Modeling and simulation of solar water heating system with Thermal storage

by

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Abstract

With the increase in electricity prices and environmental concerns, new technologies are being developed to extract energy from every available source and store the excess energy generated for later usage. One such solution is provided by Thermal Energy Storage Systems. Solar radiation in summer can be stored inter-seasonally to provide heating in winter, while the cold from winter air can be used to run air conditioning in summer. This thesis studies in detail the solar thermal energy storage system used for domestic water heating purposes in a typical detached home in St. John's, Newfoundland, Canada. It introduces the topic, discusses the background and development of the systems, and presents the basic concept of what a solar thermal energy storage system is and how it works. As well, it focuses on the availability of solar radiation, which is important for analyzing how effective the system can be, considering that the amount of solar radiation is not constant throughout the earth. In-depth information on how thermal energy storage system functions and operates, along with an extensive review of the literature, is also featured. Studies including experimental and simulation models are reviewed, which helps to compare earlier approaches to the present handling of the problem. Additionally, to establish the findings of the thesis, a simulation model of solar thermal energy storage for domestic water usage is created with the help of SAM software. Various parameters of MATLAB software are taken into consideration as well to establish the desired design of the system. These design parameters are extensively explained, together with a discussion on the assumptions and design technologies

considered for creating the model for the MATLAB and BEopt simulations. Overall, this thesis demonstrates a method of designing a solar water heating system with thermal storage that can provide hot water for a small house. SAM and HOMER, which are design models that calculate the consumption of hot water and cost for a system, are extensively utilized in the study.

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Symbol	Name	Unit
Ac	Area of collector.	m^2
A	The area of the tank storage.	m^2
C_p	Specific heat of water.	$J/Kg.k$
D	Diameter of tank.	mm
F_R	The collector's heat removal factor.	
DF	The friction of the pipe.	
G	Gravity 9.81.	m/s^2
G_T	The incident radiation.	
h_i	Heat transfer coefficient.	$w/m^2.k$
h_o	The outside convection code.	$w/m^2.k$
H	Differential head of pump.	m
K	The thermal conductivity.	$W/m.k$
K_{st1}(stainless − AISI302)	The thermal conductivity.	$W/m.k$
K_{st2}(Rock Wo	The thermal conductivity.	$W/m.k$
K_{st3}(Galvaniz	The thermal conductivity.	$W/m.k$
L_{pipe}	The total pipe length.	m
$L_{st,1}$ $L_{st,2}$ L_{st3}	The widths of each layer of the storage tank.	m
$\dot{m}_{storage}$	The Flow rate.	$\frac{Kg}{S}$
N	The number of pipes	
N_u	Nusselt number	
P	Power of pump.	kW
$P_{electrical}$	Electrical of pump.	
P_{shaft}	The shaft power of the pump.	w
Q_{demand}	The annual energy demand.	W
Q_{silar}	Specific magnetization,	w
Q	The amount of heat storage	w
$\dot{Q}$	Flow capacity.	$\frac{m^3}{h}$
$Q_{losses\ of\ tank}$	The amount of heat losses of tank	w

$Q_{\text{losses of pipe}}$	The amount of heat losses of pipes.	w
Q_{silar}	Specific magnetization, w	
Q_{DHW}	Domestic hot water.	kWh/day
Q_{SHL}	Standby heat losses,	kWh/day
Q_{CIRC}	Circulation heat losses.	kWh/day
Q_u	Rate of solar energy delivery to the tank.	w/m^2
R_1 R_2	The inner and outer tube radii.	$\frac{m^2.k}{w}$
$R_{radation}$	Total global solar radiation on the collector's surface.	$\frac{W}{m^2}$
R_e	Reynolds number	
$T_{c,o}$	Solar fluid temperature at the collector outlet.	℃
$T_{c,i}$	Solar fluid temperature at the inlet to the collector.	℃
T_{max}	The maximum temperature of the fluid in the tank.	℃
T_{min}	The minimum temperature of the fluid in the tank.	℃
T_{out}	The outlet temperature from the collector.	℃
T_{in}	The inlet temperature in solar collector.	℃
T_{amb}	The ambient temperature.	℃
T_{st}	The temperature of the storage water.	℃
ΔT	The difference of the temperature inlet and outlet of the pipe.	℃
δ_{fn}	The design solar fraction, typically 30-60%.	
S_a	The total surface area o of the tank.	
U	The overall heat transfer coefficient.	$w/m^2.k$
U_L	The overall heat transfer coefficient.	
V	The volume of the tank.	$\frac{m^3}{s}$
ΔX	The wall thickness of house.	m

List of Greek Symbols

Greek Symbols	Name	Unit
ρ	Density.	kg/m^3
θ	Angle of solar collector.	deg
η_c	The efficiency of the collector.	%
$\tau\alpha$	The absorbed solar radiation	
ε	Aspect ratio	

List of Subscripts

a	constant
b	constant
c	Collector
i	Inlet
l	Liquid
o	Outlet
s	Storage
w	Wall

Chapter 1 Thermal energy storage: An overview

1.1 Introduction

Global warming is becoming one of the most urgent problems in the world today, so we need to find the best way to utilize energy for everyone's benefit. Rapid population growth has led to an increase in energy demand globally and the use of non-renewable resources to satisfy this demand is a leading cause of global warming [1]. Thus, attention is shifting to increasing the efficiency of heating systems and reducing emissions [2, 3]. Thermal energy storage reduces consumers' electricity costs by avoiding higher peak hour tariffs. Thermal energy can be collected whenever it is available and used whenever it is needed, even in a different season. For instance, heat from solar collector equipment can be gathered in the hot months for space heating use when needed, including during the winter months. Energy storage is of particular importance because users can separate themselves from conventional energy use practices, enabling the decoupling of supply and demand [4].

Hot water storage tanks are one of the best technologies for storing thermal energy because of low cost and the high specific heat of water. Tanks can be stored in the basement or at the surface of the ground floor of a building. A cylindrical shape is preferable because it reduces the loss of heat. In addition, the heat exchange of water occurs inside the tank. A control system facilitates the charging and discharging of the thermal energy.

Solar energy is used for heating water, and solar panels are often put on the roof of buildings to capture solar energy. Many factors influence the storage of solar energy, such as the temperature in the tank and the quality of the metal used. The form of storage that causes a material to increase or decrease in temperature is called sensible heat storage. The use of thermal energy storage can reduce peak electric power loads in buildings and utilize the benefits of waste heat recovery and renewable energy [5]. In addition, thermal energy storage has a high energy storage density and can be discharged and charged through any storage system [6].

1.1.1 Solar Radiation in Newfoundland and Labrador

HOMER software tool was used for calculation of solar radiation for a specific location. Using HOMER software, for provide the model and simulation with inputs, which characterize technology options, resource availability, and component costs. Next, the input parameters of the HOMER simulation tool are presented followed by a discussion of the economic feasibility analysis parameters. Subsequently, the proposed cogeneration system is described, with economic data and various component specifications included in the description .HOMER software also can export graphs and the tables for use in reports and presentations. The model calculates theoretical solar radiation. Took imported solar irradiation data from NASA for the latitude 47.34° and longitude 52.42° on an hourly basis. The annual average value of the solar energy for Newfoundland and Labrador is about 3.153 ${}^{kWh}/_{m^2/d}$, with the months of June and

July receiving the maximum amount of solar energy. Table 1.1 below shows monthly average solar data from the HOMER simulation.

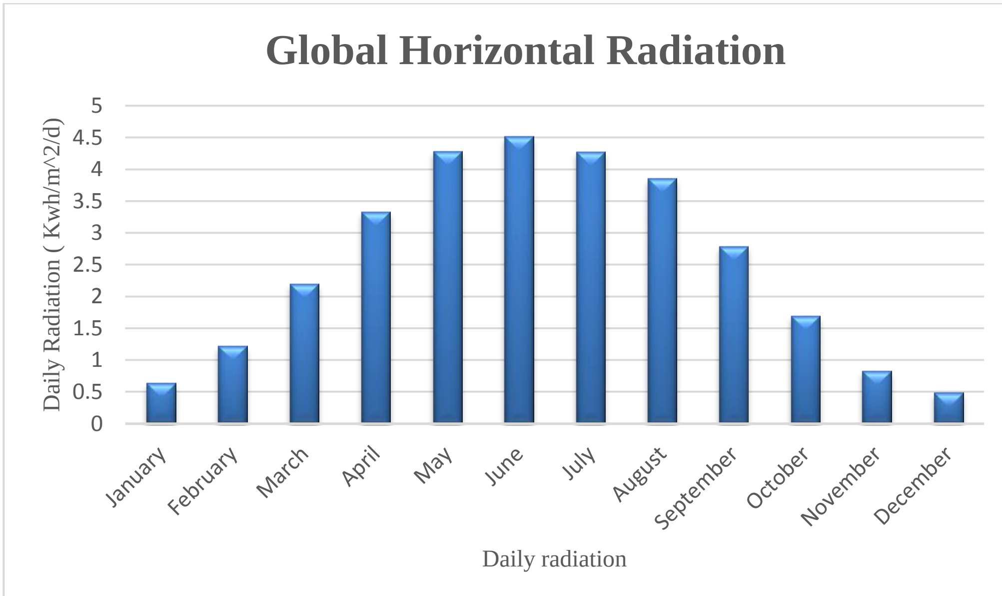

Figure 1.1: Monthly solar radiation using the HOMER software tool chart based on data from NASA.

Table 1.1: Monthly Average Solar Data from HOMER Simulation.

Month	Clearness Index	Daily Radiation (kWh/m2/d)
January	0.434	1.280
February	0.479	2.110
March	0.501	3.310
April	0.465	4.180
May	0.439	4.740
June	0.444	5.140
July	0.437	4.880
August	0.455	4.390
September	0.447	3.310
October	0.426	2.150
November	0.389	1.270
December	0.403	1.020
Average:	0.448	3.153

1.1.2 Energy storage history

Prior to the twentieth century, people used thermal storage and cooling processes such as storing items and materials in caverns in mountains to stay cool in the summer and keep warm in the winter. Then, in 1960, the US began using the seasonal storage of thermal energy. Work began on the study of thermal energy storage in Northern Europe in the late 1970s, and between 1976 and 1992, the solar system scale was developed in Europe [7] [8]. Today, there are other examples of thermal storage used in houses (e.g., electric water heaters), but these take many hours to produce hot water. Solar energy is also necessary for storage systems because it helps reduce the consumption of fossil fuels and CO_2 emissions into the atmosphere [1].

1.1.3 Uses of thermal storage

The use of thermal energy storage for example in Newfoundland and Labrador is necessary because every house consumes approximately 4000 Kw/year, and external temperatures can be extremely cold in the winter. The goals of thermal energy storage are to obtain heat from renewable energy other than fossil fuels, increase the efficiency of heating appliances, and provide energy security. One of the reasons thermal storage is used is the incompatibility between energy supply and demand [9]. An example of this is using tank of water that is connected to solar panels that can be charged during the afternoon when heating is not typically needed. Solar collectors store energy during the day and supply the necessary energy during the night [10].

Thermal storage can be used with other intermittent energy sources, such as industrial waste heat or wind sources of heat that can come from biomass appliances like outdoor wood boilers. Thermal energy storage has other functions, including being used as a thermal dump for excess electricity and converting it into heat, storing it and using it for space heating. Furthermore, storing energy in hot water tanks is the most common form of energy storage used in houses. Thermal storage can also be used as a thermal dump for excess electricity, such as when a renewable electrical source, like solar photovoltaic panels, produces more electricity is needed at that time. Excess electricity can be converted into heat, stored, and used for space heating. The heat load draws from the thermal storage, so it does not matter if the heat load is high when the heat source is unavailable [10].

There are many benefits of thermal energy storage, including the following: [11]

1. Energy consumption is reduced.
2. Large equipment is not necessary.
3. Increased flexibility of operations.
4. Reduced energy costs.
5. More efficient and effective.

1.2 Methods of Thermal Energy Storage

The methods of thermal energy storage can be placed into two classifications, as shown in the following two sections.

1.2.1 Sensible heat thermal storage

The sensible heat storage method, in which the temperature of a liquid or solid is raised, does not use phase change material, but is instead dependent on temperature change. The change occurs in the temperature of the storage material. Different forms of materials are used, such as solids, liquids, and gases. However, because solids and liquids have a higher heat capacity than gases, they are used more often in residential space heating. Liquids are used more in storage than solids because liquids have the advantage of also being potentially used for heat transfer (e.g., the liquid might run through pipes to solar thermal panels). Sensible heat storage in these types of substances is given by the equations:

$$Q = \int_{T_1}^{T_2} MC_P \, dT \qquad 1.1$$

$$Q_{sensible} = Mc_P \Delta T \qquad 1.2$$

$$\Delta T = (T_2 - T_1) \qquad 1.3$$

Where

1. Q is sensible heat storage [kW].
2. M is the flow rate of the storage substance [Kg/s].
3. C_P is specific heat capacity [$^{kJ}/_{kg.℃}$].
4. ΔT is the difference in temperature [℃].

Sensible heat systems are often thermally stratified, with controlled fluid flowing into and out of the container to minimize mixing .Water is usually used as storage medium for sensible heat storage because it has several advantages, the main ones being that water has a larger operating temperature range, is inexpensive, easy to handle, non-combustible, and widely available. Furthermore, its volumetric thermal capacity is high and natural convection flows can be utilized when pumping energy is scarce. Water has also disadvantages, however, such as freezing in cold regions or sometimes causing water erosion [12].

There are four characteristics of sensible heat storage for energy storage material: low cost, high specific heat capacity, good compatibility with its containment, and long-term stability under thermal cycling. Using of water for thermal storage first and foremost for instance Newfoundland because Newfoundland has a lot of readily available water. Equally important is that water has a high specific heat of 4186 [J/kg K] and a high density as well. Water is also suitable for operating seasonal heat storage has good compatibility with most containment material, is stable, mild, and has no corrosive chemical properties. Figure 1.2 shows a simple system of thermal energy storage for open cycle use with a solar collector and tank [13].

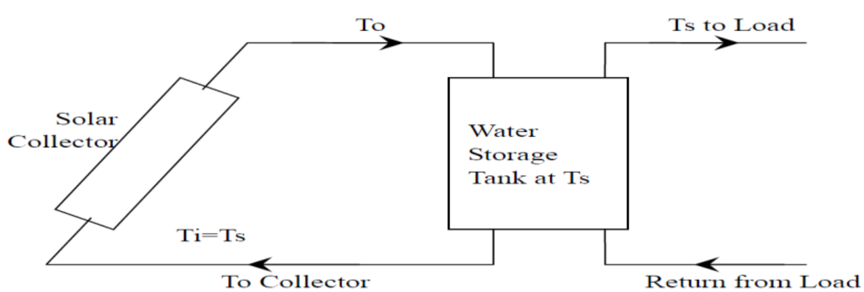

Figure 1.2: Open cycle of thermal energy storage.

Water storage technology is widely used in the solar thermal engineering field because of its minimal cost and simple implementation [14].

1.2.1.1 Seasonal water storage

Due to recently developed theoretical and concrete technology, sensible water thermal storage technology is not only used for short-term (diurnal) thermal storage, but also for long-term (seasonal) thermal storage. Seasonal thermal storage has a long thermal storage period, generally several months. Thus, seasonal energy storage can fully utilize the temperature differences between summer and winter, meeting or supplementing the cooling and heating demands for both seasons [15]. This is different from short-term thermal storage technology, as seasonal thermal storage maintains the storage material at a lower temperature than that of short-term storage, to reduce thermal losses during the long storage period. Considering the low storage temperature of the seasonal thermal storage, heat pumps are usually used to assist in supplying the heating or cooling demand [13]. BTES is a kind of sensible solid storage and GATES is a combination of sensible liquids and sensible solids. In addition, the three sensible liquid forms of storage will be only briefly introduced: HATES, ATES and CTES [16].

1.2.1.2 Water-based sensible storage

Water presents the best choice for sensible thermal energy storage due to its relatively high specific heat and high rates of charge and discharge. Thus, water tanks can be made of steel or concrete, or can have a cavity within the ground or a geological feature. Thermal energy storage can be injected into the water tank by directly circulating the storage via passing through a working heat exchanger. Figure 1.3 shows a simple water storage tank that uses direct circulation of the storage medium for heat transfer [14].

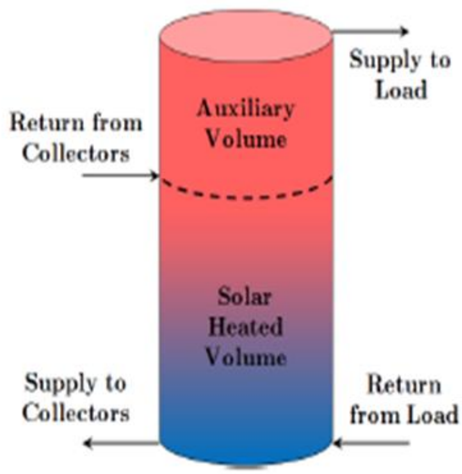

Figure 1.3: Simple solar hot water tank.

There are three requirements for using water tanks for thermal energy storage, as follows:

- Heat losses should be minimized.
- The tank should be properly designed for stratification.
- The volume in the tank should be minimized.

1.2.2 Latent heat storage

In this method, the fusibility and evaporation of heat is much greater than the specific heat. The storage capacity of latent storage materials is more volumetric than sensible storage materials and latent heat storage is at a constant temperature, which makes the choice of the material to use in the different applications easier. The following are the components of a latent heat energy storage system.

- a suitable container compatible with PCM
- a suitable heat exchange surface
- a suitable PCM with a melting point in the desired temperature range

Additionally, this method of latent heat storage is dependent on phase-changing materials (Liquid-Solid or Solid-Solid), which involves the transmission from solid to liquid by storing the heat as the latent heat of a fusion or from liquid to vapour as the latent heat of vaporization or the performance raises their temperature as they absorb heat. When the stored heat is extracted by the load, the material will again change its phase from liquid to solid or from steam to liquid. It also involves the change of one crystalline form into another without a physical phase change. In latent heat storage, heat is stored, absorbed or liberated via phase change or a chemical reaction and occurs at a constant temperature. Usually, it can be designed to melt and freeze at a suitable phase-change temperature range for air conditioning systems. This type is the focus of latent heat storage (phase-change materials) and the development of phase-change materials is still being researched [12].

In addition, the liquid-solid, liquid-gas, and solid-solid phases can be transitions. Phase-change materials (PCM) experience phase-change processes with unique features during their operation periods as well as significantly enhanced thermal properties. Thus, high latent heat has shown a promising ability to reduce the size of storage systems. When using latent heat, some important things must be taken into consideration, such as the use of suitable materials for inside the tank, and a suitable heat-carrying fluid for transferring the heat effectively from the heat source to the heat storage. Generally speaking, materials for latent heat storage are more expensive than those used in sensible heat storage. The storage capacity of an LHS system in the concrete case of solid-liquid transformation is given by Equation .Table 1.2 below illustrates data about solid-liquid materials for sensible heat storage [12].

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$$Q_{Latent} = \int_{T_1}^{T_2} C_{P.C} dT + \Delta H_{PC} + \int_{T_1}^{T_2} C_{p.J} dT. \qquad 1.4$$

where

Q_{Latent} is the sensible and latent heat storage (kW).

ΔH_{PC} is the heat of fusion at the phase change temperature of T_{PC} (°C).

C_P is Specific heat capacity ($^{kJ}/_{kg.\,°C}$).

Table 1.2: Data on Solid-liquid Materials for Sensible Heat Storage [17, 18]

MoJium	Fluid Type	Temperature (Celsius)	Density	Specific Heat
Rock		20	2560	879
Brick		20	1600	840
Concrete		20	1900-2300	880
Water		0-100	1000	4190
Caloric a HT43	Oil	12-260	867	2200
Ethanol	Organic liquid	Up to 78	790	2400
Proponal	Organic liquid	Up to 97	800	2500
Butane	Organic liquid	Up to 118	809	2400
Octane	Organic liquid	Up to 126	704	2400

1.2.2.1 Phase-change materials (PCMs)

Phase-change materials (PCMs) have higher fusion temperatures so they can absorb a lot of energy before melting and solidifying. Furthermore, their temperature remains constant during the phase change. The phase change mechanisms of PCMs have two stages. In the first stage, the heat increases until reaching the melting point at a constant temperature, whereby a specific heat is stored again [19]. In the second step, PCM storage has a slightly lower storage capacity in the solid phase below the melting point, after which PCM will begin to melt. The heat storage capacity is increased due to the heat of fusion, and the change is from solid to liquid or liquid to solid. In addition, the liquid phase helps ensure a uniform temperature throughout the container and that the temperature rises as they absorb heat. Moreover, large surface areas should be used to help with heat transfer with PCMs because they do not have high thermal conductivity via exposing more of the surface of the heating mechanism [20].

Therefore, there are a lot of advantages to using latent-heat thermal storage with phase change materials, such as a higher energy storage density, a smaller storage volume and the ability to provide thermal energy at a constant temperature .There are two main divisions or classes of phase-change materials used for thermal energy storage: organic and inorganic [20].

1.2.2.1.1 Organic PCMs

Organic materials are paraffin, fatty acids, esters, alcohols, and glycols. Paraffin stands out among organic phase change materials as it has a high latent heat of fusion, low vapour pressure, little or no sub-cooling, and is chemically stable [21].

Advantages of organic phase change materials:

I. Non-corrosive and chemically stable
II. Exhibit little or no sub cooling
III. Compatible with most building materials
IV. Vapour pressure is low
V. Non-corrosive

Disadvantages of organic phase change materials:

I. Flammability
II. Low thermal conductivity
III. High changes in volume on phase change

1.2.2.1.2 Inorganic PCMs

Inorganic phase-change materials have relatively high latent heat, high thermal conductivity and low volumetric change, with salt and salt hydrates ranking best. Additionally, PCMs are classified into the subgroups of salt hydrates and metallic and the building applications of the metallic materials are seldom used due to their scarce availability and high cost .Table 1.3 below illustrates the properties of some PCMs for domestic application [12].

Table 1.3: Properties of Some PCMs for Domestic Application [20]

Product	**Type**	**Temperature (℃)**	**Heat of Fusion** $kJ/kg.℃$	**Thermal Conductivity (w/mk)**	**Source**
RT 20	Paraffin	22	172	0.88	Rubitherm GmbH
Climsel C23	Salt hydrate	23	148	-	Climator
E23	Salt hydrate	23	155	0.43	EPS ltd
Climsel C24	Salt hydrate	24	108	1.48	Climator
TH24	Salt hydrate	24	45.5	0.8	TEAP
RT26	Paraffin	25	131	0.88	Rubitherm GmbH
RT25	Paraffin	26	232	-	Rubitherm GmbH
STL27	Salt hydrate	27	213	1.09	Mitsubishi
S27	Salt hydrate	27	207	-	Cristopia
AC27	Salt hydrate	27	207	1.47	Cristopia
RT27	Paraffin	28	179	0.87	Rubitherm GmbH
RT30	Paraffin	28	206	-	Rubitherm GmbH
E28	Salt hydrate	28	193	0.21	EPS Ltd

1.3 Solar Thermal Systems

The use of solar energy systems is a promising means of both reducing the consumption of fossil fuels and reducing CO_2 emissions into the atmosphere. Moreover, solar energy does not have the price volatility of other and can be used to create mechanical motion [22].

However, the availability of solar energy is intermittent, and the demand for heat supply is at a maximum in winter, when solar energy is less available. However, there have been significant increases in the installed capacity of renewable energy technologies such as wind turbines, photovoltaic panels and solar thermal collectors. This makes heat storage an indispensable element, especially in buildings with solar energy-based thermal systems [23].

In solar thermal systems, solar radiation is converted to heat via smooth plate collectors. Inside the collector, a fluid absorbs the heat that has been absorbed via the collector. In cold climates, the liquid should have a low freezing point and the system should have freeze protection measures in place .The Earth's surface receives solar radiation energy in two ways: direct radiation (solar parallel rays in a clear sky) and diffuse radiation (non-parallel rays of sky radiation scattered in the atmosphere in a cloudy sky) [24].

The solar system’s efficiency depends on several factors, as follows:

a. The amount of solar radiation the collector is exposed to.

b. The brightness of the sun during the day, month and year.

c. The efficiency of the thermal storage place for hot water storage.

d. The solar collector’s efficiency and the rate of loss.

Solar thermal systems possess some type of collector to gather incident solar radiation and a method to transport the collected thermal energy to end loads. These collectors may be thought of as a special type of heat exchanger that converts solar radiation into thermal energy. Systems classified as having active or forced circulation require additional energy input and controller intervention for operation. For instance, a pump is required in an active system to pass a working fluid through a collector to be charged and transported to an end load [23]. There are many types of solar thermal collectors, with flat plate and evacuated tube collectors representing 26.4% and 64.6% of all installed capacity in operation, respectively. The different types of photovoltaic-thermal (PV-T) collectors represent a promising technology, the potential of which has not yet materialized. Thus, these collectors combine solar thermal heat and PV technology in a single collector to produce both heat and electricity at a potentially higher energy yield than separate side-by-side solar thermal collectors and PV panels with half the collector area each [24].

Furthermore, the maximum reported thermal and electrical efficiency of a PV-T collector under maximum power point (MPP) operation is 79% and 10%, compared to 88% thermal efficiency under open-circuit conditions, which is on par with non-hybrid solar thermal collectors at zero reduced temperatures. Solar water heating PV-T systems for local purposes have been predicted to attain solar fractions between 50% and 70% in Europe and up to 92% in equatorial countries [25].

1.4 Performance System and Components

Solar energy is dependent on a large solar fraction to total load. Solar fraction is a relatively simple metric for assessing performance. In solar thermal systems pumps, control valves and controllers are typically used. Additional energy components are required, such as parasitic loads, which are not accounted for in solar fractions. In fact, there are some parasitic loads and increases in the solar collector array area, so there will be an increase in solar fraction. However, there must be a powerful pump for the fluid to reach the collectors. Solar water-heating systems and solar-heating systems of solar collectors take radiation from the sun, convert it into heat, and then transfer the heat to a colder fluid – "water". The solar energy collection loop focuses on a system of working fluid directly into a storage tank using pumps, pipes and collectors .There are two types of solar collector plates: flat plate collectors and evacuated tube solar collectors [26].

