage temperature 1 ℃. If this temperature is exceeded while running the collector pump, the pump will be turned off. Also, the maximum allowable storage temperature by supplying a heat source boiler and electric energy are 55 ℃ and 54 ℃ respectively, with the hysteresis for maximum storage temperature of 10 ℃ and 4 ℃.

4.6.3 Heat storage

For controlling the heat storage tank, we considered the maximum allowable storage temperature by supplying solar energy is 60 ℃ at sensor 1 with hysteresis for maximum storage temperature 1 ℃ and the sensor two is placed at the top portion of the tank with the controlling temperature 60 ℃. Also, the temperature difference for the loading of domestic hot water is 4 ℃. On the other hand, the maximum allowable storage temperature by supplying a heat source boiler and electric energy are 45 ℃ and 50 ℃ respectively, with the equal hysteresis for maximum storage temperature of 5 ℃.

4.7 Piping network of the proposed system

The necessity of the piping is significance in any solar system to avoid excessive energy loss through the system. In our proposed system, two circulating loops are considered. One is a collector or heat transfer fluid loop, and another one is the energy supply side loop. Both loops are featured with the same specification’s PEX pipe based on the North America standard [27]. The pipe materials and specifications are presented in table 2.

Table 4.2: Pipe materials and specifications of the system

Pipe features	Value	unit
Length	20	m
Diameter	0.0175	m
Wall thickness	0.0018	m
Insulation thickness	0.020	m
Conductivity insulation	0.040	$W/(m.K)$
Density pipe material	940	Kg/m^3
Thermal capacity of pipe material	1900	$J/Kg.K$

4.8 Simulation results and analysis

After sizing and selecting all components of the proposed system, the full system was simulated for one year using freeware SHW- Thermal solar system simulation software, from Austria. Version 1.02 of this simulation software was used to identify various components output as well as the system's overall performance along with various conditions [28]. In addition, to obtain a more accurate and appropriate result, a lot of suitable and convenient parameters of individual components were given as input in this simulation software. The energy requirement for heating and useful energy taken from heating storage are demonstrated by the figure (4.2). It is indicating that the overall energy production is comparatively higher than the energy demand for this proposed space heating system. The total amount of energy demand, 7887 kWh, was achieved using BEopt (Building Energy Optimization tool) [29], and the energy production from the simulation for space heating was found 8002 kWh with around 100 % heating covered under this proposed heating system. Among this amount of energy production, the percentage of solar coverage for heating was around 32, and the value was 4381 kWh.

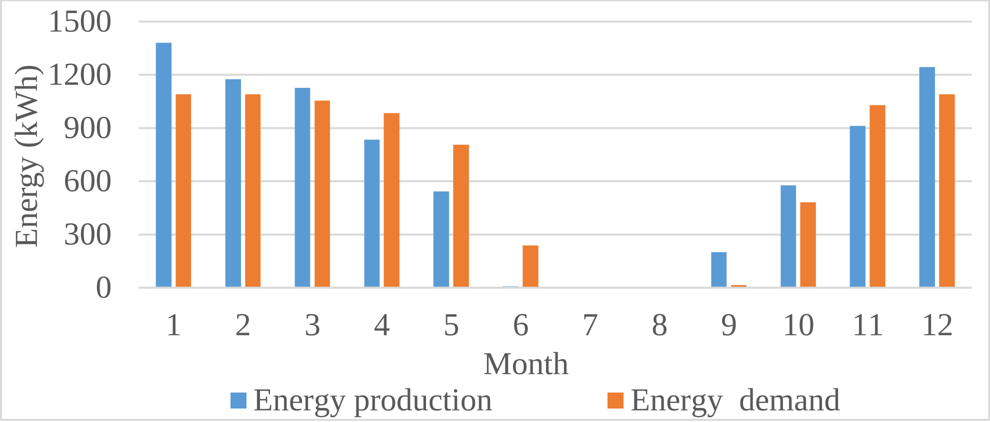

Figure 4.2: Heating energy demand and energy production for the proposed system

Space heating storage max. temperatures are shown in figure (4.3). The result showed that the maximum storage temperature in the upper edge of the tank was obtained 60°C. It happened because the collector attains the highest daily solar irradiation in the summer, and the house has the lowest heating energy requirement. On the other hand, the lowest value was found around 45°C in the heating periods and became constant throughout the coldest month.

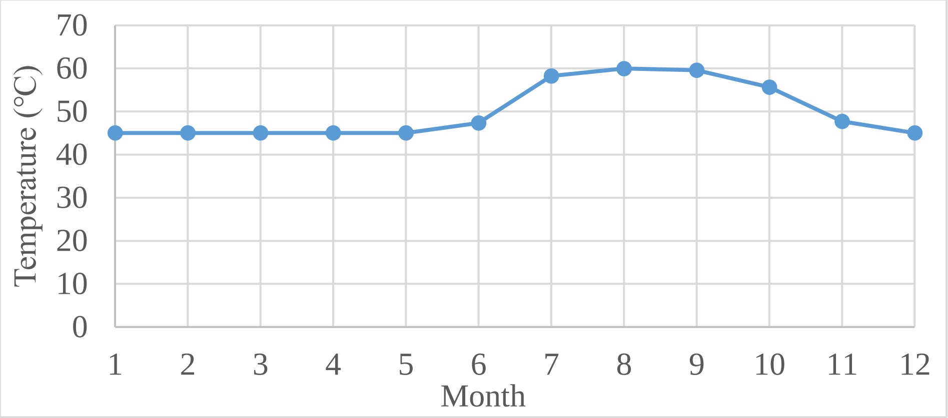

Figure 4.3: Space heating storage max. temperature

Figure (4.4) offerings the energy requirement for domestic hot water and the useful energy removed from the hot water tank. The results showed that the energy demand and energy production of domestic hot water followed the same profile. The hot water demand was comparatively higher in winter than in the summer. The total amount of energy demand and energy production for domestic hot water preparation was 4689 kWh and 4776 kWh, respectively. The proposed system covered 100% of the hot water demand of this house. Among this amount of energy coverage, 60 % of energy was supplied by the solar, and the electric heater throughout the year covered the remaining 40%.

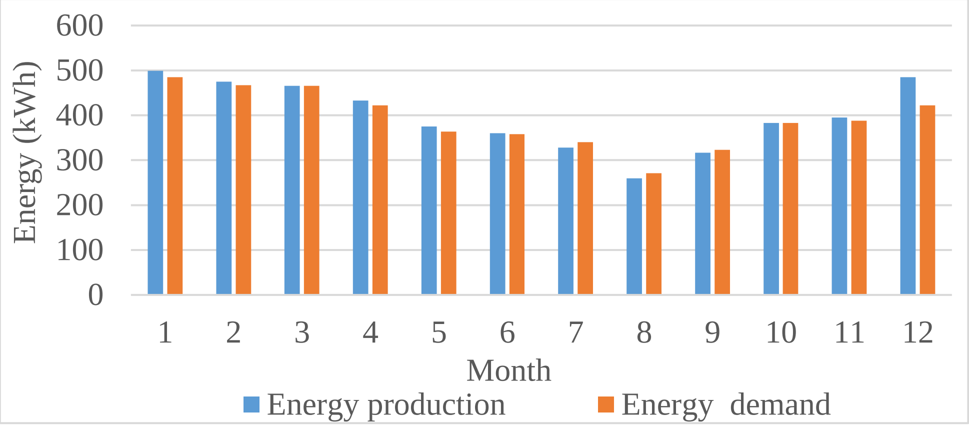

Figure 4.4: DHW energy demand and energy production for the proposed system

Figure (4.5) determines the upper edge temperature of the DHW storage tank. From the results, it is showing that the temperature of summer months was above 60 °C, but in extreme colder months, the temperature decreased at 55 °C. As the target temperature was set at 50 °C so after subtracting the pipe losses from tank to faucet, this system can able to meet the DHW demand all over the year. Also, it provides additional heat energy to heating storage to keep its temperature constant and to avoid the minimum losses.

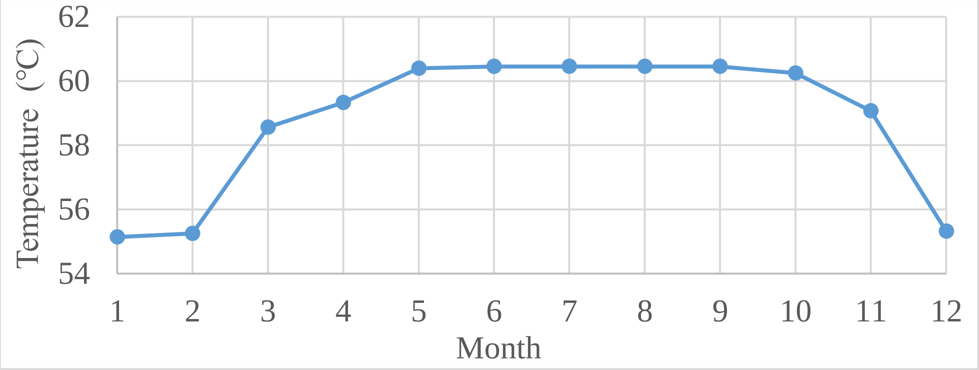

Figure 4.5: DHW storage maximum temperature of the proposed system

Figure (4.6) demonstrates the supplied solar energy for domestic hot water and space heating purposes. From the graph, it is evident that the amount of solar supply was higher in summer periods compare to winter months because solar collector extracts most of the solar energy in summer. The peak value was found 962 kWh in July. However, the total amount of solar supply energy for both space heating and DHW was 7645 kWh.

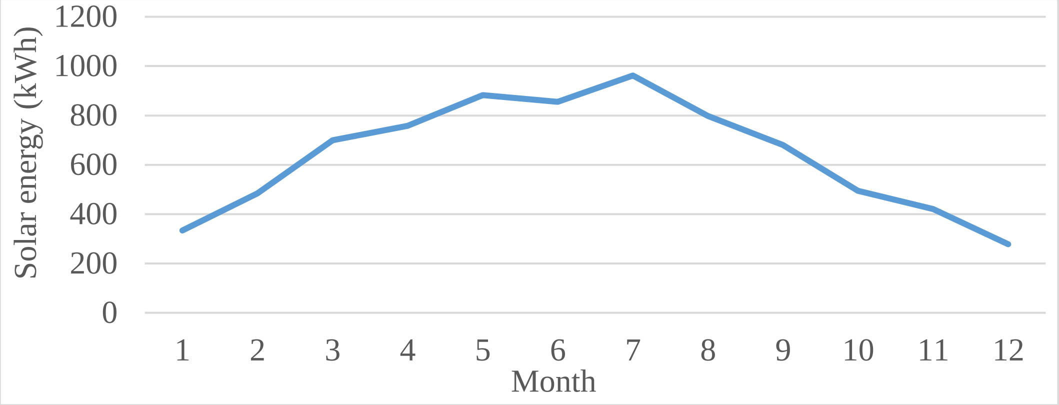

Figure 4.6: Supplied solar energy for space heating and DHW

The electrical and boiler supply energy for the full system was described by the figure (4.7). In our anticipated system, the electrical energy source, electric heater, was used directly for supplying energy to the DHW tank, not for the heating storage tank. On the other hand, the boiler was used to provide additional energy into the system to make the overall energy balance with satisfactory system efficiency. This figure concluded that the supplied electrical energy for DHW preparation was higher in colder months than summer and for space heating, the supplied auxiliary energy was followed the same pattern, but in summer, the boiler was turned off because there was no space heating demand in summer. Nevertheless, the overall supplied electric energy and boiler energy was 1905 kWh and 5504 kWh, respectively. The supplied auxiliary energy was high because of seasonal energy storage.

