

**HIGH RESOLUTION TIME-SERIES MODELING
OF DOMESTIC HOT WATER HEATING SYSTEMS**

by
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of the requirements for the Degree of

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Abstract

This thesis evaluates domestic water heating systems in conjunction with energy saving technologies such as solar water heating, drain water heat recovery, and heat pump water heating. Five dynamic models are developed using Matlab Simulink® with a time-step of one minute. Using minute resolution hot water flow, hourly solar radiation data and ambient temperature, the performance of various configurations are assessed when operating in Victoria, Kamloops, and Williams Lake, B.C. Twelve different demand profiles on a summer day and winter day are simulated. Some specific metrics, such as conventional energy consumption, system energy factor, and equivalent CO₂ emissions are used as the basis of evaluating the system efficiency.

Results indicate the potential improvements in system performance over a conventional domestic water heating system in lower conventional energy consumption and lower CO₂ emissions when applying any one of the three energy saving technologies mentioned above. For example, on a representative summer day (Day 228) in Victoria with a load profile of a low-use two-person family on a weekday, the system's energy factor can be improved from 0.50 to up to

2.84, and the corresponding conventional energy consumption and the CO₂ emissions decrease from 9.86 kwh to 1.67 kwh, and 1.77 kg/day to 0.06 kg/day, respectively depending on which energy saving technology is applied.

The modeling tool developed in this research can be used to guide the design of domestic water heating systems with various system configurations.

Nomenclature

A_c	Solar collector absorber surface area, m^2
A_o	Surface area of outlet pipe between heat exchanger and solar panel, m^2
A_i	Surface area of inlet pipe between heat exchanger and solar panel, m^2
C^*	Dimensionless capacitance rate of heat exchanger
C	Drain water heat recovery unit NTU correlation equation's dimensionless parameter
COP	Heat pump coefficient of performance
b_0	Incidence angle modifier coefficient
C_p	Specific heat capacity, J/kg.K
D_i	Diameter of pipe between heat exchanger and solar panel, m
D_o	Outer diameter of pipe including insulation, m
EF	Water heater's energy factor
F_R	Solar collector heat removal factor
F'_R	Modified solar collector heat removal factor
F_{c-s}	View factor from solar collector surface to sky
F_{c-g}	View factor from solar collector surface to surrounding ground
F_S	Daily solar fraction
G_T	Global incident solar radiation on tilted surface, W/m^2
G_{sc}	Solar constant, $1367 W/m^2$
I	Hourly global irradiation on horizontal surface, w/m^2
I_b	Hourly beam solar irradiation on horizontal surface, w/m^2

I_{CO_2}	CO ₂ intensity of a conventional energy source, kgCO ₂ /kWh for electricity or kgCO ₂ /GJ for gas fired
I_d	Hourly diffuse solar irradiation on horizontal surface, w/m ²
I_0	Hourly extraterrestrial radiation on a horizontal surface, w/m ²
I_T	Hourly global irradiation on a tilted surface, J/min.m ²
k	Insulation conductivity, w/m ² .°C
k_T	Hourly clearness index
$K_{\tau\alpha}$	Incidence angle modifier
L_{pipe}	Length of pipe between heat exchanger and solar panel, m
m	Total mass of the domestic hot water storage tank, kg
\dot{m}	Mass flow rate of delivered domestic hot water, kg/s
\dot{m}_c	Mass flow rate of heat transfer fluid volume flow rate, L/min
\dot{m}_{PHT}	Mass flow rate of delivered domestic hot water from pre-heating storage tank, kg/s
$(\dot{m}C_p)$	Heat transfer fluid heat capacitance, W/K.s
$(mC_p)_{DW}$	Shower drain water heat capacitance, W/K
$(mC_p)_{PHT}$	Domestic hot water heat capacitance, W/K
$(\dot{m}C_p)_s$	Domestic hot water heat capacitance, W/K.s
$(\dot{m}C_p)_{min}$	The smaller value of $(\dot{m}C_p)_s$ and $(\dot{m}C_p)_c$, W/K.s
NTU	Number of transfer units of heat exchanger
n	i^{th} day of year

Q_{DELVD}	Daily delivered energy, kWh
Q_{DW}	Daily recovered energy from drain water heat recovery unit, kWh
Q_{LOSS}	Daily storage tank thermal loss, kWh
Q_{HP}	Daily heating energy generated by heat pump water heater, kWh
Q_{RESIDUAL}	Daily residual energy, kWh
$Q_{\text{SC.DELVD}}$	Daily delivered solar heating energy, kWh
Q_{WH}	Daily heating energy generated by main hot water storage tank, kWh
q_{SC}	Instantaneous heat flows collected by solar collector, kW
Q_{SC}	Daily collected solar energy, kWh
Q_{TDHE}	Total heating energy generated during one day, kWh
Q_{unmet}	Total daily system unmet load, kWh
R_b	The ratio of beam radiation on tilted surface to that on horizontal surface
RSI	SI equivalent value of tank insulation
SEF	Ratio of system's delivered energy to total system conventional energy consumed
T_a	Outdoor ambient air temperature, °C
T_c	Cold make-up water temperature, °C
T_D	Demand hot water temperature, °C
T_{DW}	Shower drain water temperature, °C
T_i	Inlet temperature of Heat transfer fluid to the collector, °C
T_{PHT}	Temperature of delivered domestic hot water from pre-heating storage tank, °C
T_s	Storage tank water temperature/ Delivered domestic hot water temperature, °C

$t_{S,max}$	Delivered hot water peak demand time
U_L	Overall heat loss coefficient of the solar collector, $W/m^2\text{°C}$
U_L'	Modified heat loss coefficient of the solar collector, $W/m^2\text{°C}$
U_F	Ratio of Unmet load to the total demand hot water consumed during one day
U_p	The heat loss coefficient of the pipe between heat exchanger and solar panel, $W/m^2\text{°C}$
UA	Overall heat transfer coefficient-area product
V_d	Demand hot water consumption, m^3/day
v_i	Instantaneous volume flow rate of delivered hot water to the i^{th} plumbing fixture, m^3/s
V_S	Daily delivered domestic hot water, m^3/day
$(\dot{V})_{\text{shower}}$	Volume flow rate of shower drain water, L/min
$V_{S,max}$	Delivered hot water peak demand, L/min
W_e	Daily consumed conventional energy, kWh
W_{HP}	Daily conventional energy consumed by heat pump water heater, kWh
W_{WH}	Daily conventional energy consumed by main hot water storage tank, kWh

Greek letters

β	Angle between the sloped collector and the ground, $^\circ$
ω	Hour angle, $^\circ$
ρ	Density of water, (assumed to be 998 kg/m^3)
ρ_g	Ground reflectance

$(\tau\alpha)_n$	Transmittance- absorptance product at normal incidence for a solar collector
θ	Incidence angle of solar radiation, °
γ	Surface azimuth angle, °
δ	Angular position of the sun at solar noon, °
Φ	Latitude, °
ε	Heat exchanger effectiveness

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Chapter 1

Introduction

1.1 Residential Hot Water Energy Demand

In Canada, domestic water heating is typically the largest energy use after space heating in the residential sector [1]. As shown in Figure 1.1, approximately 17% of energy is consumed by residential use of which 19% is electricity for lighting, space cooling and appliances, 57% is for space heating and 24% is consumed by domestic water heating; therefore, ~4% of total national energy demand is consumed by domestic water heating use. Since the last century, extensive efforts have been undertaken to design and build a more energy efficient domestic water heating system by employing energy saving technologies. Among these technologies, solar water heating, drain water heat recovery, and heat pump water heating have recently been used in some residential buildings in Canada. The benefits derived from the use of these systems are subject to location (seasonal environmental conditions) as well as patterns of water usage. These benefits come with additional capital costs for a home owner which may result in minimal economic benefit.

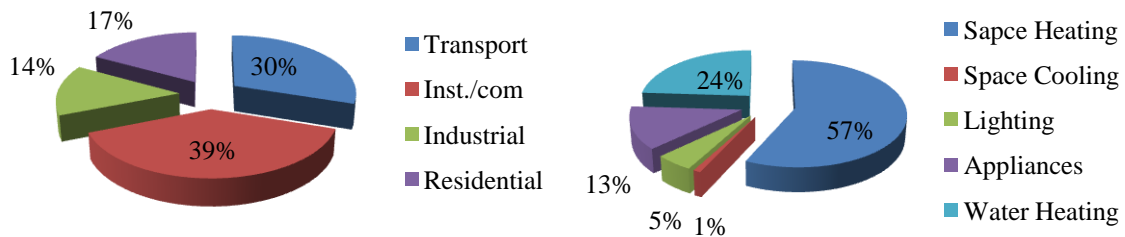


Figure 1.1 Breakdown of energy use in Canada [2].

Quantifying how the performance of a residential domestic water heating system changes by applying different energy saving technologies in different locations is of interest to system

designers, policy makers, and, of course, home owners. In practice, comparisons between different systems and components can be achieved either by experiments or through modeling and simulations. Due to the many configurations possible for domestic hot water systems and the wide variety of geographic conditions found in Canada, system modeling is often used to compare choices.

1.2 Unconventional System Components

Unconventional systems may use a conventional hot water tank in addition to other components. A brief overview of the operating principles of unconventional hot water technologies studied in this thesis follows.

1.2.1 Glazed Liquid Flat-Plate Solar Collector

A glazed, flat plate collector is a simple and common type of solar absorber and heat exchanger. Other types are available, but are usually more expensive. Figure 1.2 shows a typical flat plate collector. As shown in the figure, an absorber plate which is usually made of aluminum is installed in the frame between the copper flow tubes and the insulation at back. The flow tubes connected to a header are painted black to maximize the heat transfer efficiency. Either single or double layers of glazing are installed on top of the collector frame so that the heat absorbed can be prevented from escaping. Solar energy absorbed by the absorber is transferred to the heat transfer fluid (glycol-water solution) circulating inside the flow tubes through which the heat is brought into the domestic hot water (DHW) system. After heat is transferred into the domestic

water heating system, the fluid flows back to the solar collector where it is re-heated by absorbed solar energy.

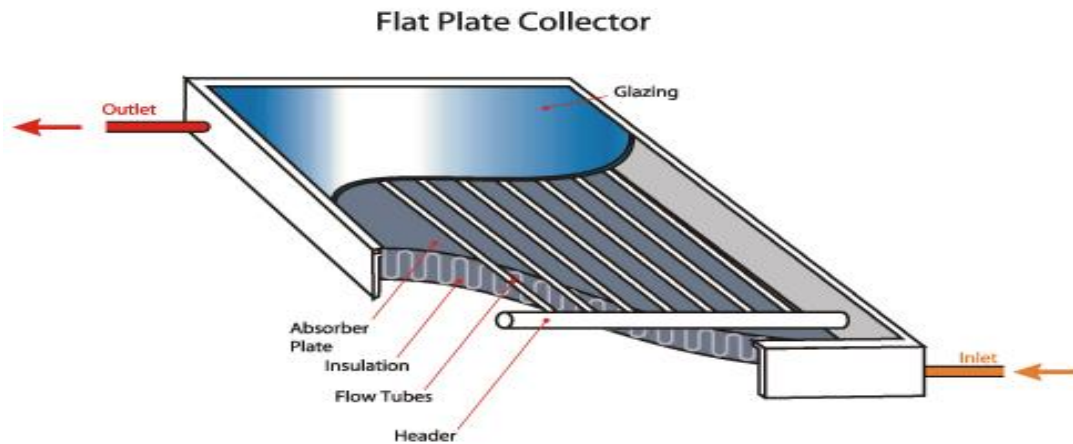


Figure 1.2 Glazed liquid flat-plate collector [3].

1.2.2 Drain Water Heat Recovery Unit

Drain water heat recovery is the practice of recovering the thermal energy which is usually lost down the drain of plumbing fixture [4]. As shown in Figure-1.3, it often consists of a series of copper coils wrapped around the drain stack. The drain water from the plumbing fixture goes down the stack in the center of the heat recovery unit; while, the cold make-up water flows through the coils. Thus, the cold make-up water is warmed by the drain water while not becoming contaminated. Figure-1.3 shows the preheated cold water may flow in two directions. In one configuration, the outlets are plumbed to the hot water tank inlet where it is further heated. Another possibility is to route the pre-heated water to the shower faucet cold-water inlet. The preferred configuration depends on the water usage profile of a facility as well as the type of loads.

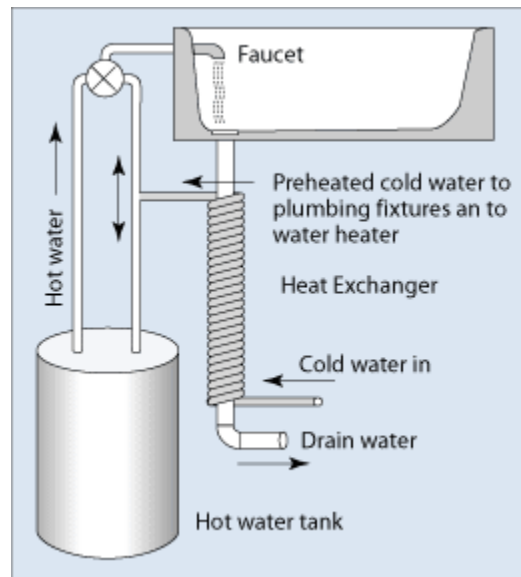


Figure 1.3 Drain water heat recovery unit [5].

1.2.3 Heat Pump Water Heating

Heat pump water heaters produce hot water efficiently by extracting the heating energy from a heat source which has a lower temperature than the hot water. Similar to a refrigerator which produces cooling by extracting the heat from the relatively cold environment (inside the refrigerator) and dumping it to the relatively warm environment (surrounding space), a heat pump water heater takes the heat from the cooler environment (surrounding air) and rejects it to a domestic hot water storage tank.

As indicated in Figure 1.4, a heat pump water heater consists of five main components: a compressor, condenser, expansion device, evaporator and the water heater (hot water storage tank). The gaseous refrigerant carries energy from the evaporator, is compressed and then flows into the condenser where it liquefies by transferring the heat through the condenser wall to heat the hot water inside the water tank. The liquefied refrigerant with medium temperature and

pressure is then routed through the expansion device whereby refrigerant becomes colder with a lower pressure. This lower pressure cold refrigerant flows into the evaporator where it evaporates by absorbing the heat from the warm surrounding air. The resulting cool air can be dumped into space during the summer time and needs to be ducted to outside or to the non-conditioned space in the winter time. Finally, the gaseous refrigerant is drawn into the compressor and the cycle is repeated. Typically, a heat pump water heater only uses about half as much electricity as a conventional electric resistance water heater. [6]

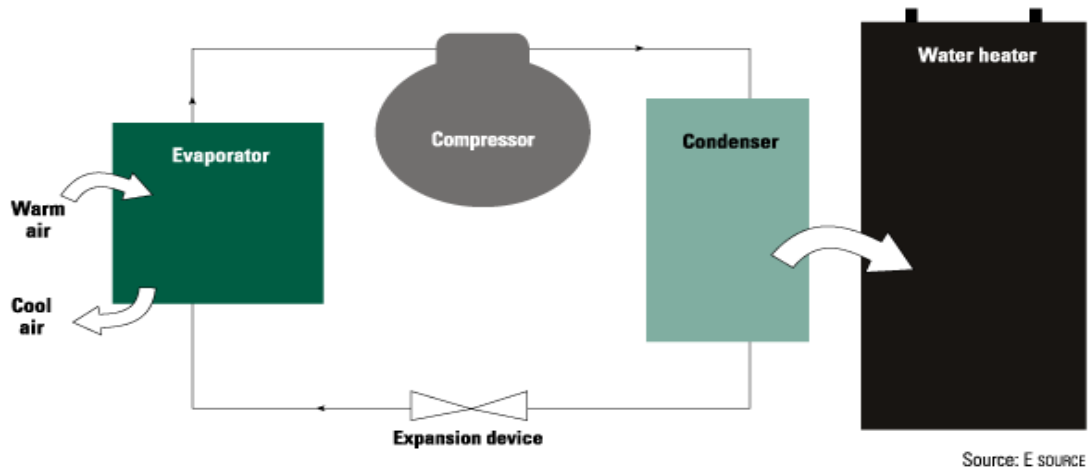


Figure 1.4 Heat pump water heater cycle [7].

1.3 Thesis Objectives

The objectives of this thesis are:

- 1) To develop models of domestic hot water components and systems that are able to take into account variations of environmental conditions and operating dynamics on a minute by minute time scale using Matlab Simulink®;

- 2) To investigate the performance of residential domestic hot water heating systems employing solar water heating, drain water heat recovery, and heat pump water heating technologies;
- 3) To compare the performance of five domestic hot water heating systems operating with different hot water usage profiles; and,
- 4) To quantify the differences in hot water system performance due to geographic variations by using resource and environmental data for Victoria, Kamloops, and Williams Lake B.C., Canada.

These objectives are described in the following chapters. Chapter 2 reviews relevant literature concerning hot water system modeling, typical domestic hot water load profiles, and simulations of advanced system configurations. Chapter 3 reviews conventional hot water systems and the common configurations using the focus technologies. To properly compare and assess systems, a number of different performance metrics are defined and discussed in Chapter 4. Chapter 5 describes various system models to be studied including key parameters and assumptions. Finally, Chapter 6 and 7 report on the model results for the various cases studied and key findings. Chapter 8 summarizes the main conclusions and makes recommendations for future work.

Chapter 2

Literature Review

The work presented in this thesis describes and evaluates the domestic hot water heating system in conjunction with three different energy saving technologies through numerical modeling. A summary of relevant research described in the literature is presented. In the following sections, a summary of previous models is presented followed by a discussion of key findings.

2.1 Modeling Tools Comparison

The use of solar assisted heating is becoming more common in many countries of the world. As a result, many computational tools have been developed to simulate the thermal performance of solar assisted DHW systems. These tools allow for the study of the effects of different design parameters have on the entire system. Three common modeling tools are TRNSYS, WATSUN and RetScreen®. These tools have been investigated and compared in a variety of studies.

TRNSYS is a transient systems simulation program with a modular structure. The latest version of this software is TRNSYS 16.02. It has been widely used in the study of solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, cogeneration, and fuel cells and their related components [8]. There have also been studies regarding solar water heating systems and its related components by using TRNSYS to evaluate the effects different design parameters and operating conditions have on system

performance. Buckles and Klein [9] compared the performance of several typical types of solar domestic water heating systems; Fanney and Klein [10] studied the effects the solar collector and tank-side heat exchanger flow rates have on thermal performance. Kleinbach et al. [11] used TRNSYS to study one-dimensional models of stratified thermal storage tanks; Shariah and Ecevit [12] studied the effect of hot water load temperature on the performance of a Thermosyphon solar water heater with auxiliary electric heater. Prapas et al. [13] analyzed and investigated the thermal behavior of large domestic hot water solar systems with distributed hot water storage tanks. Shariah and LÖf [14] studied the performance of a Thermosyphon solar water heating system with different electric auxiliary heater configurations under variable operating conditions; Kalogriou and Papamarcou [15] modeled a Thermosyphon solar water heating system and predicted the system performance by using TRNSYS with weather data of a typical mean year (TMY) file for Nicosia, Cyprus. Hobbi and Siddiqui [16] modeled a forced circulation solar water heating system for a single-family residential unit in Montreal, Canada and the corresponding optimization parameters were investigated by using TRNSYS. TRNSYS is a powerful tool; however, it requires considerable expertise and time. In addition, as a stand-alone program, it can not be easily integrated with other programs such as Matlab.

WATSUN [24] is a solar simulator developed by the University of Waterloo, and is capable of analyzing various kinds of active solar assisted DHW systems with or without heat exchangers and water storage tank. WATSUN simulates a DHW system with user defined parameters and weather data. WATSUN usually uses hourly time-step data, but a smaller, sub-hourly, time-step may be used by the numerical solver [24]. A hot water storage tank can be modeled either as mixed or stratified. This program predicts the total energy used by the hot

water load, the total energy collected by a solar collector, the fraction of the delivered load met by solar energy and several related quantities.

The result of the literature search for studies using WATSUN was scant and the only study found comparing TRNSYS and WATSUN was Long and Wood [17] in 1993. Some of the limitations of WATSUN are: it can only simulate a specific solar water heating system with all the design parameters pre-defined and subjected to one specific hourly based hot water load profile. This makes WATSUN cumbersome for studies with a large number of variables. However, WATSUN is relatively easy to use compared with TRNSYS and it will be used to validate the solar water heating system simulation model developed in this study.