1.4.1 Storage tanks

The storage tank carries the water that has been heated via the collector. The water can be stored in any receptacle appropriate for high temperatures. The tanks can be pressure estimated depending on the application and whether or not a back-up heating system is used. Solar water heating systems usually have a single solar storage tank that incorporates an electric heating element. Gas water heaters are typically not used for solar storage due to the gas incinerator being at the bottom of the storage tank. In storage tanks, cold water enters the tank and activates the gas burner, the whole tank is heated, and the gas heat reduces the contribution from the solar system. When gas water heaters are used for back-up, the system also preheats water entering the gas back-up heater. In colder regions and industrial applications, two tanks may be required to store sufficient solar-heated water over very cold or cloudy periods. In these cases, a solar storage tank to which the solar loop is plumbed is connected in a series to an auxiliary water heater or boiler that has "back-up" electric or gas heating. This auxiliary tank or boiler provides hot water in the event there is not enough solar-heated water. Solar thermal systems that supply heated water for applications other than potable domestic water such as space heating may utilize more than one storage tank [26].

1.4.2 Pump

An active system such as a pump or circulator is used to move the heat transfer of fluid from the storage tank to the solar collector in systems of pressurized. The system is a circulator and is used to transfer hot water or heat transfer fluid from the collector to storage tank. Pumps are sized to get the best static and head pressure requirements in order to supply specific system design and performance flow rate. Drain-back and other solar water heating systems demand high pressure from the pump to raise the water from the storage tank to the collector. This requires a centrifugal pump or another pump that will provide enough pressure.

Most energetic solar systems use centrifugal pumps, but pump selection depends on the following factors:

- System type (direct or indirect)
- Heat collection fluid
- Operating temperatures

• Required fluid flow rates

• Head or vertical lift requirements

• Friction losses

1.4.3 Piping

Tubing is used in a system to supply a pathway for fluid to be transported. Consequently, piping must be appropriate for the system, which depends on several factors, such as temperature, pressure, and other components. Most systems use copper piping because of its durability, resistance to corrosion, and ability to withstand very high temperatures. The piping depends on its application, local codes and tradition, with copper, brass, and bronze being the only materials that should be used in direct solar systems that utilize potable water. In instances where galvanized piping already exists, it should either be replaced or dielectric unions used to isolate the different metals. When installing long-system piping runs, the tube is commonly used for support. Depending on the type, the piping may be pliable due to high temperatures and therefore must be supported.

1.4.4 Heat exchangers

The system of indirect heat exchangers is used to transfer the energy collected in the heat-transfer fluid from the solar collector to the storage tank, and can be either internal or external to the storage tank. The heat exchanger comes in several forms, such as tub pipe, shell-in-tube, coil-in-tank, wraparound-tube and wraparound-plate, as well as side-arm designs. Heat transfer occurs when one fluid moves through the inner tube while a second fluid moves in a different direction in the space between the inner and outer tubes. This form of heat exchanger is most commonly used in smaller systems. For instance, in an indirect system using a pipe in tube heat exchanger, the collector heat-transfer solution would be in the inside tube while the potable water would be in the space between the inner tube and the outside of a tube.

Systems with heat exchangers can experience a 10-20% loss in total efficiency in the transfer of heat from the collection loop to the stocked water. However, economic savings and fail-safe freeze protection may offset that efficiency loss. For example, heat exchange systems can use corrosion-inhibiting heat-transfer fluids that allow the use of less-expensive aluminum or steel in collectors, exchangers, and piping. If aluminum is used anywhere in the system, no red metal (copper, brass or similar alloys) should be used unless the heat-transfer fluid is non-ionic or an ion trap is placed upstream of each aluminum component to reduce galvanic corrosion.

Heat exchangers are sized based on their heat-transfer capabilities, flow rates and the temperatures of incoming and outgoing fluids. For packaged and approved or certified systems, the manufacturers have sized the heat exchanger and matched its performance to the collector array and flow rates of the system. Under-sizing the heat exchanger is, unfortunately, a common mistake of home-built systems.

1.4.5 Solar collector

Solar water heating systems have components for heat collection, heat storage, heat delivery and freeze protection. Active systems need controls for pump operation and valves for safety and proper operation. Passive systems utilize many of the same components but in some cases for different reasons.

• Collectors – collect and convert the sun’s energy to heat.

• Tanks – store solar heated water and heat transfer fluids.

• Heat delivery components – include piping, heat-transfer fluids and heat exchangers.

• Freeze protection mechanisms – prevent collectors and pipes from freezing.

• Isolation, check, relief and safety valves are used to valve fluid flow.

• Gauges and meters are used for system monitoring**.**

Solar collectors capture the sun’s electromagnetic energy and convert it to heat energy. While most direct and indirect active systems use flat-plate collectors, some systems employ evacuated tube collectors or use collectors that incorporate one or more storage tanks.

1.4.5.1 Flat plate collector

A flat-plate solar collector is one of two types of solar collectors. This type is the most common solar collector used in solar water-heating systems and is usually found in houses. Some of the components of flat-plate solar collectors include a dark-colored absorber plate and a plastic cover (the glazing) of an insulated metal box with a glass. The fluid that circulates through the collector and pipes is exposed to radiation from the sun, and the radiation absorbed from the plate is then transferred to a fluid. Unfortunately, the flat plate collector tube not only has low efficiency and a high price, but cannot hold high pressure and breaks down easily. Figure 1.4 shows Glazed Flat-Plate Collectors [27].

1. frame
2. seal
3. transparent cover
4. frame
5. thermal insulation
6. absorber
7. fluid channel
8. fixing slot
9. rear wall

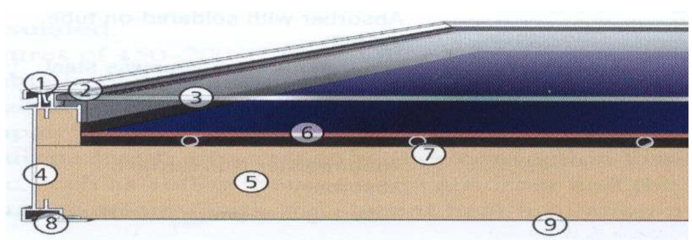

Figure 1.4: Section through a glazed flat-plate collector [28].

1.4.5.1.1 Advantages

1 Performance ratio is reasonable

2 Affordable price

3 Cheaper than vacuum collector

1.4.5.1.2 Disadvantages

I. Lower efficiency than vacuum collectors for high temperature applications

II. Not suitable for generating high temperatures (+100℃)

III. Requires more roof space than vacuum collectors due to support system being necessary for flat roof mounting.

1.4.5.2 Evacuated tube solar collectors

An evacuated tube collector system is more efficient at lower ambient temperatures and is slightly more efficient than a flat plate system due to lower heat losses. These systems use gravity-driven heat pipes and applications, and flat plate collectors are more efficient compared to evacuated tube collectors .Also, they use a barium layer to keep the vacuum between the two glass layers. The barium is exposed to high temperatures, which causes the bottom of the evacuated tube to freeze. Furthermore, in cold weather, the performance of the vacuum tubes does not have any advantages over flat plates because snow build-up hampers its performance [29].

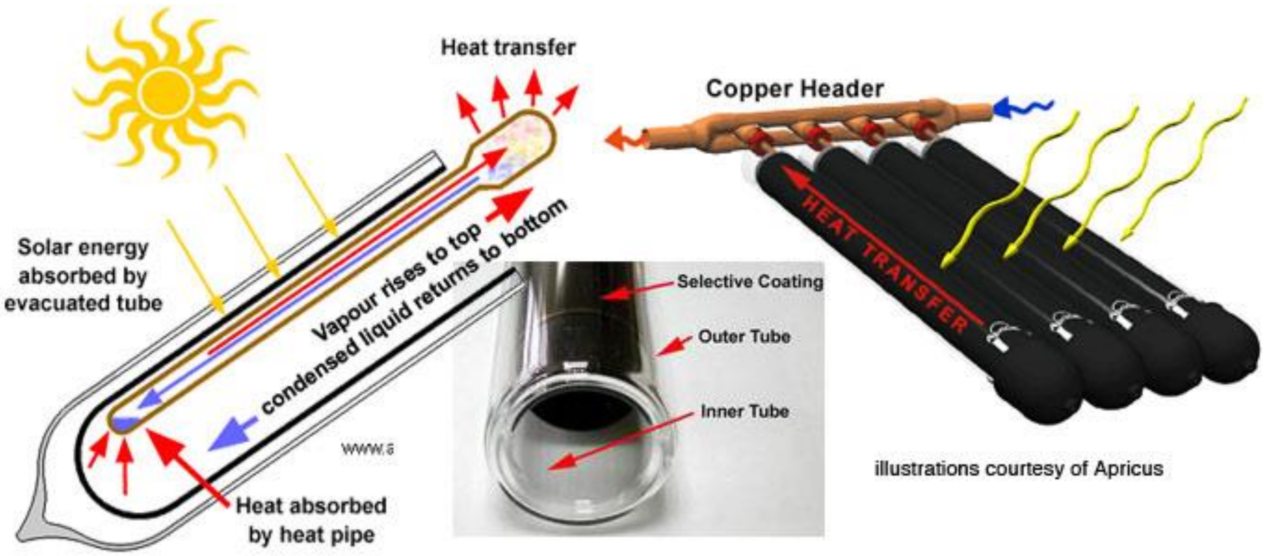

Figure 1.5: Typical liquid evacuated tube collectors [30].

1.4.5.2.1Advantages

1 Evacuated tubing has high efficiency even with large differences in the temperature absorber and surroundings

2 Applications are more effective than glazed flat-plate collectors

3 Low in weight

1.4.5.2.2Disadvantages

1. More expensive than a glazed flat-plate collector
2. Cannot be used for in-roof installation
3. Heat pipe systems need to be set to at least 25 ℃

1.4.5.3 Integral Collectors

In integral collector storage and impulse solar water-heating systems, the collector functions as a jointly solar absorber and water storage. Integral collector storage in Figure 1.6 shows a generally incorporate 4" or large diameter horizontal metal tanks connected in series through piping from a water inlet at the bottom of the tank to an outlet at the top. The tanks are coated with either a selective or moderately selective absorber end and are enclosed in a highly insulated box wrapped with multiple glazing layers. The multiple nitrification layers and selective coatings are designed to reduce the heat loss of water stored in the absorber [29].

Impulse solar water heaters as well as integral collector storage systems are made up of a water tank or tubes inside an insulated glazed box. Cold water flows via the solar collector and hot water continues on to the back-up water heating storage tank. Some water can be stored in the collector until it is needed. Integral collector storage systems have a direct solar water heating system and circulate water to be heated rather than using a heat transfer liquid to capture the solar radiation. However, this type of system is only suitable for warmer climates. The collector itself and any outdoor pipes are susceptible to freezing in chilly weather, and the batch collector can become very hot if the water is not drawn during the day. Batch systems lose heat at night time, but impulse systems are very effective for heating water during the day. This is ideal for households, as most of their hot water demand is during the day and evening [29].

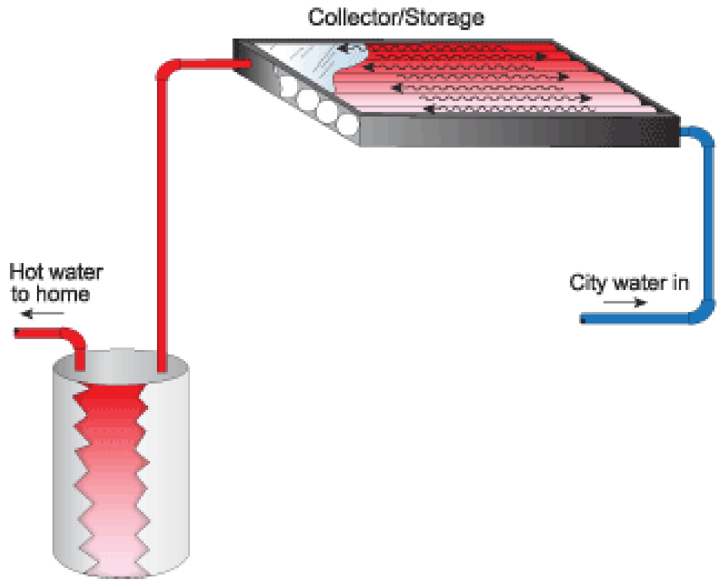

Figure 1.6: Integral collector storage (ICS) system [31].

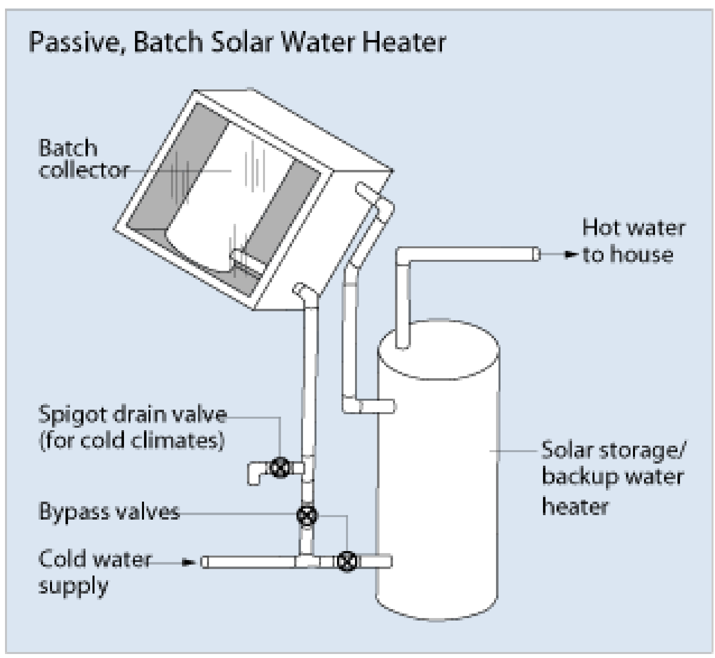

Figure 1.7: Passive solar water heater [32].

1.4.5.4 Comparison between flat plate collectors and evacuated tube solar collectors

Performance: The flat plate has better year-round performance

- Efficiency: The flat plate is best at delivering the temperatures needed for most common hot water applications.
- Cost & Value: The flat plate is generally less expensive and provides more energy per dollar than the vacuum tube.
- Cold Weather Performance: The vacuum tube does not have any advantages over the flat plate because snow build-up hampers its performance.
- Installation: Vacuum tube collectors take more time to assemble, while flat plate collectors take more effort to hoist onto the roof.
- Durability: Vacuum tube collectors are fragile and require regular maintenance.

Flat plate tube solar collectors and all-glass evacuated tube solar collectors are widely used in many types of collection tubes. Researchers have studied all-glass evacuated collectors experimentally and theoretically and found that both the flat plate collector and the all-glass evacuated collector are less than ideal for their purposes, as the flat plate collector tube has low efficiency and a high price, while the other cannot hold high pressure and breaks down easily [33-34].

1.4.5.5 Typical efficiencies of collectors

Solar collector efficiencies generally fall within specific ranges. Table 1.4 below shows the properties of flow rate corrections.

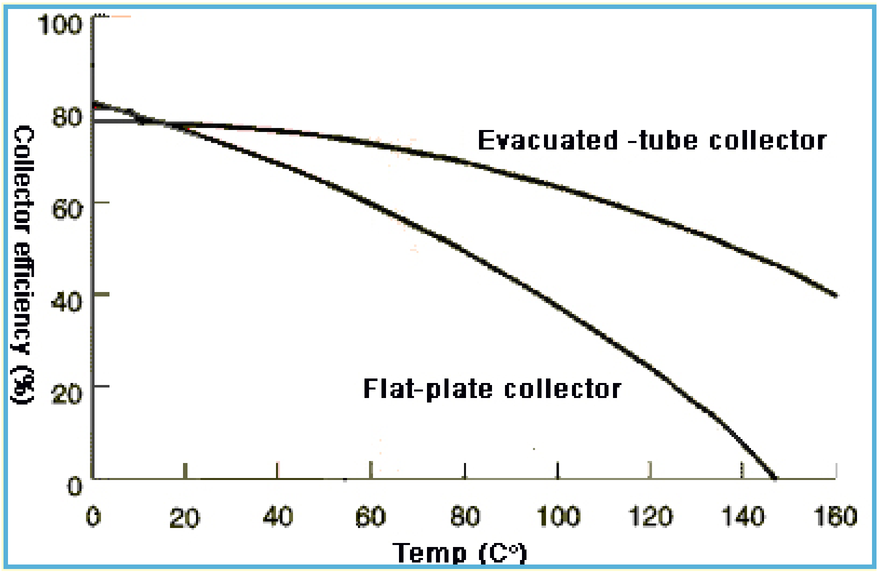

Figure 1.8: Solar Collector Performance Plots [35].

Table 1.4: Properties of Flow Rate Corrections [35]

	$F_r\,(\tau\alpha)_\epsilon$	$F_R.U_l(w/m^2{}^\circ C)$	
1	0.5-0.75	1-2	Depends on tube spacing
2	0.65-0.8	3-8	Depends on covers and absorber coating
3	0.8-0.95	10-20	Depends on wind speed

1.5 Types of Solar Water Heating Systems

This module describes the most common joint types of solar water heating systems. The elements that influence the selection of a specific system type include the amount of water that needs to be heated, the relative cost and efficiency, simplicity of operation, and climate conditions in which the system will be used. Natural and forced circulation can be further categorized. On an open system, an open container will be introduced to absorb the volumetric extension of the fluid that results from rising temperatures. The pressure in open systems is maintained at the static pressure associated with the liquid column. However, in closed systems, additional safety devices are required [36].

1.5.1 In a direct system (open system)

In a direct system, the drinkable water circulates from the storage tank to the collector and back to the storage tank. Therefore, the heat collecting liquid is the same potable water that is in the water heater [37].

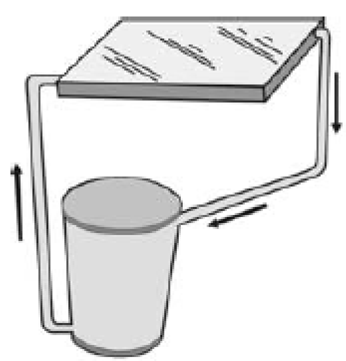

Figure 1.9: Direct solar water heating system [37].

1.5.2 Indirect system (closed system)

In an indirect system, the liquid that circulates via the collector may be water or another heat transfer fluid. This heat-collecting fluid never comes in contact with the drinkable water in the storage tank. Instead, it transfers heat to the potable water by using a heat exchanger to separate the heating fluid from the domestic hot water [38].

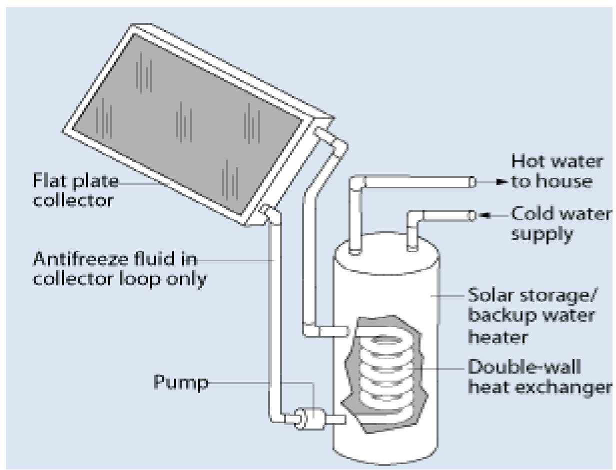

Figure 1.10: Indirect solar water heating system [38].

1.6 Heat-Transfer Fluids

Some types of solar systems use heat transfer fluids. In active direct systems, drinkable (potable) water is the most common heat-transfer fluid. Indirect systems in cold climates use a non-potable solution that will freeze only at extremely low temperatures. The most common of these fluids are:

• Propylene glycol

• Ethylene glycol

• Hydrocarbon oils

• Synthetic oils such as silicone.

Some of these fluids are toxic (notably, ethylene glycol) and require double-wall heat exchangers.

Glycols are the most commonly used heat transfer solutions for indirect systems. Special inhibitors are added to the glycol during the manufacturing process to prevent the fluid from becoming corrosive. Consequently, the "manufacturer's instructions" should be checked periodically regarding glycol fluids to ensure they remain chemically stable. The glycol can be conducted using either pH test strips or standard pH testing color charts.

1.7 Research Objectives

The main aim of this thesis is to examine the potential and applicability of heat transfer and storage. Thermal energy storage can significantly increase the technical potential of renewable energy sources by allowing heat and cold to be utilised when there is demand for it. However, the objectives of thermal energy storage depend on improving the ability to efficiently shift energy demand over days, weeks or seasons and reducing costs. This research was also intended to guide designers on system performance to these key parameters, Such as, sizing of solar collector, storage tank and pump. Thus, designed using best practices, for example, using Homer, SAM and Matlab software. Additionally, to improve measuring and testing procedures and new storage materials , performance, cost-effectiveness of new storage materials, stability, and improve multi-scale numerical models, and anticipation the performance of new materials in thermal energy storage systems,

1.8 Thesis Outline

This research studies thermal energy storage applicable to Newfoundland and Labrador, which is a region in Canada characterized by cold winters and warm summers**.** The thesis is organized as follows. Chapter 1 presents an overview of the topic and introduces the main thesis arguments. Chapter 2 provides a literature review and also focuses on house heating demands and the available data for house, solar energy for water heating and energy from waste water such as showering, clothes washing and dish washing. Chapter 3 presents the knowledge system sizing for a house, including tank size, solar collector size, pump size, pipe size and heat exchange size and Design of solar water heating system with thermal storage for a three-bedroom house in Newfoundland. Chapter 4 Modeling and Simulation of a Solar Water Heating System with Thermal Storage by using MATLAB and BEopt, while Chapter 5 presents the results and conclusions.

CHAPTER 2 LITERATURE REVIEW AND SYSTEM SIZING

2.1 Introduction

The basic principles of solar thermal systems were introduced in Chapter 1. To form the foundation for the current research, a literature review was conducted, as presented below. This review begins with the analysis of thermal energy storage options and their applicability to seasonal storage for residential buildings Newfoundland and Labrador. The case studies and analysis of seasonal solar thermal systems is then reviewed to examine the design, operation and performance of seasonal solar thermal systems in practice via used MATLAB and BEopt software. Finally, performance metrics for seasonal storage and solar thermal systems are identified and a Simulink Model of the system created**.** The use of conventional energy resources (e.g., fossil fuels) is increasingly being challenged by factors such as exponential rises in population, over-use of natural resources and pollution, thus profoundly changing the way the world views and uses energy [38].

The consequence of these changes can be seen in the recent rush by researchers and industry to find and develop alternative energy sources that highlight sustainability, efficiency, and environmental friendliness both in the residential and commercial end-user sectors. Our focus here is the residential end-user, which, as of 2011, comprised approximately one-fifth of the world's energy consumption [39].

In fact, energy consumption by residential end-users is growing at a faster rate than commercial end-users, especially in countries that are signatories to the Organization for Economic Co-operation and Development (OECD) agreement [40].

On average, residential end-users in Canada spend $26.3 billion annually powering their homes, which accounts for slightly more than one-sixth (1 360.7 PJ) of the country's secondary energy use, and slightly less than one sixth (68.4 Mt) of the secondary energy use-related GHGs emitted in the region. The primary energy usage (up to 80%) for residential consumers is home and water heating, followed by air conditioning, lighting, and powering home appliances [41]. In fact, research indicates that nearly one-fifth of the power consumed in Canadian homes is used for heating water and that this is second only to home heating in terms of power allocation of energy resources for residential end-users. Also, each resident of Canada uses on average up to 75L of hot water daily, for activities such as showering, clothes washing, and running dishwashers [42].

Given the rising costs of power derived from non-renewable energy resources, there is a clear need for governments and industry to seek alternative energy options that are cheaper and sustainable while benefitting the environment as well as residential consumers. Solar energy is a prime candidate to replace fossil fuel consumption, being both cost-effective and sustainable. Moreover, solar water heating (SWH) systems are currently the most common application of solar energy [38] for heating residential water tanks. Thus far, these systems have enjoyed a high success rate in countries such as Germany, Japan, and China [43]. In fact, they have been so successful that in some jurisdictions, SWH systems must, by law, be installed in new residential constructions [42].

The science behind SWH systems is actually quite simple. Solar radiation provides a solar collector with thermal energy which, via heated circulating fluid, is transferred to a storage tank, which then heats and stores the water until needed [38]. Smaller SWH systems are used for domestic hot water (DHW) applications, whereas larger systems heat water in commercial or industrial facilities [42]. Unlike conventional water heaters that are powered by fossil-fuel derived energy systems, SWH systems offer residential users lower heating costs (up to 50%). They also reduce greenhouse gas (GHG) emissions (up to 2 tons annually) since they do not emit any pollutants, thus leading to a cleaner environment [44].

The energy savings per domestic household depend first and foremost on water usage and the type and size of the storage tank and collectors, but they also involve factors such as temperature preference, appliance efficiency, and the amount of sunlight available in the given area [38].

Generally, the household's geographic location determines the kind of system that should be installed. There are two types of SWH systems currently available on the market for domestic end-users. The first are natural circulation or passive solar water heating systems, where differences in density cause the natural circulation of the fluid. The second type of SWH available for domestic users is forced circulation or active solar water heating systems, which combine the pump and rotary components [43].

Previous examples of passive SWH systems are integrated collector storage solar water heaters (ICSSWH), also called the batch SWH system. This system has a tank that serves as storage and as an adjunct to the solar collector. Over 100 years ago, thermo siphon systems replaced batch SWH systems due to the latter's ongoing issues with heat loss. The passive systems are most common in former third-world countries that still occasionally experience problems with the local power producers. They are also common in areas that do not experience sub-zero temperatures (e.g., Saudi Arabia) [45].

Active systems can be either direct circulation (where storage tank water is directly circulated to the collector and then warmed by solar energy), or indirect water heating systems (where heat transfer fluid is circulated to the collector, transferring warmth through a heat exchanger onto storage tank water) [38]. These systems are usually installed in areas that experience sub-zero temperatures for at least part of the year, so they offer freeze protection and this makes active systems most conducive to the needs of Canadian domestic consumers, which is the focus of this literature review. Active systems come in three possible configurations: open loop, closed loop and closed loop with drain back systems. Open-loop systems feature a solar collector loop that remains at atmospheric pressure. Under this scenario, the collectors sit empty when not producing heat, which means that high pumping power, is required whenever the collectors reach the required temperature. In closed-loop systems, however, the pumps counteract any pipe resistance through the small expansion tank and pressure relief valve situated within the solar loop; the loop then stays topped up with water under pressure [38, 46]. This approach can be problematic during warmer months, however, when higher temperatures and pressure in the loop can lead to loop leakage, which could then result in the pump running dry.