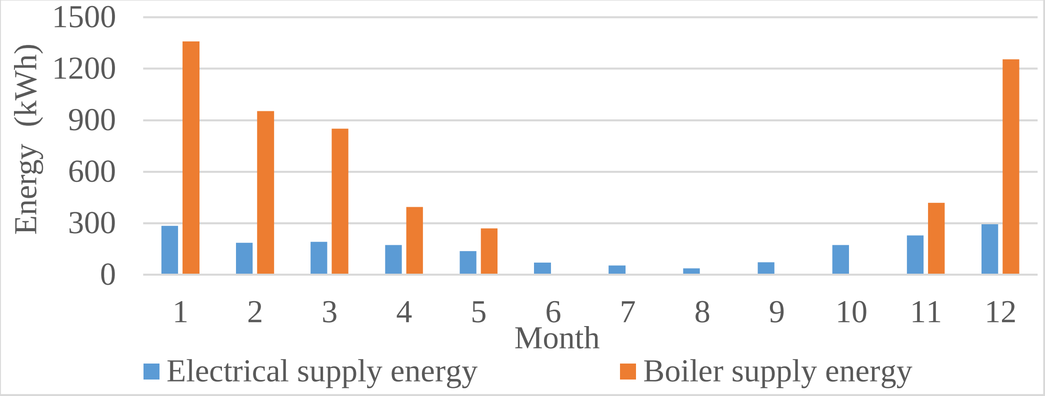

Figure 4.7: Supplied electrical and boiler energy for the proposed system

Figure (4.8) shows the supplied thermal energy from the solar collector and the energy that goes to the storage tank for space heating and DHW. The amount of solar energy from the collector was higher than the solar energy to storage. Here, the total amount of 8331 kWh useful energy from the collector was extracted by the heat transfer fluid, and on the contrary, the total amount of supplied solar energy for the hot water and space heating was 7645 kWh. Due to the system design, different losses, and simulation error, both the values were not desirable as it was expected.

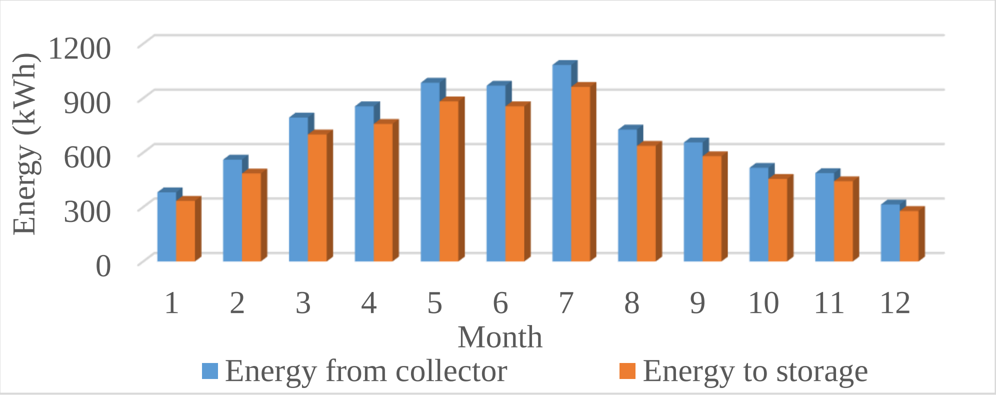

Figure 4.8: Profile of supplied solar energy from the collector and to the storage tank

Figure (4.9) reveals the collector efficiency through the entire system's operation time. It is concluded that the average collector efficiency was about 51 %. It is also noticeable that the collector efficiency was higher in winter months than in summer months, and that made a good agreement with the literature of this type of system. This collector efficiency can be increased if the circulation, collector, and storage tank losses are reduced significantly.

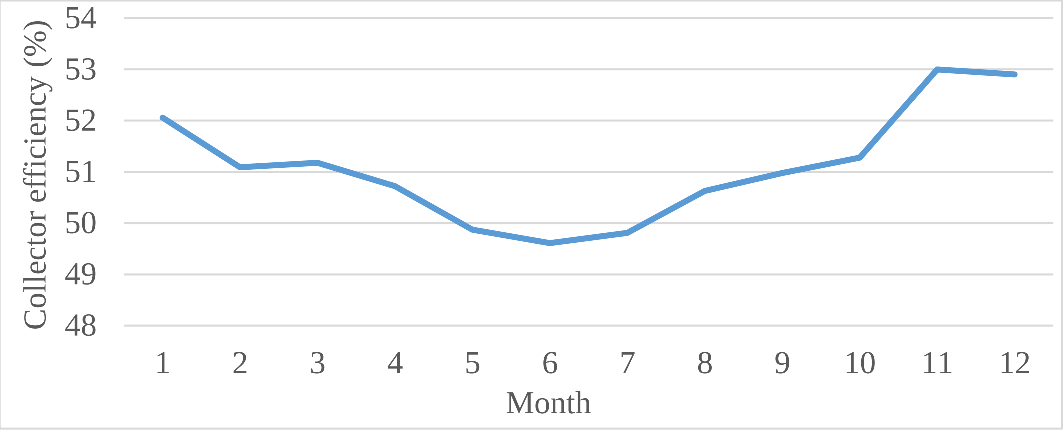

Figure 4.9: Collector efficiency of the proposed system

4.9 Conclusion

In this study, solar space and domestic hot water-based heating system was designed and simulated with freeware SHW software in order to meet the annual space heating and DHW demand with seasonal energy storage of a single-family house. The selected system consists of 18 m^2 thermal collectors, 31 m^3 proper insulated storage tank including 0.45 m^3 DHW tank, 4 KW boiler, and so on. The height and diameter for a heat storage tank were 3 m and 3.36 m, respectively, with 1.60 m height and 0.80 m diameter for the DHW tank. The outputs from the simulation result showed that the designed system was able to meet the hot water and space heating demand completely for the selected house. As the energy losses of this type of system have a significant effect on overall efficiency, necessary and proper steps should be taken into consideration to minimize the losses in order to implement this kind of system. After that, it can be said that the proposed system will be more practical, profitable, and useful in colder countries with greater seasonal differences.

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Chapter 5

Yearly heat loss analysis of a heat recovery ventilator unit for a single-family house in St. John’s, NL, Canada

Rabbani Rasha, & Dr. M. Tariq Iqbal

Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Newfoundland, Canada

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Dr. M. Tariq Iqbal provided the technical guidance with support, checked the results, reviewed the manuscript, modified the final version of this work and provided the valuable suggestions to accomplish the work.

Abstract— This paper represents an energy consumption and heat loss analysis of a heat recovery ventilator unit in a single-family detached house in St. John’s, NL, Canada. An energy-efficient house is a growing attraction to control the air infiltration, provide a comfortable environment with reduced yearly electricity cost. A mechanical induced ventilation system is inevitable to increase energy efficiency and to reduce greenhouse gas emissions of the house in order to supply fresh air. A heat recovery ventilator (HRV) is an air to air heat exchangers that recovers heat from inside of the house and delivers this preheated and fresh air to the space for maintaining the occupant’s comfort. In this paper, yearly energy consumption with the heat loss of a typical heat recovery ventilator unit is presented. MATLAB, BE opt, and Microsoft Excel are used to do all necessary simulation with calculation using one-year logged data. Methodology, results with graphs, and detailed analysis of this research are included in this paper. This research indicates that the cost of running a HRV for a year in a house in St. John’s could be as high as $484 per year with an unknown air quality improvement.

Index Terms— heat recovery ventilator, comfortable environment, energy consumption, and loss analysis.

5.1 Introduction

Energy requirements for space heating have increased, and most of the space heating source is fossil fuel-based. So, the researchers have focused on finding alternative energy sources as well as the best practice of using energy efficiently. One of the possible and successful options is to improve the existing energy systems integrated with heat recovery ventilation (HRV), also recognized as Mechanical Ventilation Heat Recovery (MVHR). A typical heat recovery unit can extract about (60 -95) % of residual heat and contribute to increasing the energy efficiency of the buildings [1]. This unit has been used not only in the residential sector but also in the industry for the last two decades, as a total of 26 % of industrial energy is still wasted as hot gas or fluid in many countries of the world [2]. In terms of industrial use, this system is usually called a waste heat recovery unit due to the massive amount of air exchange between two sources at various temperatures. The earliest study of a mechanical ventilation system with heat recovery unit of the building has been done in Denmark, and the result showed that mechanical ventilation with heat pump recovery is useful in terms of reduction in dust mite populations in mattresses and carpets [1].

Nazoroff et al. [3] studied the mechanical ventilation system with a counter-flow heat recovery unit to find out the effectiveness of this type of system, using an energy-efficient control technique. They demonstrated that this kind of system might satisfy the energy conservation goal and able to meet the indoor air quality of the house by following the strategy of building tight houses at an affordable cost. Apart from the advantages, this system has a major disadvantage because it consumes a large amount of electrical power as an input. That is why, in some cases, it mentioned that a household's electricity consumption is increased. To resolve and recover the energy loss, researchers have emphasized to build a system that can integrate with the heat recovery unit [4]. Nguyen et al. [5] have studied the overall performance of the mechanical ventilation heat pump system with heat recovery by using forced ventilation.

They used four types of different systems to recover the sensible heat during the ventilation process, and the systems are no heat recovery, separate sensible heat recovery, single heat recovery as the integration of heating ventilation, and double heat recovery with heat pump. Their result concluded that the most efficient and energy-saving system was an integrated mechanical double heat recovery system for maintaining the air quality of indoor space.

An advanced mechanical ventilation heat recovery (MVHR) unit with the help of a heat pump was developed by Riffat and Gillott [6]. Their findings showed that this type of system is less expensive, with less maintenance and air change per hour (ACH) compiled with the ASHRAE standards to provide fresh and quality indoor air. Manz et al. [7] did both the experiment and numerical simulations in order to evaluate the performance for a single-room ventilation unit with regenerative mechanical ventilation heat recovery. The result reported that it is possible to obtain the temperature efficiencies up to 78% at lower electrical energy input. Also, this unit can exchange the inside and outside air efficiently at the highest comfort level. In a cold climate country or arctic region where the seasonal difference is more, it is not easy to maintain and balance of indoor air quality by using traditional heat recovery unit because of the continuous moisture problems and the tendency of outside air drops below the freezing point.