RetScreen® [18] is a free decision support tool developed to evaluate the production of various types of renewable and energy-efficient technologies and the corresponding savings, costs, emission reductions, financial viability and risks. Device technical specifications, resource, and climate databases are included in the built-in database of this software. The latest version is RetScreen® 4.0, and it is capable of doing feasibility studies for renewable energy, cogeneration and district energy. Although RetScreen® is widely used, there are few studies regarding solar domestic water heating systems. The e-textbook [19] for this software does provide some case studies on real solar water heating projects in Canada, such as, an evacuated tube solar water heating system on a 9-unit apartment building in Montreal in 1991; a solar water heating system for a motel located in St. Côme Quebec in 1998; and, a domestic solar water heating system installed in a 2-storey, 185 m² home in North Vancouver, B.C. in 1997.

The climate database of RetScreen® provides weather data on a monthly basis; also, this software only requires the overall daily hot water consumption and the corresponding supply

temperature as the hot water load input. RetScreen® is not capable of providing analysis on a minute or hour basis, and results can only be used as a preliminary feasibility analysis for the project.

2.2 Solar Water Heating System Performance Studies

There has been extensive work regarding how to improve the performance of solar water heating systems both experimentally and analytically. A number of studies have concentrated on the relationship between performance and design variables. Some examples of the latter are: the storage tank size, the number of tanks, the solar collector area, the collector and heat exchanger flow rates, the hot water load profile, the hot water consumption, the auxiliary water heating device configurations, the cold make-up water replenishment profile, and the heat exchanger configuration.

Buckles and Klein [9] investigated the effects of the number of storage tanks, the storage capacity, insulation, hot water load profile and the tempering value. Their simulations studied four basic system configurations employing three representative collector areas and hourly weather data for Madison, WI, Albuquerque, NM, and Charleston, SC. One of the main outcomes of this work was a modified *f*-chart design method which can be used to predict the long-term performance of various types of solar water heating systems. The four system configurations studied are single tank with internal heat exchanger, double tank with internal heat exchanger, single tank with external heat exchanger, and double tank with external heat exchanger. The six hourly hot water load profiles were the RAND average profile, 24-hr constant profile, early morning profile, late morning profile, early afternoon profile, and late afternoon

profile. The authors found the performance differences between one tank and two tank systems were small and the internal heat exchanger and external heat exchanger with the same effectiveness provided the same performance was found to have little effect on the monthly average system performance. They also concluded that the overall system performance is not sensitive to the hot water load distribution during a day as long as the storage tank is sized to be sufficient and the overall daily hot water consumption remains the same.

Shariah and LÖf [14] simulated a Thermosyphon solar water heating system with an electric auxiliary heater using TMY weather data for Los Angeles, California. Using a TRNSYS simulation, the effects of hot water delivered temperature (60 and 80 °C), daily hot water load (250 and 150 litre), type of hot water load profile, and locations of auxiliary heating were studied. They found the system's annual solar fraction is largely affected by the hot water load profiles and the delivered temperature.

Fanney and Klein [10] investigated the effects of heat transfer fluid on the performance of a forced circulation solar water heating system which either directly circulates the domestic hot water through the solar collector or employs an external heat exchanger to transfer the collected solar energy to the domestic hot water. Two identical single tank solar hot water heating systems with and without an external exchanger were set up at the National Bureau of Standards Solar Hot Water Test Facility in Gaithersburg. The side-by-side experiments showed that, for the single tank direct system (without an external exchanger) equipped with conventional return tubes, the overall system performance was improved by lowering the solar collector heat transfer fluid flow rate; however, if a specially designed return tubes minimizing mixing in the storage tank was operated with the same collector fluid flow rate, only a small

improvement in system performance occurred as compared with the same system operating with the conventional fluid flow rate. A simulation of the indirect system (with an external heat exchanger) operating with a range of heat exchanger design and collector and tank side flow rates showed no improvement in system performance when reducing the collector fluid flow rate.

Solar fraction is an important performance indicator for solar water heating systems because it quantifies the conventional energy replaced by solar and reflects potential operating cost savings. Hobbi and Siddiqui [16] modeled an in-direct, forced circulation, solar water heating system employing a flat-plate collector for a single-family residential unit in Montreal, Canada by using TRNSYS. Their work examined the impact of various design parameters on solar fraction. Optimized values of design parameters for a specific system were found by performing two sets of simulations. One simulation was for the determination of optimum system parameters, and the other was for optimum collector design parameters. The system was simulated subject to only one hot water load profile (the Rand profile). The results indicated that the solar domestic hot water system being modeled was able to provide 83-97% and 30-62% of hot water demands in summer and winter, respectively.

Knudsen [20] showed that mixing of cold make-up water inside the storage tank reduces the tank's performance by destroying the thermal stratification in the tank. In reality, thermal stratification can be easily broken by either an immersed heating device which heats the water at different levels creating uniform tank temperature in short time, or high collector flow rates which result in short tank turnover times causing a nearly uniform tank temperature. Kulkarni et al. [21] proposed a novel strategy for cold water replenishment to improve the overall system

performance even without stratification. The results of a case study showed that about 14% of the annualized system cost, 13% of the collector area, and 10% of storage volume can be reduced for the cost-optimal system configuration.

The literature indicates that many of the earlier studies on solar water heating focused on how to improve solar collector performance, storage tank thermal performance, and how to manage the hot water usage pattern. In practice, mechanical systems designers are not able to change many design parameters because they are determined by equipment manufacturers. Systems designers only select the equipment with the performance closest to the design requirements using standard product catalogues. At the moment, demand side management, such as changing the hot water usage pattern, and reducing the hot water consumption, is beyond the system designer's control. The most common hot water load profiles being used by earlier studies are the Rand profile, a continuous use, an evening, and a morning profile. All of them are on an hourly basis profiles which are usually sufficient to investigate the system's long-term average performance; however, in principle, the hot water load profile is affected by several factors and can vary from day to day, season to season and family to family [16]. Hourly load profiles usually overestimates the piping heat loss and do not accurately reflect short duration hot water consumption [26].

2.3 Drain Water Heat Recovery Studies

Since the tool developed in this thesis is able to simulate DHW system equipped with a drain water heat recovery unit (DWHR), the literature of drain water heat recovery has been

searched. Charles [27] evaluated and characterized performance of eight different models of DWHR units through a series of tests. Those DWHR units were connected to the shower drain only. Experiments were performed by using two different flow configurations, three different flow rates and three different shower temperatures. A standard test and modeling method were developed in order to estimate energy savings and pressure drop through different DWHR units. The correlation of the flow rate and DWHR unit NTU value, presented in their study, is referenced in developing the simulation tool in this thesis.

The simulation tool in this thesis simulates DHW systems equipped with a solar pre-heating tank and a gas-fired domestic hot water tank with six different groups of storage tank parameters including thermal insulation, storage capacities, tank geometries, rated energy factor, and heat recovery efficiency. Configurations are subjected to twelve different hot water usage patterns using a one minute resolution with and without solar collecting components, resulting in 144 different cases being modeled and simulated. The following chapter presents common domestic hot water system configurations. Particular configurations studied in the remainder of the thesis are discussed.

Chapter 3

System Description

This chapter reviews conventional residential DHW configurations as well as the alternative systems focused on in this thesis, namely, solar, heat pump, and waste heat recovery devices.

3.1 Conventional Domestic Hot Water System

A simplified conventional domestic water heating system for residential use is shown in Figure-3.0. It is comprised of a hot water storage tank, a source to heat the water, mixing devices (faucets), the make-up cold water supply section, and the connecting piping between each component. The system efficiency can range from 50% to 85% depending on the type of water heater, the distribution system, connecting pipe length, storage tank size, and the hot water usage pattern. In order to reduce the thermal loss and achieve higher system efficiency, the domestic hot water storage tank's exterior surface and the hot water circulating piping are usually covered with insulation.

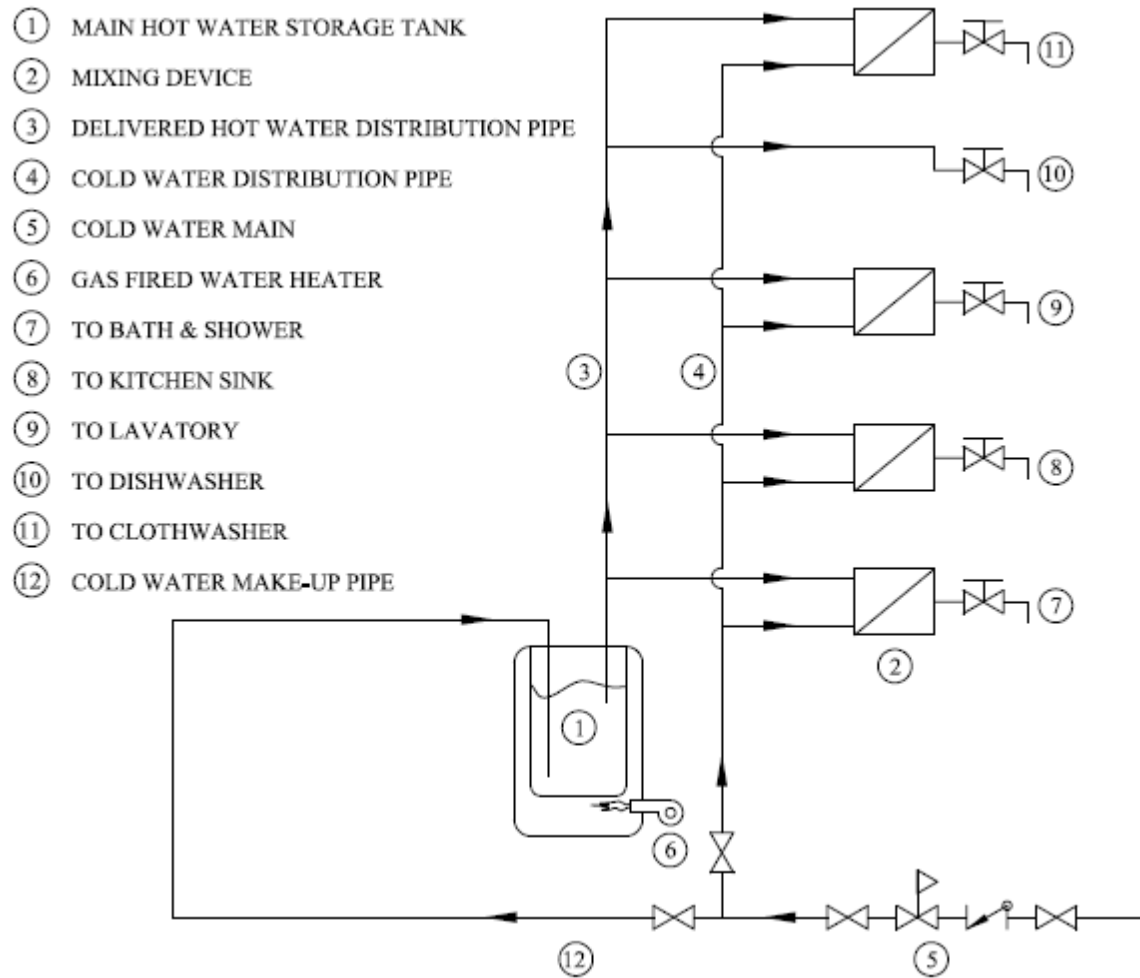


Figure 3.0 Conventional domestic hot water system configuration [22].

As indicated in the figure, the stored water is heated to the set point (pre-set temperature) by the water heater, either a gas or oil fired burner or electric resistance elements inside the tank. In Canada, the water heater's set point is usually set to be $\sim 60^{\circ}\text{C}$. Once the set point is reached, the heating device shuts down. When the domestic hot water system calls for the hot water, the stored hot water is delivered from the hot water storage tank via the distribution system to the mixing device on the plumbing fixture where the delivered hot water is mixed with the domestic cold water to achieve the desired temperature for use. At the same time, cold make-up water

from the city main is fed to the hot water storage tank, in which it is heated to the tank's set point.

3.2 Configurations of Domestic Water Heating System in This Research

This thesis examines four different domestic hot water system configurations listed in Table-3.1A. The performances are compared to a conventional domestic hot water system as described in section 3.1. Combinations of technologies (such as solar + drain heat recovery) are possible, but will not be examined in this work.

Table-3.1A Four different domestic hot water system configurations.

Configurations:	Energy Saving Technologies
Configuration-I	Solar Assisted Water Heating.
Configuration-II	Option A Drain Water Heat Recovery Unit to pre-heat cold water make-up.
	Option B Drain Water Heat Recovery Unit to pre-heat the bath fixtures cold water.
Configuration-III	Add-on Heat Pump Water Heating System served as the main hot water heating system in conjunction with conventional DHW heating system.
Configuration-IV	Add-on Heat Pump Water Heating System used as the hot water pre-heating system in conjunction with a conventional DHW heating system.

3.2.1 Configuration I- Solar Assisted Domestic Water Heating System.

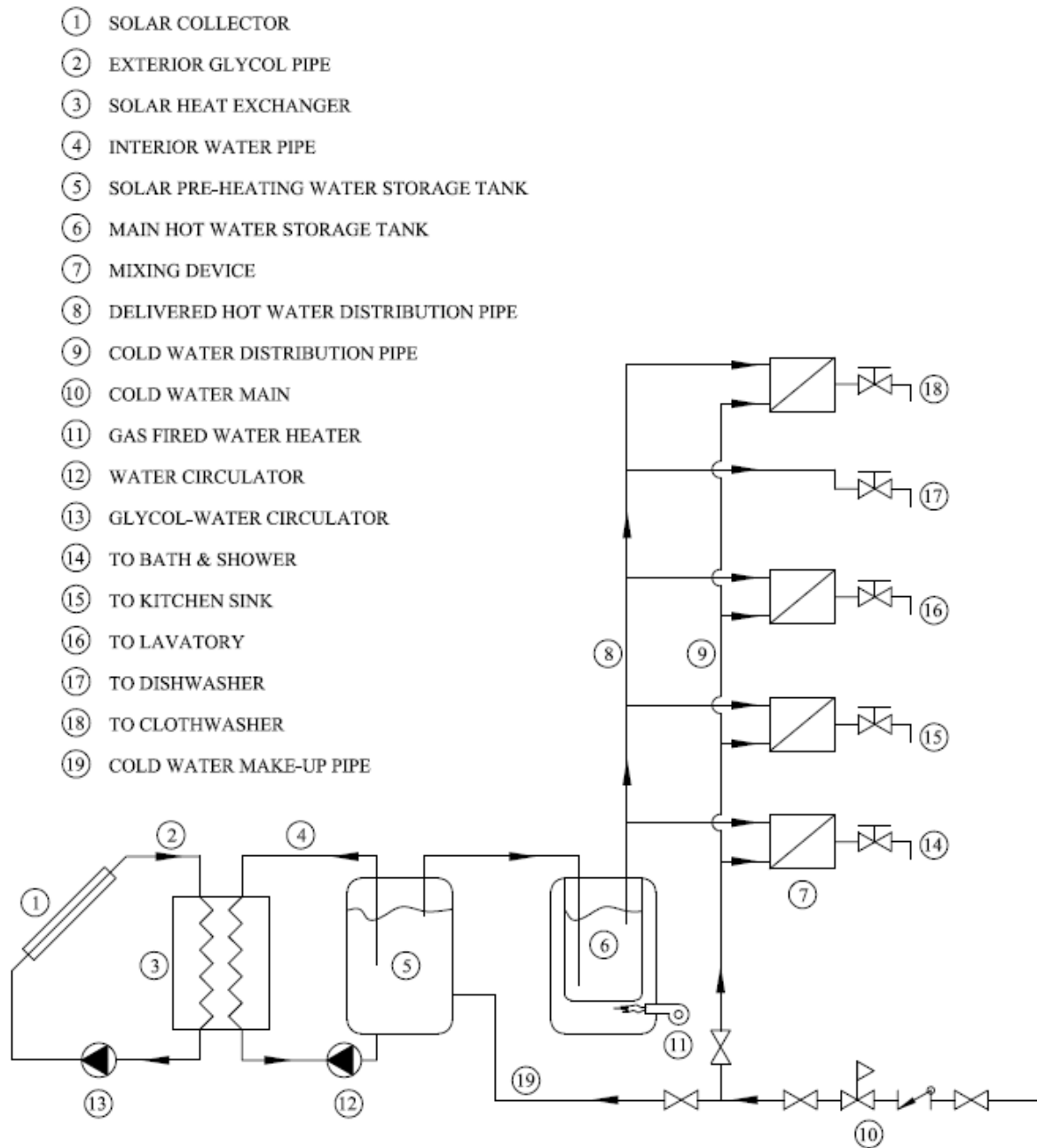


Figure 3.1 Domestic hot water system configuration I [23], [24].

Configuration I represents a solar assisted DHW system. The base configuration assumes two flat plate solar collectors, a solar heat exchanger, a pre-heating water storage tank, a main

hot water storage tank with natural gas fired water heater, mixing devices and two circulators. The solar collectors are assumed to be arrayed in a parallel arrangement so that each of them works under the same conditions.

As shown in Figure 3.1, solar radiation is absorbed and transformed into heat energy by the solar collectors. The glycol-water heat transfer fluid circulating between the solar collector and the solar heat exchanger transfers energy to the circulating domestic water from the solar pre-heating storage tank and then returns to the solar collector. When the system calls for hot water, the stored hot water is delivered from the main hot water storage tank to the outlet point (tap). The cold water make-up enters the solar pre-heating water storage tank with the same flow rate as the delivered hot water and the pre-heated water flows into the main hot water storage tank. If the temperature of the pre-heated water from the solar pre-heating water storage tank is higher than the set point of the water heater, the water heater inside the tank won't be activated and the hot water is delivered from the solar pre-heating tank through the main hot water storage tank to the system directly when the system calls for hot water. The water heater inside the main hot water storage tank is activated only when the temperature of the stored water is lower than the set-point. Once the temperature of water from the solar pre-heating tank is higher than the circulator's deactivation set point, the circulator will be shut down and no more heat is brought into the pre-heating tank. On the other hand, if hot water demand is too high, or there is insufficient solar energy available, the temperature of the delivered hot water will be lower than the set-point, and the heater will be activated. Because the system's cold water make-up is pre-heated by solar energy, energy savings are expected compared to the conventional domestic hot water heating system. Usually, the temperature of the delivered hot water from the main hot

water storage tank is higher than the demand domestic hot water temperature, so it needs to be mixed with cold water in the mixing device to achieve the desired temperature.

3.2.2 Configuration II- Domestic Hot Water System with the Assistance of Drain Water Heat Recovery Technology

Configuration II includes a drain water heat recovery unit to recover heat from the shower's drain. As indicated in Figure-3.2 and Figure-3.3, there are two different water flow options. Figure-3.2 shows Option A which pre-heats all the system's cold water make-up by routing it to the drain water heat recovery unit before it is further heated by the heater inside the main storage tank. Option B, shown in Figure-3.3, pre-heats all the incoming cold water (demand hot water) from the city main, but only some of the pre-heated water enters the storage tank to be further heated while the rest is fed to the mixing device on the bath fixture.

As can be seen in both of Figure-3.2 and 3.3, the drain water heat recovery unit is connected to the shower drain only. When the shower is not being used, this configuration is the same as the conventional domestic water heating system. Because showers typically account for ~40-45% of domestic hot water use [26], a significant energy saving is expected by using this kind of technology. Furthermore, the heat recovery device needs counter-flowing fluid to work. A service such as a bath or washing machine stores fluid so that drain flow and make-up flow are not synchronized in time.