The results of a recent lab investigation into several solar domestic hot water control systems to gauge both reliability and performance showed that 9 out of 15 thermistors failed during warmer temperatures. The failures included: drifting of sensor response; differentials being strongly dependent on system temperature; electronic failure caused by high ambient temperatures and humidity; and the failure of the equipment to meet published specification. Interestingly, the closed-loop drain back system, which is the third type of active system, resolves the issue of high temperatures by having the water in the collectors drain out whenever the pump is shut down. Hence, for areas that experience sub-zero temperatures as part of a normal climatic feature, the best system by far is the closed-loop drain back configuration [38].

SWH systems typically utilize three different kinds of stationary collectors, namely flat plate collectors (FPCs), evacuated tube collectors (ETCs), and concentrating parabolic collectors (CPCs). Of these three types, FPCs and ETCs are most popular for domestic water-heating purposes [45], but FPCs are most widely used overall [38]. In situations where water-heating temperatures do not exceed 100 °C, which is necessary for certain industrial process heat applications, forced-circulation (the active type) flat plate collector water-heating systems (described earlier) are suitable. In situations where water temperatures must exceed that temperature, ETCs or CPCs have to be used [47]. In addition to home heating, SWH systems can be used for heating swimming pools and aquaculture pools (e.g., fish farms) as well as for various commercial and industrial applications.

The success rate of SWH systems thus far has been phenomenal [48]. Chow et al. [49] measured the performance of a solar-assisted heat pump for a water heating system in swimming pools. Their simulation and modeling results indicated an energy savings of approximately 80%, resulting in a payback of less than five years [49]. Yoo [47] measured the performance of a SWH system installed in a building in Korea with 1179 households. The performance of the system was gauged over a three-year operational period, using FPCs inclined at 22° and a conventional boiler rated at 85% efficiency. They system showed a pay-back period of just over 12 years [50]. Jinghua et al. [51] evaluated the performance of a large apartment building in China, again showing a relatively short payback period of 2 to 8 years. This system also offered environmental benefits equal to 71,907 L/year of oil reductions, 50.8 TC (Tonnes of Carbon), and 186.3 TCO2 (Tonnes of Carbon dioxide) of reductions. Meanwhile, in British Columbia, which is located on the west coast of Canada, a solar water heating system utilizing 260 m^2 unglazed solar collectors was installed to heat the water for fish farms. The system assisted in increasing fingerlings production and showed a five-year payback period [52]. Finally, Attar et al. [53] measured the efficiency of a solar water heating system that incorporated capillary heat exchangers and was being used for heating greenhouses in Tunisia. The system easily heated a 1000 m^3 greenhouse and even succeeded in lowering heating expenses by over 50% [46]. Nevertheless, the researchers determined that found that the system was only optimally operational when supplying heat for a 10 m^3 greenhouse [54].

Along with the applications touched on in the above paragraphs, other solar heating systems have been developed that use various configurations. In 2012 alone, 55.4 GW (over 79 million m^2) of solar heat capacity came online globally, while the boost in installed cumulative capacity of all types of solar collectors was just under 15%, totaling 283.4 GW by 2013 [55]. As mentioned previously, SWH systems account for nearly four-fifth of the worlds installed solar thermal systems [56], so there is an ongoing concerted effort to optimize the performance of these systems. With an aim to reduce costs and enhance efficiency, Clausing [38] introduced a low-cost monitoring system that monitors solar domestic water heating systems. The system allows the user to correlate load with the availability of solar heated water for better performance [38]. Prasad et al. [56] developed a new approach for enhancing solar energy conversion efficiency via tracking systems. By using a flat plate collector SWH system, they altered the position of the solar collector in relation to the sun's position in order to maximize the beam radiation using a real-time digital tracking method. Their results showed a 30% increase compared to conventional systems without a tracking system [38].

Heating domestic water tanks in ultra-cold climates like Canada brings with it its own unique set of technical problems, the most prevalent of which is low efficiency, significant night-time heat loss, and poor solar harvesting ability. Because of these challenges, enhanced SWH designs now include phase change material (PCM), which was developed by Telkes and Raymond in the 1940s. Phase change material is a form of latent energy storage material that undergoes isothermal or near isothermal phase transformation due to the high energy storage density and compactness of the material [47]. Working from Telkes and Raymond's results, Qarnia [57] numerically analyzed and compared several different phase change materials, finally suggesting that stearic acid was the best PCM for storage vessels because of its strong heat loss reduction properties. In research carried out by Seddegh et al. [58], the integrated phase change storage vessel was discovered to be the most common method that included integration of PCM [58]. Again, working from Telkes and Raymond's earlier results, Fanney and Dougherty [59] patented a SWH system that employs photovoltaic (PV) modules to power multiple electric heating elements. In so doing, they used a microprocessor controller to match the operating characteristics of the photovoltaic modules to the electrical resistance of the load. This resulted in the photovoltaic array functioning up to near maximum power. Although the researchers' systems showed reasonable performance, they were also very expensive due to the price of PV cells, which has curtailed the widespread adoption of the high-performing system. With the expected future reductions in the cost of PV cells, this system is anticipated to become competitive with SWH systems by the mid-2020 [58].

Advancements in SWH systems have continued in recent years, with a V-trough system now commercially available and currently being modified and tested for domestic use. Chong et al. [43] investigated one of these systems that utilized direct circulation, noting that that the thermal performance could significantly improve by combining the solar absorber with a V-shaped trough reflector. The system was then measured with and without glazing and various insulating materials, with the results indicating that the prototype could obtain an optical efficiency of 71% and a maximum outlet water temperature of 82 °C and 67 °C, with and without insulation, respectively.

Moreover, in the United States, the National Renewable Energy Laboratory (NREL) [60] debuted a novel system called the photovoltaic-thermal (PV-T) solar heating technology at an 11-storey high-rise building. The system is made up of a hybrid solar PV panel with a solar thermal collector installed at the back. One of the main features of the system is that as the efficiency of the PV panel decreases with cell temperature increases, any air or water passing through the thermal collector will remove heat from the PV cells. This approach provides improved efficiency and also produces water or air heating and electricity within the same footprint. Overall, the system provided nearly one-third of the building's required hot water load.

Tackling the seemingly insurmountable challenges of efficiency and cost will require ongoing research endeavours because as soon as a system appears to resolve these issues, another problem creeps up that in turn needs to be resolved. As shown in this chapter, numerous systems have been developed already and are being used by companies and individuals world-wide. A few examples of the most popular software currently being used is f-chart, SLR, Utilizability, TRNSYS, etc. [61], while examples of software utilized in financial and environmental analyses are RETScreen [62], SolOpt, PVWatts, SAM, etc. [63].

2.2 Background

The strategic advantages of the emerging solar energy technology industry are numerous. The main and most wide-ranging advantage is that using solar energy leads to a significant reduction in emissions caused by fossil fuel-fired generators. Such emissions have been known to create greenhouse gases (GHGs) and other air pollutants. A second major advantage to using solar energy is that the sun is a free resource, which means that after solar technologies have been installed, their operation is highly cost-effective and they require very few non-solar inputs. These systems are also rarely affected by the fuel supply disruptions and price volatility that often plague conventional fuel supply resources. Further advantages of solar energy technology are the promotion of innovation as well as research and development towards energy efficiency. Such efforts can offset any adverse events that may hinder future energy security (e.g., oil spills or natural disasters) and also lead to job creation within the energy sector.

Nowadays, the majority of the world's domestic hot water (DHW) systems are heated by electric and natural gas systems. In fact, most of the heating is done by natural gas [64]. Research shows that facilities that change their hot water heating systems from either electric or gas to solar will save more money in the long run due to the increased cost of electricity on a $/MMBtu basis [60]. A recent survey in Canada regarding the potential energy savings for various provinces from installing a solar water heater indicated that savings in the range of 30% would occur in Newfoundland, should that province switch to solar. Figure 2.1 shows various places in Canada on the map and approximate energy savings [65].

Figure 2.1: Approximate energy savings for various places in Canada [65].

Given the numerous social and climate-change challenges emerging today, along with the rising number of human-induced issues around air pollution [66], the Government of Newfoundland and Labrador introduced climate legislation in 2007 aimed at lessening the effects of problems caused by fossil-fuel energy dependency and usage. Make an initial investment of $20 million over the next three years during the Energy Corporation to purchase existing proprietary seismic data for reevaluation and acquire new data to fill in gaps. The legislation enacted a Newfoundland and Labrador Technology Fund to collect payments from large polluters, the intention of which was to encourage these large-scale polluters to invest in low-emission and emission-reducing technologies. A Climate Change Foundation was also created, whose main purpose was to raise public awareness about research into low-carbon technologies [67]. The foundation made an initial investment of $5 million over the next two years through the Energy Corporation in a Petroleum Exploration Enhancement Program to boost new onshore petroleum exploration in western Newfoundland. Solar energy-related companies and technologies are well-position to contribute to Newfoundland and Labrador's energy efficiency targets [68].

Against this background, SWH can help Newfoundland achieved their aim by leading the development of the Lower Churchill Hydroelectric Project through the Energy Corporation. The Energy Corporation will coordinate all new hydro and wind developments. Extensive research related to the practical implementation of SWH systems shows promise from both a technical and economic standpoint, including long-term sustainability. For the majority of active SWH systems (especially those in residential applications), the retail electricity source at the location which is housing the system usually provides the power for the circulation pumps. However, a large portion of this electricity source still comes from the burning of fossil fuels, which is hazardous to environmental health. To date, there are very few SWH systems that are solely solar-powered.

The primary and obvious benefit of having a SWH system that is run solely by the sun is that it will function even during a power outage, which gives it increased overall system reliability. Such reliability is lacking in conventional systems, which typically cannot function during a power disruption. Moreover, in some instances, differential controllers and temperature sensors may not be necessary for SWHs on a PV-powered pump system, as the PV panel will only start the pump if the solar radiation exceeds a certain level, thus reducing the operating costs of the system. An additional advantage of the proposed system is zero GHG emissions during operation, making the approach environmentally-friendly.

2.3 System sizing

The thermal energy storage relied on a solar water-heating system model that aggregated several sub-models pertaining to individual system components, such as the PV-T collector model, the thermal storage tank model and the insulated pipe segment model. Other models implemented but not described here include the isotropic irradiance model, the horizontal solar coordinate model and the hysteretic controller model [69].

The flow measurement technique, which was discussed in a previous chapter, is essential for optimizing the energy flow in the proposed heating system. There are many more components whose design issues are to be addressed. The design is a complex and challenging task since the working system involves multi-domain subsystems (e.g., thermal, mechanical, electrical and hydraulic). The complexity of design is further increased by this system being a hybrid combination consisting of both solar thermal and conventional heating energy sources. The design of each subsystem is performed based on the worst-case conditions for a given location and heat load [70].

This system can be split into the following major components:

• Solar thermal concentrator and collector, with tracking system.

- Heat storage tank with thermal insulation.
- Heat transfer fluid, piping for circulation with thermal insulation.
- Heat exchanger system.
- Pumps for circulation of the fluid with flow-rate adjustment mechanism.
- Temperature sensors and flow meters.

2.4 Specifications

The specifications involved in the design of the proposed solar cooking system can be divided into two major parts, as follows:

2.4.1 User specifications

The user gives the specifications related to heating requirements, such as the number of hours of heating in a day, the amount of night-time heating, and the type of conventional heating source used. The distance between the kitchen and the rooftop is also an important factor affecting the design and has to be specified by the user according to the building structure [70].

2.4.2 Design parameters

The design parameters must be obtained for given user specifications, such as size of solar thermal collector, size of heat storage tank, design of heat exchanger, circulating pump, and design of sensing instrumentation. Solar energy is trapped using a concentrating collector, which raises the temperature of the circulating fluid depending on user requirements and available solar insulation.

To design a heat transport system on location, a thermal collector of appropriate size can be selected [71]. The maximum energy that can be extracted from the sun is a dynamic quantity dependent on the solar insulation available at that instant. On average, 3.153 $\mathrm{kWh}/_{\mathrm{m^2/d}}$ of energy are available per square meter on a clear-sky day. As per user specifications, the average heat load requirement per day can be estimated in kWh. The size of the collector can be calculated to meet this requirement by considering the overall efficiency of the collector. However, as the energy obtained from the solar collector is not uniform, an energy storage facility is necessary.

For a given location, the number of cloudy days or non-sunny days can be estimated. This has to be considered when designing the size of the storage tank. The amount of energy required for night-time and early morning also has to be considered during sizing. The dimensions and the design of the heat exchanger are decided according to the heating load and type of application. One pump is used to circulate the fluid, which is driven by solar collector. It is necessary to know all electrical requirements for the pump, linear actuator (for tracking), and sensing. Details of these issues are discussed in the following sections [71].

Additionally, on cloudy days when the collectors may struggle to obtain useful heat, two auxiliary heating elements located in the storage tank will serve as a backup. The auxiliary heaters will automatically begin to function as soon as a certain temperature level is not sensed by the solar thermal portion of the system. In this study, our proposed water heating system that is fully solar powered will replace a standard electrically heated water system. To evaluate the proposed solar energy system sensitivity analysis on the system to see how its functionality may be impacted by different operating and environmental conditions. Finally, I will present some recommendations to enhance and modify the proposed system for optimal operational performance, including environmental and sustainability aspects.

The overall objectives of this case study were motivated by Bill 126 (The Management and Reduction of Greenhouse Gases Act, introduced in Newfoundland and Labrador in 2010) and include developing a SWH system that features strong technical performance, low cost, high reliability, and easy availability, and is environmentally-friendly (meaning, in this case, that it is fully solar-powered). Our work also aims to improve PV production capacity and take advantage of the latest energy efficiency initiatives (e.g., feed-in-tariff and net metering programs) as well as satisfy domestic water heating requirements.

2.5 System Description and Schematics

Our proposed system is a closed-loop that is both active and indirect. It includes a collector fluid loop made up of fluid manifolds, collector plates, storage tank (with integrated heat exchanger), drain back tank, circulating pump (installed next to the collector plates on the roof of the house and driven by a PV panel-powered DC motor), controller unit, and a few other components. To guarantee the availability of hot water even on cloudy days, the storage tank has two auxiliary heating elements that are powered by the main power supply. The drain back tank is placed indoors to prevent it from freezing and is positioned at a sufficiently high level to reduce pumping power.

Inside the storage tank, the heat exchanger transfers heat via natural convection from the solar collector loop to the solar storage tank.

Meanwhile, up on the roof, there are two 4.4 m^2 glazed collectors on the roof's support framing, with foam-insulated copper piping measuring 25 mm in diameter. The system circulates water through the solar collectors only when there is sufficient energy to be gained from the sun. In other words, the collector panel will start the circulating pump only when solar radiation exceeds a certain level. The collector panel operates the DC motor through a built-in linear current booster (LCB) that features a differential temperature controller. The panel applies a proportional speed control strategy devised according to the collector module's variable output. Such a set-up guarantees optimal functioning at every level of solar irradiance and also allows the pump to start pumping with as little as one watt of power [72].

Heat-transfer fluid (HTF), which is a mixture of water and polypropylene glycol (at 60% and 40%, respectively), has a far lower freezing point than water and features low toxicity. As it is confined to an unpressurized closed loop, the HTF is pumped through the collectors separately from the end-use water being heated through a heat exchanger. When the pump is turned off, the HTF runs out of the sloped collectors and pipe and into the drain back tank. The air in the drain back tank then fills the collectors, therefore reducing any potential threats caused by stagnation conditions that may arise (in summer, for instance) due to high temperatures and pressure in the loop. Heated water from the solar collectors is contained within a 300-litre standard water tank and is made available for household use. A 12 VDC brushless DC motor drives the solar circulating pump. The motor is attached to the pump by a rotating electro-magnetic field that also drives the pump. The motor control circuit has a built-in differential temperature solar controller with linear current booster and essentially offers full control functionality for the water heater to be entirely powered by the sun. Two thermistor temperature sensors are attached to the pump to enable differential temperature control operations. Hence, by comparing the two temperature sensor values, the controller can make sure that the solar pump functions only when the solar collector sensor exceeds the storage tank sensor by a differential of 5 °C. The controller has high and low temperature limits as well as an adjustable high storage tank temperature limit cutout (at 90 °C) and fail-safe protection [73].

CHAPTER 3 DESIGN OF A SOLAR WATER HEATING SYSTEM WITH THERMAL STORAGE FOR A THREE-BEDROOM HOUSE IN NEWFOUNDLAND

Preface

A version of this manuscript has been presented at ICCE2016: 5th International Conference & Exhibition on Clean Energy the Conference was at McGill University, August 22-24, 2016 Montreal, Canada. The co-author, Dr. Tariq Iqbal, supervised the principle author, Ahmed Aisa, to develop the research on the entitled topic and helped him to conceptualize the techniques and theories available for this research. Ahmed wrote the paper, "Design of a Solar Water Heating System with Thermal Storage for a Three-bedroom House in Newfoundland", and Dr. Iqbal reviewed the manuscript and provided necessary suggestions.

Abstract

Newfoundland Power estimates that the second largest energy consumption in Newfoundland homes is water heating, which accounts for approximately 20% to 25% of household energy costs. The annual average heat of a small house load in Newfoundland is 1.3KW. In Canada, the average consumption of hot water per person is approximately 50 to 75 L per day and the average Canadian household uses 225L. This paper will demonstrate a method for designing a solar water heating system with thermal storage. The system can provide hot water for a small house. SAM and HOMER are used in this study, which are design models that calculate the consumption of hot water and cost for a system.

Keywords—thermal storage, solar water heating, renewable energy, domestic heating.

3.1 Introduction

The main goal of the present work is the thermal energy storage of a domestic solar water heating system, typically composed of a vacuum-tube solar collector, a thermal storage tank, pumps, piping and a control unit, in order to achieve optimal performance. An additional goal is to increase knowledge of design standards and operating parameters, such as mass flowing through the solar collector array, the area of solar collectors, and storage tank volume that matches domestic hot water demands. This chapter will also discuss system sizing and investigate various design procedures for the proposed system [74], given that the system is complex in design and exposed too many different temperatures and pressures. The quality of the chosen fluid needs to be known, and the geometric shapes such as diameter and length of the heat storage tank, heat exchanger system pipes, area of the solar collector, and pumps for the circulation of the fluid with a flow rate adjustment mechanism, must also be calculated [75].

Today's highly technological needs have caused a near absolute dependence on fossil fuel-powered energy sources. With the world's population estimated to increase to 12 to 15 billion by the end of this century (i.e., doubling the current population), this represents enormous challenges for the energy sector. For instance, if the anticipated population consumes energy to the same extent as it is being consumed today. Moreover, the traditional way of generating electricity has triggered numerous environmental problems that result in excessive CO_2 emissions into the atmosphere, contributing to issues around global warming [74, 76].

In light of these problems, there has been a notable spike in research into alternative energy options that are cleaner and cheaper than fossil fuels. Attention is especially growing with regard to generating power by using Concentrating Solar Thermal Power plants. In this approach, solar energy has the function of heating a working fluid. A tank is provided with a thermal energy storage facility which can provide heat during times of low solar irradiance or no sunlight at all. Storage media refers to the storage tank material or the thermal fluids used for storing heat [77].

There are different types of storage media and the individual characteristics and performance of each of these can be seen through relevant simulations. The storage tank holds thermal fluids for providing power for heat when it is needed in the home. Selecting the best thermal storage media that fulfills all these parameters requires more than just performance-based analysis, as environmental, social and economic factors must also be assimilated into modeling a system that is tailored to meet growing energy demands [78].

3.2 Heating Water in Newfoundland and Labrador Homes

Canada's far eastern provinces of Newfoundland and Labrador experience extremely cold weather in the winter, so houses there need to be heated to a comfortable level. This is one of the largest usages of energy in the region. Most houses in Newfoundland and Labrador are heated via baseboard heaters, oil-fired furnaces, or wood stoves. These methods require an enormous amount of energy, which means that home-heating costs are expensive. However, some methods can help homeowners save on energy consumption and reduce heating costs. Additionally, reducing greenhouse gases that are produced by using energy generated from fossil fuels is also an important step in the fight against climate change. After home heating, the second largest energy use in Newfoundland homes is the heating of water in tanks, which accounts for approximately 20% of household energy costs [70].

On average, the typical family of four or five uses 120 to 250L, but this depends on the demands of each person needing hot water; there are some days when they may use more or less hot water, depending on their activities .The Cold Climate Housing Research Center in Alaska used calculations about the consumption of hot water per week displayed through a Microsoft Excel spreadsheet. Tables 3.1 illustrate the average consumption of hot water per week [79, 80].

3.3 Key Assumptions of the System Design

The SAM, BEopt and Matlab software models have introduced a few limitations to the software’s range. Because of these changes, two important assumptions must be made when evaluating of Solar Water Heating Project using the SAM, BEopt and Matlab software. First, assume that the daily volumetric load is constant, regardless of the time of year or solar irradiation levels. Secondly, must assume that the four residents of the 1-storey home in St. John’s, NL, will display relatively efficient hot water usage habits (e.g., taking short showers instead of baths, turning water off while shaving, washing clothes in cold water when possible, etc.) [74].

Table 3.1: Weekly Hot Water Consumption Estimate for a Family [79, 80, 81]

Activity	Times Per Week	Water Usage (gallons)	Total
Washing face or hands	14	1	14
Shower	14	10	140
Shaving	2	2	4
Food prep	14	4	56
Washing dishes by hand	14	4	56
Dishwasher	14	6	84
Clothes washer	3	7	21
Total Weekly Usage (gallons)			375

3.4 Site Information and Data Collection

Canada's eastern-most province, Newfoundland, was chosen as the preferred location for this project since it boasts more solar resources than any other region in Canada. The structure will use in study is a 1-storey home situated in St. John's, the largest city in Newfoundland. St. John's is positioned at latitude 47.34°N and longitude -52.42 °E. For the sake of our study, we assume that the 1-storey home, which is 202.34 m², and that the roof has an area is 13.5*15 m², and faces a southerly direction. Furthermore, we assume that the home uses an electric hot water heating system, so we will position the storage tank in the basement at a horizontal distance of 4.4 meters from the collector. We will use a standard 900-litre tank and foam-insulated copper piping. From a cost perspective, we will assume that the homeowner bought the system at an interest rate of 7%, but a discount rate of 8% will be applied here for the financial analysis. As of the time of writing this thesis, Newfoundland Power's 2016-2017 General Rate Application electricity rates decreased by an overall average of approximately 7.9%, or about $7.90 on a $100 monthly electricity bill [power Newfoundland] [69]. We will use glazed solar collectors that feature a 10-year warranty and promise a life expectancy of 25 years [70]. Residents of Newfoundland who buy and install a solar domestic hot water heating system can receive a rebate of $1,000 [71].

3.5 Load Demand Calculations

There are several factors that impact the performance of an SWH system with a storage tank. The main factors are: system characteristics, available solar radiation, ambient air temperature, and heating load characteristics. Furthermore, the appropriate sizing of the system's components is necessary to achieve optimal performance of the system as well as to satisfy the required load demand. In this work, the SAM Project Model was utilized to estimate the household's hot water requirements [63, 81].

3.6 Calculation of Annual Energy Demand

An important consideration of any power generating system is load. The average heat load in Newfoundland and Labrador is 1.3(kW). In this study, the estimated load depends on annual energy demand considered to scale via calculation Equation (3.1).

The equation for calculating the annual energy demand is as follows:

$$Q_{demand} = Q_{DHW} + Q_{Losses} \qquad 3.1$$

$$Q_{Losses} = Q_{SHL} + Q_{Circ} \qquad 3.2$$

$$Q_{DHW} = {mc_p\Delta T}/{3600}\,\frac{kWh}{day} \qquad 3.3$$

$Q_{SHL} = \theta$ kWh / day 3.4

$Q_{Circ} = k. Q_{DHW}$ 3.5

K is assumed loss factor (%)

M is mass of water to be heated (kg)

C_p is specific heat capacity of water (kJ/kg. °K)

ΔT is Required temperature rise (°K)

Where Q_{DHW} is domestic hot water (kWh/day)

Q_{SHL} is Standby heat losses. (KWh/day)

Q_{CIRC} is Circulation heat losses. (KWh/day)

According to Newfoundland Power, the temperature for hot water heaters in dwelling units should be set between 54 and 60 ℃ (130 to 140 °F)[83]. This is suitable for most homes, including those with dishwashers (considering that dishwashers need very hot water to be effective). Furthermore, Newfoundland Power sets the average hot water consumption at 225 L per day and 75 L per person per day for a household with five individuals. Specifically, the tank's minimum and the maximum temperatures were determined using the application VBusTouch on March 2, 2016, at 1:51 p.m. Given that the minimum temperature was 10.9 °C and the maximum temperature 41.6℃Assume that the incoming water temperature is an average of 10°C according to the U.S. Geological Survey, so density of water is specified as 0.996 (presumably kg/L [82, 83]. From question 3.4, we can calculate.

m= number of people * personal daily demand* density of water. 3.6

m= 5*75*0.996 = 373.5kg c_p= 4.180 kJ/ kg. K

The published standby heat loss for the cylinder is 2.6 kWh/day [83], and the assumed losses of circulation can be10% [83]. Thus, from question 3.3 we get:

$$Q_{DHw} = 373.5*4.180*(60\text{-}10)/\ (60*60) = 21.68\ \mathrm{kWh/day}$$

$$Q_{SHL} = 2.6\ \mathrm{kWh/day}$$

The annual energy demand can be calculated by the question as:

$$Q_{demand} = [(1 + k)Q_{DHW} + \ Q_{SHL}] * 365\ \frac{kWh}{year} \tag{3.7}$$

$$Q_{demand} = [(1 + 0.1)21.68 + \ 2.6] * 365 = 9{,}653.52\ \frac{kWh}{year}$$

3.7 Components of a Water Heater System

A water heater uses energy to raise the temperature of cold water coming in from the municipal water system or from a well. The thermal energy storage of a domestic solar water heating system is comprised of a solar collector, a thermal storage tank, pumps, piping and a control unit.