To mitigating this issue, extensive research has been going on worldwide. Kragh et al. [8] have made an innovative mechanical ventilation heat recovery system. It is determined that this type of system can defrost itself without taking additional input energy in cold or arctic climates with high heat recovery efficiency and accomplished to defrost below the freezing point. The temperature efficiency at the freezing condition and the overall system efficiency was about 88% and 85%, respectively. Cuce and Riffat [9] conducted experimental, theoretical, simulation analysis with thermodynamic performance assessment of heat recovery systems. They also discussed the way of integrating this unit with a mechanical ventilation system and the running cost of the fans of this unit to overcome the pressure loss of it. It indicated that this unit could diminish the energy consumption for heating, cooling, and ventilation in order to make the energy-efficient house. Lu et al. [10] demonstrated a crossflow, plastic film type heat recovery unit to attain the optimal performance of it. The research ended with few conclusions like pressure drop increases with air flow rate and decreases with film thickness, film vibration enhances the heat transfer rate of this system, and the effectiveness of this type of heat exchanger varies from 0.65 to 0.85 with increasing the airflow rate.

However, maintaining the higher air quality in the house causes increasing ventilation loss. That is why researchers have been trying to develop a new design of a heat recovery ventilation system. Hviid and Svendsen [11] have constructed a state-of-the-art passive ventilation system with heat recovery unit and cooling for temperature changes. The result presented that the pressure drops, and heat transfer efficiency were about 0.37 Pa and 75.6%, respectively, for the respective air flow rate 560 l/s . Persily et al. [12] discussed an air to air heat exchanger to acquire the recovery efficiency of a typical house equipped with a heat recovery ventilator unit. The recovery efficiency relied on the fan speed of an HRV, and it mentioned around (50-60) % of heat recovery efficiency without taking the losses in fan power as well as the heat conduction through the metal case of the heat exchanger. It is likely to save energy to reduce the mismatch between energy and demand as well as to put less pressure on using conventional energy. The research revealed that it is possible to save energy from the HVAC system using the heat recovery unit. Ke and Yanming [13] focused a study on estimating the applicability of heat recovery ventilator employing various sites in China. This study exposed that a double heat-exchanger instead of a single heat exchanger ventilation system should be able to adapt the requirement of energy recovering through the ventilation system in the climate as mentioned above zones.

Cost and payback analysis of this type of system is important for making this system more affordable and familiar to people. The overall cost of this heat recovery system completely relies on the technology that they have. The payback period varies typically from a couple of years to 15 years, and their lifespan is mostly higher than 30 years [1]. Among the numerous heat recovery technologies, mechanical ventilation with heat recovery is more efficient in terms of cost and the amount of recovered energy. Tommerup and Svendsen [14] mentioned that mechanical ventilation with heat recovery can be installed for approximately 30 $Euro/m^2$ however, from the literature search, it was found that the operational cost of air to air heat recovery system is quite high due to the running electrical cost of fans of this system.

From the literature search, it is found that the heat recovery unit with mechanical ventilation plays an essential role in order to make energy efficient with low energy consumed. This system can contribute significantly to reduce the heating demand of the house, as the waste heat or exhaust heat of occupied space is used to preheat the incoming air for enhancing thermal comfort. Most of the researchers have performed and did a cost analysis of different types of mechanical ventilation heat recovery system. In our research, we discussed the energy consumption and heat loss scheme of a heat recovery unit in a house for 12 months' period. No such study has been done for Newfoundland, Canada.

In this research, section 2 will present the HRV components and operation. section 3 will describe the methodology and experimental setup. The calculation method, simulation results with discussion will be discussed respectively, and the paper will end with a conclusion.

5.2 HRV components and operation

Heat recovery ventilation (HRV) is an energy-efficient appliance and plays a significant role in maintaining the indoor air quality of the house. It also contributes to making an energy-efficient house by incorporating the HVAC system. This system provides cost-effective and environmentally friendly energy to mitigate energy consumption and the operating cost of the building [15]. This type of system consists of fans, filters, airtight insulated casing, heat exchanger or core, drain, sensors with controllers, and inlets and exhaust passage. The air streams can flow in cross flow or counter flow directions. In our research, a crossflow type HRV was used that is showed by the figure (5.1). The working principle of this system is simple as stale air from indoor passes through the core and exchange the heat with fresh air that comes from outside. After taking the heat, the incoming air gets heated, and then this preheated fresh air directly goes to the indoor space to provide the excellent quality air in order to continue the highest level of thermal comfort for the occupants. Finally, the exhaust air goes outside by releasing its heat. Thus, a heat recovery unit works efficiently to exchange the indoor and outdoor air. When heat is transferred from the exhaust to the outdoor air stream during the heating season, condensation can form inside the heat exchange core. For this reason, drain pans are located inside the HRV to collect any water buildup, and the HRV is connected to a sanitary drain [16].

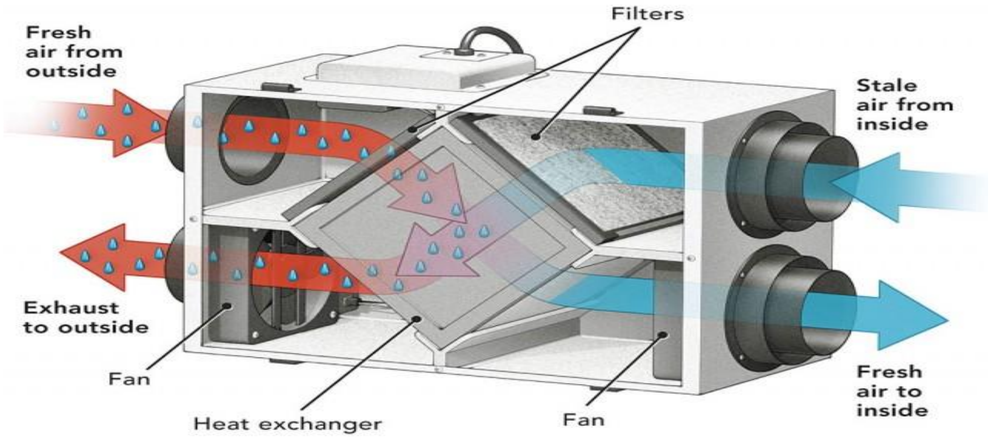

Figure 5.1: A typical heat recovery unit [17]

5.3 Experimental setup with the methodology

Our selected house was in St. John’s, NL, Canada, with latitude (47.56 °N) and longitude (52.71 °W). A heat recovery ventilator (HRV) was installed there. The model of the HRV was VENMAR AVS CONSTRUCTO 1.5 with dimensions (height: 419 mm, width: 768 mm, depth: 438mm). The main objective of it is to provide comfortable, healthy fresh air for the building’s occupants. However, the problem is heat loss from it. So, we built an experimental set up that is showed by the figure (5.2), with the help of HRV, data logger, computer, and so on to find out the amount of yearly heat loss through HRV. The working principle of this set up is modest like, during the winter, the inlet air fan takes the outside air, and at the same time, the exhaust air from room exchange heat with this incoming air to make preheated and fresh air for the room. After that, this incoming air goes directly to the room, and the exhaust air directly goes into the environment by releasing the heat. The temperature sensor LM 35 sense both the temperature of the incoming air and exhaust air. The temperature data are amplified with the amplifier that has gain 13.42. Then the amplified data are logged by the national instrument data logger (Model: USB 1208LS). Finally, these logged data were displayed in the Laptop, running with MATLAB code. The block diagram of this operation procedure is shown in figure (5.3).

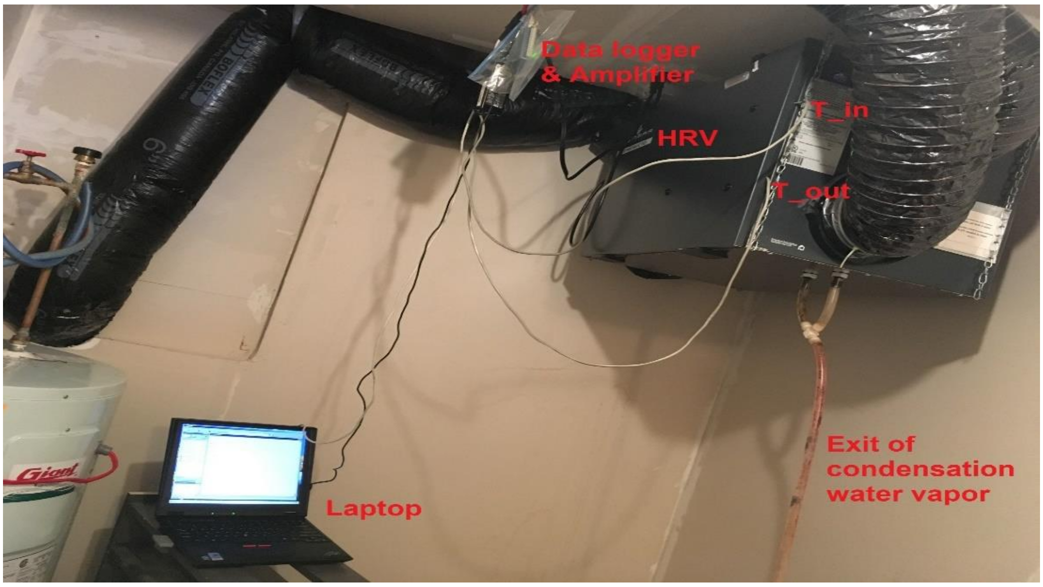

Figure 5.2: Experiment set up of HRV

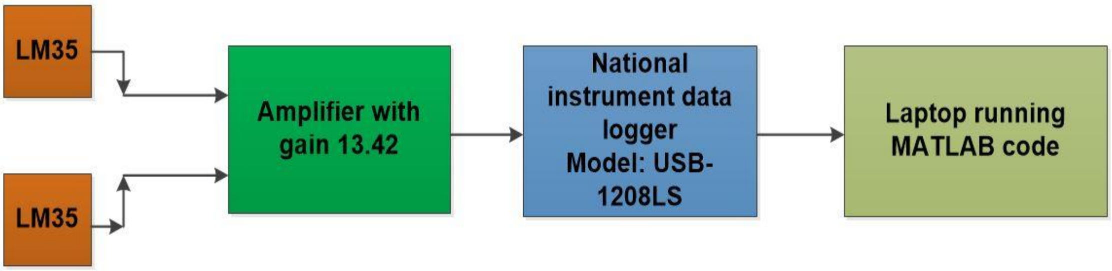

Figure 5.3: Block diagram of the experiment procedure

5.4 Calculation method

To calculate the heat loss through a heat recovery ventilator, we logged the monthly inlet and outlet temperature difference data by using MATLAB. We set up the data logger like a way that can log data per minute. So, it can log about 525600 data in one year. The diameter of the inlet and outlet air duct connected to HRV is 0.1524 meter. We also measured the air velocity through the duct using an anemometer and got around 2.75 m/s .These parameters were used to calculate the flow rate through the duct. We used several equations to get heat loss, as well as the flow rate. These equations are as follows,

$$\text{Heat loss through, } HRV = Q_v * d * C_p * \Delta T \qquad (5.1)$$

Where, the flow rate of air, Q_v=$A * V$= $3.1416 * (0.0762)^2 * 2.75$

= $0.0501\ m^3/s$

Density of air, d= $1.293\ Kg/m^3$

Specific heat of air, $C_p = 1005\ J/Kg.K$

ΔT =Temperature difference of inlet and exhaust air of HRV

After putting all the values in equation (5.1), we calculated the heat loss of the heat recovery ventilator per minute. We took 44640 data for January, March, May, October, and December. Also, we took 43200 data for April, September, November, and 40320 for February. It is evident that we turned off the HRV for June, July, and August, so for these three months, the heat loss through HRV is equivalent to zero. All the necessary graphs are shown in the result and discussion section. Here, the heat recovery ventilator also consumes electricity over the year to run its motor. The electricity consumption of the HRV is calculated using equation (5.2),

$$\text{Electrical energy consumption} = \text{Power} * 24 * 273 \tag{5.2}$$

Here, the power of the HRV is measured using the Kill a Watt device. Kill a Watt is an electrical device that can be used to measure volt, current, power, and frequency of any electrical equipment. Our measured power of the HRV is 110 Watt. After putting this value in equation (5.2), the total electricity consumption of the HRV is 720 kWh, excluding the summer months June, July, and August as in these months the windows of the house were open for natural air circulation to maintain the air quality of the house. That is why the HRV was turned off for these months. So, the total HRV losses are found by the equation (5.3),

$$\text{Total HRV losses} = \text{HRV losses} + \text{electrical energy consumption} \tag{5.3}$$

Here, we got the HRV losses 2508 kWh from equation (5.1) for the whole year and electrical energy consumption of HRV 720 kWh from equation (5.2) excluding the summer months. So, the total HRV loss (2508+720) =3228 kWh per year. That is a very significant heat loss. The cost of that will be about (3228*0.15) = $484 per year.