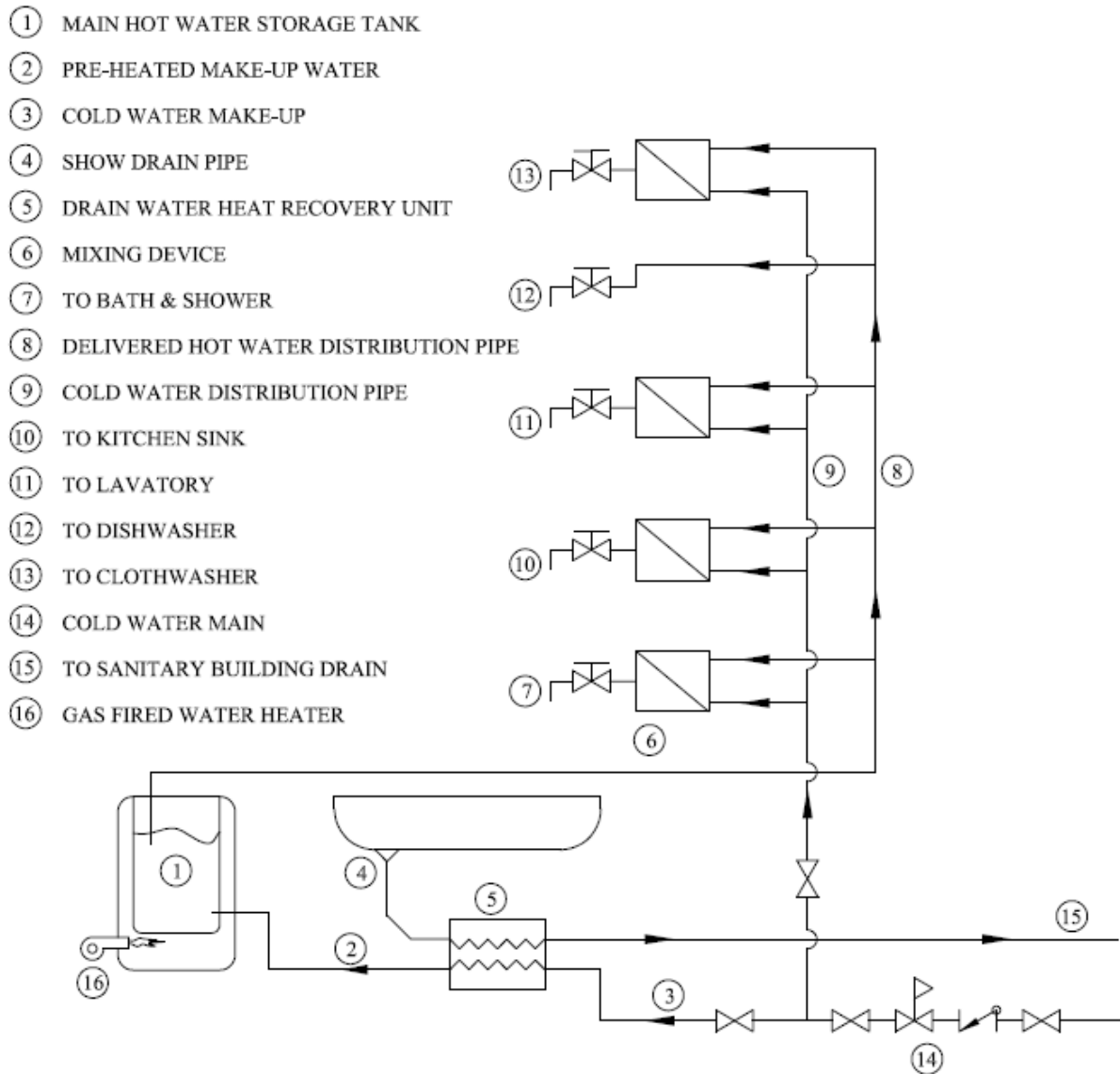


Figure 3.2 Domestic hot water system configuration II option A [27].

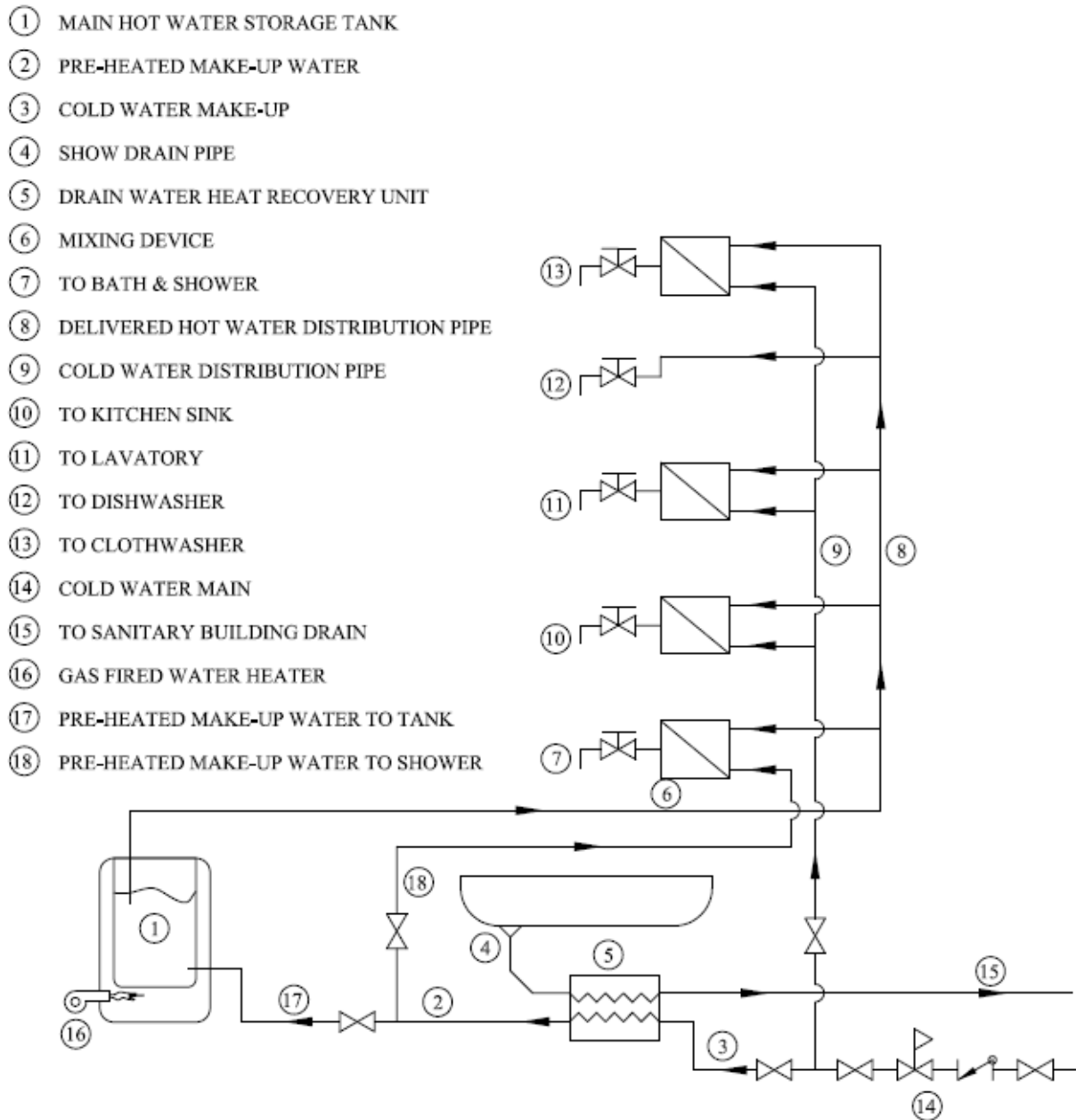


Figure 3.3 Domestic hot water system configuration II option B [27].

3.2.3 Configuration III- Add-on Heat Pump Assisted Domestic Hot Water Heating System

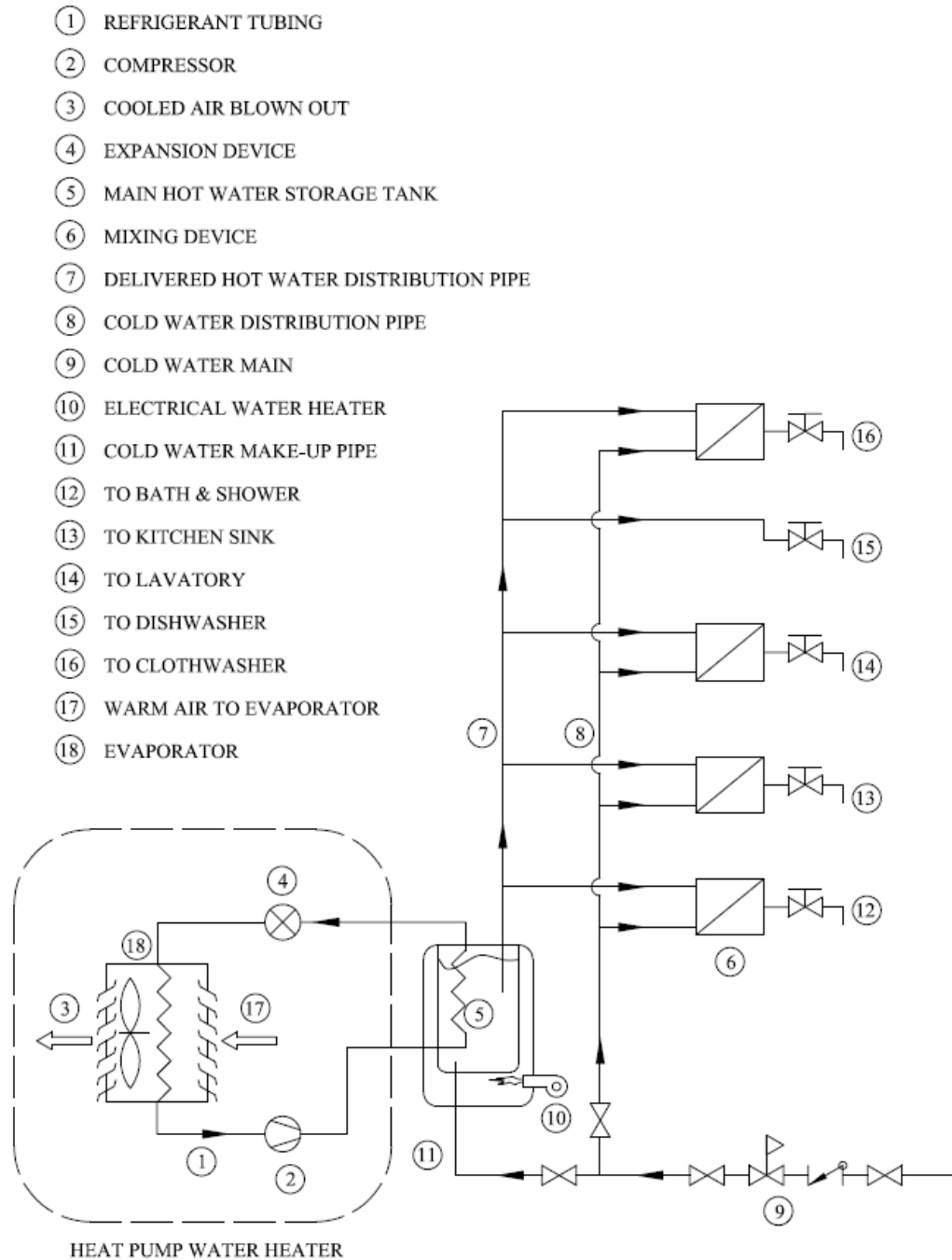


Figure 3.4 Domestic hot water system configuration III.

Configuration III uses a heat pump in conjunction with a conventional DHW system. Unlike configuration I and II, the heating source for the water heater inside the main hot water storage tank is electric. As indicated in Figure-3.4, an add-on heat pump is installed on top of the conventional electric hot water storage tank and the water is heated up to 50°C by the heat pump water heater's condenser which is extended into the main hot water storage tank. When the heat pump heating mode is on, the electric water heater is deactivated so that once the stored hot water temperature is lower than the set point, only the heat pump water heater is activated and keeps running until the hot water temperature reaches 50°C. The electric water heater inside the main hot water storage tank is activated to heat the water only when the ambient temperature is either lower than 7°C or higher than 40°C which is the heat pump water heater's ambient operating range (*Refer to [28] for the heat pump water heater's technical specification*). It is important to note that, unlike the other configurations, Configuration III can only provide hot water with the maximum temperature of 50°C. Furthermore, the heat pump water heater is a compact unit so that the evaporator is located in the same space (usually basement) where the unit is installed.

3.2.4 Configuration IV- Domestic Hot Water Heating with Heat Pump Water Heater Assisted Make-up Water Preheating System

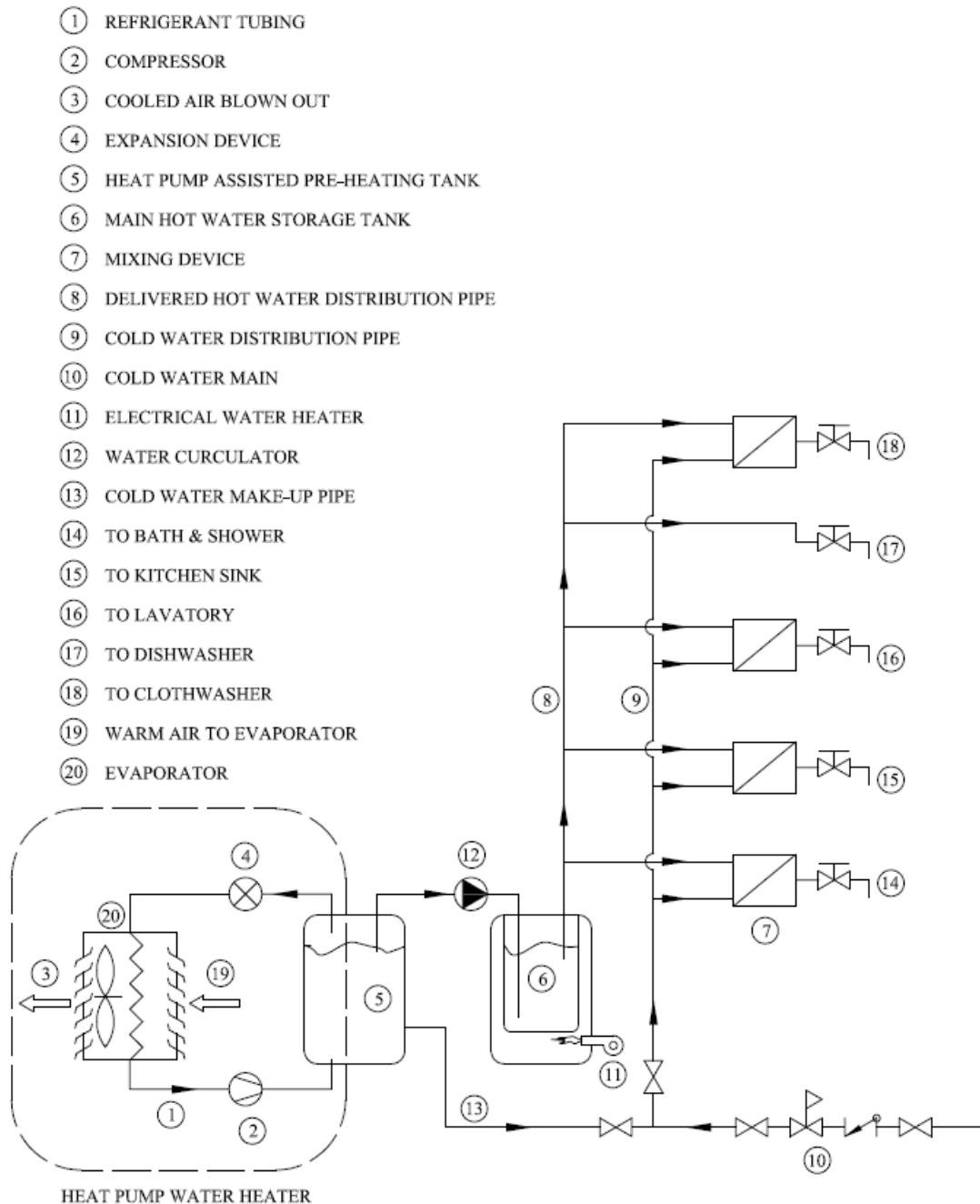


Figure 3.5 Domestic hot water system configuration IV

Configuration IV pre-heats the cold make-up water by using the same heat pump technology as in configuration III. As shown in Figure-3.5, this configuration has two water storage tanks - one is the pre-heating tank and the other is the main hot water tank. The add-on heat pump water heater is installed in conjunction with the pre-heating tank so that the cold make-up water is pre-heated by the heat pump water heater and then stored in the pre-heating tank. The pre-heating tank is assumed to have the same storage volume and the same insulation value as the main hot water storage tank in this research. If there is no call for hot water from the system, which means no cold water make-up is supplied to the pre-heating tank, the heat pump will shut down when the stored water temperature reaches 50°C (*the maximum temperature the heat pump can work*). When the system calls for hot water, pre-heated water flows into the main hot water tank from the pre-heating tank. The electric water heater inside the main hot water tank is activated to heat the water only when the delivered hot water temperature to the system is lower than the set point of the electric water heater or the heat pump heating mode is off. Unlike configuration III, which can only deliver hot water to the system with the maximum temperature of 50°C , configuration IV is able to produce hot water with the same temperature as any conventional DHW system. This is because there is no circulation of hot water between the pre-heating storage tank and the main hot water storage; therefore, the higher temperature water inside the main hot water storage tank will not cause the heat pump water heater to shut down.

Since the average COP value of most heat pump water heaters is ~ 2.0 , both of configuration III and configuration IV are expected to have significant energy savings compared with the conventional electric DHW system although comparisons between Configuration III and the others are less meaningful if different hot water temperature set-points are used.

Chapter 4

Metrics

Conventional residential hot water systems are usually rated by the energy factor (EF) of the DHW tank. The EF is determined using standardized test procedures. This metric is not appropriate for many unconventional hot water systems because it does not capture the efficiency of the entire hot water system. For example, pipe length and insulation values are not included in a tank EF rating. A number of metrics are defined in this chapter to quantify and compare the impacts of using different energy saving technologies for residential domestic hot water heating.

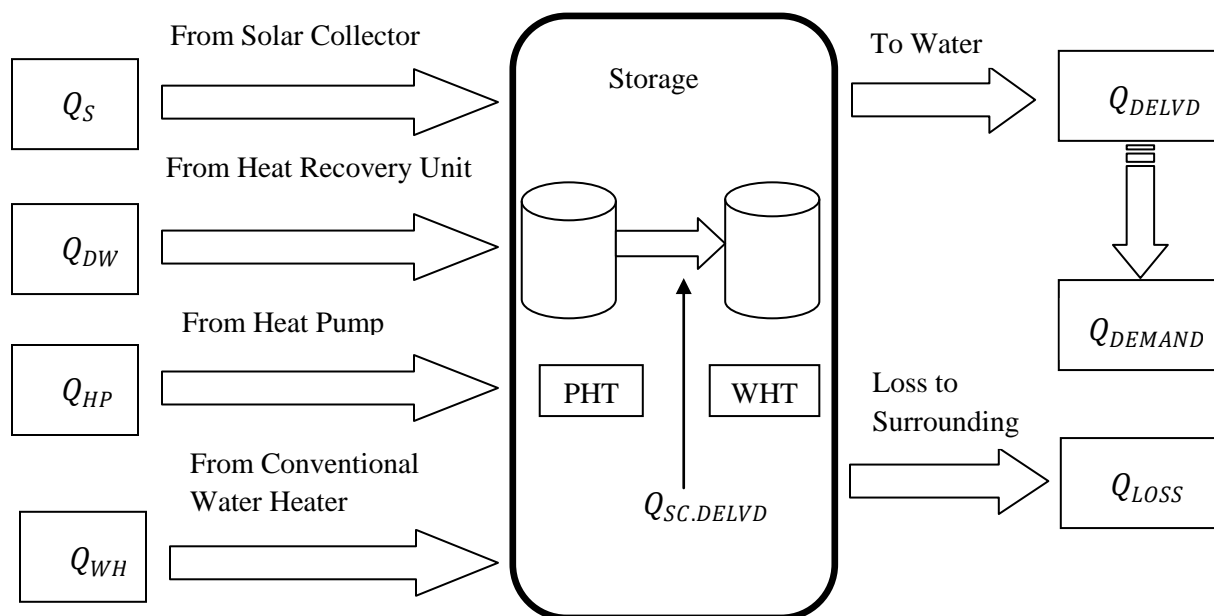


Figure 4.1 Energy flow of an unconventional domestic water heating system.

The daily energy flow of an unconventional domestic water heating system is shown in Figure 4.1. As can be seen from the figure, the *total heating energy* Q_{THE} flowing into the

storage tank, as indicated to the left side of the tank, could include solar energy Q_{SC} from solar collector, recovered energy Q_{DW} from drain water heat recovery unit, energy from the heat pump water heater Q_{HP} , and supplemental energy from auxiliary heating device Q_{WH} . All the energy flowing out of storage tank includes the *daily delivered energy* Q_{DELVD} to the domestic hot water system and the *daily storage tank's thermal loss* Q_{LOSS} from storage tank to the ambient space. The outflow and the inflow of energy are not necessarily in balance for a specific short period such as one day. If the total inflow energy is larger than the total outflow energy, then there is residual energy in the system causing the final stored water temperature to be higher than its initial temperature. If the total inflow energy is smaller than the outflow energy, then the tank temperature decreases and an unmet load may occur.