3.7.1 Sizing of a solar collector

The solar collector is considered the core of any solar system that utilizes a collector to increase the temperature of the heat transfer fluid that is used to transfer heat to the heat exchanger and convert energy from the sun into electricity. The converted energy is then used to power electrical equipment and will also be used in proposed system [78]. There are many types of solar collectors, and they are generally classified according to operating temperature. In system, an Evacuated Tube Collector is type of solar collector is utilized, which is made of double-layer borosilicate glass tubes that are evacuated to provide insulation. It also helps with the absorption of solar radiation and transfers the heat to the water, which flows through the inner tube .Water tubes of solar collectors are usually made of copper. These pipes absorb heat energy directly from the solar radiation as well as by conduction from the solar collector. In fact, to suppress thermal losses through convection, the volume enclosed in the glass tubes must be evacuated to less than 10-2 bar. Evacuation prevents losses through thermal conduction, but radiation losses cannot be reduced by creating a vacuum [84].

Additionally, an absorber is installed as either flat or upwards vaulted metal strips or as a coating applied to an internal glass bulb in an evacuated glass tube. In this way, all the water will flow directly through the collector and then accumulate in the thermal storage tank. By applying this method, to improve the thermal behavior of the solar collector. The inlet temperature to the collector equals the ambient temperature, and at this point we have maximum efficiency. Moreover, we decreased the volume of the storage tank because some of the load will be extracted instantaneously from the collector. This is because collectors may be less effective during cloudy weather and are usually more expensive than flat plate systems; however, they can produce higher temperatures than flat plates and help to reduce convective heat losses [78].

HOMER software is used to calculate solar radiation for a specific location. The model calculates theoretical solar radiation [79]. Imported solar radiation data from NASA for the location at (latitude 47.5605 °N and longitude 52.7128 °W) on an hourly basis. The annual average value of solar energy for Newfoundland and Labrador is about $3.153\mathrm{kWh/m^2/day}$, this is global horizontal irradiance, and this location receives the maximum solar irradiance during the months of June and July. Figure 3.1 charts the monthly solar radiation. Table 3.2 below shows the location and station identification [79].

Table 3.2: Location and Station Identification

Requested Location	**St. John's NL**
Weather data source	(INTl) St. John's,
Latitude	47.5605° N
Longitude	52.7128° W

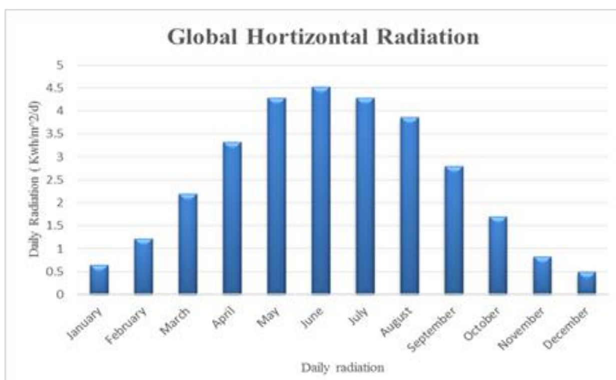

Figure 3.1: Monthly solar radiation using HOMER software based on data collected from NASA.

3.7.2 Sizing calculation for annual energy demand of the solar collector

The solar collector is considered the core of any solar system. These systems use a solar thermal collector to raise the temperature of the heat transfer fluid, which then transfers heat to the heat exchanger [83, 84]. As mentioned previously, there are many types of solar collectors, all of which are classified according to operating temperature. Most of the water tubes in the collectors are made of copper. The pipes absorb heat energy directly from solar radiation as well as by conduction from the solar collector. In fact, to suppress thermal losses through convection, the volume enclosed in the glass tubes must be evacuated to less than 10-2 bar, which prevents losses through thermal conduction. The radiation losses cannot be reduced by creating a vacuum.

Additionally, an absorber is installed as either flat or vertical vaulted metal strips, or as a coating applied to an internal glass bulb in an evacuated glass tube. In this way, all the water will flow directly through the collector and then accumulate in the thermal storage tank. The solar collector area was calculated by using the following procedure [83].

$$Q_{\mathrm{Solar}} = Q_{\mathrm{demand}} * \delta_{\mathrm{fn}} \quad 3.8$$

Where δ_{fn} is the design solar fraction, typically 30-60% [83]. Consequently, the assumed value of the solar fraction is 50%.

$Q_{\mathrm{solar}} = 9{,}653.52 * 0.5 = 4826.76$ KWh/year

The annual radiation in St. John's, Newfoundland, is about 3kWh/m^2/day

3*365 = 1095 kWh/$\frac{\mathrm{m}^2}{\mathrm{year}}$

$A_{\mathrm{collecter}} = \frac{Q_{\mathrm{solar}}}{R_{\mathrm{radation}}} = \frac{4826.76}{1095}$ = 4.4079 m^2

The collector can be derived by using Equation 3.9 but is dependent on some data assumptions, such as the temperature inlet and outlet collector. The first iteration used an estimate of the plate temperature of 15 and 50 ℃. Furthermore, three values of the overall heat transfer coefficient U_L were chosen (2, 4, and $8 \, {}^{W}/_{m^2\ °C}$) [85].

$$\eta_{\text{collecter}} = \frac{Q_u}{A_c G_T} \qquad 3.9$$

$$Q_u = A_c F_R [G_T (\tau\alpha) Q_{av} - U_L (T_i - T_a)] \qquad 3.10$$

Where, are Q_u,rate of solar energy, A_c bank area of collector F_R the collector's heat factor, U_L, while the overall heat transfer coefficient, G_T the incident of radiation and $\tau\alpha$ absorbed solar radiation. In this thesis, we will be using the value of the annual daily average incident solar energy in Newfoundland, which is about 3kWh/$\frac{m^2}{day}$. F_R of the collector's heat removal factor ,F_R is approximately (0.70) [85]. The absorbed solar radiation $\tau\alpha$ is about 0.96 and the overall heat transfer coefficient $U_L$is approximately (2 ${}^{W}/_{m^2\ °C}$)[85].

$\tau\alpha * F_R$ =0.70 *0.96 = 0.672, so $F_R(\tau\alpha)_{av} = 0.672$

$F_R * U_L$ =0.70*2 = 1.4 ${}^{W}/_{m^2\ °C}$

$$Q_u = 4.4079[3 * 1000 * 3600/(24 * 3600) * 0.672 - 1.4 * (50 - 15)]$$

$$Q_u = 4.4079[125 * 0.672 - 49] = 154.27 \, {}^{W}/_{m^2}$$

$$\eta_{\text{collecter}} = \frac{154.27}{4.4079 * 125} = 0.28 \ 28\%$$

Additionally, the losses of the tank and pipe can be calculated by first assuming them to be well-insulated. The storage tank is assumed to be of the high insulated type (Energy Star rated). In this thesis we will be using 4% of the fraction of the storage tank losses, and 1% of the value fraction of the pipe [83, 85].

Storage losses of the tank can be expressed as follows:

$$Q_{\text{losses of tank}} = Q_{\text{daily}} * 4\% \qquad 3.11$$

$$Q_{\text{losses of tank}} = 154.27 * 0.04 = 6.1708 \ {}^{\text{W}}/_{\text{m}^2}$$

Losses of the pipe can be calculated as in the following equation:

$$Q_{\text{losses of pipe}} = Q_{\text{daily}} * 1\% \qquad 3.12$$

$$Q_{\text{losses of pipe}} = 154.27 * 0.01 = 1.5427 \ {}^{\text{W}}/_{\text{m}^2}$$

System simulation in SAM software relied on available components and types in the library. The model of the solar collector implemented was selected based on the library of SAM software. Table 3.3 shows the parameters of the collector.

Table 3.3: Parameters of Solar Collector

Quantity	Value
SRCC number	20060 15D
Type	Glazed flat-plate
Area	4.49
FRta	0.658
Test flow rate	0.0617

3.7.3 Sizing of storage tank

Using a hot water tank for thermal energy storage is the best approach. The objective is to save enough energy when it is applied, such as through an energy supply system with cogeneration or a solar tap water system, and the majority of today's hot water tanks improve the efficiency of the electricity supply [70, 86]. Generally speaking, the storage tank volume is determined by the amount of water consumed in the house, keeping in mind that the temperature is raised by using a heat storage tank that stores solar energy. When sunlight is not available, the stored energy is utilized by the house for heating, washing, cooking, etc.

The sizing of a water storage tank also depends on the use of a bulk storage tank system. The storage capacity of the tank is very important for the efficient operation of a water supply system. Additionally, the tank should be large enough to store a sufficient amount of water to meet the peak daily demand. Therefore, the demand for water and how it varies during the year, such as whether people use more water in particular months or on special holiday occasions due to entertaining guests, needs to be taken into consideration. Determining the adequate storage tank capacity volume requires the estimation of the monthly and annual value according to volume changes .This system uses a heat storage method, so the energy is stored by raising the temperature of the material [87].

The storage tank volume is determined by the amount of water used in the household and the temperature acquired by using a heat storage tank that stores solar energy. According to Newfoundland Power, size selection is based on family and house size. For a family of five living in a 3-to-5-bedroom house, normal hot water use would be for showering, clothes washing, and dishwashing. For these needs, the capacity of the tank should be approximately 124 and 227 L. Furthermore, when choosing a size for the water storage tank, the major determining factors are the storage tank cost and its useful energy delivery. A rule of thumb is that 1 .5m^2 of the collector is required for each 75 L of hot water to be delivered .The storage tank should be large enough to hold about a 4-to-5-day supply of hot water [88].

Based on the above criteria, and also considering the non-recoverable heat losses from the storage, a storage tank of 900L would be ideal. The selected storage tank is equipped with an integral heat exchanger in the tank, the latter which provides ample hot water for households with five or more people. Water is usually moved from the solar water storage tank to a standard water-heater tank. Hot water can be obtained via solar water and also produces a temperature that is much higher than is needed in the house. However, the system has some special valves which are used to protect the temperature from rising too high. When a faucet is turned on, hot water flows from the storage tank and cold water flows into the tank to displace the hot water [89]. A thermostat turns on the burner or electric element to maintain the water temperature in the storage tank. The average heat load consumption of hot water in Newfoundland and Labrador is 1.3 (kW). Based on these data, the minimum and the maximum temperatures of the tank were determined using application (VBusTouch) on March 2, 2016 at 1:51PM, as shown in Table 3.4. The equation for calculating the flow rate of the storage tank is:

$$\mathrm{Q} = \dot{\mathrm{m}}_{\mathrm{storage}} \mathrm{C_p} (\mathrm{T_{max}} - \mathrm{T_{min}}) \tag{3.13}$$

$$\dot{m}_{storage} = \frac{1.3*1000}{4181(41.6-10.9)} = 0.010120 \frac{Kg}{s}$$

Also based on this equation, the size of the storage tank can be calculated as:

$$\dot{m}_{storage} = \rho VA \tag{3.14}$$

$$V = \frac{\dot{m}_{storage}}{\rho A} \tag{3.15}$$

Where Q is the amount of heat storage (W)

$\dot{m}_{storage}$ is the Flow rate ($\frac{Kg}{S}$)

ρ is the density of the fluid ($\frac{Kg}{m^3}$)

A is the area of the tank storage (m^2)

V is the volume of the tank ($\frac{m^3}{s}$)

T_{max} is the maximum temperature of the fluid in the tank (℃)

T_{min} is the minimum temperature of the fluid in the tank (℃)

A cylindrical-shaped tank has the best temperature stratification. Consider such a tank with diameter D, height L, and volume V. The volume of the tank is expressed as in the following equation.

$$V = AL \quad V = \pi L \frac{D^2}{4} \ (m^3) \tag{3.16}$$

The total surface area S_ao of the tank with these dimensions is given by:

$$S_a = \pi \frac{D^2}{4} \times 2 + \pi \times D \times L \ (m^2) \tag{3.17}$$

The parameters listed in Table 3.4 illustrate correspond to a glazed solar collector design. The reference efficiency is based on the absorber area covered by cells as well as the incidence angle modifier coefficient [85].

Table 3.4: Parameters of Tank Storage [90, 91]

Parameter	Value	Unit
$\mathbf{V_{tank}}$	900	L
$\mathbf{\dot{m}_{storage}}$	0.010120	$\frac{Kg}{s}$
Item depth	24	inches
Item weight	174	In LBS
$\mathbf{T_o}$	41.6	℃
$\mathbf{\Delta T_{aux}}$	30.7	℃
$\mathbf{T_i}$	10.9	℃
$\mathbf{Q}$	1.3*1000	W
$\mathbf{K_{st1}(stainless - AISI302)}$	15.1	$W/m.K$
$\mathbf{K_{st2}(Rock\ Wo}$	0.045	$W/m.K$
$\mathbf{K_{st3}(Galvaniz}$	18	$W/m.K$
$\mathbf{D_{diameter\ of\ tank}}$	500	mm
$\mathbf{C_{p\ specific\ heat\ of}}$	4181	$\frac{J}{Kg.k}$
$\mathbf{\rho_{density\ of\ water}}$	1000	Kg/m^3

3.7.4 Design of heat exchanger

The heat transfer that needed to be designed as well as the performance of a heat exchanger that may have applications and uses in engineering. A heat exchanger is a device that is 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. For instance, if the device separates fluids via heat transfer through the surface and the fluids do not mix or leak with other fluids, the system is called a closed system. Depending on the design of the heat exchanger, fluid movement is diverse and can be described variously as parallel flow, counter flow, multi-pass and cross-flow. Some assumptions can be made when designing, including factors such as constant properties, negligible heat loss to the surroundings, and negligible tube wall thermal resistance and fouling factors. The required heat transfer rate may emerge from the energy balance for a hot fluid [92, 93].

A heat exchanger is typically used according to flow. The average temperature of the water inlet to the heat exchanger is between 25 and 50 ℃, and the outlet temperature is between 15 and 25 ℃, while the flow rate varies in temperature and the amount of heat which it gets from the solar collector. In this paper, we used the effectiveness of the heat exchanger in the range 0.6 to 0.8. Also, some data can be found in the ASHRAE 93-2003 standard and the parameter of heat exchangers is listed below in Table 3.5 [75].

$$Q = \dot{m}_c C_p \left(T_{co} - T_{ci}\right) \tag{3.18}$$

$$T_i = T_{co} - \frac{Q}{\dot{m} C_p} \tag{3.19}$$

The required tube length from Equation

$$Q = UAF\Delta T_{1m,CF} \tag{3.20}$$

where $U = \frac{1}{(\frac{1}{h_i}) + (\frac{1}{h_o})}$ 3.21

where we can calculate h_i by using R_{eD} 3.22

$$\dot{m} = \frac{\dot{m}_c}{N} \quad 3.23$$

$$R_{eD} = \frac{4\dot{m}_1}{\mu\pi D}$$

If the flow is turbulent using Equation (N_{uD})

$$N_{uD} = 0.023 R_{eD}^{4/5} P_r^{0.4} \quad 3.24$$

$$\text{So } h_i = \frac{K}{D} N_{uD} \quad 3.25$$

The correction factor F may be from the following equations:

$$R = \frac{T_i - T_o}{T_o - T_i} \qquad P = \frac{T_o - T_i}{T_i - T_i} \quad 3.26$$

$$\Delta T_{1mCF} = \frac{(T_i - T_o) - (T_o - T_i)}{\ln[\frac{T_i - T_o}{T_o - T_i}]} \quad 3.27$$

The length of the tube is determined by Equation (3.28).

$$L = \frac{Q}{UN\pi DF\Delta T_{1mCF}} \quad 3.28$$

Table 3.5: Parameters of Heat Exchanger [104,105]

Parameter	**Value**	**Unit**
$K_{heat,exchanger}$	400	W/mk
$d_{heat,exchanger}$	0.025	m
$D_{heat,exchanger}$	0.028	m
$L_{heat,exchanger}$	17	m
Density of ethylene glycol	1113.2	$\frac{Kg}{m^3}$

3.7.5 Solar heat pump and design size of pump

The cycle of heating in solar energy can absorb the high efficiency of the solar collector and accumulate hot water inside the storage tank. During the cycle of the solar heat pump, the temperature of the cooling system can be improved by between 20 ℃ to 30 ℃, which is partitioned to serve the heating system. A solar heat pump system mainly consists of solar collectors such as heat pump units, a heat storage water tank, and ancillary equipment. In the winter, it will convert heat through solar collectors flowing to the energy storage tank and then revert to the solar collectors. Energy stored in the storage tank is thus extracted and transferred to the evaporator in the heat pump unit to supply the heat source. In this system, a pump is used to circulate the fluid through the solar thermal collector. One type of pump is called the centrifugal pump .The overall purpose of a pump is to give the necessary pressure head to control the flow rate and hence the energy collection, thus increasing the heat pumps evaporator temperature and decreasing the collector operating temperature. The pump depends on the flow rate to circulate the fluid from the storage tank to the solar collector and back to the tank during steady flow conditions in a closed circuit. The pump has to supply only friction head, so the rating of the pump depends on the static head to which the fluid has to be pumped as well as on the flow rate [80, 94].

The units of high pumping are m (H), maximum volume flow rate $(\frac{m^3}{s})$ (Q) and the efficiency of the pump (η). A centrifugal pump uses a rotating impeller to increase the pressure and flow rate of the fluid. As the liquid radiates outward, the velocity increases due to centrifugal force. The benefits of a centrifugal pump are its flat flow, uniform pressure in the discharge pipe, low cost, and high operating speed [94, 95]. The pump power of a system can be calculated as shown in Equation (3.29).

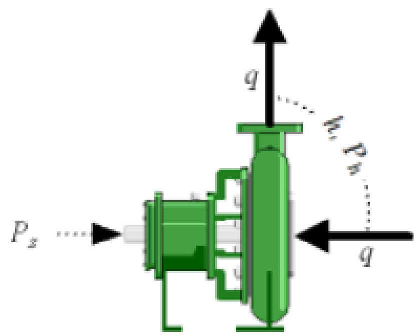

Figure 3.2: Cross-section of a centrifugal pump [95].

$$P = \rho g Q h \qquad 3.29$$

$$P_{shaft} = \frac{P_h}{\eta} \qquad 3.30$$

P= Power of pump (kW)

$\rho =$ density of fluid ($kg/m3$)

g = gravity (9.81 m/s2)

$Q =$ Flow capacity (m3/h)

$h =$ Differential head (m)

In this thesis, the estimated assumed flow rate for r heat transfer fluid is (0.5 $\frac{m^3}{h}$), for differential heat is (10 m), and for type of fluid is Ethylene glycol (1113.2 $/m3$).

$$P= \frac{1113.2* 9.81 * 0.5* 10}{3600} = 15.167 \text{ W}$$

Therefore, assuming a typical pump efficiency of 60% and a motor efficiency of 80%:

$$P_{electrical} \frac{15.167}{0.6*0.8} = 31.6 \text{ W}$$

The shaft power of the pump can be calculated by the following equation (3.30) [85, 81].

$$P_{shaft} = \frac{P_h}{\eta} = \frac{15.167}{0.6} = 25.27 \text{ W}$$

Table 3.6 below shows illustrates parameters used in SAM software for simulation.

Table 3.6: Parameters Used in SAM Software

Parameter	Value	Unit	
Location (St. John's NL)			
Latitude	47.5605° N		Given
Longitude	52.7128° W		Given
Storage tank			
Solar tank volume	0.9	m^3	
Solar tank height to diameter	1.4	m	Assumed
Solar tank heat loss coefficient	1	$^{W}/_{m^2}$ ℃	
Solar tank maximum	90	℃	
Heat exchanger			
Effectiveness	75	%	Assumed
Outlet set temperature	50	℃	Assumed

Parameter	Value	Unit	
Room temperature	25	℃	Assume d
Piping			
Total piping length	25	m	
Pipe diameter	0.04	m	selected
Conductivity coefficient of copper pipe	0.043	$W/_{m.K}$	selected
Thickness	25	mm	
Pump			
Pump power	15.167	W	
Pump efficiency	60	%	
Solar collector			
Area	4.4079	m^2	
Tilt	60	°	
Azimuth	180	°	

3.8 Economic Performance and Installed Cost Analysis

A summary of the cost analysis for this project performed using analysis tool. This system is eligible for financial incentives provided by the government of Newfoundland. The applicable incentive currently available is the Energy Efficient Rebate program. Under this program, residents who purchase and install a solar domestic hot water heating system are eligible to receive a rebate of $1,000 [96]. The periodic cost represents recurrent costs that are incurred at regular intervals to maintain. The only recurrent cost associated with this system considered as a periodic cost. This system is maintenance free and hence, has no associated O&M costs. Results show that the heating system accounts for about 66.3% of the total project cost [68].

3.9 Financial Analysis

The financial input parameters used in the financial analysis for this project is presented in table 3.7. In this model, the incentive provided is deemed not to be refundable and is treated as income during the development/construction year. The discount rate is used to calculate the annual life cycle savings. In North American, a discount rate of 6 to 11% is common amongst electric utilities. For this thesis, a discount rate of 7.61% / year is used for the financial analysis. In table 3.8 shows provides a summary result of the key output indicators of the financial viability of the thesis. Results show that the thesis has very positive viability based on all key financial indicators used for the thesis – Net present value (NPV), internal rate of return (IRR) and payback period. Also the weighted average cost of capital (WACC) is 7.32% [68].

Table 3.7: Financial Parameters

Parameter	Value	Unit
Loan parameters		
Debt fraction	15	%
Loan term	20	years
Loan rate	7	years
Analysis parameters		
Analysis period	20	years
Tax and insurance rates		
Federal income tax rate	15	% year
State income tax rate	7	% year
Sales tax	15	% of

		total direct cost
Insurance rate (annual)	0.7	% of installed cost
Salvage value		
Net salvage value	8	% of installed cost

Table 3.8: Project Cost Analysis Summary

Parameter	Value	Unit
Loan parameters		
Debt	1616.45	years
WACC	7.32	years
Analysis parameters		
Inflation	2	% years
Real discount rate	5.5	% years
Nominal discount rate	7.61	% years
Property tax		
Assessed percentage	100	% of installed cost
Assessed value	10776.32	$
Annual decline	1	% year
Property tax rate	10	% year
Salvage value		
End of analysis period value	862	$

3.10 Simulation in System Advisor Model and Results

The ideal solar thermal system was modeled in SAM software (Transient System Simulation Tool) using equivalent components from the simulation studio platform. In addition, initial a volume of water using a 237.755-gallons volume of water. Also, System Advisor Model (SAM) software uses information that is by the user (installation/operating costs and design parameters) to estimate energy costs and performance levels of grid-connected power. On the customer side, they can buy and sell electricity at retail prices [97].

Table 3.9 shows some data results, such as capacity factors (15.7%), annual energy saved (3128kWh), and levelized costs of energy (COE) (130.06 ¢/kWh). It is a time-series hourly simulation program that can simulate the performance of photovoltaic and SWH systems using weather data. The operating requirements set for the thesis, as well as the parameters obtained from the components sizing, were used to build the SAM model and results show that the model performed as expected over the simulated period. The collector temperature and useful energy gain characteristics are presented. This condition is linked to the pump control actions, where at certain times of the day the pump stops, letting stagnate for a few minutes in the collectors, resulting in elevated temperatures of the in the collectors.

Table 3.9: Simulation Results System at 237.755 Gallons

Metric	Value
Annual energy saved	3128 kWh
Solar fraction	0.09

Metric	Value
Aux with solar	32282.7 kWh
Aux without solar	35438.1 kWh
Capacity factor	15.7%
Levelized COE (nominal)	130.06 ¢/kWh
Levelized COE (real)	116.11 ¢/kWh
Electricity cost without system	$624
Electricity cost with system	$125
Net savings with system	$4369
Net present value	$-18442
Net capital cost	$10776
Debt	$1616

Figure 3.3, shows the decrease in energy production by SAM software throughout several years due to the normal degradation of the system.

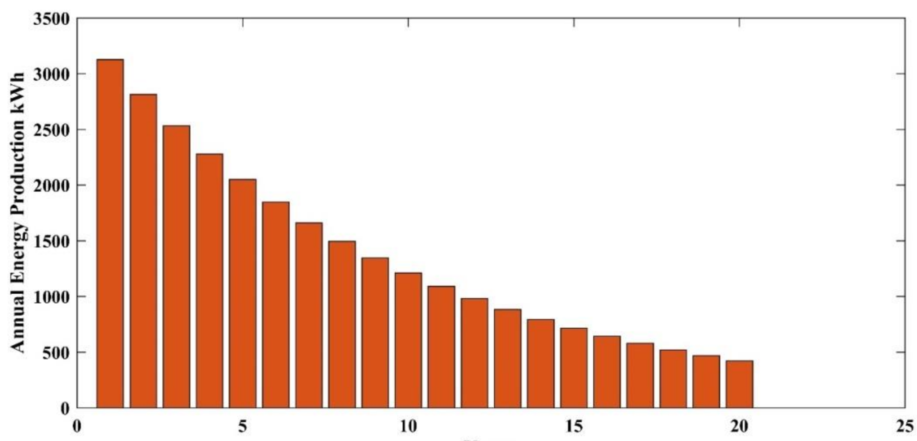

Figure 3.3: Annual energy production over a period of 20 years.

In Figure 3.4, monthly energy production varied over time but was highest in April and lowest in December. The monthly energy production depends on the temperature, which explains why it is high in the summer months and low in the winter months.

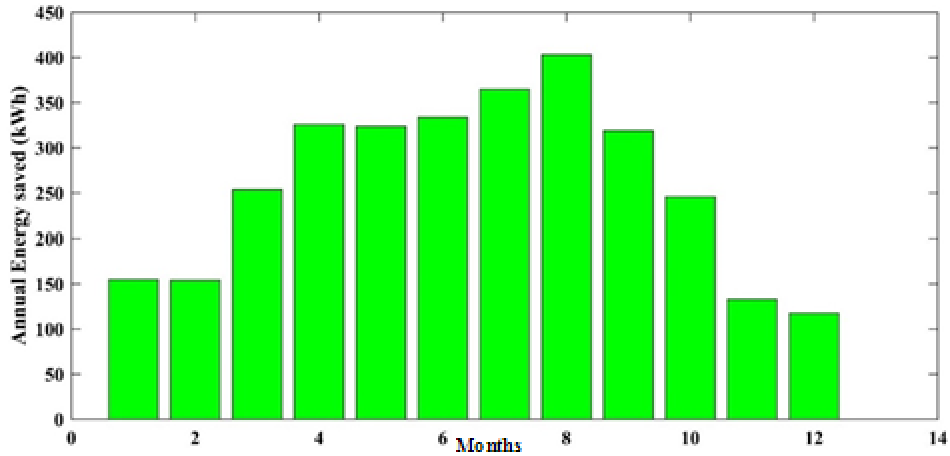

Figure 3.4: Monthly energy production over a period of 12 months.