5.5 Experimental results and discussion

After logging the temperature difference data for one year, we calculated the energy loss as well as the power consumption of the HRV. After that, we analyzed these data through proper way and plotted using Microsoft Excel. Figure (5.4) shows the monthly heat loss of the heat recovery unit. From the result, it can be said that the heat loss was high in winter because the need of heating load is comparatively higher in winter months than the summer months. The total yearly heat loss was found 2508 kWh with the highest value of 402 kWh in December.

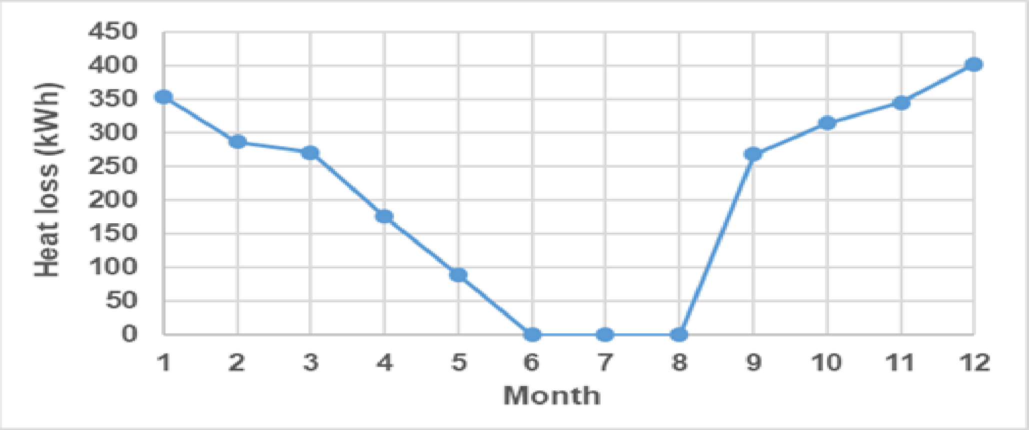

Figure 5.4: Monthly HRV energy loss

Figure (5.5) demonstrates the heat loss per minute of the HRV throughout the whole year. The heat recovery unit was turned off in the summer months. That is why the accumulated loss in summer is zero. As the temperature difference of incoming and exhaust air is high in extreme cold months, so the heat loss from HRV was high in those months. From the analysis, it is noticeable that the maximum value of heat loss was 1134 W in December when it was icy outside.

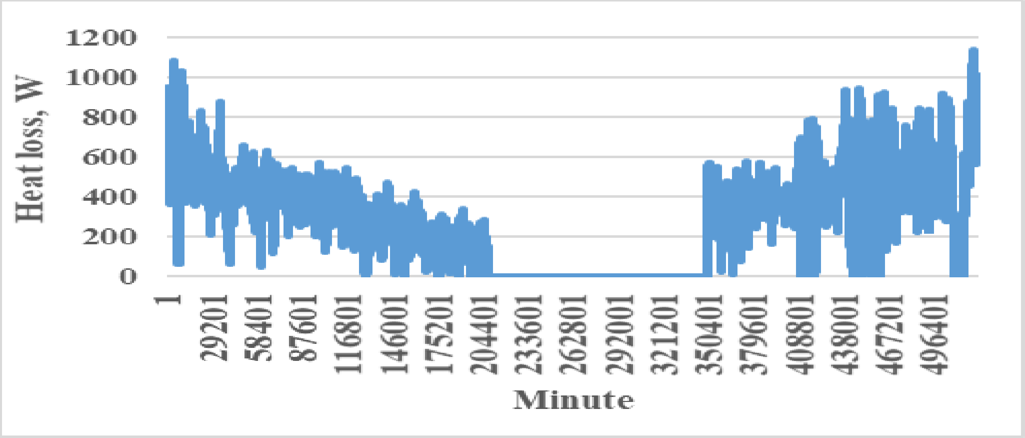

Figure 5.5. Heat loss per minute from HRV

Figure (5.6) offers the BE opt software analysis with heat recovery losses annually. Building Energy Optimization (BE opt) is a thermal modeling software that can be used to find out the different thermal loads of the selected house. For this software requirement, various house parameters with physical properties of the appliances are given as an input in this software. Among these loads, Mechanical ventilation unit (2010, HRV, 70%), specified as a fraction of ASHRAE standard 62.2, is mentioned in this software. The result showed that the total amount of energy loss from this software is 700 kWh that is converted from Btu to kWh, but from the experimental result, the value was obtained 2508 kWh. Simulation error and the wrong selection of HRV properties are responsible for these discrepancies.

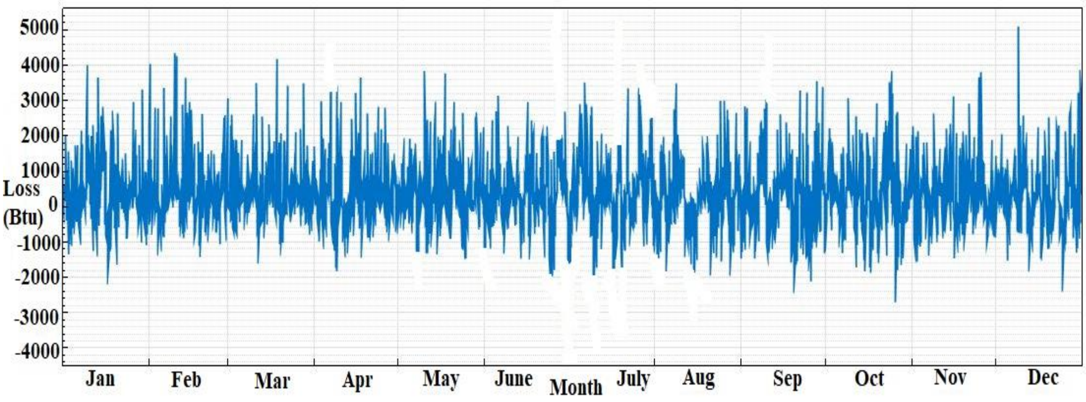

Figure 5.6: HRV loss from BE opt software

Relative humidity of the house from BE opt is shown by the figure (5.7). As the thermal comfort and indoor air quality are the matter, we kept the controller knob in the comfort zone in winter, and in the summer, the knob was placed in summer mode. The relative humidity comfort zone range was (30-60) %. In the user guide, it is mentioned that humidity level should not be selected below 30 % to avoid the excessive dryness in the air. This dryness makes the discomfort for the occupants. From figure (5.7), it is concluded that the relative humidity is reached at the highest level at 70 % in summer and maintained within the comfort zone during the winter. The result showed a good agreement with the literature.

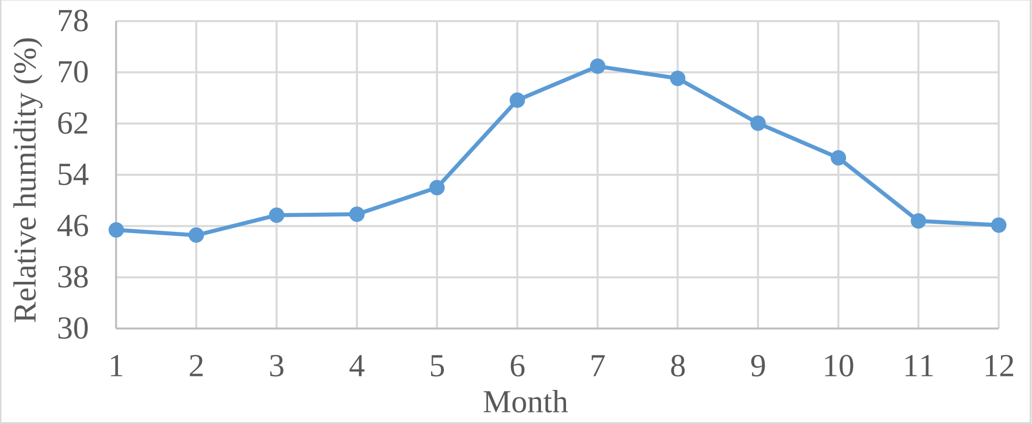

Figure 5.7: Relative humidity of the house from BE opt software

5.6 Conclusion

In this research, yearly power consumption and heat loss analysis of a heat recovery ventilator was done experimentally in a cold climate area's house. The electrical energy consumption of the HRV was calculated 720 kWh per year with a constant running fan. A simple calculation approach is used to find out the heat loss of the HRV annually. The total amount of heat loss is obtained around 2508 kWh. As the heating energy demand is high in winter months, so the HRV loss followed the same trend with the highest heat loss amount of 402 kWh in December. A heat recovery ventilator is a valuable part in order to make the house more energy-efficient, energy savings, and proper utilization of energy. Though the system has enormous advantages in various sectors, especially in domestic buildings for their potential of saving energy and mitigating greenhouse gas emissions in the environment, it has a certain amount of cost including power consumption as an input, maintenance and operation cost and the labor cost for making the condensation water vapor pan empty. In a nutshell, it can be said that a house with a heat recovery ventilator enhanced indoor air quality, but there is an associated cost that could be as high as $484 per year.