4.1 Daily Delivered Energy

The *daily delivered energy* Q_{DELVD} is the actual thermal energy (kWh) delivered by the domestic hot water system. The value of *daily delivered energy* depends on the daily hot water usage profile, the cold make-up water temperature and the actual delivered hot water temperature. It is defined as:

$$Q_{DELVD} = \int (\dot{m}C_p)_s (T_s - T_c) dt \quad (4.1.1)$$

where, $(T_s - T_c)$ is the temperature difference between the actual delivered hot water and the cold make-up water. \dot{m} is the actual mass flow of the delivered domestic hot water from the main hot water storage tank and can be further calculated by

$$\dot{m} = \rho * \sum_{i=1}^n \dot{V}_i \quad (4.1.2)$$

ρ is the density of the water (998kg/m³), and $\sum_{i=1}^n \dot{V}_i$ is the instantaneous total volume flow rate of the hot water delivered to ‘ n ’ plumbing fixtures.

4.2 Daily Collected Solar Energy

The *daily collected solar energy* Q_{SC} (kWh) is the total solar energy collected by a solar collector over a given period, τ . It is defined as:

$$Q_{SC} = \int_0^{\tau} (q_{SC}) dt \quad (4.2)$$

where, q_{SC} is the instantaneous heat flows collected by a solar collector.

4.3 Total Heating Energy

The *total heating energy* is the total heat energy generated during one day, which is the sum of the heating energy collected by a solar collector, the energy recovered from the drain water heat recovery unit, the energy produced by the heat pump water heater, and the auxiliary energy provided by either the gas fired or the electric water heater inside the main hot water storage tank. The *total heating energy*, Q_{THE} , can be presented as equation (4.3)

$$Q_{THE} = Q_{SC} + Q_{DW} + Q_{HP} + Q_{WH} \quad (4.3)$$

where, Q_{SC} , Q_{DW} , Q_{HP} , and Q_{WH} are heating energy (kWh) generated from the solar collector, the drain water heat recovery unit, the heat pump water heater, and the water heater inside the main hot water storage tank, respectively.

Storage tanks allow for energy to accumulate in excess of that delivered. When this happens, the system will have gained *residual energy* at the end of the day. This means the temperature of the water storage tank at the end of the day is higher than the beginning of the day. In some cases, even though, there is insufficient solar energy available in the morning, the residual energy is large enough to cover the first hour's hot water consumption of the day. From an energy balance, the *total heating energy* can also be presented as equation (4.3a)

$$Q_{THE} = Q_{DELVD} + Q_{RESIDUAL} + Q_{LOSS} \quad (4.3a)$$

where, Q_{LOSS} is the *daily storage tank's thermal loss*, and $Q_{RESIDUAL}$ is the *daily residual energy*.

4.4 Daily Delivered Solar Heating Energy

The *daily delivered solar heating energy* $Q_{SC,DELVD}$ (kWh) is the amount of solar energy delivered to the domestic hot water which is actually consumed during one day. In other words, some amount of conventional energy is replaced by the *delivered solar heating energy*. This quantity is determined by the enthalpy change of the water flowing through the pre-heating tank. The value depends on the mass flow rate of the delivered pre-heated water from the solar pre-heating tank, \dot{m}_{PHT} , the actual temperature of the delivered pre-heated water T_{PHT} , and the cold make-up water temperature T_c . Because the mass flow rate of the delivered pre-heated water and its temperature are dynamically changing within one day, the *daily delivered solar heating energy* is defined as:

$$Q_{SC,DELVD} = \int_0^{1day} \dot{m}_{PHT} C_p (T_{PHT} - T_c) dt \quad (4.4.1)$$

The mass flow rate of the delivered pre-heated water from the solar pre-heating tank is the same as the water delivered from the main hot water storage tank to the domestic hot water system, i.e. $\dot{m}_{PHT} = \dot{m}$.

4.5 Conventional Energy

The *conventional energy* W_e (kWh) is the total conventional energy being consumed to provide the supplemental heating by either the water heater inside the main hot water storage tank or the heat pump water heater compressor or both of them. Conventional energy includes electricity use, natural gas, or any other chemical fuel (based on the heating value). It is defined as:

$$W_e = (W_{HP} + W_{WH}) \quad (4.5)$$

where, W_{HP} and W_{WH} are the amount of conventional energy consumption by the heat pump water heater's compressor and the heating device inside the domestic hot water tank.

4.6 CO₂ Emission

CO₂ emission quantifies the total emitted CO₂ (kg/day), generated either directly from the gas fired water heater or indirectly from the electric water heater inside the main hot water storage tank. This quantity can be calculated by:

$$CO_2 = I_{CO_2} W_e \quad (4.6)$$

where, I_{CO_2} is the CO₂ intensity of a conventional energy source. When the system's conventional energy is electricity, the unit of this conversion coefficient is kgCO₂/kWh and in B.C. the value is 0.036 [29] which is much lower than most provinces in Canada since the

electricity is generated mainly by hydro in BC. If the system's conventional energy is natural gas, the intensity is ~ 49.7 kgCO₂/GJ [29]. The CO₂ emission is an important indicator to determine if a specific technology has environment benefits and to put a value on them.

4.7 Delivered Hot Water Consumption

The total *delivered hot water consumption* V_{DELVD} is the volume of hot water being delivered from the main hot water storage tank to all the plumbing fixtures in one day. The delivered hot water needs to be mixed with cold water in the mixing device to achieve an appropriate temperature before being used; therefore, the higher the delivered hot water temperature is, the less hot water that needs to be delivered. This value is determined by:

$$V_{DELVD} = \sum_{i=1}^n \int (\dot{v}_i)_s dt \quad (4.7)$$

where, V_{DELVD} is the total hot water delivered in one day with the unit of litre/day. The subscript 's' of the bracket indicates the water is delivered from the main hot water storage tank. The domestic water heating system's storage tank sizing is based on this quantity.

4.7.1 Delivered Peak Demand

The *delivered hot water peak demand*, $V_{S,max}$, reflects the maximum volume flow rate of the delivered hot water from the main hot water storage tank. This value is used to size a tank's hot water outlet pipe and cold water make-up inlet pipe.

4.7.2 Delivered Peak Demand Time

The *delivered hot water peak demand time*, $t_{S,max}$ is the instant when the system's delivered hot water demand or load reaches the peak. Usually, that happens when more than one

plumbing fixture is used at the same time, for example, in the morning, the kitchen sink and the shower might be used at the same time.

4.8 Demand Water Consumption

The *demand water consumption*, V_d , measures the actual volume of demand hot water being consumed in one day and can be presented as:

$$V_d = \sum_{i=1}^n \int ((\dot{v}_i)_s + (\dot{v}_i)_c) dt \quad (4.8)$$

V_d can be considered the volume of warm water actually leaving a faucet in one day- this is water from the hot water tank as well as any cold water that has been used to temper it. $(\dot{v}_i)_s$ is the volume flow rate of the delivered hot water to the i^{th} plumbing fixture, and $(\dot{v}_i)_c$ is the volume flow rate of cold water being mixed with the delivered hot water to achieve an appropriate water temperature before use.

To reiterate, *demand* and *delivered* hot water are two different quantities. The former is a measure of what the user wants from the system, whereas the latter, *delivered*, is the hot water coming from the DHW system (tank) to the fixtures.

4.9 Maximum Hot Water Tank Temperature

This measurement records the maximum water temperature in the main hot water storage tank for one day. Usually, the *maximum tank water temperature* of the domestic hot water system should be the same as the tank's set point; however, if sufficient solar heating energy is available, the water make-up from the solar pre-heating storage tank might have a much higher temperature thereby increasing the water tank temperature when the system calls for hot water.

4.10 Unmet Load

If the actual delivered hot water temperature from the main hot water storage tank is lower than the demand hot water temperature desired by any one of the plumbing fixtures when the plumbing fixture is being used, then the system is considered to have an unmet load. *Unmet load* is the energy deficit defined by the difference between the demand, T_D , and delivered temperatures, T_S can be presented as:

$$Q_{unmet} = \sum_{i=1}^n (\int \dot{m} C_p (T_D - T_S) dt)_i \quad (4.10)$$

Q_{unmet} is the total system unmet load during one day in kWhs, and the subscript ‘ i ’ indicates the ‘ i^{th} ’ plumbing fixture being used during a specific period. This measurement is recorded only when T_D is higher than T_S .

The *unmet load ratio*, U_F , is an indicator of the system’s unmet load relative to the demand energy and is defined as:

$$U_F = \frac{Q_{unmet}}{Q_{demand}} \quad (4.11A)$$

Where Q_{demand} is the demand energy is consumed and is defined as:

$$Q_{demand} = \sum_{i=1}^n (\int \dot{m} C_p (T_D - T_C) dt)_i \quad (4.11B)$$

where T_C is make-up cold water temperature.

4.11 Solar Fraction

The *solar fraction* F_s is the fraction of daily total heating energy produced during one day provided by solar. In other words, it indicates how much of the system's actually produced heating energy is from solar energy. It is defined as:

$$F_s = \frac{Q_{SC}}{Q_{THE}} \quad (4.12A)$$

Where, F_s is the solar fraction, Q_{THE} is the daily total heating energy flow into domestic water heating system, and Q_{SC} is the amount of solar energy collected in one day. It is important to note that based on these definitions, it is possible for the daily collected solar energy Q_{SC} to exceed the actually delivered energy Q_{DELVD} to the system. This can occur because energy is lost through various components (pipes, storage tank, etc.) and, because of the presence of storage, it is possible for solar energy to be absorbed and stored in the storage tank to form the residual energy. Another definition of solar fraction might be:

$$F_{s2} = \frac{Q_{SC.DELVD}}{(Q_{DELVD} + Q_{LOSS})} \quad (4.12B)$$

Where, $Q_{SC.DELVD}$ is the portion of solar energy actually delivered to the domestic water heating system.

4.12 System Energy Factor (SEF)

The *system energy factor*, SEF, is the ratio of the delivered energy to the total conventional energy consumption. Because of the component inefficiencies, only a portion of the heating energy generated is delivered as hot water or stored, the rest is the thermal loss; therefore, this measurement can also be called system efficiency. The *system energy factor*, SEF , is defined as:

$$SEF = \left(\frac{Q_{DELVD}}{W_e} \right) \quad (4.13)$$

where, W_e is the system conventional energy consumption; while, Q_{DELVD} is the system's daily delivered energy. The SEF can be greater than one.

4.13 Cycling

Cycling measures the total times a water heater is activated to heat the domestic water. This will occur when any alternative energy saving technologies are not able to provide enough energy to maintain the desired hot water temperature.

While not a primary focus of this study, cycling can also be a useful parameter when one is interested in tracking the impact of a DHW system component on electrical demand. For example, electric tank-less water heaters are used in modern households. These devices provide a high quality hot water service; however, they can impose large and frequent power demands at a time of day when electrical system use is high.

Chapter 5

Component Modeling and Parameters

This chapter describes the mathematical models for each of the main hot water system components. The parameters defining the specific component properties are described as is the method of creating a hot water load profile.

Individual components are modeled by creating their own blocks in Matlab Simulink®. This makes creating a model of a particular configuration easy by pasting a copy of a component block and connecting the blocks. Device parameters are set by calling external files in excel where different devices are listed. Likewise, a load profile is defined in an Excel file and is made into a daily time series with minute scale resolution using a Matlab script. The script also runs the system dynamic simulations with the desired configurations, season and location information input automatically.

5.1 Main Hot Water Storage Tank's Modeling

All water tanks are modeled assuming they are well-mixed so that the water has a uniform temperature and can be represented by an ordinary differential equation in time. The general equation describing the instantaneous energy balance of a tank as a function of time in terms of temperature is,

$$mC_p \frac{dT_s}{dt} = \sum \dot{m}C_p(T_i - T_s) + Q_{Source} - Q_{LOSS} \quad (5.1)$$

where, T_s is the water temperature in the tank, m is the total mass of fluid in the tank (determined by the volume), C_p is the heat capacity, \dot{m} is the flow rate of water into the tank, and Q

represents generic energy source terms. The tank model balances the time variation in energy stored in the tank by losses, heat inputs such as a heater, and energy transfer due to water flows in and out.

The solar pre-heating tank model balances energy accumulation with solar gain, losses due to imperfect insulation, and energy flux from cold water flow:

$$(mC_p)_{PHT} \frac{dT_{PHT}}{dt} = \underbrace{q_{SC}^+}_{Solar\ Gain} - \underbrace{q_{LOSS}}_{Thermal\ Loss} - \underbrace{\dot{m}C_p(T_{PHT} - T_c)}_{Delivered\ Energy} \quad (5.2)$$

T_{PHT} is the water temperature inside the solar pre-heating water storage tank, T_c is the temperature of cold water make-up, and \dot{m} is the mass flow rate of the cold water make-up entering the solar pre-heating water storage tank whenever the system calls for hot water. This model assumes good heat exchange between make-up water and the tank so that the water exiting the tank is at T_{PHT} . The calculation of solar gain will be described in detail in Section 5.4.1 .

The heat pump pre-heating storage tank is modeled with the same equation used for the solar pre-heating tank; however, the thermal source is now the heat pump instead of solar gain.

5.2 Other Component Models

5.2.1 Glazed Liquid Flat-Plate Solar Collector

A solar collector is a special kind of heat exchanger that absorbs radiant energy and transforms it into heat. A flat plate solar collector, as shown in Figure 5.1, is one of the simplest and most common types.

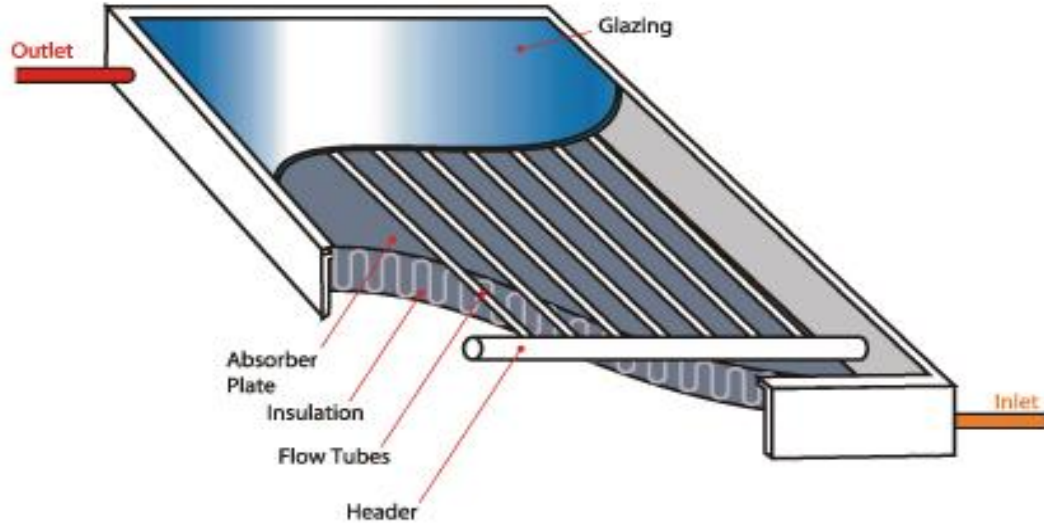


Figure 5.1 Glazed liquid flat plate collector [3].

The useful solar energy transferred to the solar pre-heating tank (including the effectiveness of the heat exchanger) is modeled using equation 5.3 following the methods described in [23].

$$q_{SC} = A_c F'_R (\tau\alpha)'_n K_{\tau\alpha} G_T - A_c F'_R U'_L (T_{PHT} - T_a) \quad (5.3)$$

where, G_T is the global incident solar radiation (W/m^2) on the tilted surface and can be further calculated from the global solar irradiation, I_T , ($\text{J}/\text{m}^2 \cdot \text{min}$).

$$G_T = I_T * \frac{1}{60} \quad (5.4)$$

I_T is the global solar irradiation on a tilted surface whose mathematical model is discussed in section 5.5.

In Equation 5.3, $(\tau\alpha)'_n$ is the transmittance-absorptance product at normal incidence for a flat plate solar collector. The transmittance-absorptance product at any angle of incidence can be

calculated by introducing the incidence angle modifier $K_{\tau\alpha}$ and its general expression as suggested by *Souka and Safwat (1966)* is described as the following:

$$K_{\tau\alpha} = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right) \quad (5.5)$$

where b_0 is a constant called the incidence angle modifier coefficient and can be found from a solar collector's technical specifications. The detailed calculation procedure of incidence angle of solar radiation, θ , can be found in [23].

F'_R accounts for the effectiveness of the counter-current heat exchanger between the solar pre-heating water storage tank and the solar collectors, and is the modified heat removal factor of the flat plate solar collector under the actual use conditions. The ratio F'_R/F_R is a function of solar heat exchanger effectiveness ε .

$$\frac{F'_R}{F_R} = \left[\left(1 + \frac{A_c F_R U'_L}{(\dot{m} C_p)_c} \right) \left(\frac{(\dot{m} C_p)_c}{\varepsilon (\dot{m} C_p)_{min}} - 1 \right) \right]^{-1} \quad (5.6)$$

In Equation 5.3, T_{PHT} is the temperature of water entering the solar heat exchanger from the solar pre-heating tank and is assumed to have the same value as the temperature of the water inside the pre-heating tank. T_a is the solar collector ambient air temperature and $U_L(T_s - T_a)$ represents the thermal losses per unit area from the collector to the surroundings by conduction, convection, and radiation. With the ratio of $\frac{F'_R}{F_R}$ shown in equation (5.6), $F'_R(\tau\alpha)'_n$ and $F'_R U'_L$ values can be calculated by knowing $F_R(\tau\alpha)'_n$ and $F_R U'_L$ which take into account the connecting pipes loss. The detailed calculation procedure following the methodology in [23] is presented in Appendix-B.

5.2.2 Solar Heat Exchanger Modeling

The solar energy collected is transferred to the pre-heating storage tank through a heat exchanger. A schematic of an adiabatic counter current heat exchanger with inlet and outlet temperatures and capacitance rates of the heat transfer fluid and circulating domestic hot water is shown in Figure-5.2.

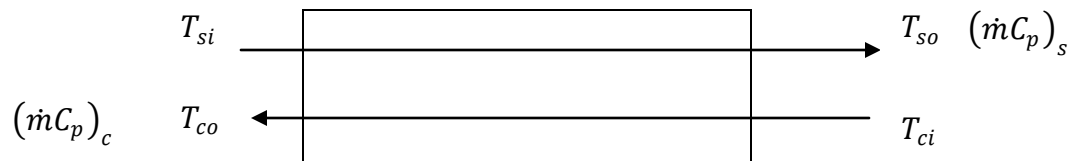


Figure 5.2 Schematic of an adiabatic counter-flow heat exchanger [23].

Equation 5.6 accounts for the effects of solar heat exchanger by using the effectiveness which can be determined by:

$$\varepsilon = \begin{cases} \frac{1 - e^{-NTU(1-C^*)}}{1 - C^* e^{-NTU(1-C^*)}} & \text{if } C^* \neq 1 \\ \frac{NTU}{1 + NTU} & \text{if } C^* = 1 \end{cases} \quad (5.7)$$

where, NTU is the number of transfer units and is defined as:

$$NTU = \frac{UA}{(\dot{m}C_p)_{min}} \quad (5.8A)$$

The denominator of equation 5.8A is the smaller value of $(\dot{m}C_p)_s$ and $(\dot{m}C_p)_c$ which are the circulating domestic hot water heat capacitance (W/K) and solar collector's heat transfer fluid heat capacitance (W/K), respectively. In this research, the volume flow rate of heat transfer fluid and the circulating domestic hot water were assumed to be the same (*See 5.3.1*); however, water's heat capacity and mass flow rate are larger than the heat transfer fluid; therefore,

$$(\dot{m}C_p)_{min} = (\dot{m}C_p)_c \quad (5.8B)$$

And

$$(\dot{m}C_p)_{max} = (\dot{m}C_p)_s \quad (5.8C)$$

In equation (5.7), C^* is the capacity rate ratio and is defined by

$$C^* = \frac{(\dot{m}C_p)_{min}}{(\dot{m}C_p)_{max}} \quad (5.9)$$

The heat exchanger's overall heat transfer coefficient-area product UA , and the solar collector heat transfer fluid's specific heat capacity can be found in sections 5.3.1 and 5.3.2. The model of the thermal process for the solar heat exchanger is incorporated in the solar collector model as shown in equation 5.3; therefore, a separate model block for the solar heat exchanger is not needed.