Figure 3.5, shows the transmitted irradiance being high in the summer months and low in the winter ones. This is due to Earth receiving more sun radiation in summer than in winter.

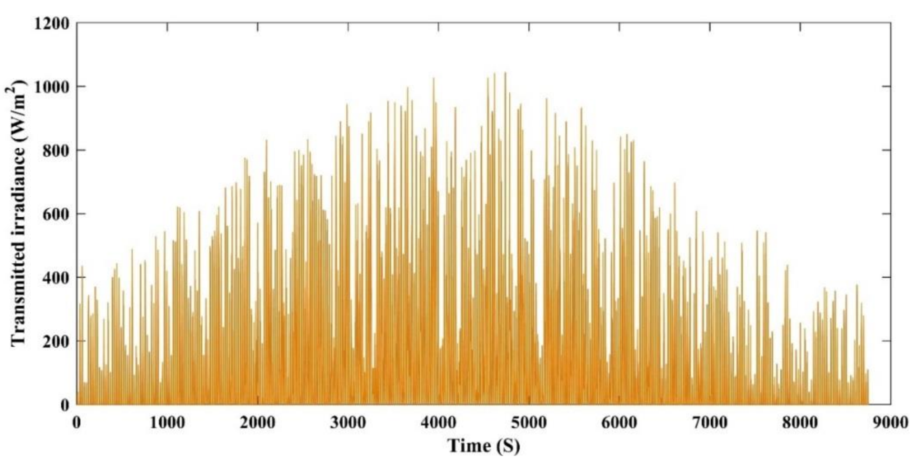

Figure 3. 5: Transmitted irradiance over a period of 12 months.

Figure 3.6, shows the highest temperatures throughout the whole year that can be used for storage energy. Once again, summer months have a much higher temperature than their winter counterparts.

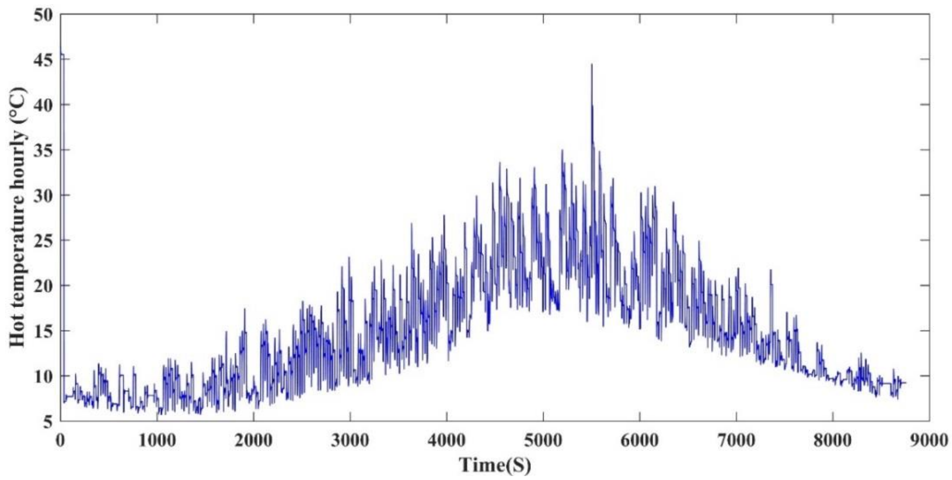

Figure 3.6: Temperature (Hot, in °C) over a period of 12 months.

When using a 237.755-gallon volume of water, Table 3.10 shows the differences in monthly temperatures. As can be seen, the maximum is in August (11.517 °C), the minimum is in February (5.679 °C) and the mean is 15.110 °C. The lowest temperatures are in February and the highest in August.

Table 3.10: Monthly Temperatures (°C) at 237.755 Gallons

Time	Mean	Min	Max
Jan	9.8692	5.9207	11.517
Feb	8.1113	5.6795	11.9178
Mar	9.6952	5.7044	17.4467
Apr	12.3617	6.6987	19.3111

May	14.9219	8.8113	23.1608
Jun	19.1975	10.9667	29.935
Jul	23.4787	14.9314	33.6642
Aug	24.136	15.4058	44.4962
Sep	21.0719	13.1662	30.9666
Oct	16.4307	11.181	24.9275
Nov	12.066	9.3135	21.7801
Dec	9.4416	7.3618	12.5493

Figure 3.7, shows that there is a lot of stored heat (i.e., high temperature) in the summer months compared to the winter months, since the tank is much warmer during the summer. This is directly correlated to Figure 3.6, because whenever there is more heat available for storage, there is more stored energy. In both figures, the temperature is highest in September and lowest in December and January.

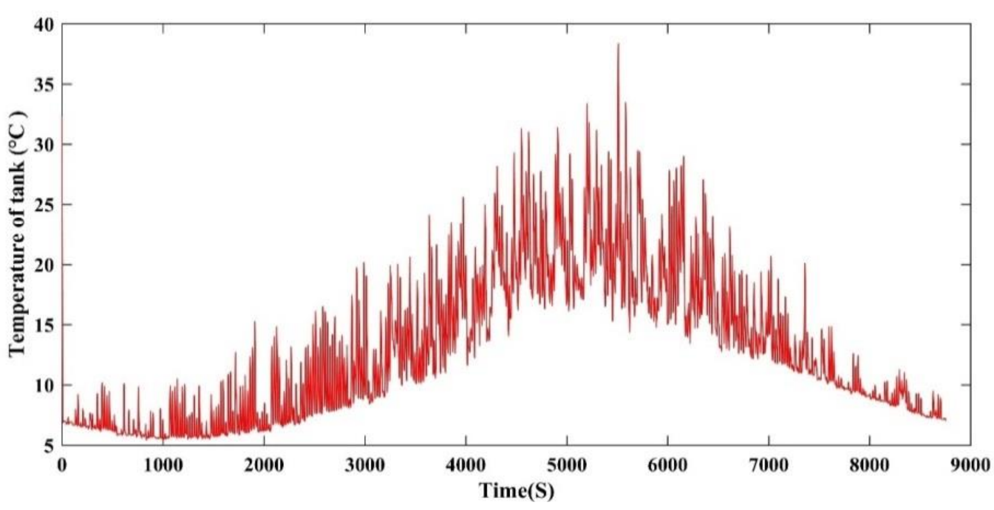

Figure 3.7: Temperature (in °C) of the tank over a period of 12 months.

Table 3.11 shows the monthly averaged tank temperatures when using a 237.755 gallon volume of water. The maximum is in August (38.385 °C), the minimum is in February (5.395 °C), and the mean is 12.900 °C.

Table 3.11: Monthly Tank (°C) at 237.755 Gallons

Time	**Mean**	**Min**	**Max**
Jan	6.8177	5.6686	32.3354
Feb	6.2992	5.3954	10.5276
Mar	7.3855	5.4933	15.2978
Apr	9.5286	6.4751	17.467
May	12.4502	8.43	20.6216
Jun	16.9655	10.5387	28.1795
Jul	21.0961	14.0477	31.3921
Aug	21.5184	14.3736	38.3854
Sep	18.6819	12.7713	29.0009
Oct	14.4349	11.1035	23.1448
Nov	10.7789	8.7696	20.1199
Dec	8.3474	7.0398	11.2926

In Figure 3.8, the volume of hot water in the tank was the highest in July and August, which is yet again correlated to external temperature, since there is a higher volume in the summer months.

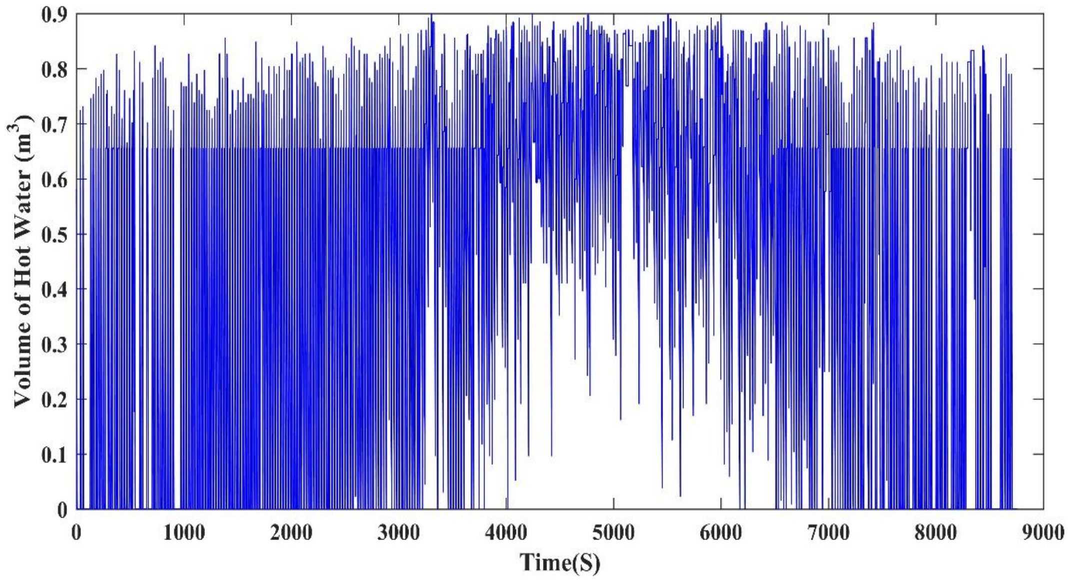

Figure 3.8: Volume of hot water (m^3) in tank storage during a period of 12 months.

Table 3.12 shows the monthly volume of hot water (m^3) in tank storage when using a 237.755 gallon volume of water. The maximum is in May and June 0.9 (m^3), the minimum is most months 0(m^3), and the mean is 0.431 (m^3).

Table 3.12: Monthly Volume of Hot Water (m^3) at 237.755 Gallons

Time	Mean	Min	Max
Jan	0.2111	0	0.8415
Feb	0.2284	0	0.8561
Mar	0.3062	0	0.8488
Apr	0.3667	0	0.8561
May	0.472	0	0.9
Jun	0.6092	0	0.9
Jul	0.6778	0.0958	0.8976

Aug	0.6609	0.0227	0.8988
Sep	0.5958	0	0.8927
Oct	0.4578	0	0.8854
Nov	0.3006	0	0.883
Dec	0.2675	0	0.8415

In the winter months, hot water consumption is a lot higher than in the summer due to colder temperatures. This is shown in Figure 3.9, where the usage of hot water was measured over the course of a whole year.

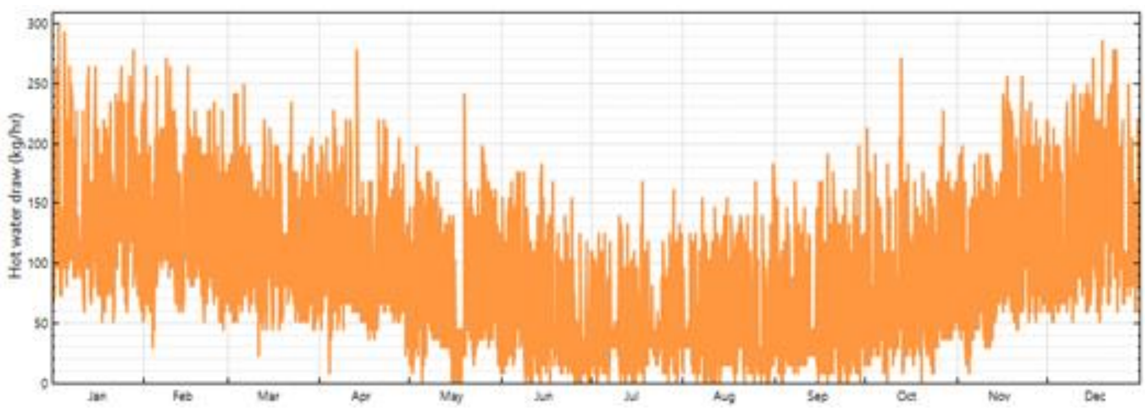

Figure 3.9: Hot water usage (in kg/hr) over a period of 12 months.

Figure 3.10, shows the amount of energy saved over the course of a year, indicating that it is higher in the summer.

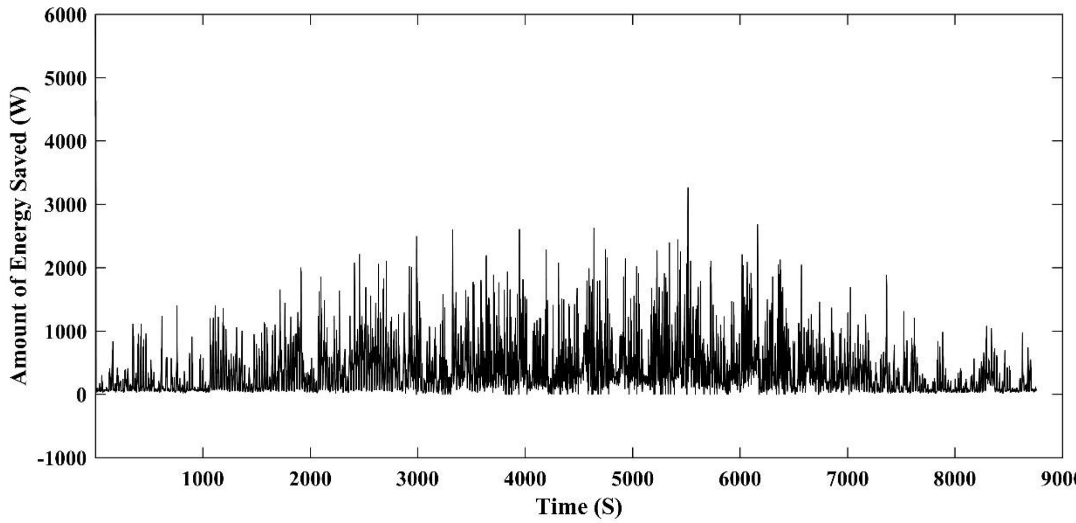

Figure 3.10: Amount of energy saved (in W) throughout the course of one year.

A parametric analysis was conducted on the energy saved when the initial volume of water was 237.755 gallons. Table 3.13 shows the energy saved. The maximum savings occurred in January (6435.475 W), the minimum occurred from May to October (9.100 W), and the mean was 357.126 (W).

Table 3.13: Energy Saved (W) at 237.755 Gallons

Time	**Mean**	**Min**	**Max**
Jan	208.3174	21.9801	6435.4746
Feb	229.5825	15.3631	1406.6437
Mar	340.5173	20.5799	2002.931
Apr	452.2805	5.8415	2211.0439
May	435.1441	-9.1002	2606.0518
Jun	463.4154	-9.1002	2608.6387
Jul	490.381	-9.1002	2632.3

Aug	541.5781	-9.1002	3262.5283
Sep	442.7131	-9.1002	2685.6758
Oct	329.9323	-9.1002	2046.0781
Nov	184.7171	11.4801	1882.342
Dec	158.289	8.6663	1078.8971

Figure 3.11, shows the Q loss (of energy) through the year, with the summer months having the highest loss of energy.

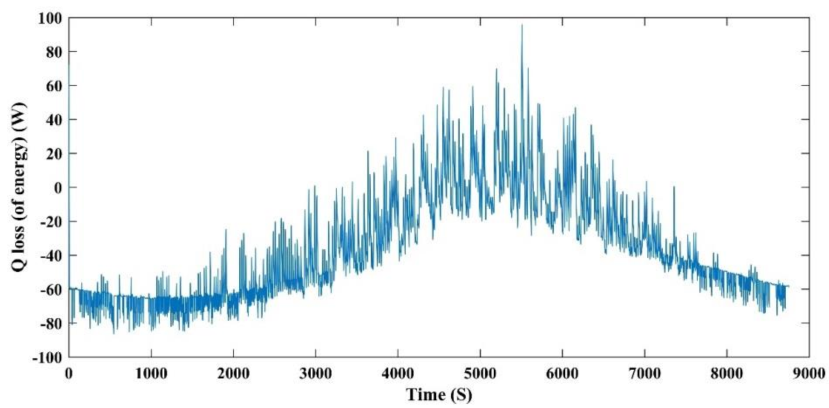

Figure 3.11: Q Loss (in W) over a period of 12 months.

In Figure 3.12, we can see that monthly energy production varied over time when using a 1000-gallon volume of water. Production also depends on temperature, which explains why it is highest in the summer months and lowest in the winter. Therefore, energy decreased from 9350 to 240 kWh from January to February, and then increased to a maximum of 410 kWh from April to August.

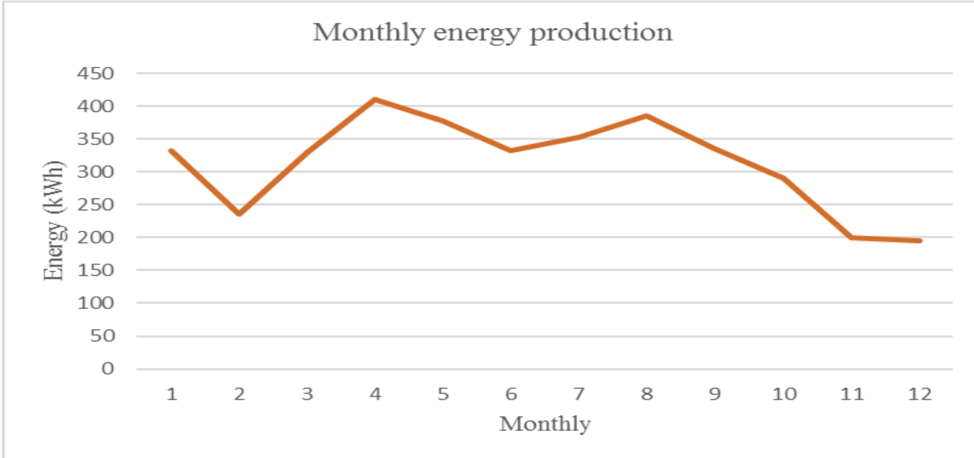

Figure 3. 12: Monthly energy production over a period of 12 months.

Table 3.14 shows the monthly average for tank temperatures when using a 1000-gallon volume of water. As can be seen, the maximum of 37°C occurred in January, the minimum of 5.7°C occurred in February, and the average was 13.9°C.

Table 3.14: Temperature of Tank (°C) at 1000 Gallons

Time	Mean	Min	Max
Jan	7.7865	6.0397	37.0545
Feb	6.9788	5.6876	8.999
Mar	8.3993	6.4604	14.0669
Apr	11.0014	8.171	14.4701
May	13.8553	10.2853	17.3365
Jun	17.948	14.4917	22.6248
Jul	22.0022	18.6894	25.4912
Aug	22.227	18.7937	25.6873
Sep	20.3482	15.2382	25.0374

Oct	15.7996	12.4337	19.338
Nov	11.5916	9.2924	15.4686
Dec	8.8836	7.4656	10.39

Table 3.15 shows the different monthly temperature readings when using a 1000-gallon volume of water. As can be seen, the maximum of 46.494°C occurred in January, the minimum of 6.209°C also occurred in January, and the means was 15.029°C. A decrease in temperature occurred in February and an increase in August.

Table 3.15: Hot Temperature Monthly at 1000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	10.9712	6.2095	46.4939
Feb	7.8646	6.3185	13.5539
Mar	9.2362	6.6356	25.9999
Apr	12.0604	8.4815	30.2067
May	14.8593	10.9237	30.389
Jun	18.8709	14.7679	24.9871
Jul	22.9318	19.0604	28.1858
Aug	23.2291	18.8626	28.4654
Sep	21.4082	17.387	35.6841
Oct	16.5238	12.6701	21.5972
Nov	12.2178	9.4967	17.3059
Dec	9.6211	8.024	11.9663

Table 3.16 shows the monthly volume of hot water (m^3) in tank storage when using a 1000-gallon volume of water. The maximum of 3.785 (m^3) occurred in May and June, the minimum 0 (m^3) occurred in other months, and the means of 2.975 (m^3) occurred in March.

Table 3.16: Monthly Volume of Hot Water (**m^3**)

Time	Mean	Min	Max
Jan	1.9803	0	3.7271
Feb	2.3368	0	3.7697
Mar	2.9036	1.5117	3.7806
Apr	3.0872	1.7091	3.7794
May	3.2341	1.2046	3.7854
Jun	3.4576	2.4109	3.7854
Jul	3.5517	2.952	3.7781
Aug	3.5082	2.8715	3.7708
Sep	3.3906	1.3289	3.7818
Oct	3.2888	2.0161	3.7745
Nov	2.6937	0	3.7587
Dec	2.2267	0	3.7624
Total	2.9748	0	3.7854

In Figure 3.13, we can see that monthly energy production varied over time when using a 2000-gallon volume of water, and is highest in the summer months and lowest in the winter months. Thus, in January and February, energy decreased from 540 to 290kWh, and the maximum was in January.

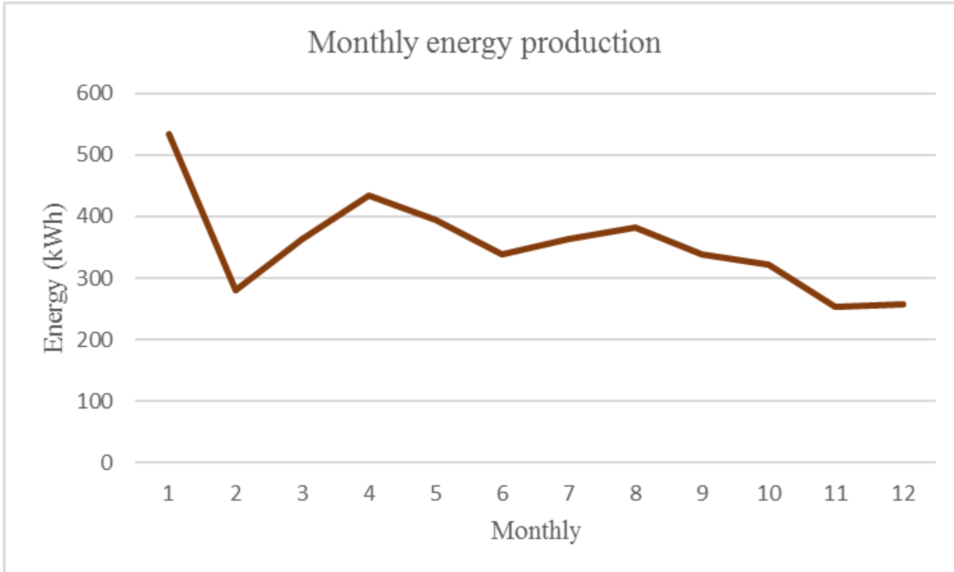

Figure 3. 13: Monthly energy production over a period of 12 months.

Table 3.17 shows the difference in monthly temperatures when using a 2000-gallon volume of water. As can be seen, the maximum of 3.9 °C occurred in May and June, and the minimum of 0 °C occurred in other months.

Table 3.17: Monthly Data hot (°C) at 2000 Gallons

Time	Mean	Min	Max
Jan	1.9803	0	3.7271
Feb	2.3368	0	3.7697
Mar	2.9036	1.5117	3.7806
Apr	3.0872	1.7091	3.7794
May	3.2341	1.2046	3.7854
Jun	3.4576	2.4109	3.7854
Jul	3.5517	2.952	3.7781
Aug	3.5082	2.8715	3.7708
Sep	3.3906	1.3289	3.7818

Oct	3.2888	2.0161	3.7745
Nov	2.6937	0	3.7587
Dec	2.2267	0	3.7624

Table 3.18 shows the monthly average tank temperatures when using a 2000-gallon volume of water. The maximum of 37.797 °C occurred in January, the minimum of 6.052 °C occurred in February, and the mean was 14.50 °C.

Table 3.18: Monthly Tank Data (°C) at 2000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	8.8267	6.5976	37.7969
Feb	7.6703	6.0521	8.8024
Mar	9.0734	7.5493	11.3923
Apr	11.6821	9.3629	14.2176
May	14.3585	12.2405	16.469
Jun	18.206	15.2001	21.1155
Jul	22.4136	19.5477	26.8784
Aug	22.3067	20.0288	24.0457
Sep	20.6948	17.7111	23.5503
Oct	16.5311	13.4685	19.1437
Nov	12.2432	10.2056	14.8279
Dec	9.4919	7.8417	10.5218

Table 3.19 shows the monthly volume of hot water (m^3) in tank storage when using a 2000-gallon volume of water. The maximum of 7.571 (m^3) occurred in January,

February and December, the minimum of 0 (m^3) occurred in May, and the mean was 0.931 (m^3).

Table 3.19: Monthly Volume of Hot Water ($\mathbf{m^3}$) at 2000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	2.2632	0.0036	7.5708
Feb	1.6612	0.0157	7.5708
Mar	0.8937	0.0145	2.2737
Apr	0.7191	0.006	2.1714
May	0.5602	0	2.6758
Jun	0.329	0.0036	1.4183
Jul	0.2361	0.0012	0.8335
Aug	0.288	0.0146	0.9431
Sep	0.4069	0.0036	2.4565
Oct	0.5219	0.0109	1.7912
Nov	1.4282	0.0121	7.4353
Dec	1.9062	0.023	7.5708

Figure 3.14, shows how monthly energy production varied over time when using a 3000-gallon volume of water. The monthly energy production was highest in the summer months and lowest in the winter months. In January and February, energy decreased from 700 to 310kWh, after which a simple increase of energy occurred to steady state conditions.

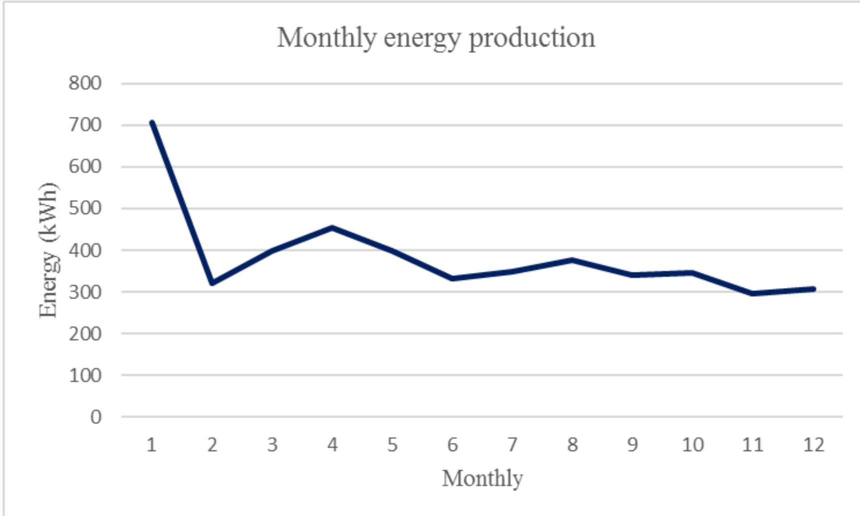

Figure 3. 14: Monthly energy production over a period of 12 months.