Appendix – MATLAB code

```
% MATLAB data acquisition toolbox example using    USB-    1208LS

% Analog Input CH0, CH1, single ended mode. Range is +/- 10V

% amplifier gain 13.42; supply 5V, LM35 sensor 10mV/C'

% Gain change is only possible in differential mode

daqhwinfo('mcc')

% read and review information. USB-1208LS is devic'0'

ai=analoginput('mcc',0)

% add channels say 0 to 1 (all for inputs)

addchannel (ai, [0 1])

% Save date and time as a file name

name=datestr (clock, ‘yyyymmddTHHMMSS');

filename=strcat (name, '.txt');

% datetime=fix(clock);

fid=fopen (filename, 'wt.');

% fprintf (fid,'%4.0f %4.0f %4.0f %4.0f %4.0f %4.0f\n’,           datetime);

% create file in current directory

% get 1000 samples per each channel at 1000           sample/second (default setting)

for x=1:43200

start(ai)
```

```
% wait complete configuration
x
%sampling time is 10s
pause (10)
rawdata=getdata(ai);
data0=rawdata (:1);
data1=rawdata (:2);
d0=mean(data0);
d1=mean(data1);
temp_in=d0/13.42/0.01
temp_out=d1/13.42/0.01
fprintf (fid,'%6.4f %6.4f\n', temp_in, temp_out);
end
fclose(fid);
% Cleanup workspace
delete(ai)
clear ai
```

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Chapter 6

Dynamic simulation of a solar space heating system

6.1 Introduction

The proper utilization of solar energy in terms of designing solar systems for space heating and domestic hot water preparation for residential or commercial applications depends on various factors. Among them, the dynamic simulation is essential to study the transient response of the system. Such a study helps to select, optimize, and do precise models of various components of any renewable energy system. Various simulation software can be used to do this simulation. In this research work, MATLAB/Simulink is used to do the dynamic simulation with control of a solar water heating system to get the output space heating temperature of the house, storage tank output temperature, and pressure. There are two energy sources used, one is solar energy, and another one is a conventional boiler to make the hot water that can be circulated in the house through the radiator for providing the necessary heat in the winter season. Many pieces of research have been conducted about the simulation process of the solar water heating system to find out the output results based on the input parameters of the Simulink blocks.

6.2 Literature review

The numerical and experimental approach works with the storage hot water tank's temperature distribution based on the charging and discharging mode. In some cases, researchers have focused on temperature distribution as well as the system thermal performance that means the heating effect and system coefficient of performance in terms of charging and discharging mode. The authors of reference [1] used a numerical approach to find out the solar water heating system's thermal performance using ANSYS Fluent 15.0. They also validated and compared the numerical results with experimental data and found a good agreement. The result showed that the system coefficient of performance reached 3, which was comparatively higher than the electrical heating system. They also indicated that the south-facing room has a higher average temperature of 20 ℃ than the north-facing room 17 ℃ and met the heating demand of the house. Dehghan et al. [2] conducted numerical simulation of a vertical hot water storage tank to look for the transient thermal behavior of it using a mantle type heat exchanger during discharging mode. The result concluded that it was possible to increase the thermal performance of the domestic solar water heating system by controlling and proper monitoring of the cold-water flow rate in the tank with an accurate inlet and outlet pipe size.

Erdemir et al. [3] studied about the effects of obstacles and positions based on thermal stratification within the vertical mantled hot water tank. They put four obstacles in the tank bottom at four distances. They also mention that the thermal stratification is increased after putting the obstacles inside the storage tank and compared various aspects with the ordinary tank. Hao et al. [4] [5] studied the various performance parameters of a new system called solar energy and gas heat pump system using Simulink and TRNSYS. They normally compared the result of evaporation temperature, heating capacity, and coefficient of performance using two software. The result demonstrated that when the thermal storage tank temperature and condenser inlet temperature increases by 1 ℃, the evaporating temperatures and condensing temperature increase by 0.84 ℃ and 1.46 ℃, respectively with the coefficient of performance 4.76. A dynamic approach was used to analyze the solar collector performance using MATLAB/Simulink and f-chart by Dongellini et al. [6]. Solar coverage factor of the predicted Simulink and F-chart method was compared based on the various solar collector, the volume of the storage tank connected to the solar collector, and the hourly hot water consumption profile. The result revealed that among all the mentioned parameters, the solar fraction is highly dependent on the daily hot water consumption profile. Dynamic simulation of a solar heating system was done by the researcher of reference [7]. The main objective of this MATLAB/Simulink based system was to predict the outlet temperature of a collector working fluid and the storage tank temperature. The result of this work depicts that around (50-60) ° of the inclination angle of solar collector help to achieve more and stable energy with the heat collector efficiency at 0.65. Also, it showed that the maximum outlet temperature of a collector working fluid was 35.4 ℃ and 71.1 ℃, respectively, in winter and summer, and the storage tank temperature found 55 ℃ in summer and 31 ℃ in colder months. Yao et al. [8] performed the modeling and simulation of a solar thermal central receiver system in China using the HFLD tool and TRNSYS simulation software. This simulation aimed to do the energy balance for analyzing the thermal performance of the system. They also studied the noise factor, change in operational input on the transient response of the thermodynamic variables, and the result suggested that the simulation is helpful in terms of designing the complex system.

Pernigotto and Gasparella et al. [9] studied and compared the building's heating and cooling load using two dynamic simulation software TRNSYS and EnergyPlus. They have taken several parameters in their studies like the wall insulation, heat capacity, glazing dimensions with orientation, glazing insulation and solar transmittance, internal gains, etc. The results of these two software's were very close to each other by using the inferential statistics method. Tong et al. [10] evaluated the thermal performance and exposed the energy balance of an evacuated tube solar collector. The research concluded that the collector efficiency changes quickly with lower solar radiation and ambient temperature but remains steady with increasing the solar radiation and depends on the collector inlet and outlet temperature changes. Also, they mentioned that the efficiency and outlet temperature of the collector is mostly affected by the collector tilt angle variations.

Kiyan et al. [11] designed a model to investigate the thermal effect of the hybrid solar heating system for greenhouse applications in Turkey using the MATLAB/Simulink software. The objective of this model was to see the storage tank temperature variations, the temperature inside the greenhouse, and the energy consumption of the auxiliary heating system based on the greenhouse location, dimensions, and weather data of this selected area. The result showed that the fossil fuel-based proposed hybrid system is cost-effective and reliable in many cases. This simulation approach can be used to optimize and select the solar collector and the storage tank in the solar energy field. Besides, reference [12] studied the solar fraction to optimize the solar water heating system. They considered the collector area, collector's aspect ratio, storage tank volume and height, heat transfer fluid with mass flow rate, the effectiveness of the heat exchanger, size and length of the liquid circulation pipe, and the materials of absorber plate as their optimization parameters. They found that a typical solar water heating system should have the solar fraction range (83-97) % in summer and (30-62) % in winter with overall annual solar fraction 54%.

From the literature search, it came to know that dynamic simulation with control has a good prospect in terms of analyzing a solar water heating system. Most of the dynamic simulation was done by taking the different aspects of the solar collector and storage tank for analyzing the thermal effect on charging and discharging operation mode.

In chapter 6, Section 6.1 and 6.2 will deliberate the introduction and literature search. Section 6.3 will discuss the Simulink model with methodology. MATLAB/Simulink design of the system components and simulation result will be represented by sections 6.4 and 6.5. This chapter will be ended with a conclusion.

6.3 Simulink model and methodology

Before performing the simulation, it is necessary to design the system's components using Simulink blocks and to make similarity to the primary physical system. The prime components of the system were designed and mentioned in chapters 3 and 4 with necessary equations. Also, the other parts of the system were chosen based on the design criteria and gave all the design and selected parameters as an input in the Simulink block. Figure 6.1 and 6.2 represents the block diagram and Simulink design of the full system in details. At the starting of the operation, the collector is heated by the sun and transferred the heat into the circulating working fluid (ethylene glycol). After that, the heat transfer fluid released the heat in the storage tank using the heat exchanger and return to the solar collector through the pump 1. In the house, there are four rooms, and each room is facilitated with one radiator. Pump 2 is used to carry the hot water from the storage tank to the house radiator for discharging the heat in each room through convection and helps to return the water in the storage tank to repeat the cycle. On the other hand, the sum of each indoor room's average temperature is compared with the expected temperature in the control section and sent a signal using a relay to control the mass flow rate of the fuel supply into the boiler. The expected temperature is around 24 ℃. Finally, the boiler is used to provide the additional energy in the storage tank to keep the storage tank temperature for more extended periods and meet the house's expected heating demand.