5.2.3 Heat Pump Water Heater

The heating energy contributed to a domestic hot water system by a heat pump water heater can be described by:

$$Q_{HP} = \int (COP \times \dot{W}_{HP}) dt \quad (5.10)$$

where, Q_{HP} is the overall heating energy provided by the heat pump in a day, and \dot{W}_{HP} is the electric power consumed by the heat pump's compressor. The COP is the heat pump coefficient of performance which is dependent on both of the evaporating and condensing temperature. In this study, the temperature of the condenser's inlet water is that of the pre-heating tank; thus, this is a time-dependent value which makes the COP vary in time. The COP performance curve is specific to the heat pump model chosen. The curve used in this work is discussed later in section 5.3.3.

5.2.4 Drain Water Heat Recovery Unit

The drain water heater recovery unit is a counter-current heat exchanger, and equation 5.7 can be applied to calculate the unit's effectiveness ε . The fluid entering on one end of the unit with the higher temperature is the shower's drain water. Cold water from the domestic water supply line enters the other end. Equation 5.9 is applied to calculate the dimensionless capacitance rate C^* .

In option A of configuration III, $(\dot{m}C_p)_{min}$ is determined by the shower's cold water make-up mass flow rate; while, $(\dot{m}C_p)_{max}$ is the shower's drain water. The dimensionless capacitance rate C^* in configuration III's option A is not equal to one; therefore, the unit effectiveness ε is calculated using equation 5.7 when $C^* \neq 1$:

$$\varepsilon = \frac{1 - e^{-NTU(1-C^*)}}{1 - C^*e^{-NTU(1-C^*)}}$$

In option B of configuration III, the dimensionless capacitance rate C^* is equal to one because the fluid entering the drain water heat recovery unit from both ends has the same mass flow rate which is the mass flow rate of the shower's demand hot water (cold water make-up plus the delivered hot water from the main hot water storage tank for the shower), thus $(\dot{m}C_p)_{min}$ has the same value of $(\dot{m}C_p)_{max}$; therefore, the unit effectiveness ε is calculated by equation 5.7 when $C^* = 1$:

$$\varepsilon = \frac{NTU}{1 + NTU}$$

The total heat energy recovered by the drain water heat recovery unit Q_{DW} can be determined with:

$$Q_{DW} = \int \left(\varepsilon (\dot{m} c_p)_{DW} (T_{DW} - T_C) \right) dt \quad (5.11)$$

where, c_p is the water specific heat capacity, kJ/kg °C; T_{DW} is the temperature of the shower drain water and is assumed to be 6 °C lower than the shower's demand hot water temperature [3], and T_C is the cold water make-up temperature. During the periods when the shower is not being used, the fluid's heat capacitance $(\dot{m} c_p)_{DW}$ is zero resulting in zero recovered heating energy from the unit.

5.3 Simulation Assumptions and System Parameters

The performance of each domestic water heating system configuration is simulated, (described in Chapter 3), for a typical summer (Day 228) and a winter day (Day 16) in three different locations in B.C. (Victoria, Kamloops, and Williams Lake). Each simulation is performed with a one minute time-step using load profiles described in Section 5.4.

The main components for each configuration are modeled based on actual product technical specifications provided by the manufacturer. The following sections describe the key parameters and any assumptions.

5.3.1 Solar Collector:

The solar collector's main parameters are summarized in Table-5.1. As shown in the table, two G series flat plate solar collectors manufactured by Thermo Dynamics Ltd. are selected. Two collectors are used as the total area created is consistent with industry recommendations for domestic hot water consumption larger than 250 l/day [30]. The total aperture area of the two solar collectors is 5.566 m². They are assumed to be arrayed in a parallel arrangement so that each of them operates under the same working conditions.

Table-5.1 Solar collector simulation model parameters

Parameters	Value
Type of Solar Collector	G Series Glazed Liquid Flat Plate
Number of Solar Collector	2
Collector Arrays	Parallel
Total Collector Aperture Area, A_C [m ²]	5.566 [25]
$F_R(\tau\alpha)$ [-]	0.7 [25]
$F_R U_L$ [W/m ² C]	4.933 [25]
Heat Transfer Fluid Volume Flow Rate, \dot{V}_C [L/min]	1.2 [25]
Heat Transfer Fluid Specific Heat Capacity, c_p [J/kg-K]	3746
Incident Angle Modifier Coefficient, b_0	-0.154 [25]
Solar Collector Slope, β [Degree]	Local Latitude
Surface Azimuth Angle, γ [Degree]	0

The tested values of $F_R(\tau\alpha)$ and $F_R U_L$ for each collector are 0.7 and 4.933 W/m²C, respectively according to the first order efficiency equation provided in the product technical specifications (*Refer to [25] for detailed collector specifications*). The heat transfer fluid of the solar collector is a water-glycol solution (40% glycol + 60% distilled water) and the volume flow rate of the heat transfer fluid is 1.2 l/min which is recommended by the manufacturer.

According to the specifications, the incident angle modifier of the collector is $K_{\tau\alpha} = 1 - 0.154 \left(\frac{1}{\cos\theta} - 1 \right)$, where θ is the incidence angle; thus, the corresponding incidence angle modifier coefficient b_0 is -0.154. Most solar energy is assumed to be absorbed by the solar collector when the incidence angle of solar radiation θ is between -60° to 60° [25]. In other

words, the solar radiation accumulated by solar collector from 8:00AM to 4:00PM is considered as the useful solar energy contribution to the domestic water heating system during one day. In this research, the solar collector is assumed to be installed at a fixed slope which is the same as the local latitude and the surface azimuth angle γ is assumed to be zero. Wind effects on the overall loss coefficient U_L are not included since the $F_R U_L$ value is provided as a group parameter from the first order efficiency equation by the manufacturer.

5.3.2 Solar Heat Exchanger

The solar heat exchanger is the means by which absorbed solar energy is transferred to the domestic hot water system. The heat exchanger is an adiabatic counter flow exchanger with an overall heat transfer coefficient and area product (UA) of 260 W/K [23]. The circulating domestic hot water entering the solar heat exchanger from the solar water pre-heating tank is assumed to have the same temperature as the water in the tank since in most practical application, this heat exchanger is installed inside the solar pre-heating water storage tank as shown in Figure-5.3. The solar heat exchanger's effectiveness ε is a calculated value which is 0.90 (Refer to 5.2.2, equation 5.7).

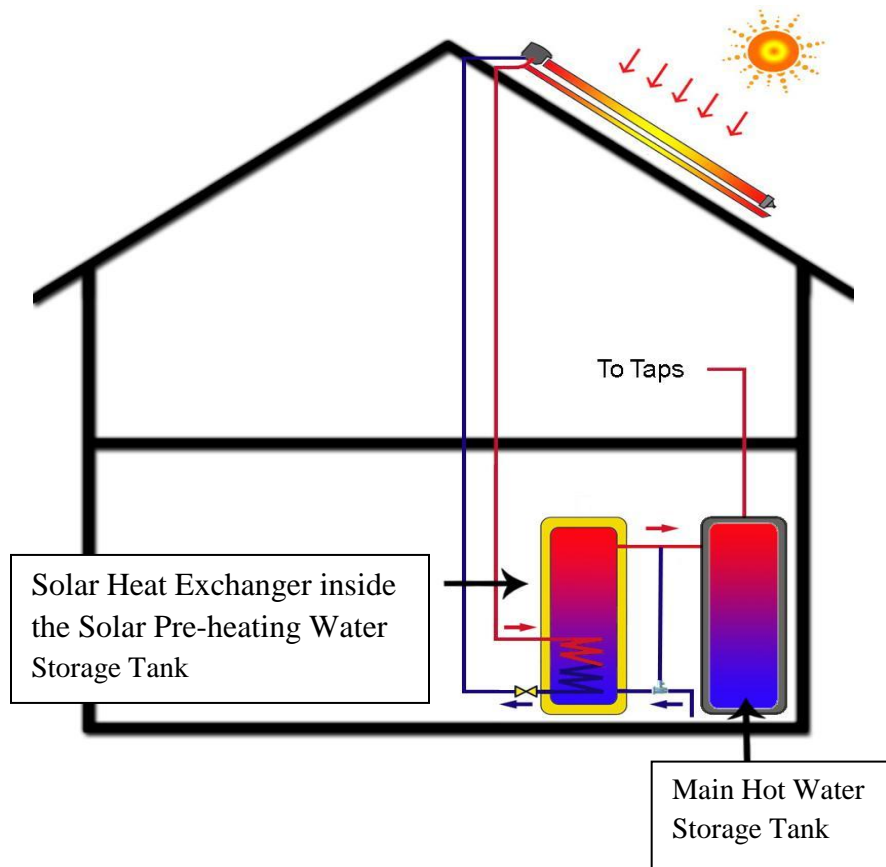


Figure 5.3 Solar heat exchanger inside solar pre-heating water storage tank [31].

5.3.3 Heat Pump Water Heater

A RH-106 heat pump water heater manufactured by E-TECH with a heating capacity of 3.66 KW (12,500 Btu/hr) and cooling capacity of 2.58 KW (8,800 Btu/hr) is assumed for Configuration III and IV. The maximum delivered hot water temperature is 50°C and the ambient operating range for this heat pump water heater is between 7°C and 40°C. If the ambient temperature is out of this range, the system will be switched from heat pump mode to conventional electric resistance heating mode. In this research, the ambient temperature is assumed to be 18°C as it is assumed to be installed in the residence. Thus, the heat pump always

gets activated when the water temperature of either the main hot water storage tank in Configuration III or the heat pump pre-heating water storage tank in Configuration IV is lower than the water storage tank's set point. Table-5.2 lists the key parameters of the heat pump water heater. Figure-5.4 shows the heat pump's COP as a function of the stored tank water temperature curve as provided by the manufacturer. According to this figure, the corresponding COP value at different tank water temperature can be easily fit with a line equation (equation 5.12).

Table-5.2 Heat pump water heater simulation model parameters.

Parameters	Value
Heat Pump Model	RH-106
Manufacturer	E-TECH
Heating Capacity [KW]	3.66
Cooling Capacity [KW]	2.58
Maximum Water Temperature [°C]	50
Ambient Operating Range [°C]	7 - 40

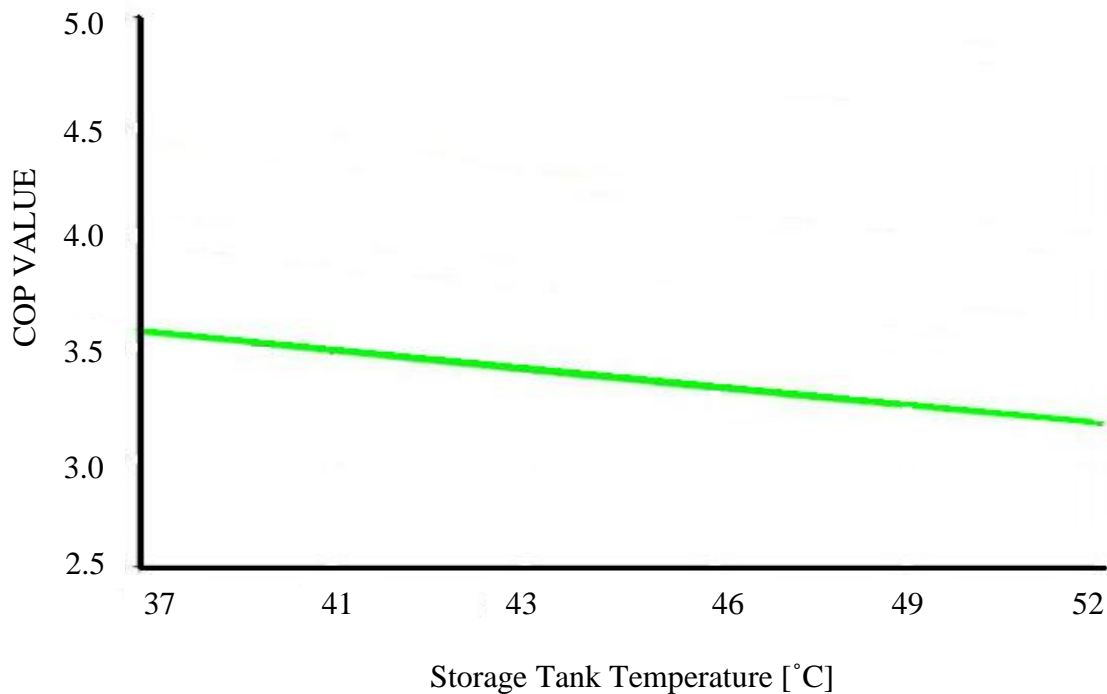


Figure 5.4 Heat pump water heater COP vs. final tank temperature [28].

$$COP = -0.0172 * T + 5.32 \quad (5.12)$$

The curve is assumed to be continuous and the COP value is allowed to be extrapolated when the tank water temperature is lower than 37°C (100 °F) which is the left border of the chart (*Refer to [28] for detailed technical specifications of the heat pump water heater*).

5.3.4 Drain Water Heat Recovery Unit

Table 5.3 lists eight different drain water heat recovery devices as well as the characterization parameters taken from Zaloum [27]. The ‘C’ and ‘n’ values are the fitted parameters for the NTU correlation equation where the NTU of a device is a function of drain water volume flow rate. The NTU is found using the following:

$$NTU = C(\dot{V})_{shower}^{-n} \quad (5.13)$$

where, C and n are the correlation equation's dimensionless parameters whose value is listed in Table-5.3 for all of the units. $(\dot{V})_{shower}$ is the volume flow rate of shower's drain water in L/min because, in this research, the heat recovery unit is assumed to recover the heat from the shower's drain water only.

The model described here is capable of simulating the performance of all the units; however, only model GFX-40 is used in this research because the empirical data fits the correlation NTU equation the best. Also, Model GFX-40's NTU is lower than Model PWP-60 and GFX-60 and better than Models RET-40, RET-60 and PWP-36, reflecting an average among the units listed in Table-5.3.

Table-5.3 Drain water heat recovery unit data [27].

Type	'C' Value	'n' Value	Manufacturer	Model
GFX-40	3.7669	0.6452	GFX	G3-40
GFX-60	4.2096	0.6458	GFX	G3-60
RET-40	3.4053	0.7028	Retherm	C3-40
RET-60	3.0710	0.5996	Retherm	S3-60
PWP-36	2.8869	0.7219	Power Pipe	R3-36
PWP-60	4.7622	0.6355	Power Pipe	R3-60

According to Zaloum's report, the time spent on a shower is assumed to be less than 11 minutes and the temperature of the shower's drain water entering the heat recovery unit is about 6°C lower than the shower's demand temperature.

5.3.5 Solar Water Pre-Heating Tank

The base-case solar pre-heating tank is assumed to have the same physical size and thermal insulation as the main hot water storage tank. The initial temperature of the solar pre-heating tank in the selected summer day and winter day are assumed to be 60°C and 30°C, which is the pre-heating tank temperature at midnight. Those values are based on simulations over a sufficient number of days so that cyclic steady-state is reached. Figure 5.5A shows the solar pre-heating water storage tank's temperature profile for 5 consecutive summer days (Day 226 to Day 230) based on Victoria's climate data and hot water load profile of Load01_2LD. Figure 5.5B shows the temperature profile for 5 consecutive winter days (Day 14 to Day 18). (Refer to *Table-5.6 for the load profile*).

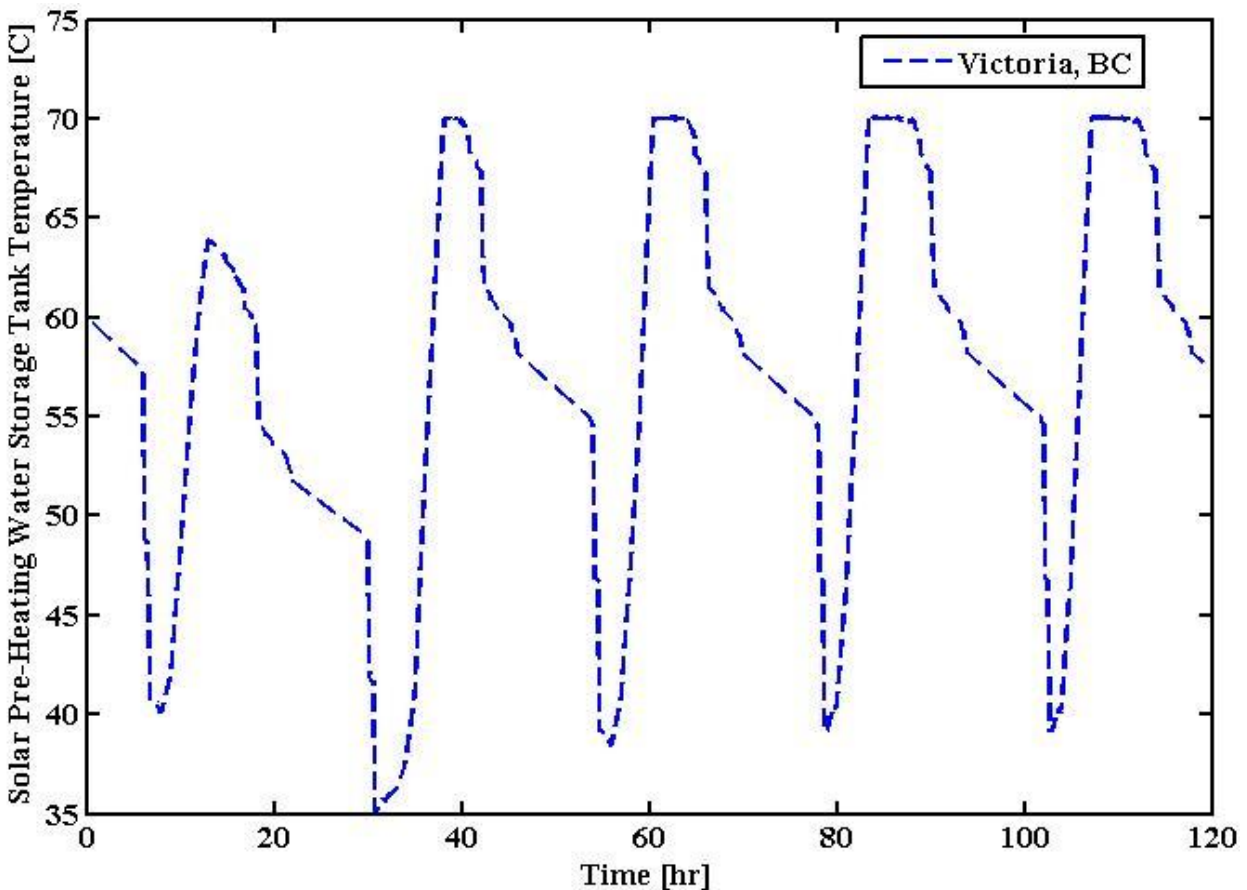


Figure 5.5A Five consecutive summer days (Day 212 to 218) solar pre-heating tank temperature

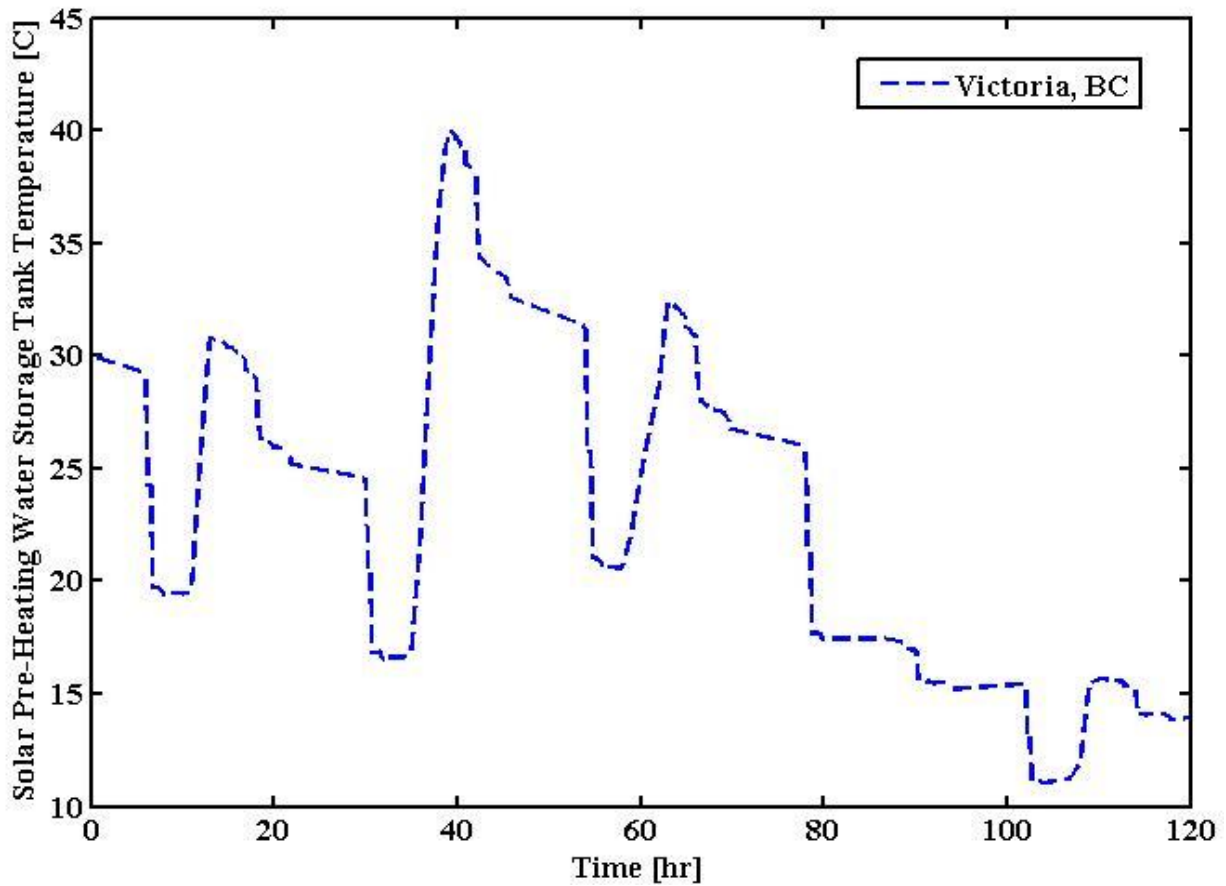


Figure 5.5B Five consecutive winter days (Day 14 to 18) solar pre-heating tank temperature.