Table 3.20 below shows the monthly differences in temperature when using a 3000-gallon volume of water. The maximum of 55.552 °C occurred in July and the minimum of 7.0171 °C occurred in February.

Table 3.20: Monthly Data for Hot Water (°C) at 3000 Gallons

Time	Mean	Min	Max
Jan	12.0888	7.5309	46.5165
Feb	8.6081	7.0171	9.9596
Mar	9.9679	8.3824	15.6089
Apr	12.6044	10.3033	29.0677
May	15.1086	13.0784	21.2951
Jun	18.7538	15.325	28.8519
Jul	22.7328	19.8451	55.5525
Aug	22.9447	20.7148	27.1537
Sep	21.4728	19.3524	37.7505

Oct	17.4202	14.4276	22.3809
Nov	13.2776	10.9775	17.5141
Dec	10.443	8.2808	12.4138

Table 3.21 shows the monthly average tank temperatures when using a 3000-gallon volume of water. The maximum of 38°C occurred in January, the minimum of 6.691 °C occurred in February, and the mean was 14.8°C.

Table 3.21: Monthly Tank Data (°C) at 3000 Gallons

Time	Mean	Min	Max
Jan	9.9294	7.469	38.046
Feb	8.1334	6.6908	9.0051
Mar	9.5669	8.2687	11.3923
Apr	12.0624	10.0734	14.0707
May	14.5069	12.8229	16.0833
Jun	18.1499	15.2333	20.5386
Jul	22.0506	19.7208	24.9929
Aug	22.268	20.6095	23.4364
Sep	20.8441	18.7208	22.793
Oct	17.0079	14.2697	19.4192
Nov	12.8005	10.8834	14.9671
Dec	9.9335	8.0019	10.9337

Table 3.22 shows the monthly daily volume of hot water (m^3) in tank storage when using a 3000-gallon volume of water. The maximum of 11.356 (m^3) occurred in May, the minimum of 0 (m^3) occurred in December, and the mean was 10.358 (m^3).

Table 3.22: Monthly Data Hot Water (m^3) at 3000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	8.9403	1.2475	11.3198
Feb	9.5343	1.6983	11.3123
Mar	10.4625	9.0825	11.3417
Apr	10.6322	9.1848	11.3502
May	10.6961	7.2474	11.3562
Jun	11.0274	9.9379	11.3526
Jul	11.129	10.5447	11.355
Aug	11.0672	10.4131	11.3416
Sep	10.9517	8.8997	11.3526
Oct	10.8217	9.565	11.3416
Nov	9.7969	3.8404	11.3502
Dec	9.192	0	11.3332

As can be seen in Figure 3.15, monthly energy production varied over time when using a 4000-gallon volume of water. Furthermore, monthly energy production was highest in the summer months and lowest in the winter months. However, in January and February, energy decreased from 840 to 350kWh, followed by a simple increase of energy to steady state conditions.

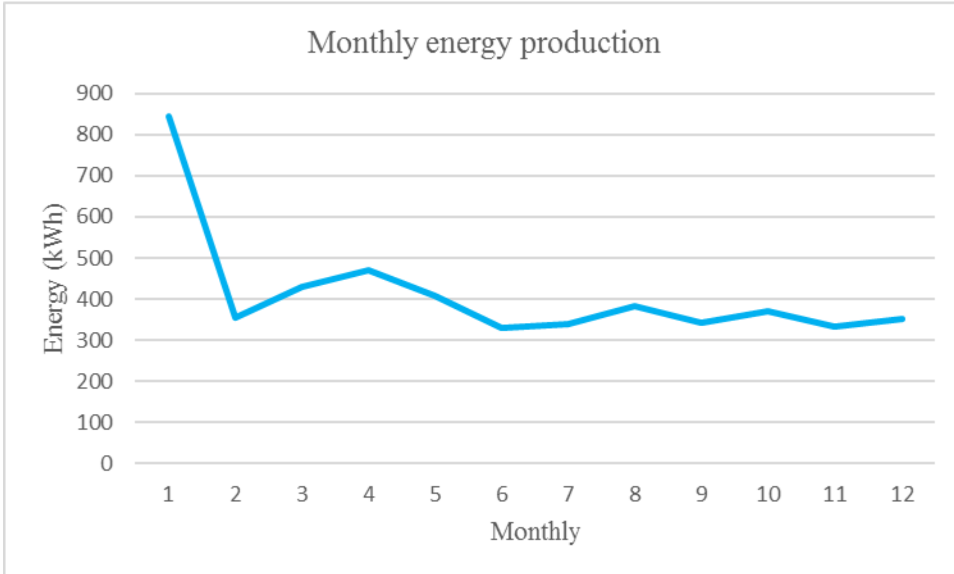

Figure 3. 15: Monthly energy production over a period of 12 months.

Table 3.23 shows the different monthly temperatures when using a 4000-gallon volume of water. As can be seen, the maximum of 54.3°C was in July and the minimum of 7.7°C was in February.

Table 3.23: Monthly Data Hot Water (°C) at 4000 Gallons

Time	Mean	Min	Max
Jan	15.0022	8.1293	46.5212
Feb	8.9713	7.6882	10.2146
Mar	10.2982	8.8504	15.9408
Apr	12.7997	10.7754	29.1893
May	15.2654	13.3839	21.1485
Jun	18.6781	15.5424	28.4725
Jul	22.4449	19.8155	54.2764
Aug	23.0459	21.0165	40.0856

Sep	21.5052	19.7285	37.8832
Oct	17.7916	14.9892	22.6831
Nov	13.6916	11.4763	17.851
Dec	10.7802	8.594	12.7628

Table 3.24 shows the monthly average tank temperatures when using a 4000-gallon volume of water. The maximum of 38.2°C occurred in January, the minimum of 7.45°C occurred in February, and the mean was 15°C.

Table 3.24: Monthly Tank Data (°C) at 4000 Gallons

Time	Mean	Min	Max
Jan	10.4452	7.8855	38.1711
Feb	8.571	7.4527	9.3039
Mar	9.9456	8.7787	11.5082
Apr	12.3281	10.5915	14.0179
May	14.7379	13.1913	16.0833
Jun	18.1152	15.4739	20.2107
Jul	21.7972	19.7227	24.0152
Aug	22.386	20.9082	23.6462
Sep	20.934	19.2669	22.3761
Oct	17.4072	14.853	19.7337
Nov	13.2876	11.3836	15.2374
Dec	10.3227	8.5216	11.4037

Table 3.25 shows the monthly volume of hot water (m^3) in tank storage when using a 4000-gallon volume of water. The maximum of 15.142 (m^3) occurred in May, the minimum of 0 (m^3) occurred in January, and the mean was 14.032 (m^3).

Table 3.25: Monthly Data for Hot Water (m^3) at 4000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	11.6899	0	15.1052
Feb	13.2902	5.4837	15.0977
Mar	14.2003	10.9743	15.1271
Apr	14.4131	12.9702	15.1356
May	14.4811	11.0328	15.1416
Jun	14.8128	13.7233	15.138
Jul	14.9177	14.3301	15.1404
Aug	14.8545	14.1985	15.1404
Sep	14.734	12.6851	15.138
Oct	14.5407	11.9613	15.127
Nov	13.6067	8.028	15.1356
Dec	12.8171	1.4773	15.1076

In Figure 3.16, we see that monthly energy production varied over time when using a 5000-gallon volume of water. The monthly energy production is highest in the summer months and lowest in the winter months. Between January and February, energy decreased from 1000 to 400kWh, after which it experienced a simple increase to steady state conditions.

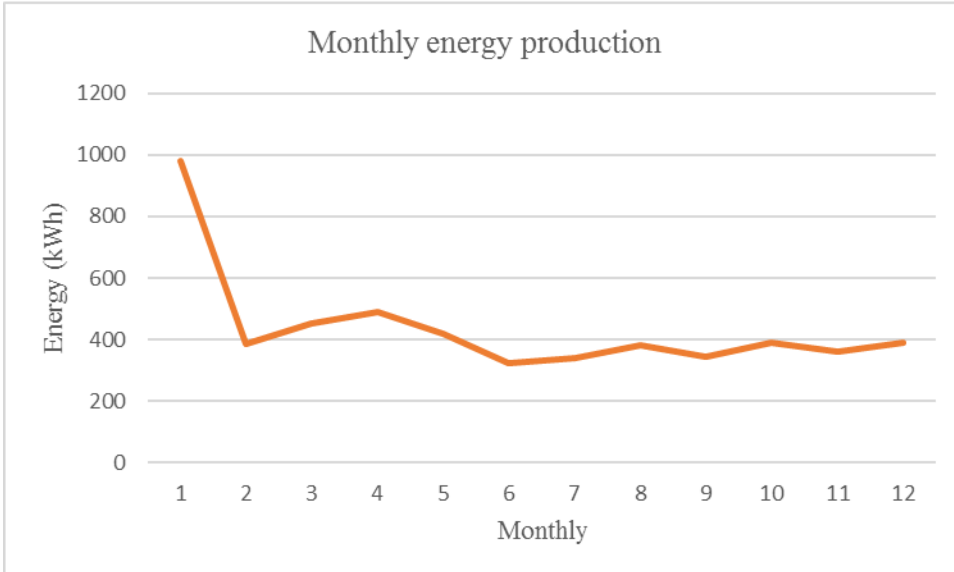

Figure 3. 16: Monthly energy production over a period of 12 months.

Table 3.26 shows an monthly temperature difference when using a 5000-gallon volume of water. As can be seen, the maximum of 57.423°C occurred in July and the minimum of 8.15°C occurred in February.

Table 3.26: Monthly Data Hot Water (°C) at 5000 Gallons

Time	**Mean**	**Min**	**Max**
Jan	15.2952	8.1524	46.5245
Feb	9.2857	8.1986	10.4867
Mar	10.5746	9.3205	21.6252
Apr	13.0213	11.206	29.4898
May	15.3977	13.638	21.0898
Jun	18.6039	15.7253	28.1655
Jul	22.5599	19.7566	57.4294
Aug	22.988	21.2695	40.1651
Sep	21.5344	19.9979	37.9824
Oct	18.0927	15.7876	22.9316

Nov	14.0484	11.8641	18.1434
Dec	11.1265	9.2139	13.1109

Table 3.27 shows the monthly average tank temperatures when using a 5000-gallon volume of water. The maximum of 38.246 °C occurred in January, and the mean was 15.314°C.

Table 3.27: Monthly Tank Data (°C) at 5000 Gallons

Time	Mean	Min	Max
Jan	11.1416	7.9363	38.2466
Feb	8.9385	8.0142	9.6178
Mar	10.2548	9.2021	11.9267
Apr	12.5917	11.0497	14.0288
May	14.9147	13.4832	16.1031
Jun	18.0659	15.6559	19.986
Jul	21.8942	19.6828	24.37
Aug	22.3498	21.1782	23.3414
Sep	20.9972	19.6365	22.1277
Oct	17.7352	15.3082	19.9775
Nov	13.6813	11.7779	15.4865
Dec	10.7225	9.1688	11.7958

Table 3.28 shows the monthly volume of hot water (m^3) in tank storage when using a 5000-gallon volume of water. The maximum of 18.927 (m^3) occurred in most months, the minimum of 0 (m^3) occurred in January, and the mean was 17.786 (m^3).

Table 3.28: Monthly Data Hot Water (m^3) at 5000 Gallons

Time	Mean	Min	Max
Jan	15.2195	0	18.8992
Feb	17.0757	9.2692	18.8832
Mar	17.9681	14.7598	18.9223
Apr	18.1986	16.7557	18.9211
May	18.2661	14.8183	18.9271
Jun	18.5988	17.6111	18.9235
Jul	18.7024	18.1156	18.9259
Aug	18.6395	17.984	18.9259
Sep	18.5182	16.4706	18.9235
Oct	18.2945	15.7468	18.9125
Nov	17.3332	11.7184	18.9199
Dec	16.5993	5.2628	18.9138

Table 3.29 below illustrates a comparison between differences in volumes of water, showing the results for different temperatures.

Table 3.29: Simulation Results System

Volume of water (gallon)	Mean temperature of tank (°C)	Minimum temperatu re of tank (°C)	Maximum temperatu re of tank (°C)	Area of collector (m^2)	Number of collector s
1000	13.9442	3.6876	37.0545	4.4	2
2000	14.5003	6.0521	37.7969	4.4	2
3000	14.8126	6.6908	38.046	4.4	2
4000	15.0635	7.4524	38.1711	4.4	2
5000	15.3144	7.9363	38.2466	4.4	2

3.11 Conclusions

The design was intended for a solar water heating system with thermal storage for a small house, with the main objectives of the system being optimal technical performance, minimal cost, high reliability, and availability. The location of the proposed site (St. John's, Newfoundland, Canada) receives an average incident solar radiation of approximately 3.153 (kWh/m^2/day). Newfoundland Power estimates that the second largest energy consumption for domestic users is water heating, which accounts for approximately 20% to 25% of household energy costs. Further, they estimate that the annual average heat load of a small house in Newfoundland is 1.3KW, and that the average consumption of hot water per person is approximately 50 to 75 L per day, with the average household using 225L.

This thesis proposed using a storage tank with an initial volume of water of 900-litre. When the heated water comes from the solar collectors, it is stored and made available for use by the home as required. This thesis demonstrated a method of designing a solar water heating system with thermal storage that can provide sufficient hot water for a typical house size in Newfoundland. SAM and HOMER, which are design models that calculate the consumption of hot water and cost for a system, were used in the study. Some results which were calculated mathematically include the annual energy demand, which was 9,653.52 kWh/year, and the collector area, which was 4.4079 m^2. The efficiency of the solar collector was 28%, and the losses of the tank and pipe were 6.1708 w⁄ (m^2) and 1.5427 w⁄ (m^2), respectively. The pump provided power for the system at 15.167 W. In addition, some results obtained through simulation were for monthly energy production, such as the annual energy savings (3128 kWh) and costs of energy (COE) (130.06 ¢/kWh).

CHAPTER 4 MODELING AND SIMULATION OF A SOLAR WATER HEATING SYSTEM WITH THERMAL STORAGE

Preface

A version of this manuscript has been published in the conference proceedings of IEEE IEMCON 2016, the 7th IEEE Annual Information Technology, Electronics and Mobile Communication Conference University of British Columbia, Vancouver, Canada, 13-15 October, 2016. This paper was also presented at that conference. The co-author, Dr. Tariq Iqbal, supervised the principle author, Ahmed Aisa, in developing the research on the topic and helped him to conceptualize the techniques and theories available for this research. Aisa wrote the paper, "Modelling and Simulation of a Solar Water Heating System with Thermal Storage", while Dr. Iqbal reviewed the manuscript and provided necessary suggestions.

Abstract

This paper presents a solar thermal energy storage system used for domestic water heating purposes in a detached house setting. Solar heating systems with seasonal energy storage have attracted growing attention in recent decades. However, because the availability of solar energy is discontinuous, heat storage is an indispensable element in a building's solar energy based thermal system. The objective of modeling is to determine the temperature of a tank and the heat loss of a system. System design is dependent on certain equations and data, such as temperature, time, and flow rate estimated in a lab. A BEopt and Matlab / Simulink model is used to determine the storage water temperature of the tank. Additionally, the house has two heat sources: the

hot water of the storage tank, and the solar used for heating. The maximum temperature of the storage tank was found to be 82.4 ℃ and the temperature inside the house ranged from 18 to 25.11 ℃. Overall, the heating of the house needed 12,268 kWh/yr.

Keywords — thermal storage; renewable energy; solar water heating; modeling and simulation.

4.1 Introduction

With the increase in electricity prices and growing environmental concerns, various technologies are being developed in order to extract energy from every available source and store the excess energy generated for later usage. One such solution is provided by Thermal Energy Storage Systems, which stores excessive energy for future applications. In the summer, solar radiation can be stored inter-seasonally to provide heating in the winter, and the cold from winter air can be used to run air conditioning in the summer. Energy storage is of particular importance, since it enables the decoupling of supply from demand. This is a valuable feature when dealing with variable renewable energy technologies and variable system demand. Additionally, the presence of energy storage units is a driver for the self-production and self-consumption of energy [61].

Interest is growing in the generation of power using Concentrating Solar Thermal Power plants, in which solar energy is concentrated to heat a working fluid. The trough approach is provided with a thermal energy storage facility, as it can provide heat during hours of low solar irradiance or even no sun. Storage media refers to the storage tank material or the thermal fluids used for storing heat. There are different types of storage media, and also can observe their individual characteristics and performance through relevant simulations. For instance, heat from solar collector equipment can be gathered in the hot months for space heating use when needed, including during winter months. Energy storage is of special importance because users can separate themselves from conventional energy use, enabling the decoupling of supply from demand [98].

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. Tanks can be stored in the basement or at the surface of the ground floor of a building. A cylindrical shape is preferable because it reduces the loss of heat. In addition, the heat exchange of water occurs inside the tank, which is often located in the basement of buildings. Using a control system can help in the achieving of the charging and discharging of thermal energy. Solar energy is used for heating water and solar panels are often placed on the roof of buildings to capture solar energy [99]. Many factors influence the storage of solar energy, such as the temperature in the tank and the quality of the metal used [100].

4.2 Seasonal Water Storage

Due to recently developed theoretical and concrete technology, sensible water thermal storage technology is used not only for short-term daily thermal storage but also for long-term seasonal thermal storage. Seasonal thermal storage has a long thermal storage period (generally several months), so seasonal energy storage can entirely utilize the temperature differences between winter and summer to meet or supplement the cooling and heating demands for both seasons This is different from short-term thermal storage technology, as seasonal thermal storage maintains the storage material at a lower temperature than short-term storage in order to reduce thermal losses during the longer storage period [101].

Considering the low storage temperature of seasonal thermal storage, heat pumps are usually used to assist in supplying heating or cooling demands [102]. Water presents the best choice for sensible thermal energy storage due to its relatively high specific heat and high rates of charge and discharge. Thus, water tanks can be made of steel or concrete or can have a cavity within the ground or geological feature. Thermal energy storage can be injected into the water tank by directly circulating water through a working heat exchanger. Figure 4.1, shows simple water storage tank that uses direct circulation of the storage medium for heat transfer. There are three requirements for using water tanks for thermal energy storage [103].

1. Heat losses should be minimized.

2. The tank should be properly designed for stratification.

3. The volume in the tank should be minimized.

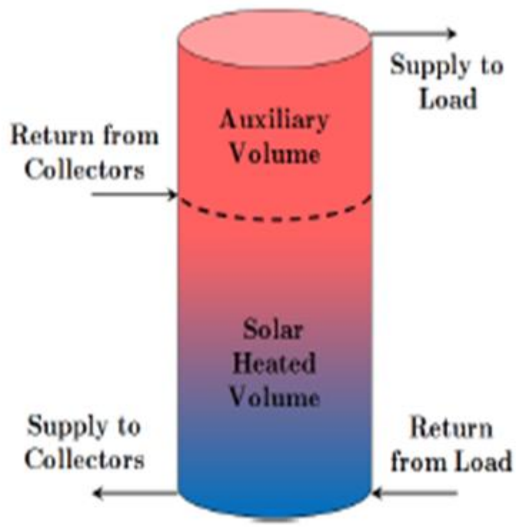

Figure 4.1: A simple water storage tank that uses direct circulation.

4.3 Mathematical Models and Methodology

The software MATLAB and BEopt, its optional add-on SIMULINK, were selected as simulation environments. Each simulation was solved using the discrete solver included in Matlab/Simulink. The simulations relied on solar water heating system model, of which several models pertain to individual system components. These include the solar collector model and the thermal energy storage of the tank model (which circulates water temperatures between solar collectors and the storage) as well as the insulated pipe segment model. Figure 4.2, illustrates the Simulink design of the system storage tank, pipes, solar collector, and heat exchanger. Re and Nu explain the theory undergirding the approach, and all equations are shown in the parameters table below.

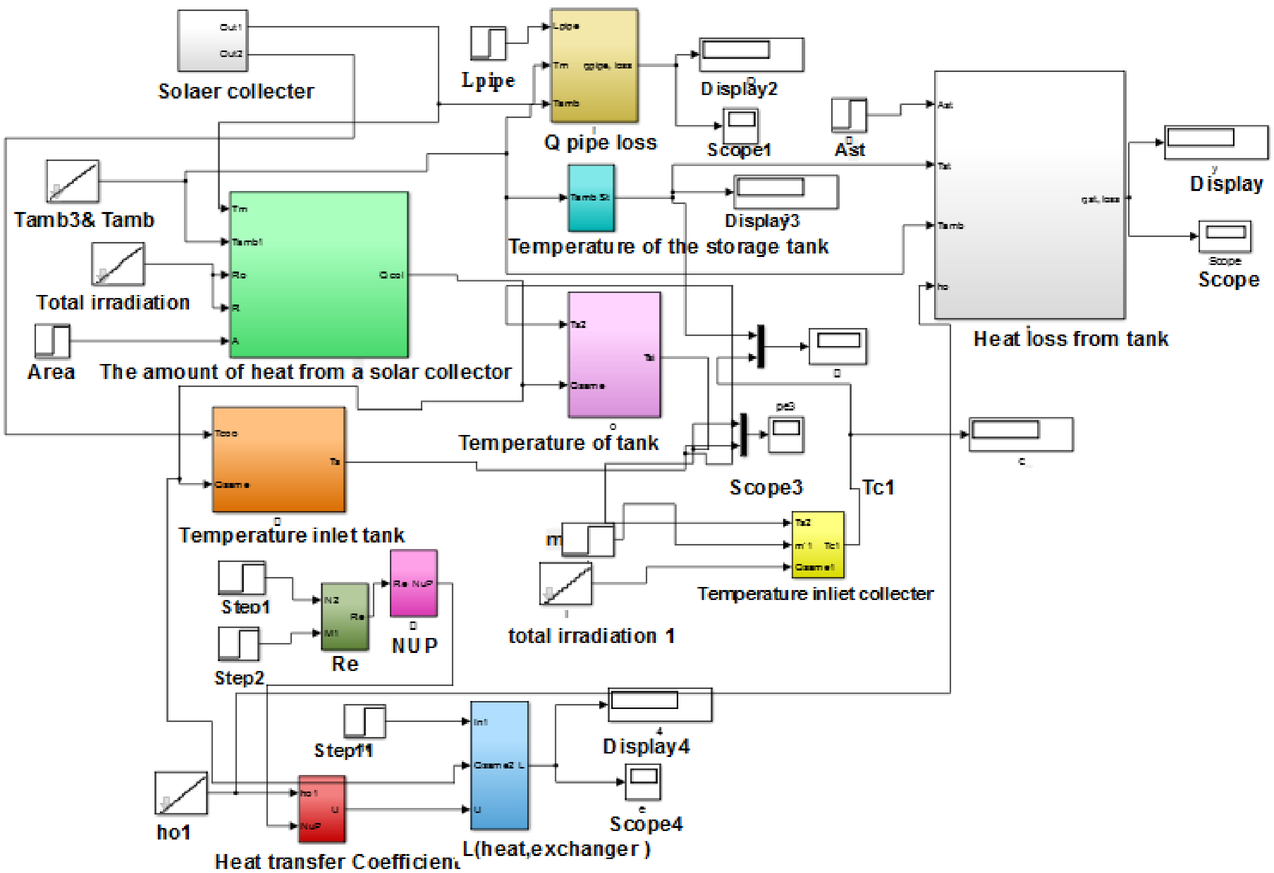

Figure 4.2: Simulink design of thermal energy storage system for a house.

4.4 Model of the Solar Collector

4.4.1 Heat of the solar collector

The heat of the solar collector can be calculated by the following equation:

$$\dot{q}_{col} = R_{tot} A_c \eta_c \tag{4.1}$$

Where R_{tot} is the total irradiation on the tilted surface, A_c is the collector net area, and η_c is the efficiency of the collector. Here, η_o, a, are constant and T_m is the circulating water mean temperature between the solar collector and storage [90].

$$\eta_c = \eta_o - a\left(\frac{T_m - T_{amb}}{R_{tot}}\right) - b\frac{(T_m - T_{amb})^2}{R_{tot}} \qquad 4.2$$

4.4.2 Heat collected by solar collector

The solar collector is dependent on the inlet and outlet temperatures. Additionally, as shown in Figure 4.3, below, the Simulink simulation of the solar collector and the temperature can be calculated using mass flow by the following equation [90,104].

$$\dot{q} = \dot{m}C_p(T_{out} - T_{in}) \qquad 4.3$$

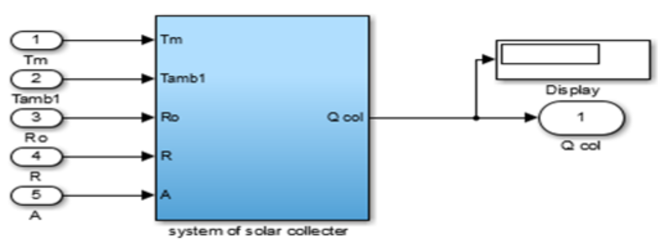

Figure 4.3: Simulink simulation of solar collector.

where $\dot{m}$ is the mass flow rate, C_p is the specific heat constant for water, T_{out} is the outlet temperature from the collector, and T_{in} is the inlet temperature in the Simulink simulation block shown in the figure.

4.5 Thermal Storage Tank Model

The thermal storage tank model was implemented based on the one-dimensional multi-node. Figure 4.4 shows the Simulink of heat loss from the storage tank based on Equation 4.7. The storage tank volume is determined by the amount of water used in the house along with the rise in temperature caused by using a heat storage tank that stores solar energy.