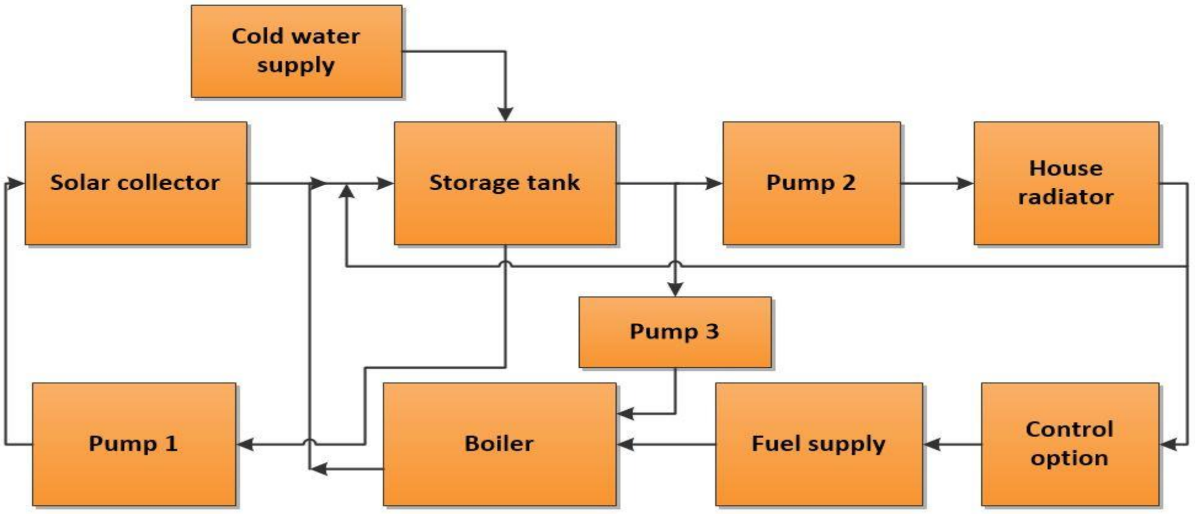

Figure 6.1: Simulink block diagram of the system

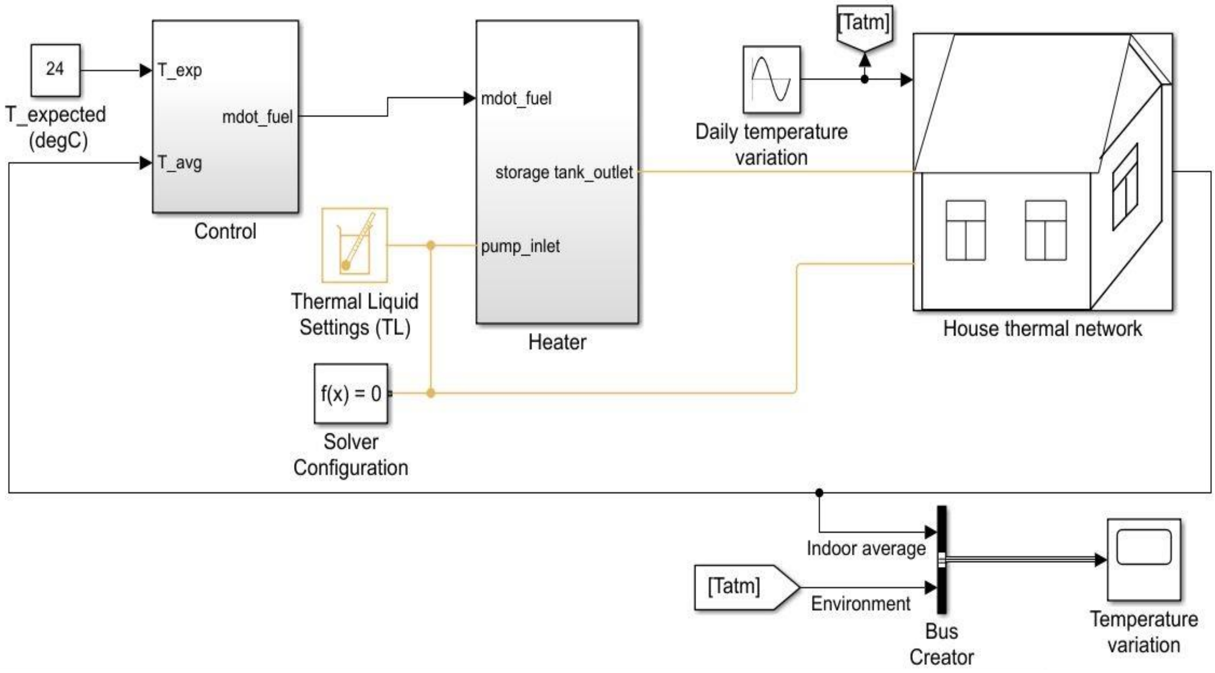

Figure 6.2: Simulink design of the full system [13]

6.4 MATLAB/Simulink design of the system components

The full system consisted of several components like the solar collector, storage tank or seasonal heat storage tank, pumps, radiator, boiler, controller, and house. All the components described with Simulink configuration are as follows. Figure (6.3) shows the solar collector Simulink model. Here, the typical one-day solar irradiance value was given as an input in the block, and the ideal heat flow source converts this solar heat into useful energy with the help of other related blocks that showed in the below solar collector model. The useful energy worked like the input of the storage tank.

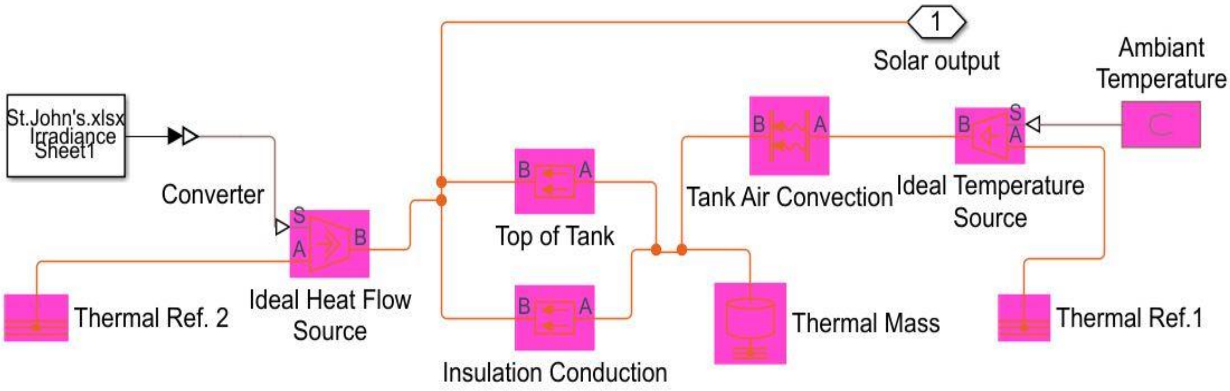

Figure 6.3: Simulink design of the solar collector [14]

The storage tank Simulink design block is shown by figure (6.4). The groundwater reservoir with a temperature of 290 K and solar output data was given as the input in the storage tank. The storage tank length and hydraulic diameters were 3 m and cross-section area 7.06 m^2. Pressure and temperature sensors were used to see the variations of storage tank output pressure and temperature.

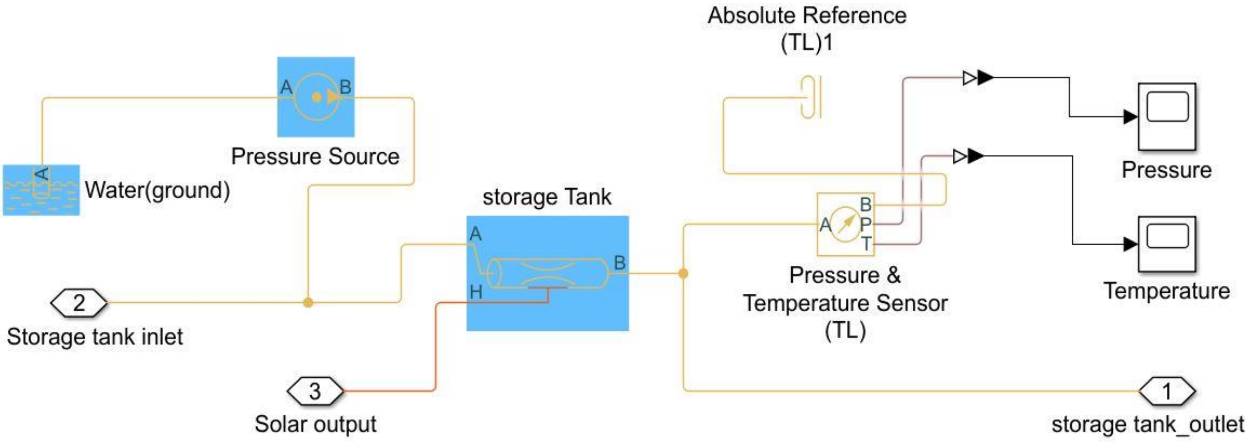

Figure 6.4: Simulink design of the storage tank [14]

Figure (6.5) shows the overall Simulink diagram of the house thermal network. The output from the storage tank is considered as the input of the house. Each radiator thermal mass was converted into heat through convective heat transfer for each room of the house. The output hot water of the rooms goes typically back to the storage tank for repeating the cycle.

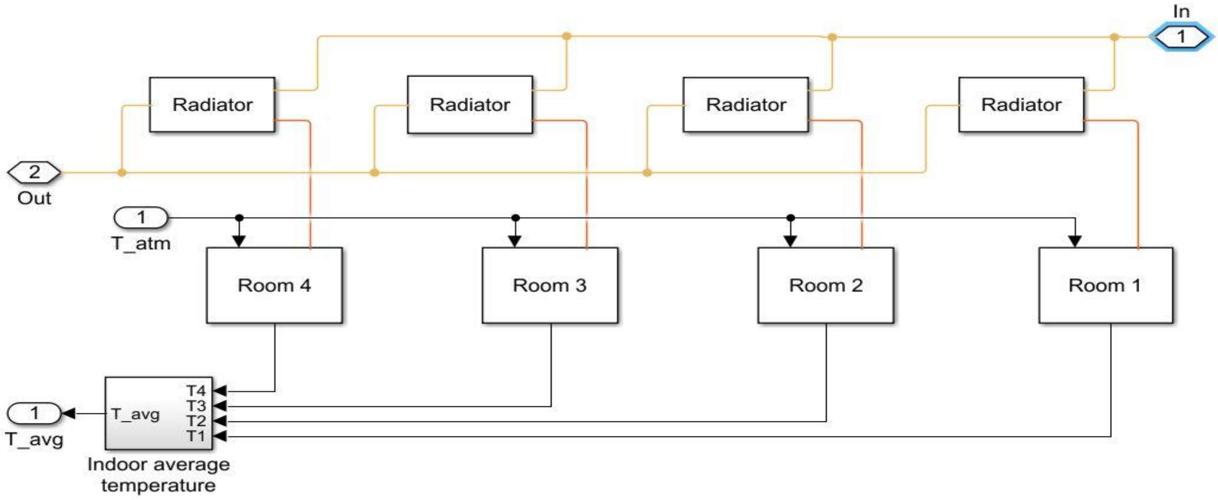

Figure 6.5: Simulink design of the house thermal network

Figure (6.6) presents the radiator Simulink model of the house. The house has a total of four rooms with four radiators. Each radiator has surface area 2.5 m^2 with the heat transfer coefficient 200 $W/m^2.K$.

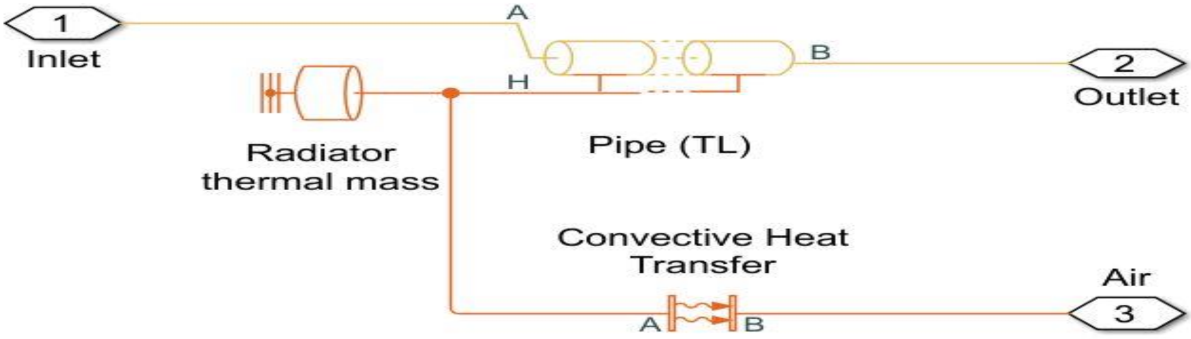

Figure 6.6: Simulink design of the radiator

Figure (6.7) shows the Simulink model of the room of the selected house. The dimensions and thermal characteristics of the house mentioned in chapter 4. Roof, wall, and window of each room was considered as the main features of the room and put all the correct values in the Simulink block in order to get the average temperature of these features. The percentage of atmospheric leakage of roof, wall, and window are 0.05, 0.10, and 0.15, respectively. Also, the density of the roof, wall, and window materials are 1900 Kg/m^3, 177 Kg/m^3, and 2500 Kg/m^3 [15].