As can be seen, the initial tank temperature of 60°C and 30°C during the selected summer and winter day is a reasonable assumption. Because the assumed initial temperature is higher than the cold water make-up, the solar fraction may be larger than zero even if the day is overcast.

5.3.6 Main Hot Water Storage Tank

Two types of domestic hot water tanks are used in this work - electric and gas fired. In Configurations I and II, natural gas fired tanks are used with two different tank volumes and three different energy factors for each volume. Table- 5.4 summarizes the key performance data

of the tanks. More detailed technical specifications can be found in Table-C1 and Table-C2 in Appendix- C.

Eight key parameters describing a hot water tank are used. The last three columns in Table-5.4 list performance measures which impact overall system efficiency. RSI is the SI equivalent value of tank insulation. The R value determines the energy factor, or how much energy is lost to the surroundings due to thermal leaks. Typical commercial tanks have values ranging from 1.408 to 2.816. Recovery efficiency is specific to gas fired hot water tanks and is the measure of combustion efficiency and thermal design. A tank with a poor design may lose a large amount of energy in combustion product exhaust due to high flue temperatures. An efficient design, like a condensing boiler, will extract most of the energy from the combustion product and transfer it to the water resulting in a recovery efficiency higher than 0.9. Typical values for recovery efficiency of conventional natural gas fired tanks are between 0.78 and 0.85.

Table-5.4 Gas fired domestic hot water tank data

Group	Max Heating Rate [W]	Vol. [m³]	Set Point [°C]	Dead Band Setting [°C]	Insulation Thickness [mm]	RSI	Recovery Efficiency	EF
Group 1	11710	0.151	60	3	25	1.408	0.80	0.63
					25	1.408	0.81	0.65
					50	2.816	0.82	0.67
Group 2	11710	0.189	60	3	50	2.816	0.80	0.63
					25	1.408	0.82	0.65
					50	2.816	0.82	0.67

As indicated in Table- 5.4, the first group assumes a 151 liter (40 gallons) storage tank; while, the second group is for a 189 liter (50 gallons) tank. Both of the groups have the same heat rate of 11.71 kW. Each group has three models with the EF value ranging from 0.63 to 0.67 and the heat recovery efficiency ranging from 0.80 to 0.82. In this research, the domestic hot water tank's set point is assumed to be 60°C [32].

For both of Configurations III and IV, two groups of electric domestic hot water tanks are used as indicated in Table-5.5.

Table-5.5 Electric domestic hot water tank data

Group	Max Heating Rate [W]	Vol. [m ³]	Set Point [°C]	Dead Band Setting [°C]	Insulation Thickness [mm]	RSI	Recovery Efficiency	EF
Group 1	4500	0.151	60	3	76	4.224		0.95
					64	3.520		0.93
					50	2.816	N/A	0.92
Group 2	4500	0.189	60	3	76	4.224		0.95
					64	3.520		0.93
					50	2.816		0.92

Similar to the gas fired main hot water storage tanks, the first group has a volume of 151 liters (40 gallons) and the second group has a volume of 189 liters (50 gallons) tanks. Both are equipped with a 4.5 kW maximum heating capacity. Each group includes three different models with the EF value ranging from 0.91 to 0.95 and, since electricity is used as the heating source, the recovery efficiency is not applicable.

5.3.7 Pipe Data

Piping connects the water tank to fixtures and all other water heating components. In a conventional system, most of the piping is located in a residence. In cases where solar systems are used, some of the pipe work connecting the solar collectors and the heat exchanger inside the solar pre-heating tank is located outdoors. Piping networks contribute to system inefficiency due to losses and thermal mass. In this work, the effects of piping are accounted for in a simplified manner.

The total length of interior (indoor) pipe between the solar pre-heating tank and the solar collectors is assumed to be 10 meters whereas the total length of the exterior (outdoor) pipe is assumed to be 20 meters. The diameters of both are assumed to be 25 mm. The convection coefficient of air on the outer surface of pipes is assumed to be $10 \text{ W/m}^2\text{-K}$. The thermal insulation of a pipe is assumed to be 25 mm thick and the corresponding thermal conductivity is assumed to be 0.02 W/m-K . The temperature of hot water inside pipe is assumed to be constant at all locations inside the pipe.

5.4 Domestic Hot Water Load Profile

The performance of a hot water system configuration is also a function of the hot water load profile. To account for different usage patterns, a total of twelve domestic hot water load profiles are used. Household size, water use habits and day of the week are considered. The model is able to simulate the system performance based on either one specific load profile or all the load profiles listed in Table-5.6.

Table-5.6 Domestic hot water load profile summary.

Group	Load Profile	Household Size	Demand Level	Weekday/Weekend	Domestic Hot Water Consumed [litre/day]	Total Energy [kWh/day]
I	Load01_2LD	2	L	D	174	11.3
	Load02_2MD	2	M	D	233	15.1
	Load03_2HD	2	H	D	293	18.6
	Load04_2LE	2	L	E	222	13.8
	Load05_2ME	2	M	E	296	17.7
	Load06_2HE	2	H	E	370	22.4
II	Load07_5LD	5	L	D	280	16.4
	Load08_5MD	5	M	D	374	21.8
	Load09_5HD	5	H	D	468	26.9
	Load10_5LE	5	L	E	353	20.1
	Load11_5ME	5	M	E	474	27.1
	Load12_5HE	5	H	E	592	33.7

Note: e.g: 2LE= 2 persons, Low demand, Week End; Temperature of cold make-up water is assumed to be 4°C.

As indicated in Table-5.6, load profiles are classified into two groups based on the household size. Group I includes the hot water load profiles for a two-person family and group II's hot water load profiles are for a five-person family. The profiles of each group can be further divided into two sub-groups to distinguish the difference in usage patterns between a typical weekday and the weekend. Families with same household size do not necessarily have the same domestic hot water consumptions, so hot water profiles are further labeled as 'L', 'M', and 'H' demand levels representing low, medium and high hot water consumption. Those profiles reflect

various levels of daily household hot water use from a high range of 374 to 592 liter/day for a five-person family to a low range of 174 to 370 liter/day for a two-person family. In order to accurately simulate the outlet hot water energy and the delivered temperature, the hot water flow data is set for each minute. Also, the desired demand temperature and the time a particular plumbing fixture is being used are considered. The plumbing fixtures are selected to be representative of new single family homes and are based on the typical home which includes a bathtub, shower head, kitchen sink, lavatory, dishwasher, and clothes washer. The hot water load profiles can also reflect the difference of the hot water usage pattern between a typical weekday and the weekend. For example, the hot water peak demand happens one or two hours earlier in a weekday than weekend because people usually get up a little bit later in the weekend; however, the hot water peak load might be much higher at weekend because people often do laundry then (*Refer to Appendix-D for detailed hot water load profiles.*)

5.5 Weather Data

The performance of each configuration is simulated using hourly meteorological data for global solar irradiation, I (W/m^2), and the outside ambient air temperature T_a ($^{\circ}\text{C}$) from WATSUN's TMY database. The hourly *global solar irradiation* on a horizontal surface is the sum of *beam solar radiation* I_b and the *diffuse solar radiation* I_d :

$$I = I_b + I_d \quad (5.14)$$

The *diffuse radiation* I_d is evaluated using the correlation of Erbs et al. [23]:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604 k_T + 4.388k_T^2 - 16.638 k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.8 \\ 0.165 & \text{for } k_T > 0.8 \end{cases} \quad (5.15)$$

The beam solar radiation I_b is calculated as $I_b = I - I_d$. In Equation (5.15), k_T is the *hourly clearness index* and is defined as:

$$k_T = \frac{I}{I_o} \quad (5.16)$$

where I_o is the *extraterrestrial radiation on a horizontal surface* for an hour period and can be described as the following:

$$I_o = \frac{12 \cdot 3600}{\pi} G_{sc} \left(1 + 0.033 \cos \frac{360n}{365} \right) * \left[\cos \phi \cos \delta (\sin \omega_2 - \sin \omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180} \sin \phi \sin \delta \right] \quad (5.17)$$

where G_{sc} is the *solar constant*, 1367 W/m^2 and n is the day of year.

In order to maximize the beam solar radiation on the solar collector, the solar collector is usually tilted from the horizontal with the angle β which is equal to the local latitude. The *global solar irradiation on the sloped collector surface* is the contribution from both of the beam solar radiation on the tilted surface calculated as $I_b R_b$ and the diffuse on a horizontal surface I_d . Since the solar collector is tilted, a portion of the global irradiation reflected from the surrounding ground to the collector surface needs to be counted as part of diffuse solar radiation, too.

Based on the isotropic diffuse model in [23], if the ground has the reflectance of ρ_g , a *view factor* from the collector to ground is $F_{c-g} = \left(\frac{1-\cos\beta}{2}\right)$, and a *view factor* from the collector to the sky is $F_{c-s} = \left(\frac{1+\cos\beta}{2}\right)$, the *global solar irradiation on the tilted collector surface* can be calculated as:

$$I_T = I_b R_b + I_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g (I_b + I_d) \left(\frac{1-\cos\beta}{2}\right) \quad (5.18)$$

where, R_b is the ratio of beam radiation on a tilted surface to that on horizontal surface:

$$R_b = \frac{\cos(\Phi-\beta)\cos\delta\cos\omega + \sin(\Phi-\beta)\sin\delta}{\cos\Phi\cos\delta\cos\omega + \sin\Phi\sin\delta} \quad (5.19)$$

Figure 5.6 shows three consecutive summer days (Day 227 to Day 229) of calculated global solar irradiation on tilted surface in three different locations in B.C. The complete set of hourly-basis meteorological data and the corresponding calculated global solar irradiation on the tilted collector surface on the selected summer day (day 228) and winter day (day 16) for three locations in B.C. Canada (Victoria, Kamloops, Williams Lake) are presented in Appendix- A.

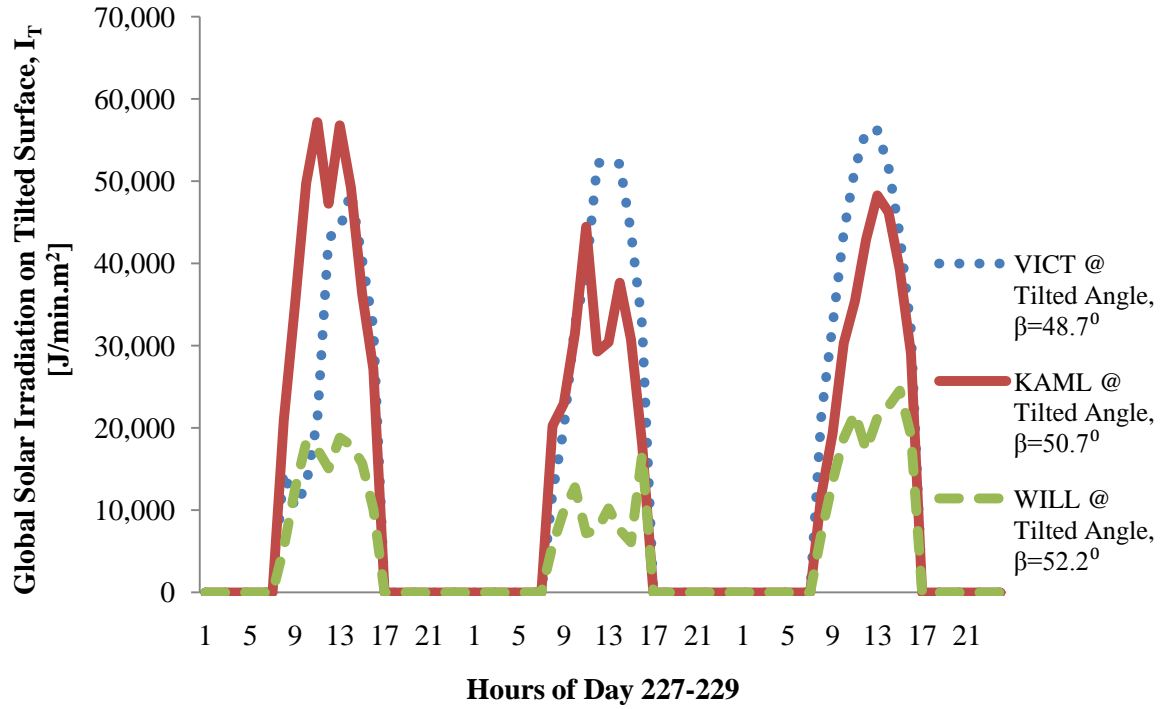


Figure 5.6 Three consecutive summer days (Day 227 to 229) global solar irradiation on a tilted surface in Victoria, Kamloops, and Williams Lake with different tilted angles

Chapter 6

Validation

6.1 Components validation

In this section, the validation of the main component models described in Chapter 5 is presented. To perform a validation, each component is fed a group of test parameters to calculate equipment performance. The prediction is then compared with the same information provided by another method or model.

6.1.1 Solar Collector and Solar Heat Exchanger

The solar collector model is validated by comparing model calculations against long-hand calculations based on examples from John A. Duffie and William A. Beckman's *Solar Engineering of Thermal Processes, Third Edition* [23](i.e. Example 10.8.1 on page 441.) The parameters used for validation and the predicted results are summarized in Table-6.1 and Table-6.2, respectively. As can be seen, the parameters of the solar collector model were set to match the ones used in Example 10.8.1. The predictions by both simulation and long-hand calculation are well matched.

Table-6.1 also shows the product of the overall heat transfer coefficient and area of the solar heat exchanger ' UA ' and the connecting pipes ' $U_p A_o$ ' between the solar collector and the solar heat exchanger, the corresponding connecting pipe length ' L_{pipe} ' and the thermal properties of the pipe insulation ' k '. The solar collector model is based on modified equations which account for the combination of the solar heat exchanger and the connecting pipe. Thus, as

described earlier, the model of the solar heat exchanger and the connecting pipes are mathematically embedded in the solar collector model. A comparison of the key parameters calculated by both the computer model and the long-hand calculation of Example 10.8.1 are summarized in Table-6.2.

Table-6.1 Solar collector computer model inputs

Input Parameter	Value in Example 10.8.1[23]
A_c	5.9 m ²
G_T	1010 W/m ²
\dot{m}_{test}	0.020 kg/m ² -s
ρ_{test}	998 kg/m ³
\dot{m}_{use}	0.110 kg/s
ρ_{use}	1034 kg/m ³
\dot{m}_{water}	0.122 kg/s
$F_R(\tau\alpha)_n$	0.753
$F_R U_L$	3.79 W/m ² C
T_a	13 C
T_s or T_i	34 C
θ	35
b_0	-0.18
UA	260 W/C
k	0.0342 W/m-C
$U_p A_o$	2.17 W/C
L_{pipe}	24.4 m

Table-6.2 Solar collector long-hand calculation results and computer model predictions comparison

Results	Example 10.8.1	Solar Collector Computer Model
NTU	0.63	0.6303
ε	0.40	0.4011
r	0.995	0.9955
$F_R'(\tau\alpha)'_n$	0.680	0.6808
$F_R'U_L'$	4.08	4.076
$\frac{F_R'}{F_R}$	0.913	0.913
Q_u	3390 W (Note)	3390.6 W

Note: Example 10.8.1 shows the final useful solar gain is 3190 W which is a mistake. Based on the parameters provided by the example, the correct answer is 3390 W.

As can be seen, the model results match the long-hand calculation results.

6.1.2 Drain Water Heat Recovery Unit

In order to validate the drain water heat recovery unit model, performance predictions for a selected drain water heat recovery unit - GFX-G3-60 - are compared to predictions for the same drain water heat recovery unit using the experimental data in Section 8.1 of [27].

Table 6.3 lists all the required input parameters and Table 6.4 summarizes the resulting unit performance predictions. The difference between the simulation results and the manual calculations shown in Table-6.4 is due to the accuracy of the NTU correlation provided by [27]. The model determines NTU based on the correlation equation whereas, the long-hand calculation

determines the NTU number based on the reported experimental measurements of inlet and outlet temperature of both the cold water make-up and the shower's drain water; therefore, the results of the latter are more accurate. In practice, NTU correlations can often deviate by up to 20% [38].

Table-6.3 DWHR unit validation parameters

Input Parameters [3]	Value
DWHR UNIT MODEL	GFX-G3-60
Cold Water In Temperature (°C)	8.2
Cold Make up Water Flow Rate (L/min)	7.0
Shower Drain Water Temperature (°C)	40.4
Shower Drain Flow Rate (L/min)	10.5

Table-6.4 DWHR unit long-hand calculation results and computer model predictions

	Results in Section 8.1 of Zaloum's Final Report ^[1]	Predictions of DWHR Model In this Research	Difference (%)
Heat Transfer (KW)	9.22	8.14	13.2
Effectiveness	0.59	0.52	13.2
NTU	1.17	0.92	26.5

6.2 System validation

To perform a system validation, model predictions for Configuration I are compared to results from WATSUN [24]. Because the model developed in this research performs simulations using a one minute resolution, the outputs are averaged to hourly or daily values to compare results. The performance of a solar assisted domestic hot water heating system for a two person family located in Victoria, B.C. is simulated. The water usage time-series defined by the low hot water consumption profile (Load01_2LD) is used with resource data for the 16th day of each month over a one year period (WATSUN TMY weather data). The input parameters are summarized in Table-6.5 and the daily predictions for WATSUN and the model described here are shown in Figure-6.1 to Figure-6.3.

There is good agreement for auxiliary energy input, Q_{WH} , (Figure-6.1), collected solar energy, Q_{SC} , (Figure-6.2) and daily delivered energy, Q_{DELVD} , (Figure-6.3). Here, the auxiliary energy input is the overall conventional energy input which accounts for the effects of heat recovery efficiency of the domestic hot water tank. Also, only some collected solar energy is actually delivered to the load (delivered solar energy); the rest of it becomes the solar pre-heating tank's residual energy causing the final tank temperature to be higher than the initial temperature; furthermore, the daily delivered energy doesn't include any thermal loss through the storage tank to the space.

As can be seen, the model predicts lower values compared to WATSUN. The model developed here calculates the solar energy using the modified collector equations accounting for the solar collector, the heat exchanger and the connecting pipe. WATSUN models the solar collector, the solar heat exchanger and the connecting pipes, separately so that the solar heat exchanger can be treated as an option for some systems.