According to Newfoundland Power, size selection is based on family and house size for 5 families and 3-5 bedrooms. Normal hot water use powers an electric clothes washer and dishwasher, and the capacity of the tank is approximately 227 to 124 L. In sizing the water storage tank, major determining factors are the storage tank cost and useful energy delivery. A general rule of thumb is that 1.5 m^2 of the collector is required for each 75 L of hot water to be delivered [88]. The storage tank should be large enough to hold a 4-to-5-day supply of hot water. Based on these criteria and also considering the non-recoverable heat losses from the storage, a storage tank of 5,000 gallons is selected for this thesis**.** The annual energy demand can be calculated by the following equation:

$$Q_{demand} = [(1 + k)Q_{DHW} + Q_{SHL}] * 365 \frac{kWh}{year} \tag{4.4}$$

$$Q_{demand} = [(1 + 0.1)21.68 + 2.6] * 365 = 9{,}653.52 \frac{kWh}{year} \tag{4.5}$$

$$Q_{Solar} = Q_{demand} * \delta_{fn} \tag{4.6}$$

Where δ_{fn} is the design solar fraction, which is typically 30-60% [85]. Consequently, the assumed value of the solar fraction is 50% [85].

$Q_{solar} = 9{,}653.52 * 0.5 = 4826.76$ KWh/year

Annual radiation in St. John's is about 3kWh/m^2/day

3*365 = 1095 kWh/$\frac{m^2}{year}$

$A_{collecter} = \frac{Q_{silar}}{R_{radation}} = \frac{4826.76}{1095}$ = 4.4079 m^2

In order to determine the number of collectors required, we can calculate the number of collectors that we would need to meet the required aperture area. So, using SAM software and an LLC Radco 308C-HP Glazed Flat-Plate (aperture area 2.2 m^2) [83, 97].

The number of collectors is n = $\frac{A_{apmin}}{A_{308C-HP}}$ = $\frac{4.4}{2.2}$ = 2, so the array aperture area is 4.4m^2. We can now calculate the annual yield from the solar array as:

$Q_{solar} = R_{radation} * A_{apmin} = 1095 * 4.4 = 4818$ kWh/year

The region has an insufficient number of sunny days to heat water, with radiation in St. John's in January and December averaging only 1kWh/m^2/day.

1*365 = 365 kWh/$\frac{m^2}{year}$

$A_{collecter} = \frac{Q_{silar}}{R_{radation}} \quad \frac{4826.76}{365}$ = 13.224 m^2

Assuming that the residents want to begin using the system in August, the first step to determine how many collectors are needed is to calculate how much heat energy is required each day. We make these calculations with SAM software, using LLC Radco 308C-HP Glazed Flat-Plate (with an aperture area of 2.2 m^2) [83, 105].

The number of collectors is n = $\frac{A_{apmin}}{A_{308C-HP}}$ = $\frac{13.224}{2.2}$ = 6.011, so the array aperture area is 13.224m^2. We can now calculate the annual yield from the solar array as:

$$Q_{solar} = R_{radation} * A_{apmin} = 365 * 13.224 = 4826.76 \text{ kWh/year}$$

If the thermal storage system is 80% efficient (accounting for some standby loss from the tank, heat loss from the pipes, and heat exchanger inefficiencies), then the system output would be:

Q = 4826.76* 6.011*2.2 = 63830.04 kWh/year

Assuming 80% efficiency for the system, then:

Q = 63830.04 *0.8= 51064.031 kWh/year

Finally, also need to know if the tank can hold this amount of heat. Assume the minimum and maximum temperature of the tank as:

Minimum tank temperature 55 °C

Maximum tank temperature 90 °C

$$Q_{st,loss} = \frac{A_{st}(T_{st}-T_{amb})}{\frac{1}{h_o}+\frac{L_{st,1}}{K_{st,1}}+\frac{L_{st,2}}{K_{st,2}}+\frac{L_{st,3}}{K_{st,3}}} \quad 4.7$$

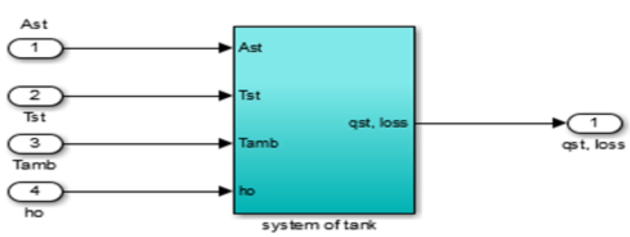

Figure 4. 4: Simulation of heat loss of a tank.

where $Q_{st,loss}$ is the heat loss from the storage tank, A_{st} is the area of the storage tank, T_{st} is the temperature of the storage water, T_{amb} is the ambient temperature, h_o is the outside convection code, and $L_{st,1}$ $L_{st,2}$ L_{st3} are the widths of each layer of the storage tank. Also, $K_{st,1}$, $K_{st,2}$ and $K_{st,3}$ are respective thermal conductivities [90].

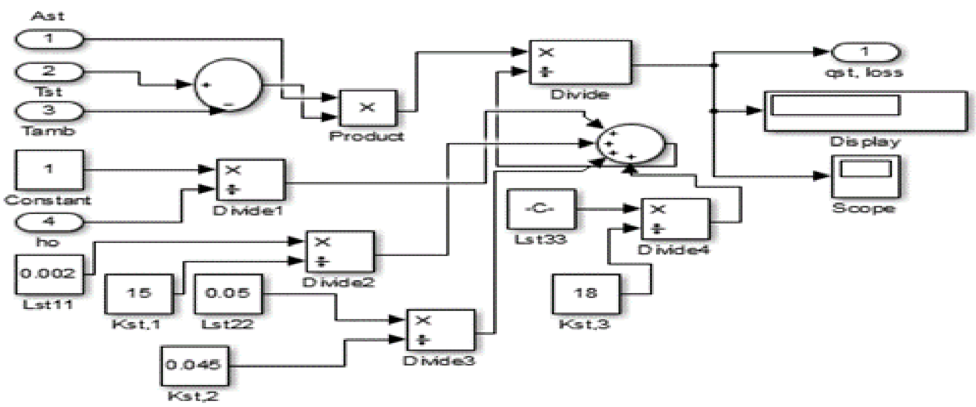

Figure 4. 5: Simulink model of heat loss from the storage tank.

Because the system has many pipes, heat loss can occur throughout the overall radius of the pipes. The heat transfer in pipe losses can be found by equation 4.8, [90].

$$q_{pipe,loss} = \frac{L_{pipe}(T_m - T_{amb})}{\frac{1}{2\pi R_1 h_i} + \frac{Ln(R_2/R_2)}{2\pi K_{pipe}} + \frac{Ln(R_3/R_2)}{2\pi K_{ins}} + \frac{1}{2\pi R_0 h_o}} \quad 4.8$$

Where $q_{pipe,loss}$ is the heat loss of the pipe, L_{pipe} is the total pipe length, R_1 R_2 are the inner and outer tube radii, and R_3 is the radius of the pipe with insulation. Additionally, h_i and h_o are the convective heat transfer coefficients, h_i is calculated via the Nusselt number correlation, and K_{pipe} and , K_{ins} are thermal conductivities. Additionally, $L_{heat,exchanger}$ Can calculate the heat loss of the exchanger pipe via an equation, where U is the overall heat transfer coefficient, N is the number of pipes, DF is the friction of the pipe, and ΔT is the difference of the temperature inlet and outlet of the pipe [90, 106].

$$L_{\text{heat exchanger}} = \frac{Q}{UN\pi DF\Delta T_{1mcf}} \quad 4.9$$

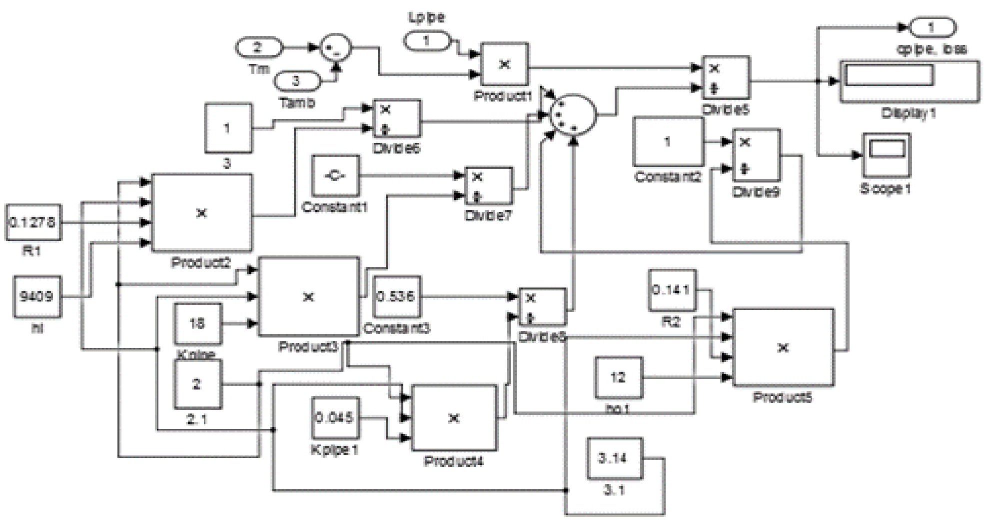

Figure 4.6: Simulink model of heat loss from the pipes.

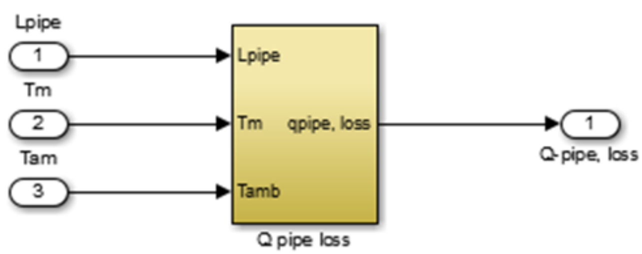

Figure 4.7: Heat loss through a pipe.

4.6 Model Used for a House

Using house data from St. John's, Newfoundland, will be calculating heat loss through the walls of the house as well as through the windows and roof. Additionally, all the walls, windows and roof of the house are exposed to both convective and conductive heat transfer. In addition, used the thermal mass of the walls, windows, and roof. We can calculate the conductive heat transfer through the walls via an equation. Figure 4.8, shows the Simulink system of a house's heat losses and temperatures.

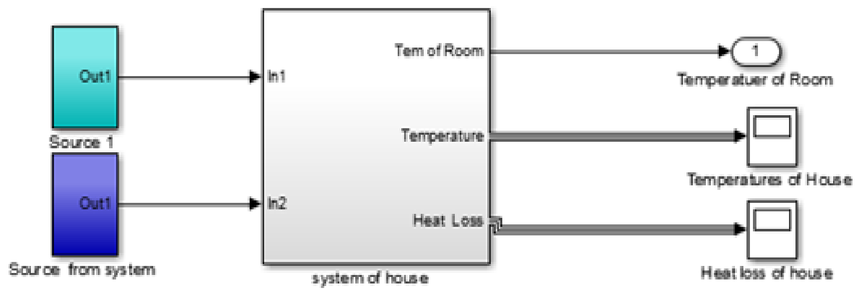

Figure 4.8: Simulink system of a house's heat loss and temperatures.

$$Q = AK\frac{\Delta T}{\Delta X} \tag{4.10}$$

Q is the amount of heat (W)

K is the thermal conductivity (W/m.k)

A is the surface area (m^2)

ΔX is the wall thickness of house (m)

ΔT is difference in temperature (°C)

4.6.1 Thermal simulation of house through walls.

Figure 8 shows the convective heat transfer (walls) and conductive heat transfer through the walls inside and outside of the house using wall sheathing-OSB and exterior finish-vinyl light on the walls of the house.

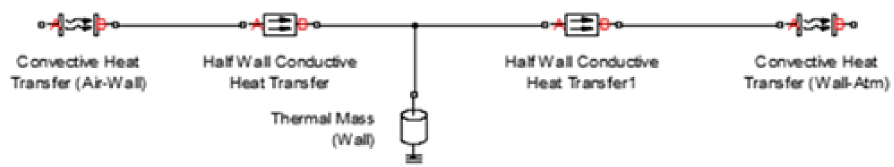

Figure 4.9: Model of heat loss through walls.

4.6.2 System used for the windows of the house

This figure shows the convective heat transfer and conductive heat transfer through the windows.

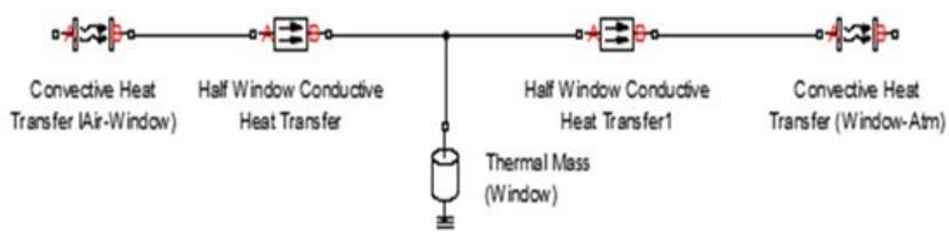

Figure 4.10: Model of the house heating for the windows.

4.6.3 System used for the roof of the house

Figure 4.11, shows that convective heat transfer and conductive heat transfer occurs through walls.

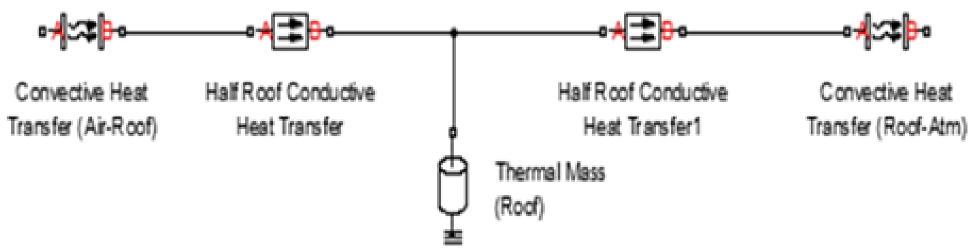

Figure 4.11: Model of house heating for windows.

4.7 BEopt-based House Design

This software was developed by the National Renewable Energy Laboratory to support the U.S. Department of Energy Building America program. The BEopt (Building Energy Optimization) software provides capabilities to evaluate residential building designs. The building will use in St. John's Newfoundland and Labrador is designed to identify optimally efficient designs for new and existing houses at the lowest possible costs. In addition, the total area of the house is (180 m^2) and the inputs from the options screen have been selected according to the passive house requirements. The windows have been created with a new option using the options manager “design" in the options screen. Table 4.1 below illustrates the parameters used for the house.

Table 4.1: Parameters Used for House

Parameter	Value	Unit
Walls of house		
Wood stud (R-19 fiberglass Batt)		
Equivalent resistance	16	$(\boldsymbol{h.ft^2.R/Btu})$
Conductivity	0.1 - 0.15	$\boldsymbol{W/_{m.K}}$
Roof of house		

Parameter	Value	Unit
Double wood stud (R-33 cellulose)		
Equivalent resistance	33	$(\boldsymbol{h.ft^2.R/Btu})$
Conductivity	0.23	$\boldsymbol{W/_{m.K}}$
Gap depth	0.0889	m
Windows of house		
Clear, double, metal		
Convective	0.76	Btu/ $\boldsymbol{h.ft^2.R}$
Conductivity	0.96	$\boldsymbol{W/_{m.K}}$

4.8 Simulation Output of BEopt

The output is visible in the design mode or process optimization. In the design mode, one option per category is selected according to the parameters of the house. Here, the heating is 12,268 kWh/relights energy is 1832 kWh/yr., Misc energy is 2254 kWh/yr., and the output total is 19,537 kWh/yr. Some BEopt simulation results are shown in Figure 4.12, where we see that lighting is the major power consumption.

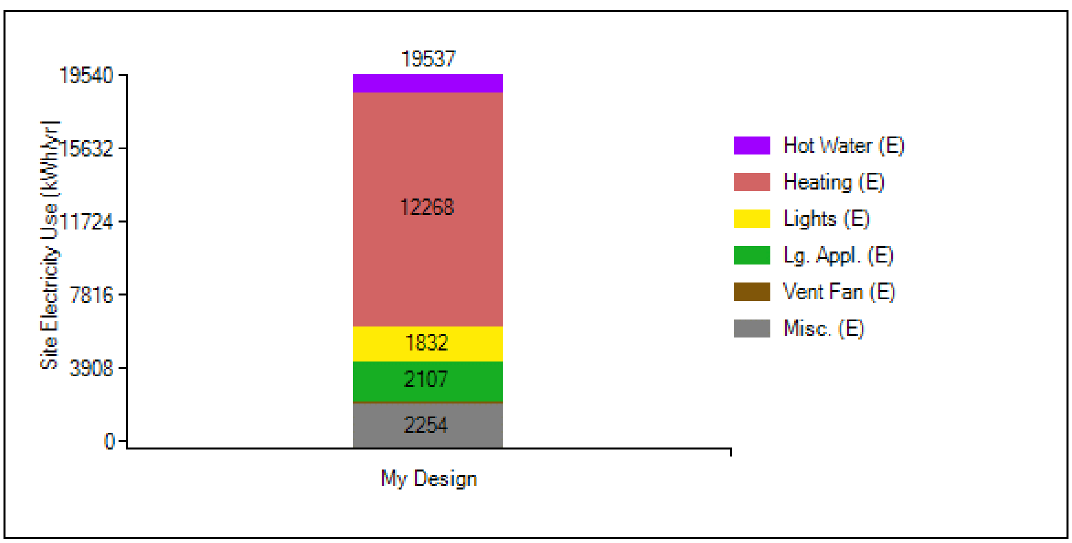

Figure 4.12: Total of output in design mode.

Figure 4.13, indicates hourly average values of total energy. As can be seen, the total energy of the mean power is 2.230 kWh, the total energy of the minimum is 0.294 kWh, and the total energy of the maximum is 8.443 kWh.

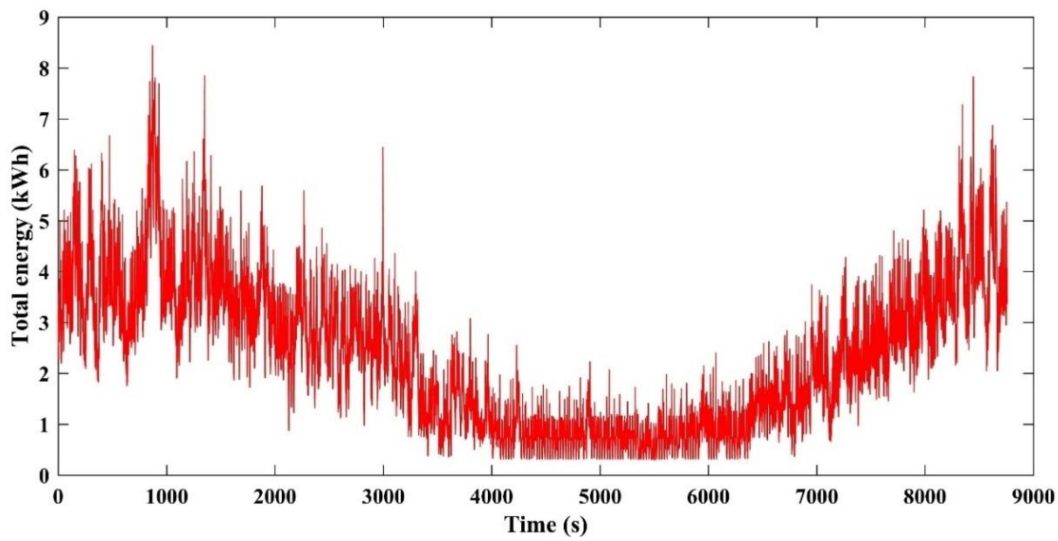

Figure 4.13: Hourly output in D-view.

Table 4.2, shows the monthly total energy (kWh). The maximum is in February (8.443 kWh), the minimum is in August (0.294kWh), and the mean is 2.230kWh.

Table 4.2: Monthly Total energy (kWh)

Time	Mean	Min	Max
Jan	3.5045	1.7484	6.6803
Feb	4.1163	1.9027	8.4426
Mar	3.178	0.8685	5.6917
Apr	2.7333	0.9718	5.5992
May	1.862	0.3515	6.4498
Jun	1.0882	0.3123	3.0865
Jul	0.7411	0.3111	2.2326
Aug	0.6994	0.2945	1.9816
Sep	0.9647	0.3123	2.6004

Oct	1.6942	0.3625	4.2858
Nov	2.6205	0.9648	5.2159
Dec	3.6961	1.8736	7.833

Figure 4.14, shows hourly average values of hot water energy. The total energy of mean hot water is 0.105 kWh, while the maximum is 2.065 kWh.

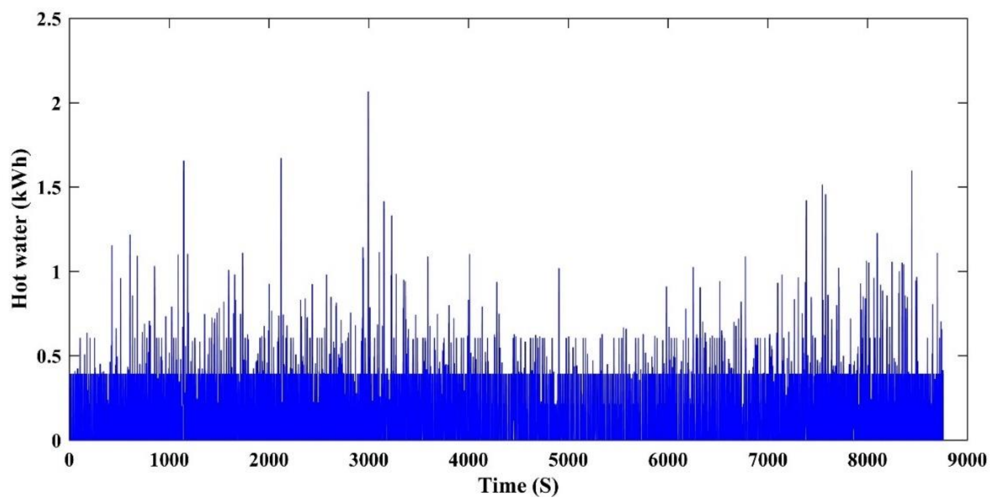

Figure 4.14: Hourly hot water energy of system.

Table 4.3 shows hourly hot water energy usage of the system. The maximum is in March (2.065 kWh), while the minimum is 0 for all months (kWh), and the mean is 0.105 (kWh).

Table 4.3: Hourly Hot Water Energy (kWh)

Time	Mean	Min	Max
Jan	0.0849	0	1.2178
Feb	0.1075	0	1.6562
Mar	0.1141	0	1.6712
Apr	0.1125	0	0.9817
May	0.1234	0	2.0652
Jun	0.1144	0	1.103
Jul	0.1002	0	1.0189

Aug	0.0911	0	0.6683
Sep	0.1052	0	1.0243
Oct	0.0977	0	1.0892
Nov	0.1102	0	1.5146
Dec	0.0978	0	1.5975

In Figure 4.15, we can see that the volume of heating energy usage for heating was the highest in January and February, which shows a mean heating amount of 1.401 kWh and a maximum amount of 7.802 kWh.

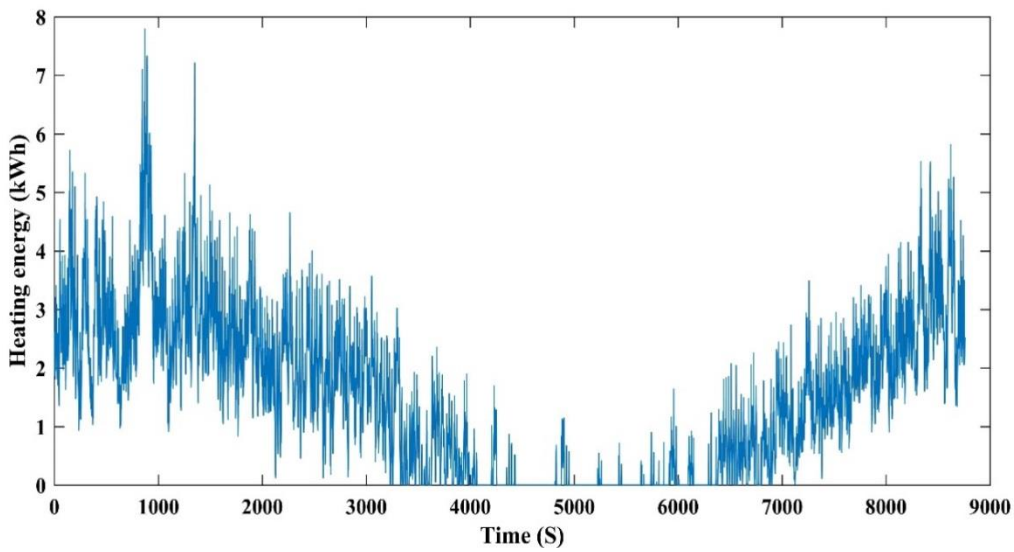

Figure 4.15: Hourly heating energy of system.

Table 4.4 shows the monthly heating energy of the system. The maximum is in February (7.802 kWh), the minimum is most months (0 kWh), and the mean is 1.401 (kWh).

Table 4.4: Monthly Heating Energy of System (kWh)

Time	Mean	Min	Max
Jan	2.5357	0.9313	5.7274
Feb	3.1669	0.9064	7.8021

Mar	2.3339	0.114	5.1318
Apr	1.9345	0.1156	4.6618
May	1.0884	0	3.5753
Jun	0.3719	0	2.3588
Jul	0.0419	0	1.149
Aug	0.0212	0	0.9044
Sep	0.1961	0	2.0832
Oct	0.8349	0	3.4964
Nov	1.6956	0.107	3.7409
Dec	2.7128	0.9004	5.8252
Total	1.4007	0	7.8021

Figure 4.16, shows the domestic water system of the inlet temperature. The volume of temperature indicates a mean heating of 96.137 °F, a minimum of 76.071 °F, and a maximum of 126.758 °F.