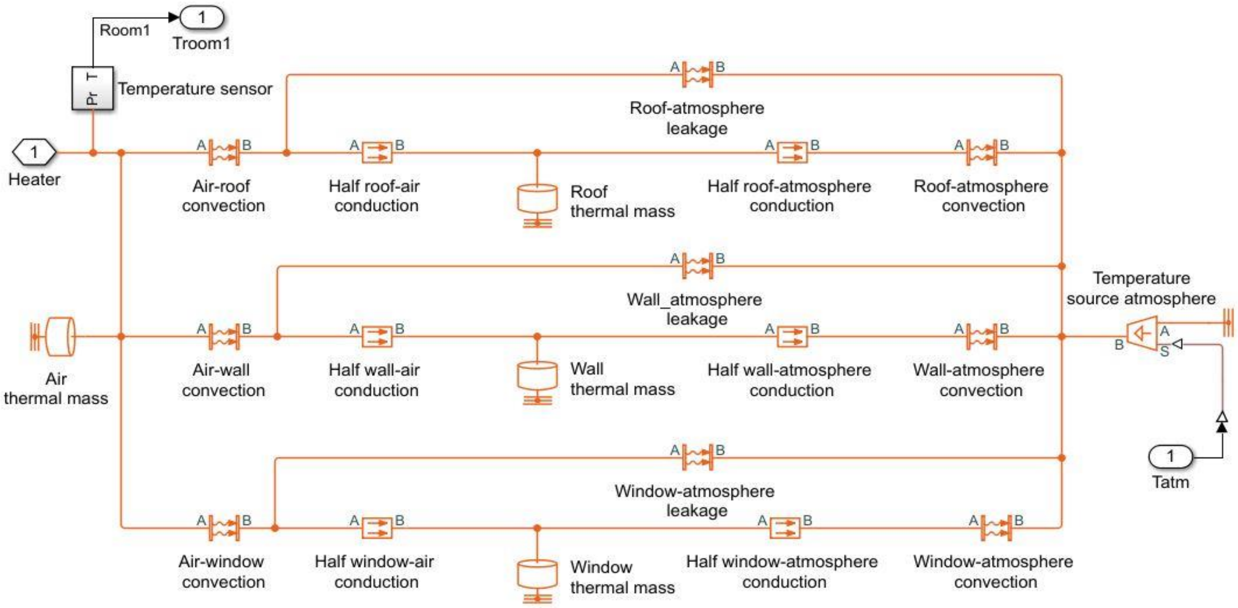

Figure 6.7: Simulink design of the room

Figure (6.8) reveals the controller of the system. In this simulation, a relay was used to work as an on/off controller. The sum of the average outdoor temperature of each room is compared with the set temperature 24 ℃, and based on the comparing result, the mass flow rate valve becomes open or closes with the help of the relay on/off controller. When the average indoor temperature was lower than the expected temperature and demand of hot water was higher, the valve was opened and ensure the exact amount of fuel supply to cover the demand and vice-versa.

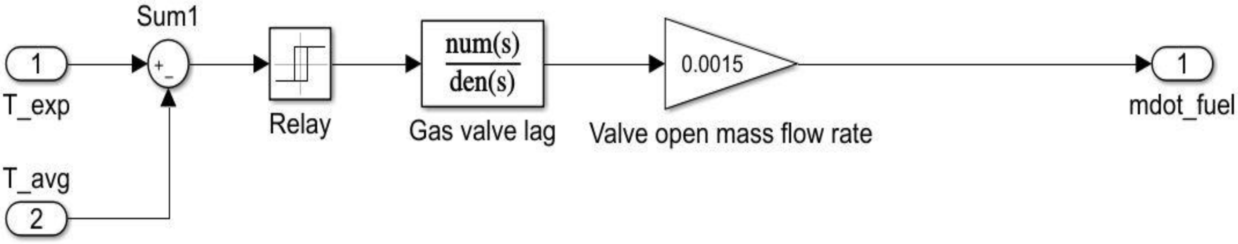

Figure 6.8: Simulink design of the controller

A gas fuel type boiler was chosen for the simulation work and shown by the figure (6.9). The mass flow rate of the fuel that was decided by the controller with proper temperature, humidity ratio of the air and air temperature were given as the input of the boiler. The task of the boiler was to provide extra energy to incorporate the system and keep the storage tank temperature in a range for seasonal use. A heat exchanger was used to transfer the heat from the boiler combustion chamber to the water before feeding into the storage tank.

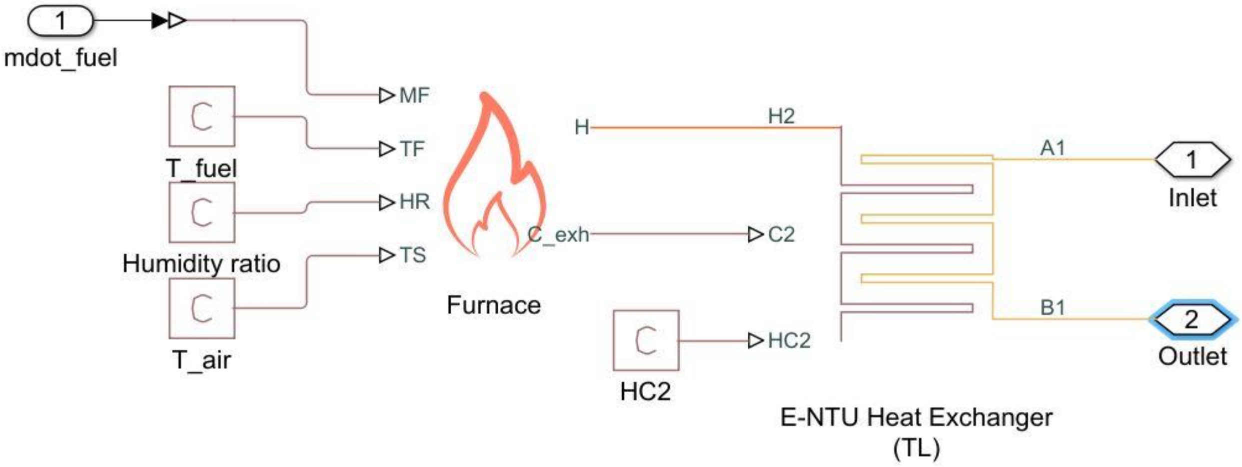

Figure 6.9: Simulink design of the Boiler

A fixed displacement type pump was used to circulate the hot water and heat transfer fluid in the system. The Simulink block diagram of the pump is shown by figure (6.10). In this work, a total of three pumps were used, and all pumps were designed using the same type of block diagram mentioned in the below figure. A constant speed pump was designed for this simulation.

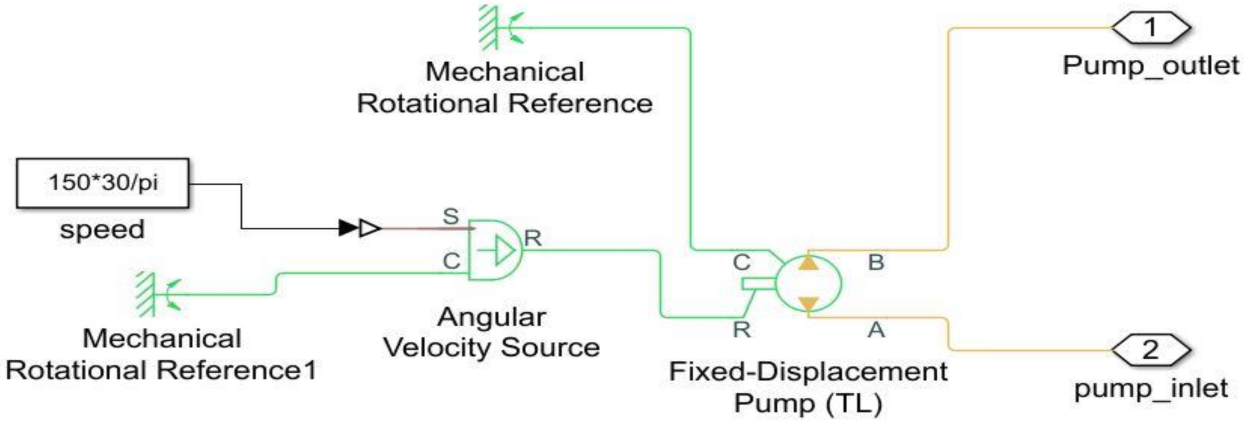

Figure 6.10: Simulink design of the pump

6.5 Simulation result

After completing the sizing of all components of the system, dynamic simulation and control were done using MATLAB/Simulink R2018b version. In the model block diagram, many input parameters have been given from system sizing and analysis. Also, some of the parameters were selected based on the design and simulation criteria of the system. Figure (6.11) shows the simulation output temperature of the storage tank. Here, the simulation step size was around 50 hours, with the initial liquid temperature 11 °C. The sum of collector and boiler output heat considered the input of the storage tank, and some storage losses occurred in the storage tank. After starting the simulation, the liquid temperature was started to rise and reach 52 °C after that the value was fluctuating in the range of 49 °C to 44 °C and showed the excellent prospect of this simulation work.

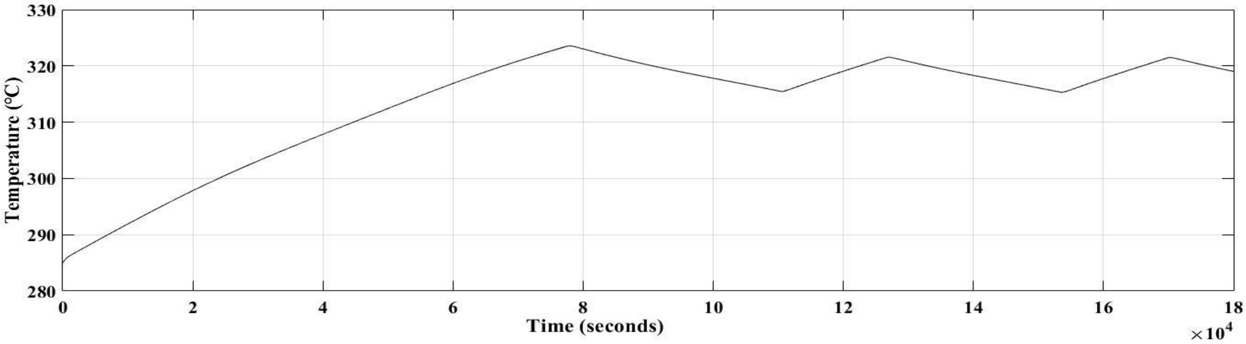

Figure 6.11: Storage tank output temperature

Figure (6.12) demonstrates the comparing result of indoor average temperature with outdoor temperature. From the result, it seems that the output graph of the indoor average temperature is an increasing function over the time of the simulation. At the beginning of the simulation, the average indoor temperature was below 15 ℃ and over the time of simulation, the indoor average temperature was reached above 25 ℃ and satisfied the temperature range in the house rooms as the expected temperature was 24 ℃ and the outdoor temperature was ranged between 0 ℃ to 10 ℃.