WATSUN's predicted value of total delivered energy is calculated by the multiplication of the hourly domestic hot water flow rate, the water specific heat capacity, and the temperature difference between the cold water make-up and the delivered hot water. Since the temperature of the delivered hot water from the tank is recorded hourly, it is usually the same as the domestic hot water tank's set point (60 °C); while, the model developed here outputs the delivered hot water temperature on the minute basis, which means when the system calls for hot water the cold make up water enters the system and causes the domestic hot water tank temperature to drop immediately because of the assumption of a fully mixed tank. When the tank temperature decreases below the controller deadband setting, the auxiliary heater is turned on. In most cases, it is impossible for the system to bring the hot water temperature back to the set point (60 °C) within one minute. This causes a small temperature difference between the tank set point and the actual delivered load temperature resulting in a smaller value for delivered energy as compared to WATSUN predictions.

Table-6.5 Solar assisted domestic hot water system main parameters

System Parameter	Description
Collector	Glazed, 2 x 2.783 m ²
Slope	49 degree facing south
Solar Collector Heat Transfer Fluid	water-glycol solution (40% glycol + 60% distilled water) with the specific heat capacity of 3746 J/kg-K
Preheating Tank Side Water Flow Rate	0.414 kg/s
Solar Preheating Tank	Fully mixed, 0.151 m ³
Solar Heat Exchanger	90.7% effectiveness
Domestic Hot Water Tank	Fully mixed, 0.151 m ³ gas-fired, maximum 10000 W heating capacity
Pipes	Φ15 mm outer diameter, 20 meters long exterior pipe between the solar heat exchanger and solar collector
Insulation	RSI-2.816 for the water tank, 0.0891 W/m°C per unit pipe length
Load Profile	Load01_2LD
Desired Load Temperature	60 °C
Initial Tank Temperature	30 °C for solar pre-heating tank, 60 °C for domestic hot water tank
Average Indoor Temperature	18 °C
Mains Temperature	4°C for Jan. Feb. Mar. Apr. Nov. Dec. 10 °C for May, Jun. Jul. Aug. Sept. Oct.
Date	The 16 th day of each month
Location	Victoria, B.C. , Canada

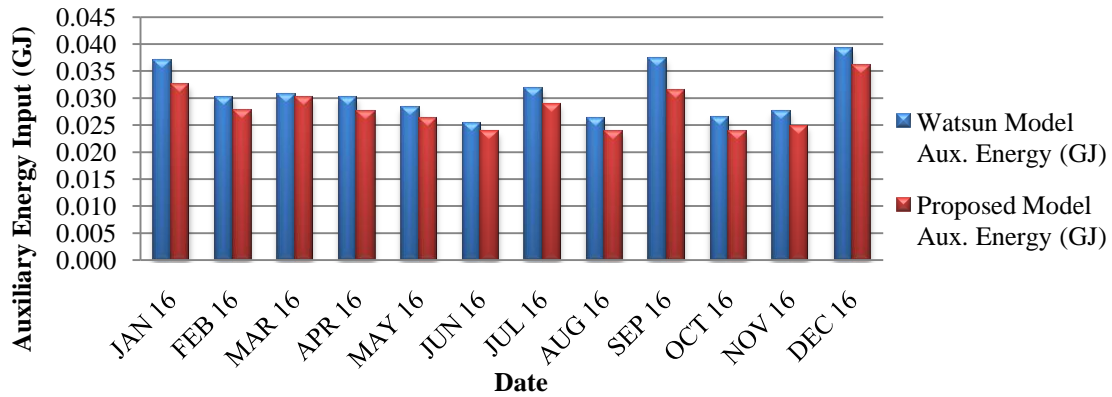


Figure 6.1 Auxiliary energy consumption comparison between WATSUN and the SHW model.

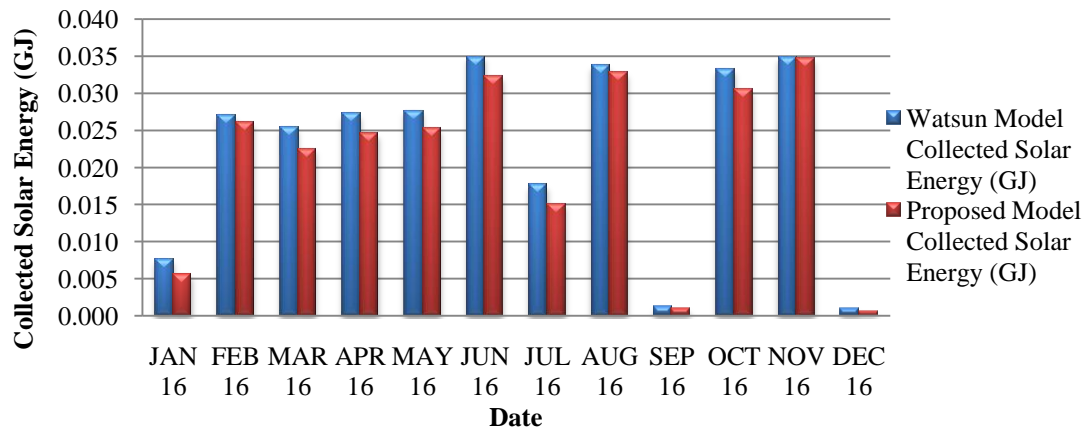


Figure 6.2 Collected solar energy comparison between WATSUN and the SHW model.

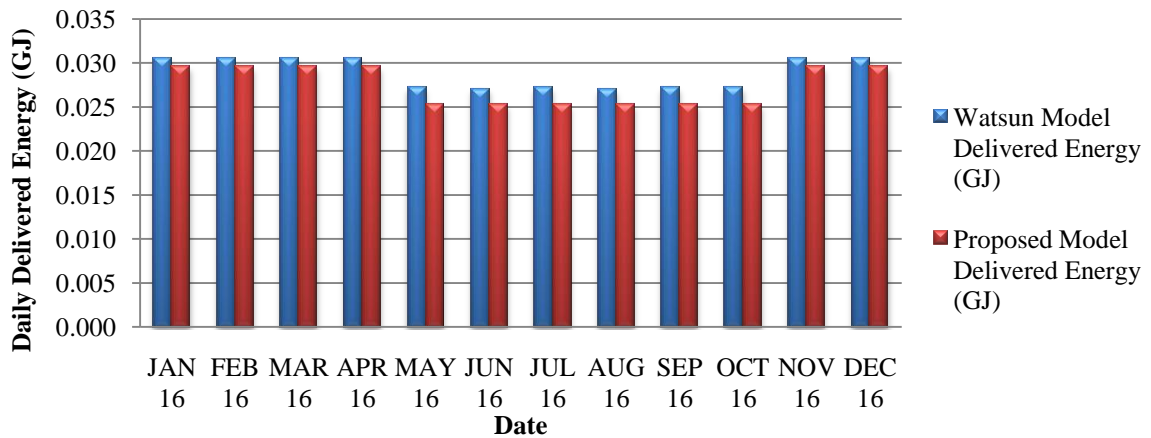


Figure 6.3 Daily delivered energy comparison between WATSUN and the SHW model.

Chapter 7

Results and Discussion

The simulation model developed for this research can simulate a very large parameter space. For the scenarios described in Chapter 3, there are 144 cases for Configuration I, 72 cases for Configuration II, 74 cases for both of Configurations III and IV in conjunction with different load profiles. As a result, only a subset of possible cases are examined and discussed in detail.

7.1 Key Results of Selected Scenarios

The hot water system configurations described in Chapter 3 are analyzed for three locations in British Columbia for a single summer day and winter day. The main differences and findings will be discussed in the following section.

Table-7.1 summarizes results of daily simulations for each configuration during a summer day (Day 228) in Victoria, BC. For Configuration I, the selected case employs a 151.63 liter capacity hot water storage tank equipped with an 11.71 kW gas fired water heater (Model: M-I-TW40L6BN, Refer to Appendix- C), and two solar panels with the total aperture area of 5.566 m². For Configuration II, the selected case employs a GFX 40 drain water heat recovery unit and a main hot water storage tank which is the same one used in Configuration I. The selected cases for configurations III and IV include a main hot water storage tank with 151.63 liters storage capacity and a built-in 4.5 kW electric resistance water heater (Model: EPX40_DXRT, Refer to Appendix- C). A five-person weekday load is applied.

Table-7.1 Performance summary of day 228 simulation based on 5HD load profile in Victoria, B.C.

VICTORIA Load09_5HD	Base Configuration	Configuration I	Configuration II		Configuration III	Configuration IV
			A	B		
Energy Source	Natural Gas	Natural Gas	Natural Gas	Natural Gas	Electricity	Electricity
Conventional Energy Consumption [kWh/Day]	22.90	8.89	20.37	19.44	4.68	8.95
CO2 Emission [kg/Day]	4.10	1.59	3.64	3.48	0.17	0.32
Unmet Load [kWh]	0	0	0	0	0.39	0
System Energy Factor	0.67	1.21	0.90	0.94	3.18	1.69
Water Heater Cycling Times	13	9	13	13	6	7

The comparison of performance indicators between the un-conventional DHW and the conventional DHW system - the base configuration in this research (*Refer Figure-3.0 for the configuration schematics*) is illustrated in Figures 7.1 to Figure 7.4. As shown, all the unconventional DHW systems have higher system energy factor and lower conventional energy consumption with lower CO₂ emissions compared with the conventional DHW system. Results show that configuration III has the highest system energy factor, the lowest conventional energy consumption, and the lowest CO₂ emission. Configurations II, III and IV have a higher system energy factor on the selected winter day (*Day 16*) than for the selected summer time (*Day 228*) while, configuration I shows the reverse situation.

In general, for configurations III and IV, as more daily domestic hot water is consumed, the higher the system energy factor, whereas for configuration I, the reverse occurs. Table-7.2 and Table-7.3 indicate that increasing daily hot water consumption does not necessarily cause the system energy factor to increase or decrease for either option A or option B of configuration II. Because the drain water heat exchanger recovers waste energy from shower drain, the effectiveness of the drain water heat exchanger is affected by the shower's drain water flow rate. The effectiveness decreases as flow rate increases, so there is less impact between daily hot water consumption and the system energy factor in configuration II. Because of this, option A performs better than option B.

As shown in Figures 7.1 to Figure 7.4, system performance is lower in winter and increases with respect to daily hot water consumption. Because available solar energy and the make-up water temperature are lower in the winter time than in summer, the conventional energy consumption, and the associated CO₂ emissions are higher.

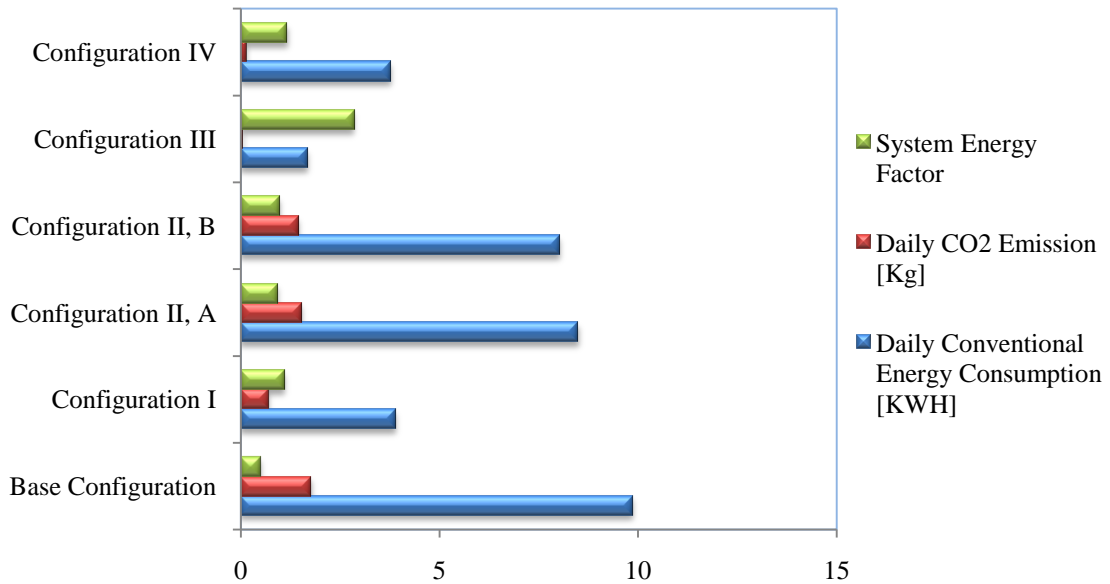


Figure 7.1 Comparison of system energy factor, daily CO₂ emission and daily conventional energy consumption on day 228 for load profile of 2LD in Victoria, BC.

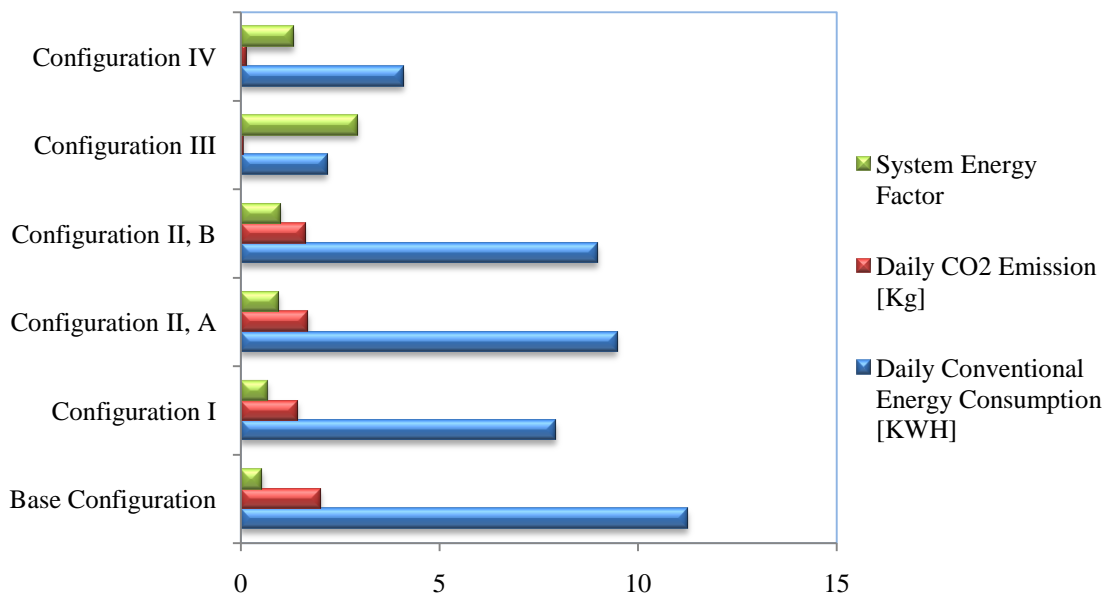


Figure 7.2 Comparison of system energy factor, daily CO₂ emission and daily conventional energy consumption on day 16 for load profile of 2LD in Victoria, BC.

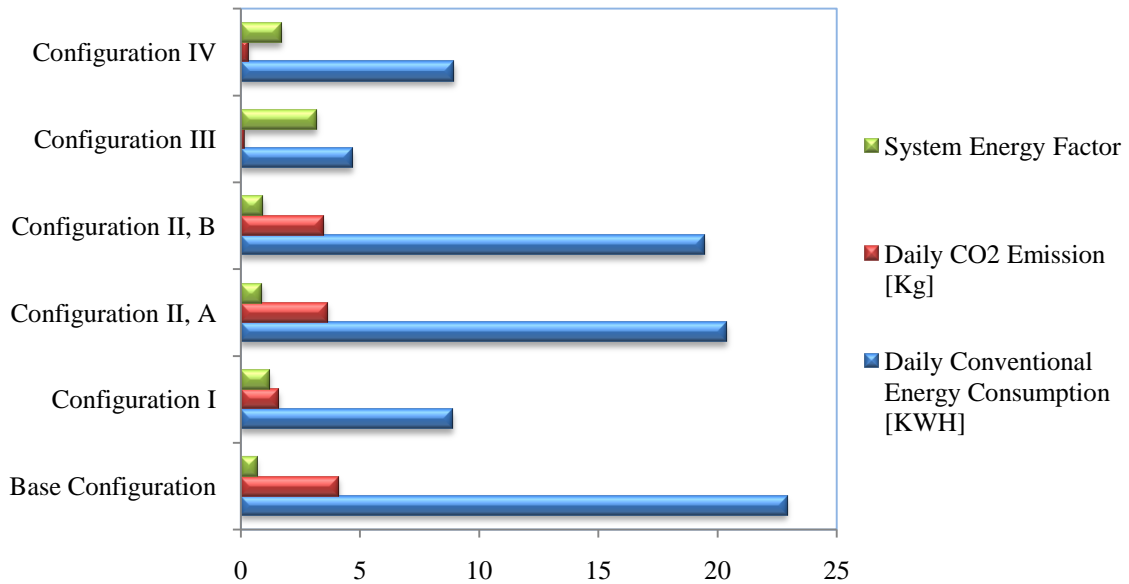


Figure 7.3 Comparison of system energy factor, daily CO₂ emission and daily conventional energy consumption on day 228 for load profile of 5HD in Victoria, BC.

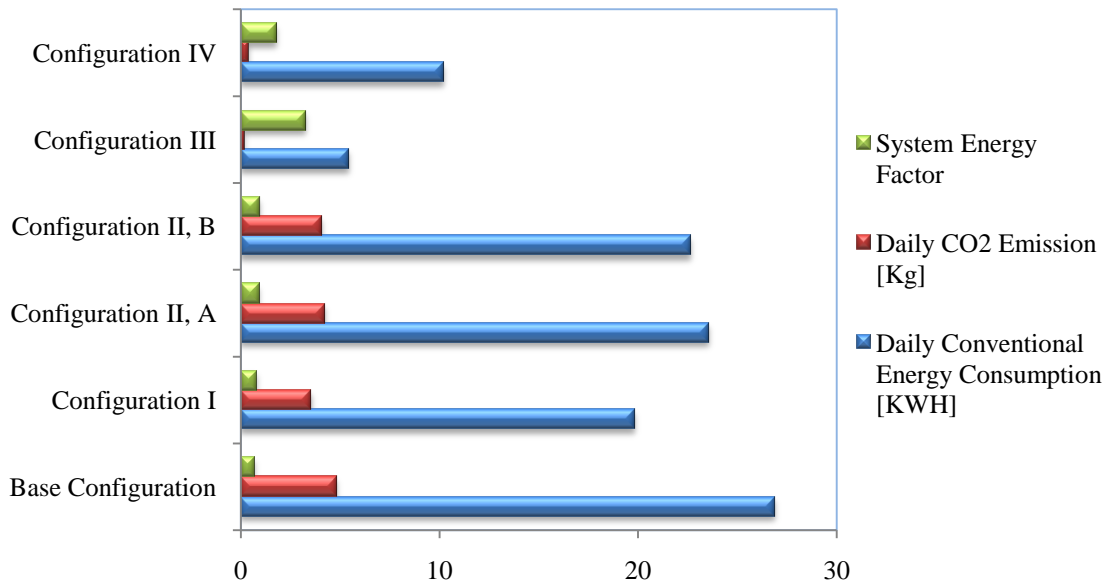


Figure 7.4 Comparison of system energy factor, daily CO₂ emission and daily conventional energy consumption on day 16 for load profile of 5HD in Victoria, BC.

Table-7.2A Solar fraction summary of configuration I with a 151.63 liter main hot water tank and a 151.63 liter solar pre-heating tank for three locations on day 228.

Load Profile	Solar Fraction [%], (Defined as $\frac{Q_{SC}}{Q_{THE}}$)					
	Victoria, BC		Kamloops, BC		Williams Lake, BC	
	Day 228	Day 16	Day 228	Day 16	Day 228	Day 16
2LD	65.6	26.4	65.2	40.2	4.4	44.6
2MD	61.8	23.9	62.0	35.4	10.8	37.8
2HD	60.4	20.5	60.5	30.9	10.9	33.1
2LE	66.9	25.2	63.8	37.0	7.6	39.7
2ME	64.6	20.6	63.2	32.2	6.2	35.0
2HE	62.2	17.6	58.8	27.8	7.0	30.2
5LD	61.7	20.3	60.9	33.3	3.1	36.7
5MD	60.0	18.1	59.7	28.4	8.6	30.8
5HD	53.4	15.3	52.9	24.1	7.9	26.2
5LE	62.3	19.4	60.7	30.0	7.6	32.6
5ME	57.8	15.8	53.3	24.2	9.0	26.4
5HE	54.1	12.8	47.4	19.9	6.5	22.0

Table-7.2B System energy factor of configuration I with a 151.63 liter main hot water tank and a 151.63 liter solar pre-heating tank for three locations on day 228.