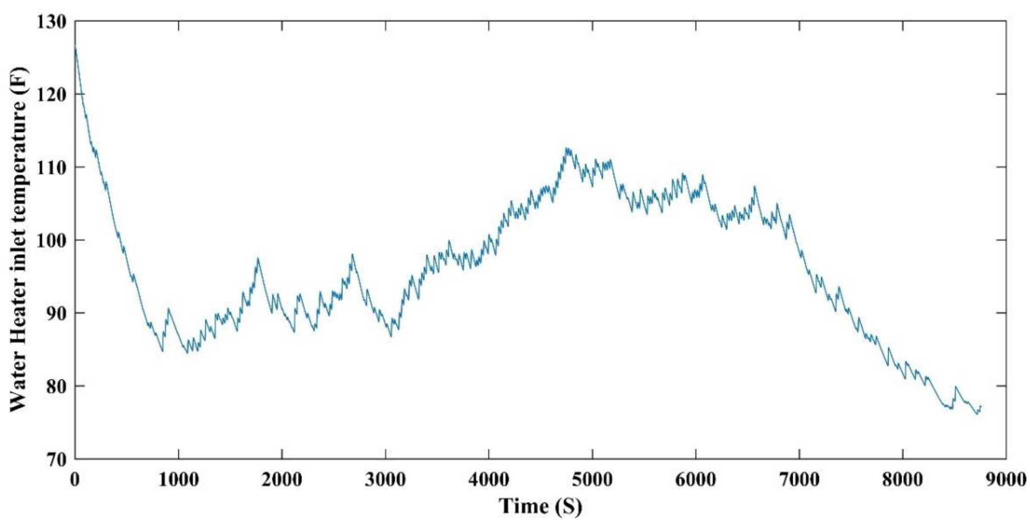

Figure 4.16: Hourly domestic water heater inlet temperature (°F).

Figure 4.17, shows a domestic water system of the delivered temperature and the volume of temperature. The mean heating is 124.329 °F, the minimum is 119.723 °F, and the maximum is 126.421 °F.

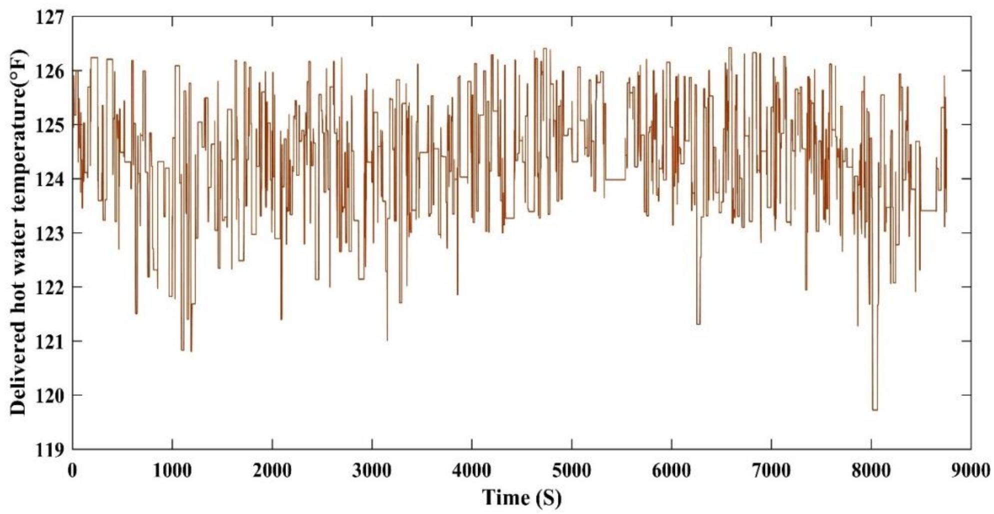

Figure 4.17: Hourly domestic water heater delivery temperature.

4.9 Simulation in System Advisor Model and Results by Mathlab software

System Advisor Model software uses information that is input by the user installation and operating and design parameters to estimate the consumption of energy and water heating. Figure 4.18 shows diagrams of the simulated solar water heating systems, featuring two resources as a solar collector, tank heater, pump, and reservoir included in the house. Table 4.5 shows the temperature in °C and heat losses by watts for each component of the house. The highest temperature comes from the storage tank and the highest heat values of losses come from the windows, as shown in the table.

Table 4.5: Simulation Results of System

Types	values	Unit
Temperature of walls	10.8	℃
Temperature of windows	12.44	℃
Temperature of roof	10.78	℃
Temperature of house	25.1	℃
Heat loss of walls	102.7	W
Heat loss of windows	574.9	W
Heat loss of roof	48.16	W
Temperature of storage tank	82.4	℃

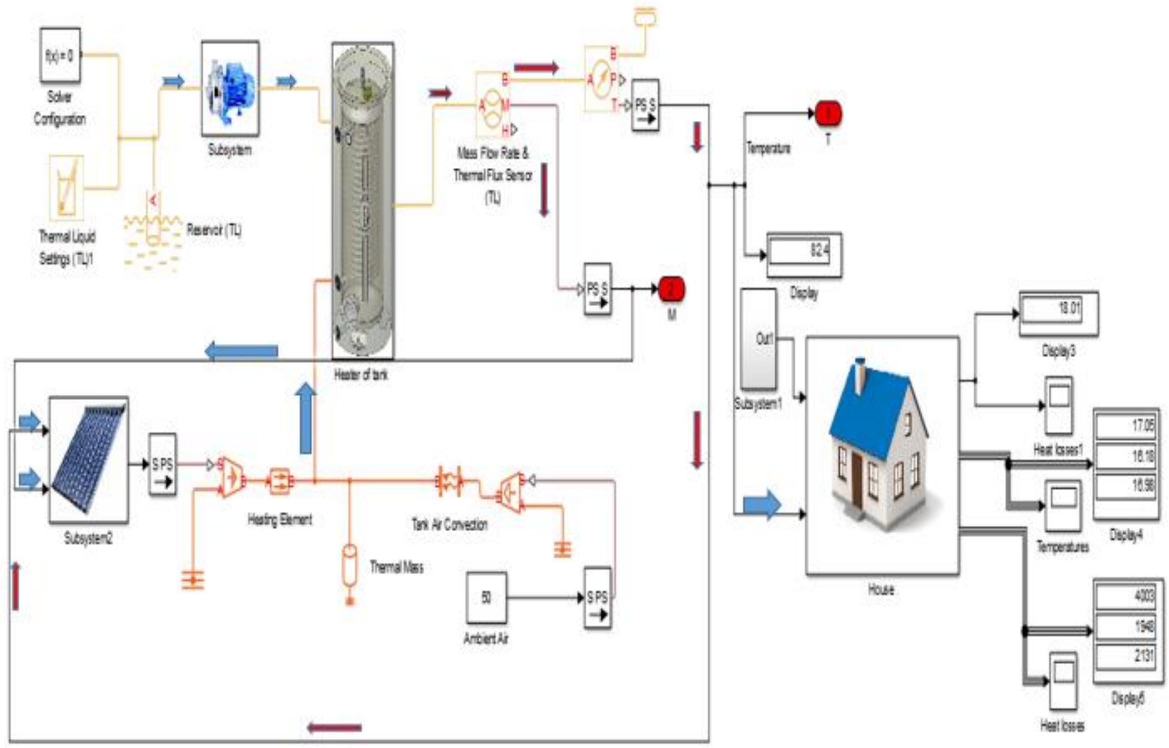

Figure 4.18: Simulink simulation of house.

The water temperature that comes from the tank is 82.4℃. This temperature is used to supply the heating for the house, while the distribution of temperature inside the house in each room is around 18 ℃ . Figure 4.19 shows the relationship between temperature and time, which means the temperature increases with time until it reaches 25.11℃ and t, at which point it achieves a steady-state condition.

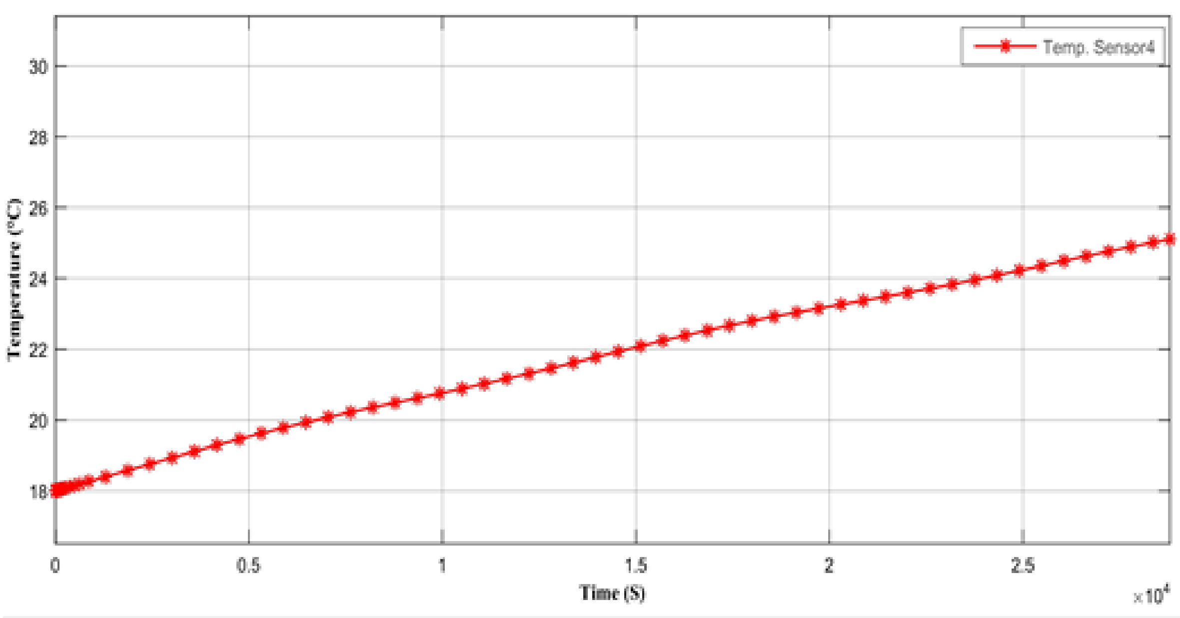

Figure 4.19: Simulink model of temperature of house.

Figure 4.20, illustrates heat losses in watts through the walls, windows and roof. The losses are based on thermal conductivity (k) in the building. In this task, a double-wood stud (R-33 cellulose) house was chosen. The K value of the roof is 0.23, $^{W}/_{mk}$ and the windows are 0.96 W/m.k. In addition, the maximum heat loss through the windows is 574.9 W, as shown in the blue line in Figure 4.20. Additionally, the black on the walls indicates the volume of heat loss (102.7W) and the red on the roof indicates a loss of 48.16W.

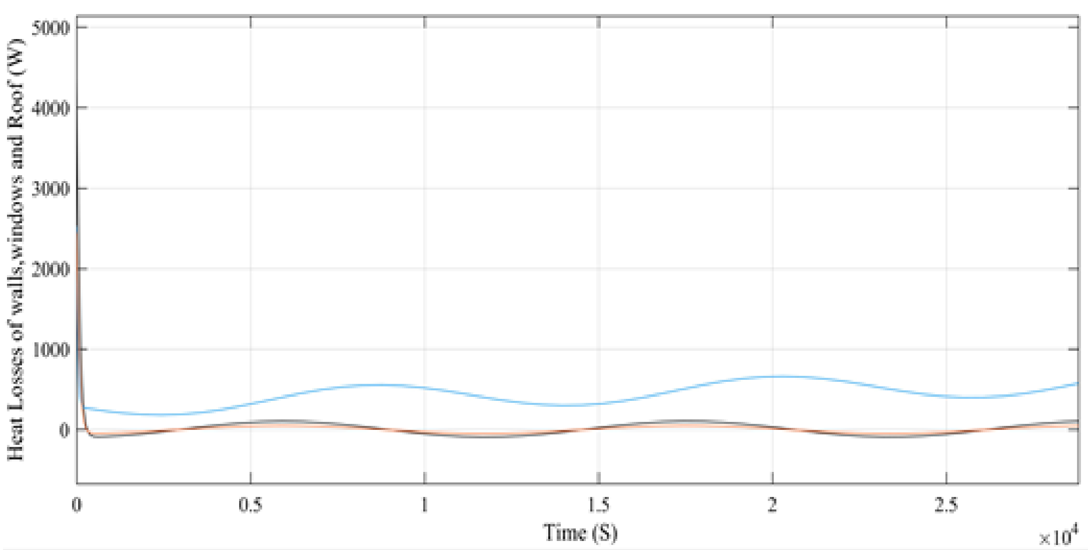

Figure 4.20: Heat losses according to part of house (walls, windows and roof).

Figure 4.21, shows heat temperature exiting the house through the walls, windows, and roof. However, as can be seen, the temperatures gradually decrease until achieving a state of stability. The figure shows the three additional colors of black, blue and red. The temperatures (10.97 ℃, 11.3 ℃, 10.85 ℃) are of walls, windows and roof, respectively.

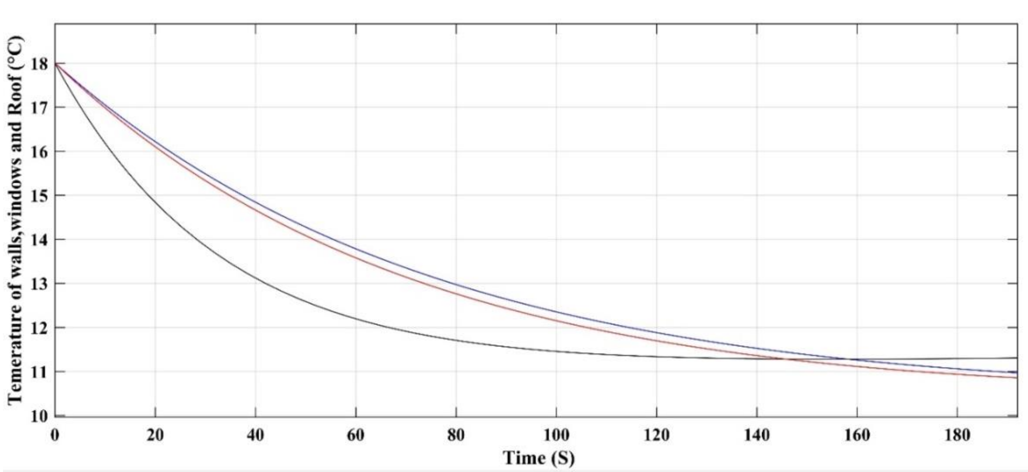

Figure 4.21: Graph of house part temperatures.

4.10 Conclusion

Thermal energy storage is useful in solar thermal systems, especially in regions with a temperate and cold climate and larger seasonal differences. The modeling and simulation of a solar water heating system with a thermal storage system was conducted for the solar collector, storage tank, and pump. This chapter presented results derived from two different software, BEopt and MATLAB. Some results that emerged from the BEopt software calculations include Miscellaneous Energy Loads (2,254 kWh/yr), heating energy (12,268 kWh/yr), and light energy (1,832 kWh/yr), with an overall output total of 19,537 kWh/yr. Additionally, for the heat storage mode via the MATLAB simulation, results showed that the temperature of the storage tank was 82.4 ℃ with variable mass flow rate, and that this temperature was used to supply the heating for the house. Meanwhile, the distribution of temperature inside each room of the house was around 18 ℃, and the temperature of the walls, windows and roof was 10.97 ℃, 11.3 ℃, and 10.85 ℃, respectively. The performance of the system as well as system losses such as pipe and heat losses in the house (walls, windows, and roof), which showed as 48.6W, 574.9W, and 102.7W, respectively.

CHAPTER 5 DISCUSSION, CONCLUSIONS, AND FUTURE SCOPE

5.1 Discussion

Created and designed our system intending it to function throughout the summer while maintaining a water temperature of 40 to 50 °C. In so doing, we based our design on the observed hot water usage in the winter season. In this system, and as shown in Chapter 4, by using two software such as BEopt and Mathlab, the discrepancies between power derived from collectors and that transferred to tank water are mainly caused by the efficacy of the heat exchanger as well as energy deficits within the pipes themselves. The behavior of our proposed system was accurately predicted by the models utilized for calculations. So, for instance, the temperatures that was assumed at the collector inlet the water temperature of the tank bottom, and is estimated to be somewhat close.

Noteworthy as well is that the collector calculated efficiency (0.28) lines up with the stated value listed on the collector's manufacturer datasheet (0.28). From this, we can assert a validation of the adopted models. Overall, can see that the operational performance of above-described system points to performance results that are significantly above the acceptable range, which in fact is normal for similar types of solar energy-based systems. Moreover, the power usage of the pump unit is contingent on precisely when (i.e., the time of day or level of solar radiation) the pump is actually working. System which we have proposed in this thesis offers performance capabilities that rival the abovementioned system.

5.2 Conclusions

The created and designed system intending it to function throughout the summer while maintaining a water temperature of 40 to 50 °C.. In this system, and as shown in Chapter 4, by using BEopt and MATLAB software, that the discrepancies between power derived from collectors and that transferred to tank water were mainly caused by the efficacy of the heat exchanger as well as energy deficits within the pipes themselves. The behavior of our proposed system was accurately predicted by the models utilized for calculations. So, for instance, the temperatures that were assumed at the collector inlet and the water temperature of the tank bottom were estimated to be somewhat close. Specifically, the tank's minimum and the maximum temperatures were determined using the application VBusTouch on March 2, 2016, at 1:51 p.m. Given that the minimum temperature was 10.9 °C and the maximum temperature 41.6°C, can calculate the flow rate of the storage tank as 0.010120 Kg/s and use this parameter in the SAM and MATLAB software.

Noteworthy as well is that the collector calculated an efficiency of (0.28). From this, can be assert a validation of the adopted models. Overall, the operational performance of our above-described system points to performance results that is significantly above the acceptable range, which in fact is normal for similar types of solar energy-based systems. Moreover, the power usage of the pump unit is contingent on precisely when (i.e., the time of day or level of solar radiation) the pump is actually working. The system proposed in this thesis offers performance capabilities that rival the other system describe in this work.

5.3 Future Scope

This section discusses some recommendations for moving forward and some ideas for future work. While a high level of complexity was included in the models developed for this study, there is also room for potential further improvement of the models and assumptions. Explaining the details of the simulations created opportunities to answer interesting questions and explore other aspects of single house-scale solar thermal systems. Additionally, the results of this study can be useful in determining the feasibility of using similar systems to supply the demands of domestic hot water in other locations and for other applications. In every instance, however, energy efficiency and profitability will be determined by the irradiation in the area, the required hot water temperature, and the demand curve for the specific application.

With the continuous increase and forecasted upward trend in electricity rates across Canada, SWHs are becoming more viable, even for low-income households. However, various barriers have hindered the full-scale adoption and implementation of SWHs, such as high initial capital cost, inadequate financing, lack of awareness, and inadequate long-term support from the government (in the form of policies and attractive incentives). Despite these minor drawbacks, individuals can still make smart changes in behavior and efficient water use practices, and huge environmental and energy security benefits can be realized with full-scale implementation of SWHs.

Moreover, while the promising results of the simulations give hope for eventual mass domestic implementation of the systems, future designs of the thermal energy storage portion of the system should address a few as yet unresolved issues. For example, the heat exchanger design should either be improved or entirely redesigned with an eye to utilizing vessels of varying sizes, but without altering the device. To accomplish such changes, it might be possible to use a conventional cooking stove with the heat exchanger. Additionally, it should be noted that current solar thermal concentrating collectors are able only to absorb beam radiation, not create heat energy from diffused radiation; thus, the device cannot be used on cloudy days. Given this issue, the redesign of the thermal collector should include a means to transform diffused radiation, which comprises around 20 to 40% of total radiation. The efficiency of the collector would be substantially improved if the diffused radiation were absorbed in this system.

Another aspect that warrants a second look is the thermal insulator positioned around the pipes and heat storage tank, as was shown in the prototype. It should be improved in order to lessen the temperature drop along the pipe carrying hot fluid. In this system, even minimal minor improvements in the thermal insulation can vastly improve the system's overall efficiency.

Finally, a few of the ideas and approaches presented in this work can be revised to suit other applications. For instance, heat energy from the sun can be maximized by adjusting the flow rate. As well, maximum power point tracking may be suitable for active solar thermal systems (e.g., solar water heaters and space heating/cooling systems), with the overall aim to improve the system's optimal functionality.

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Appendix A

The USGS Water Science School

Water Density (water properties), USGS Water Science School**.** in table A 1. We used the density 0.99975 grams/cm^3 that was used in question 3.4 for calculation. Also assuming temperature inlet is 10 ℃ .

Table. A 1. Density and weight of water.

Temperature	Density	Weight
°F/°C	grams/cm^3	pounds/ft^3
32°/0°	0.99987	62.416
39.2°/4.0°	1.00000	62.424
40°/4.4°	0.99999	62.423
50°/10°	0.99975	62.408
60°/15.6°	0.99907	62.366
70°/21°	0.99802	62.300
80°/26.7°	0.99669	62.217
90°/32.2°	0.99510	62.118
100°/37.8°	0.99318	61.998
120°/48.9°	0.98870	61.719
140°/60°	0.98338	61.386
160°/71.1°	0.97729	61.006

Appendix B
MATLAB-Simulink® Blocks

This is modeling system of pipeline with centrifugal pump, that was used something in this system in chapter4, such as pipes, pump and tank.

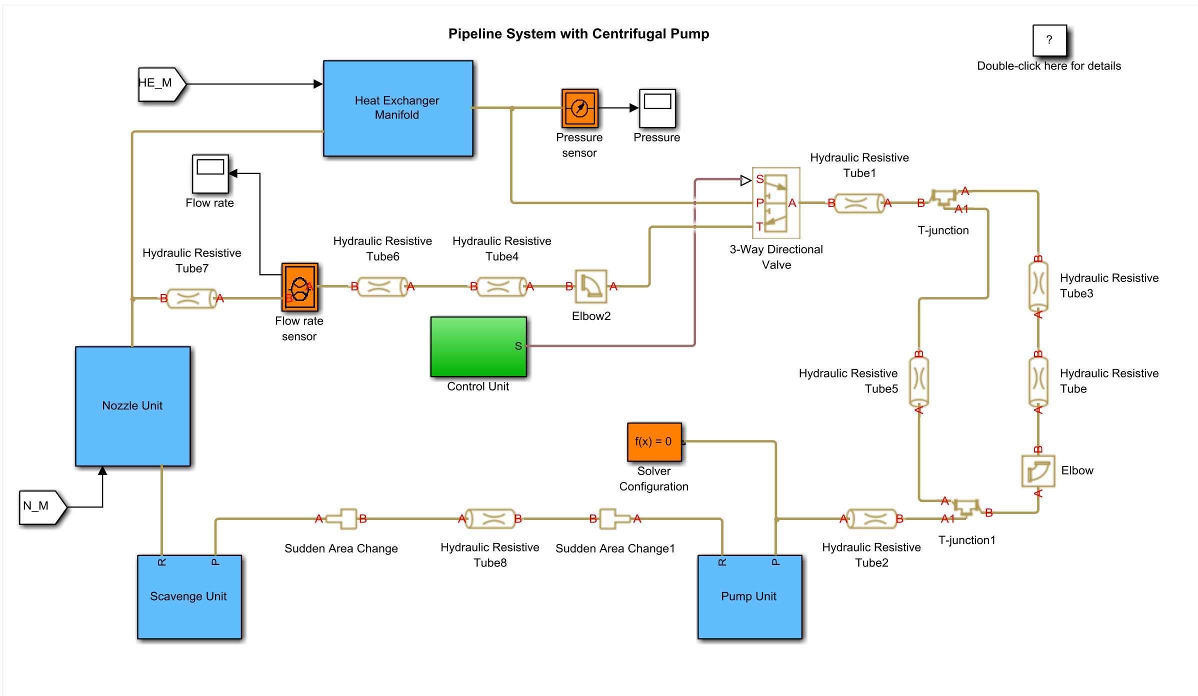

Figure B. 1 Simulink block diagrams for Pipeline System with Centrifugal Pump.

The MATLAB code of pressure and temperature for sensor is as follows:

```
component pressure_temperature_sensor
% Pressure & Temperature Sensor (TL)
% This block represents an ideal pressure and temperature sensor, that
% is, a device that converts pressure and temperature differentials
% measured between two thermal liquid ports into physical measurement
% signals P and T.
% The sensor returns a positive pressure if the pressure at port A is
% greater than the pressure at port B. Similarly, the sensor returns a
% positive temperature if the temperature at port A is greater than the
% temperature at port B.

% Copyright 2012-2013 The MathWorks, Inc.

nodes
    A = foundation.thermal_liquid.thermal_liquid; % A:left
    B = foundation.thermal_liquid.thermal_liquid; % B:right
end

variables(Access = protected)
    mdot = {0, 'kg/s'}; % Mass flow from A to B
    Phi  = {0, 'W' };   % Thermal flux from A to B
end

outputs
    P = { 0, 'Pa' }; % P:right
    T = { 0, 'K'  }; % T:right
end

branches
    mdot : A.mdot -> *;
    Phi  : A.Phi  -> *;
end

equations
    % Measured across variables
    P == A.p - B.p;
    T == A.T - B.T;

    % Set mass flow rate & thermal flux through sensor to zero
    mdot == 0;
    Phi  == 0;
end

end
```

The MATLAB code of flow rate for sensor is as follows:

```
Component flow rate

% Hydraulic Flow Rate Sensor
% The block represents an ideal flow meter, that is, a device that
% converts volumetric flow rate through a hydraulic
% line into a control signal proportional to this flow rate.
%
% Connections A and B are conserving hydraulic ports connecting
% the sensor to the hydraulic line.
% Connection Q is a physical signal port that outputs the flow rate
% value.
%
% The sensor positive direction is from port A to port B.

% Copyright 2005-2013 The MathWorks, Inc.

outputs
    Q = { 0, 'm^3/s' }; % Q:right
end

nodes
    A = foundation.hydraulic.hydraulic; % A:left
    B = foundation.hydraulic.hydraulic; % B:right
end

variables(Access = protected)
    q = { 1e-3 ,  'm^3/s' };        % Flow rate
    p = { 0 ,        'Pa' };        % Pressure differential
end

branches
    q : A.q -> B.q;
end

equations
    p == A.p - B.p;
    p == 0;
    Q == q;
end

end
```

The MATLAB code of component reference.

```
% Mechanical Rotational Reference :0.5
% This block represents a mechanical rotational reference point, that
% is, a frame or a ground. Use it to connect mechanical rotational ports
% that are rigidly affixed to the frame (ground).

% Copyright 2005-2013 The MathWorks, Inc.

nodes
    W = foundation.mechanical.rotational.rotational; % :top
end

variables(Access = protected)
    t = { 0, 'N*m' };    % Torque
end

branches
    t : W.t -> *;
end

equations
    W.w == 0;
end

end
```