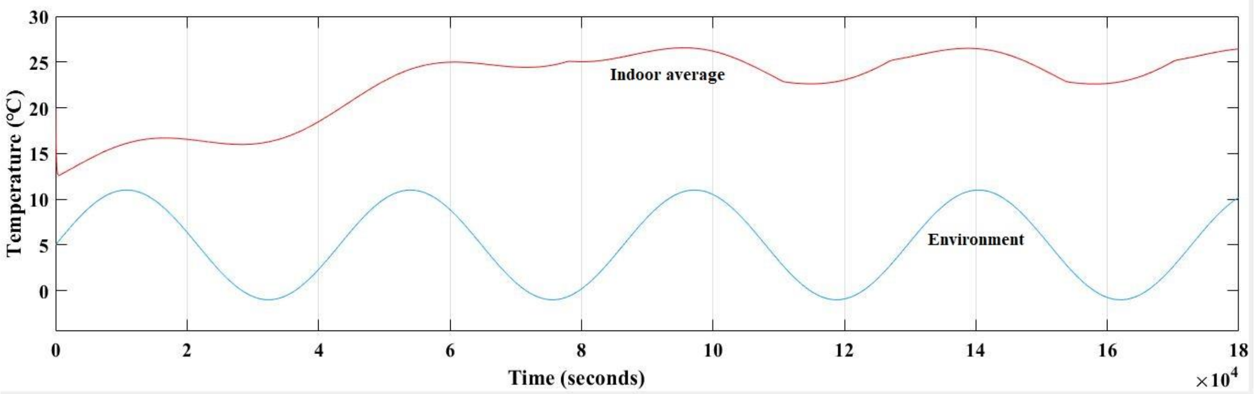

Figure 6.12: Comparing the outdoor and indoor average temperature

Figure (6.13) reveals the indoor room temperature of four rooms. Here, the indoor room temperature depends on the storage tank output temperature and the input temperature of each radiator. The highest output temperature of the storage tank found around 52 ℃ and the designed input temperature for the room's radiator was 45 ℃ that makes the right combination of putting heat in the room. From the result, it is noticeable that all rooms possess the temperature above 21 ℃ and reached the expected temperature zone between the simulation time step 64800 seconds to 180000 seconds. Before the simulation step 648000 seconds, the temperature of the rooms was close to 15 ℃ and did not show in the below graph. Room 3 achieved the highest temperature among all rooms in this research work.

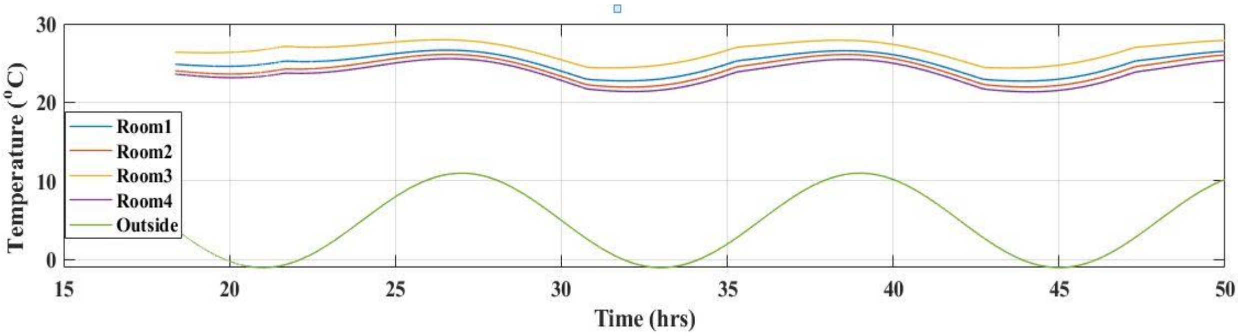

Figure 6.13: Different indoor room temperature

Figure (6.14) represents the average temperature of the room’s roof, wall, and window of the house. The results indicate that the roof having the highest temperature during the simulation period as the percentage of atmospheric leakage was lower through the roof. The temperature of the roof was always near or above 15 ℃. The most temperature fluctuation occurs in the window section because the percentage of air leakage through the window was considered 0.15. Lastly, the temperature of the wall was slightly less than the roof and reached the range between 11 ℃ to 14 ℃. A total of 10% of air leakage was considered through the wall.

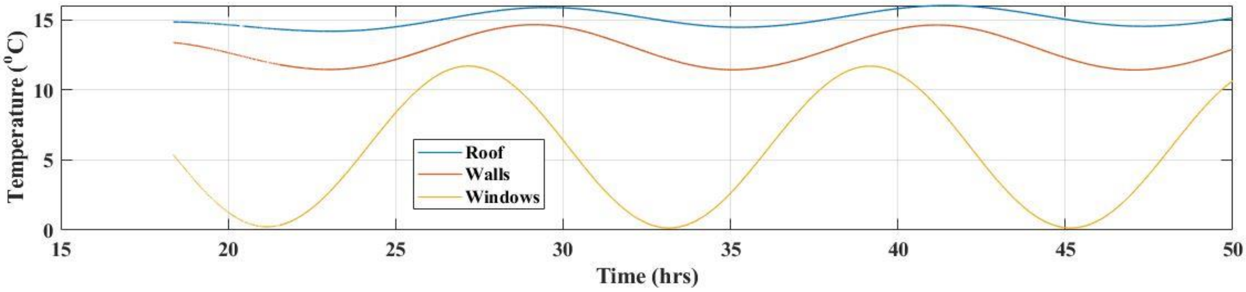

Figure 6.14: Average temperature of roof, wall, and window

6.6 Conclusion

After analyzing the simulation results, it is obvious to say that dynamic simulation of a solar water heating system for space heating is essential during the charging and discharging mode in order to get the thermal performance and temperature distribution among various components like the collector, storage tank, heat exchanger, etc. The simulation result showed that the highest output temperature of the storage tank was 52 ℃, and the lowest value was 44 ℃, which is in the range of house radiator's input temperature. Also, the indoor average temperature of the house reached above 25 ℃ that demonstrated a good agreement with the expected house temperature at 24 ℃. Moreover, the highest average temperature of the roof was 15 ℃ during the simulation period because the percentage of air leakage through the roof was considered as the lowest, and the value was 5%.

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Chapter 7

Conclusion

7.1 Summary

This chapter consists of the main contribution of this research work along with the proposed future works on the solar water heating system. The main objective of this research work was to design, model and analysis of a solar water heating system for meeting the annual space heating and domestic hot water demand for a single house in St. John's, NL, Canada. Each chapter of this thesis worked with a specific task to meet the overall thesis goal. The individual chapter's summary is as follows,

In Chapter 1, the literature review of a solar water heating system, their classification, various methods were discussed. Also, different thermal energy storage system was considered in order to get the most feasible option for designing and modeling a solar water heating system. Though many parameters depend on each other but after evaluating the first chapter, it is obvious to say that the sensible heat energy storage system is suitable and more efficient for achieving the thesis aims.

In chapter 2, the thermal modeling of a house was done to find out the annual energy demand of individual loads as well as the thermal properties of the house materials with various characteristics. These aspects tend to design the most energy-efficient and energy-saving houses. This chapter concluded that the annual energy consumption of the house was about 19511 kWh with space heating, and domestic hot water consumption was 7887 kWh and 4689 $kWh,$ respectively.

In chapter 3, a solar water heating system was introduced and analyzed for space heating purposes in Newfoundland with seasonal energy storage. The output results depend on the actual sizing of the system components as well as the inputs. The result of this proposed system includes 16 m^2 flat plate collector area, 47 m^3 proper insulated storage tank with a height and diameter of 3.91 m and a 5-kW heat pump. This proposed system is more practical and efficient in colder countries where the seasonal differences more.

In chapter 4, a solar-assisted water heating system was designed and evaluated for space heating and domestic hot water purposes in Newfoundland with seasonal energy storage. The proposed system consists of 18 m^2 thermal collectors, 31 m^3 proper insulated storage tank, including a 0.45 m^3 DHW tank. The height and diameter for a heat storage tank were 3 m and 3.36 m, respectively, with 1.60 m height and 0.80 m diameter for the DHW tank. A 4-kW boiler is used to boost up the system, providing the extra energy in heating periods.

In chapter 5, an experimental investigation was done to find out the power consumption and energy losses throughout the year of a heat recovery ventilator. The 12 months of logged data were used to analyze the results. From the results, it showed that a HRV consumed energy around 720 kWh per year. The total amount of heat loss over the year was 2508 kWh with the highest heat loss amount of 402 kWh in December. Though a heat recovery ventilator system enhanced indoor air quality, there is an associated cost that could be as high as $484 per year in Newfoundland.

In chapter 6, a dynamic simulation of a solar space heating system was done to know the thermal performance and temperature distribution of various components of the space heating system during charging and discharging mode. The result showed that the highest and lowest output temperature of the storage tank was 52 ℃ and 44 ℃, which works perfectly as radiator's inlet. Besides, the indoor average temperature was around 25 ℃ as the expected temperature was 24 ℃.

After analyzing all chapters of this thesis, it is noteworthy to say that an active, closed-loop water heating system for supplying space heating and domestic hot water is suitable for St. John's, Newfoundland, Canada.

7.2 Future work

- ✓ In this thesis, a solar water heating system was designed with seasonal thermal storage, so a hybrid system can be considered to meet the space heating and domestic hot water demand entirely without using a boiler or heat pump.
- ✓ A study could be done about design of such system with a heat pump and check its effectiveness.
- ✓ Cost analysis is an essential factor in designing and analyze this kind of system. So, extensive cost analysis of the full system can be done to know the exact initial, running, and maintenance expenditure.
- ✓ In this thesis, a dynamic simulation of space heating system was done, so a full system including space heating and domestic hot water can be simulated for a few hours. A simulation method or software needs to be identified that can simulate performance of such a system for a year.
- ✓ An alternative technique with proper insulation can be used to reduce the energy losses of the standby storage tank and other system components.
- ✓ No control system was proposed in this study. Design of a proper control system is essential that should be considered for further work.
- ✓ Newfoundland gets a lot of snow. A study is required to determine impact of snow on solar collectors and a method needs to be determined for snow removal from the collector.
- ✓ Installation issue of the proposed system and proper drawings could be done in further work.

Publications list

Journal papers

[1] Rabbani Rasha and M. Tariq Iqbal, Design and analysis of a solar water heating system with thermal storage for residential applications, accepted and published with Journal of sustainable Energy, (ISSN: 2067-5534 & Vol. 10-Nr. 2), 2019.

[2] Rabbani Rasha, M. Tariq Iqbal, Yearly Heat Loss Analysis of a Heat Recovery Ventilator Unit for a Single-Family House in St. John’s, NL, Canada, European Journal of Electrical Engineering & Computer Science (EJECE) Vol 3 No 5. 2019.

Conference papers

[1] 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.

[2] Md. Habibur Rahaman, Rabbani Rasha, M. Tariq Iqbal, Design and Analysis of a Solar Water Heating System for a Detached House in Newfoundland, presented at CCECE 2019.

Non-refereed local IEEE conference papers

[1] Rabbani Rasha, Debobrata Gupta and Mohammad Tariq Iqbal, Design and modeling of a solar water heating system for a house in Bangladesh, presented at 27th IEEE NECEC St. John's, Nov.13, 2018.

[2] Debobrata Gupta, Rabbani Rasha and Mohammad Tariq Iqbal, Energy Analysis and PV System Design for a House in Bangladesh, presented at 27th IEEE NECEC St. John's, Nov.13, 2018.

[3] Rabbani Rasha and Mohammad Tariq Iqbal, Experimental investigation of yearly energy loss through a heat recovery ventilator unit in Newfoundland, presented at 28th IEEE NECEC St. John's, Nov.19, 2019.

Poster presentation

[1] Rabbani Rasha and M. Tariq Iqbal, Sizing, modeling and analysis of a solar seasonal energy storage for space heating in Newfoundland, Presented in poster session at Ryerson University, Toronto, ON, during NESTNet 3rd annual technical conference, June 17-19, 2019.