Load Profile	System Energy Factor					
	Victoria, BC		Kamloops, BC		Williams Lake, BC	
	Day 228	Day 16	Day 228	Day 16	Day 228	Day 16
2LD	1.1	0.7	1.1	0.9	0	1.0
2MD	1.3	0.8	1.3	0.9	0.3	1.0
2HD	1.3	0.8	1.3	0.9	0.5	0.9
2LE	1.3	0.7	1.3	0.9	0.2	0.9
2ME	1.4	0.8	1.3	0.9	0.4	0.9
2HE	1.4	0.8	1.3	0.9	0.5	0.9
5LD	1.1	0.7	1.1	0.9	0.3	0.9
5MD	1.3	0.8	1.3	0.9	0.5	0.9
5HD	1.2	0.8	1.2	0.9	0.6	0.9
5LE	1.3	0.8	1.3	0.9	0.5	0.9
5ME	1.4	0.8	1.2	0.9	0.6	0.9
5HE	1.3	0.8	1.2	0.9	0.7	0.9

7.2 Performance of Configuration I in Three Locations

Table-7.2A and B show the solar fraction and system energy factor for configuration-I. Both Victoria and Kamloops have higher solar fraction values and system energy factor in the selected summer day; while, in the selected winter day, configuration I has better performance in Williams Lake. As for Victoria and Williams Lake, they have the lowest solar fraction and the corresponding system energy factor on Day 16 and Day 228, respectively; however, that doesn't necessarily mean that the solar assisted hot water heating technology is not suitable for those

areas. The reason for the lower performance indicated in Table-7.2A and B is simply because day 16 in Victoria and day 228 in Williams Lake do not have sufficient solar radiation energy.

The solar pre-heating tank temperature is an indicator of when and how much solar radiation is available for a specific day. Figure-7.5 and 7.6 illustrate the daily solar pre-heating tank temperature profiles for each location employing the 2LD load profile. As shown in Figure-7.5, on day 228 in Victoria, B.C., the solar pre-heating tank's temperature starts at 60 °C which is the assumed initial temperature during the summer day. During the period between 0:00 AM and 6:45AM, the temperature decreases because of the heat loss through the surface of the solar pre-heating tank. Then it starts to drop at about 6:45 AM and keeps going down reaching the lowest temperature of 39 °C at about 7:30 AM. After that, the solar pre-heating tank's temperature starts to rise and reaches the peak point at about 3:00 PM followed by another decrease at 6:30 PM. The solar pre-heating tank's temperature profile on day 16, shown in Figure-7.6, is similar to Figure-7.5 except the pre-heating tank initial temperature is 30°C and the peak temperature occurs at 2:45 PM. As can be seen there is insufficient solar radiation on day 228 in Williams Lake so that no major temperature increase occurs resulting in the relatively flat temperature profile.

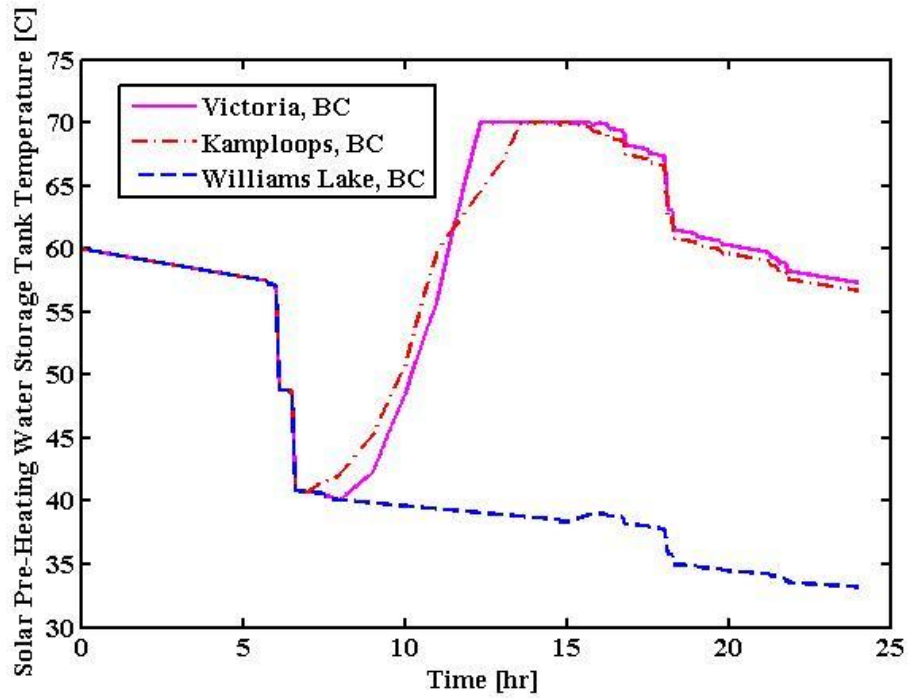


Figure 7.5 Solar pre-heating tank temperature for Load01_2LD on day 228 with 60°C initial temperature.

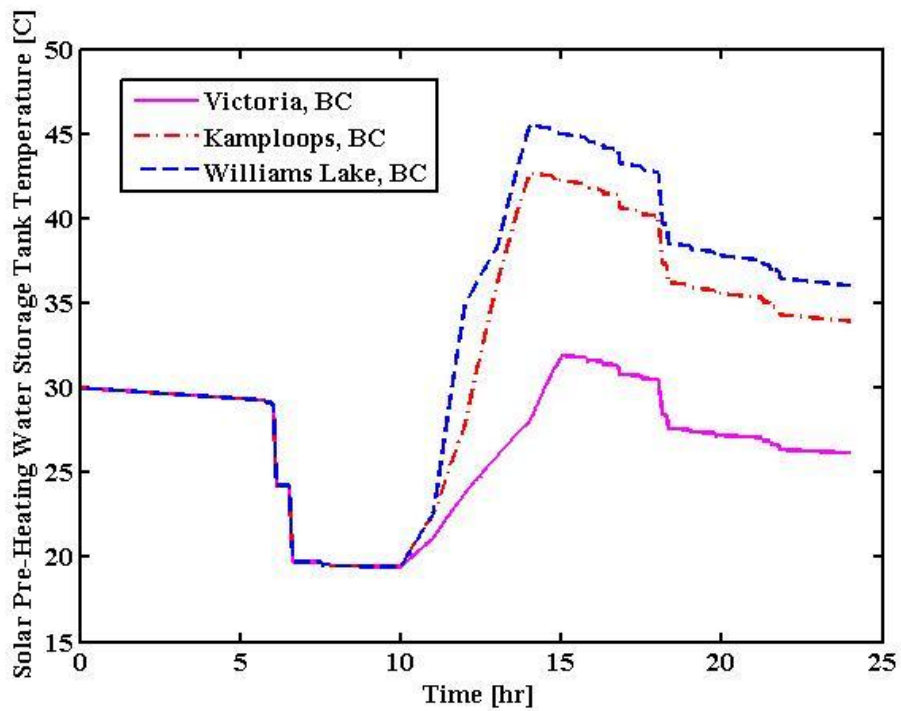


Figure 7.6 Solar pre-heating tank temperature for Load01_2LD on day 16 with 30°C initial temperature.

Figure 7.7 and Figure 7.8 indicate the daily cumulative energy quantities of configuration I in Victoria, B.C. on day 228 and day 16, respectively. They indicate the cumulative daily heating energy generated and quantify the contributions from solar and conventional energy. Figure-7.9, 7.10 and Figure-7.11, 7.12 show the daily cumulative energy quantities of the same configuration and load profile in Kamloops, B.C. and Williams Lake, B.C., respectively. As can be seen, most conventional energy is consumed between 6:45AM to 8:00AM since there is insufficient solar energy available during that period. The system has higher solar contribution in the selected summer day than the winter day in both Victoria and Kamloops. In Williams Lake, the system's solar contribution in the selected summer day is small.

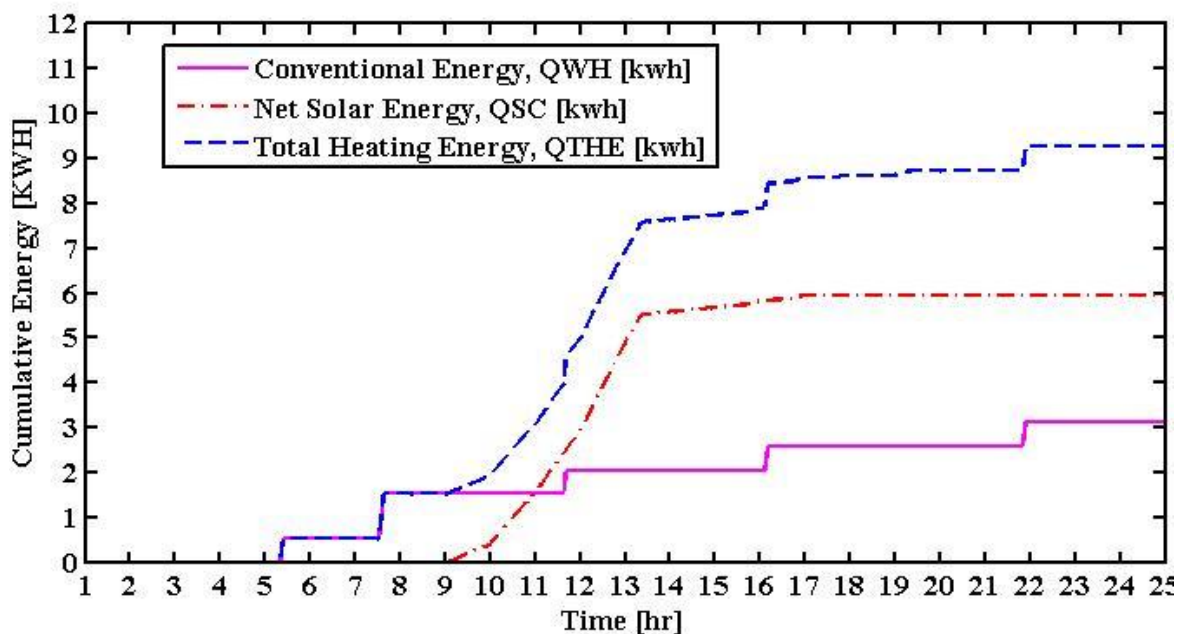


Figure 7.7 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Victoria on day 228.

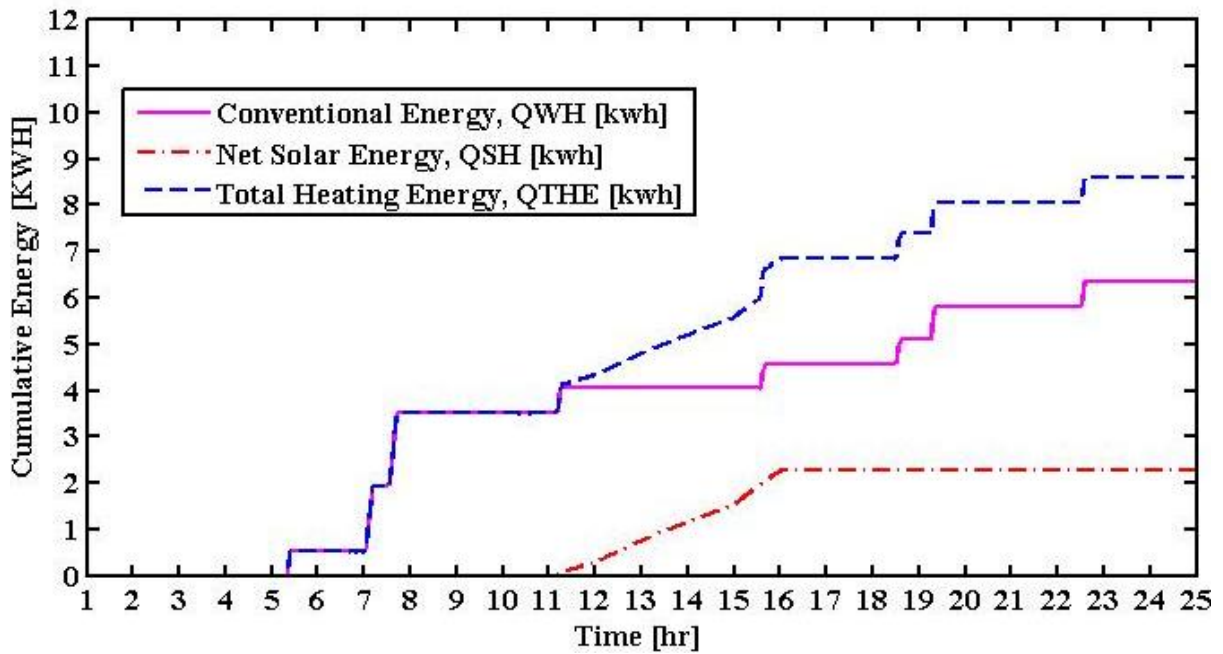


Figure 7.8 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Victoria on day 16.

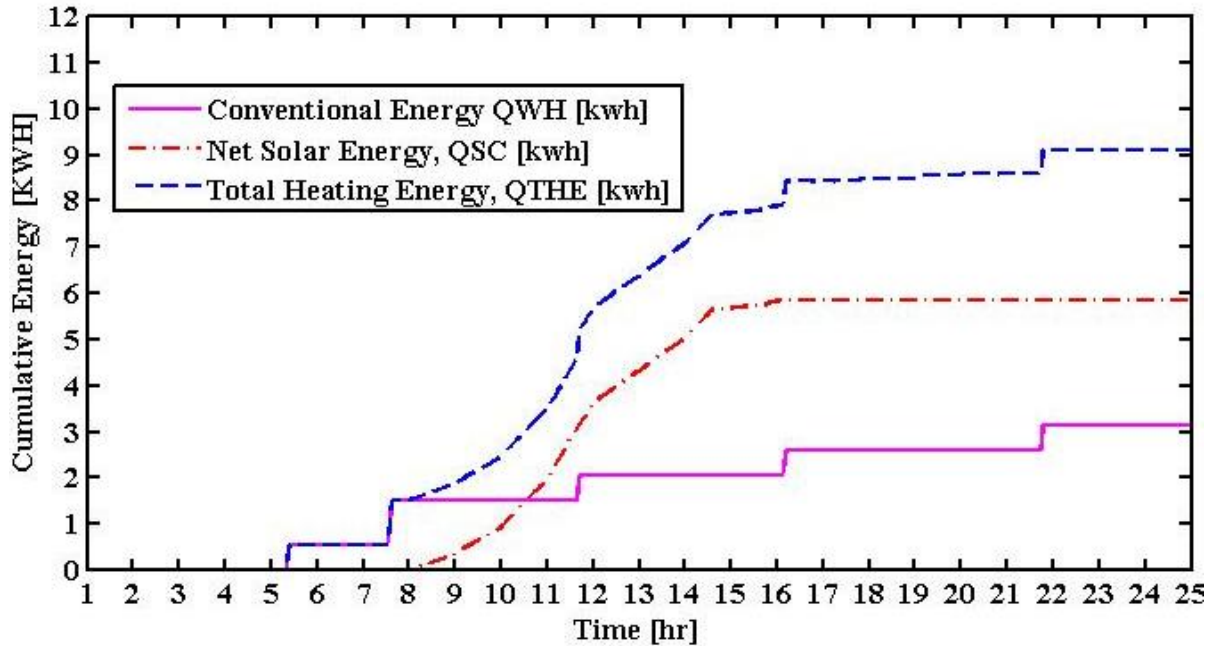


Figure 7.9 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Kamloops on day 228.

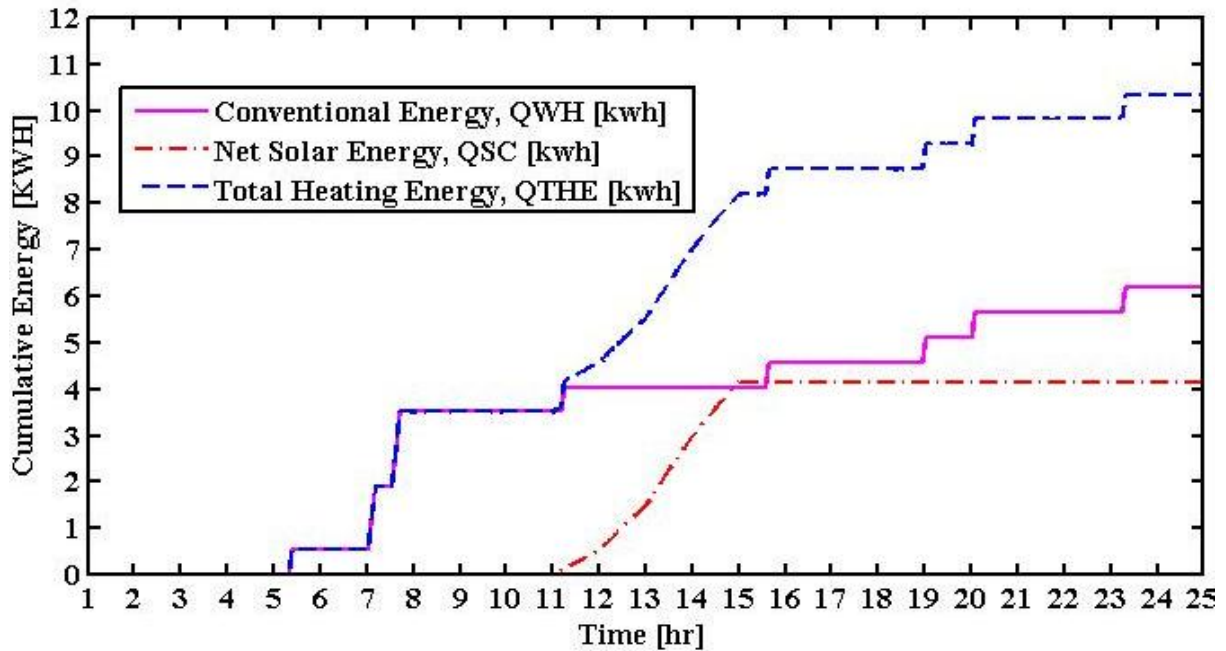


Figure 7.10 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Kamloops on day 16.

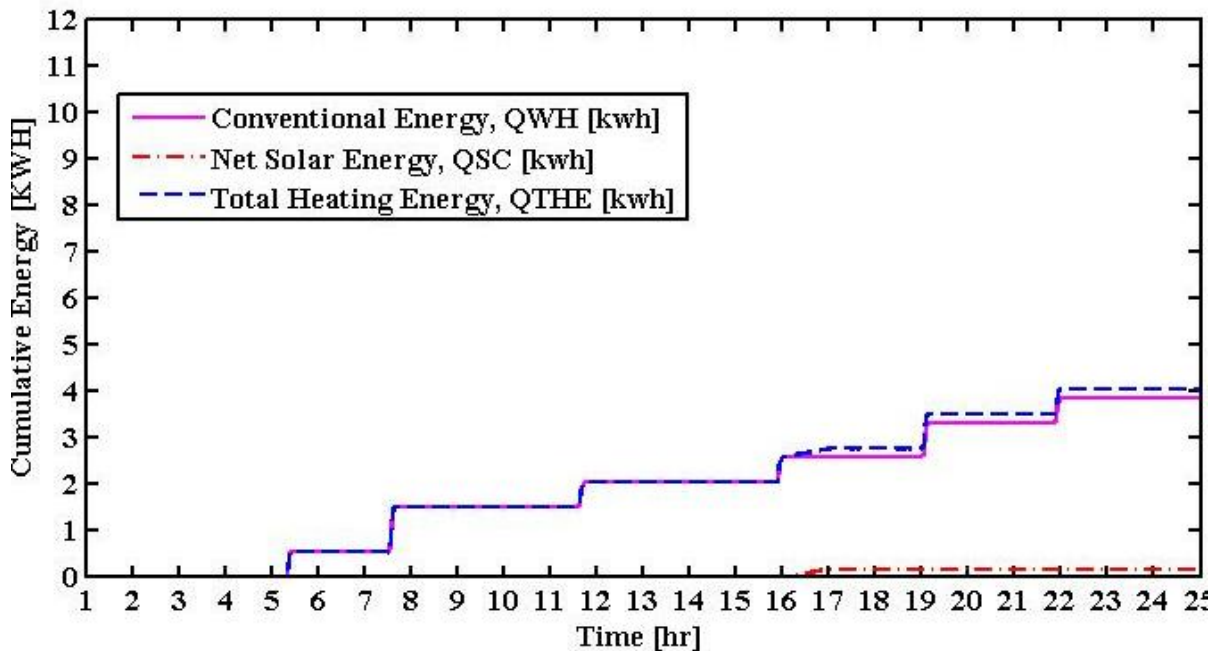


Figure 7.11 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Williams Lake on day 228.

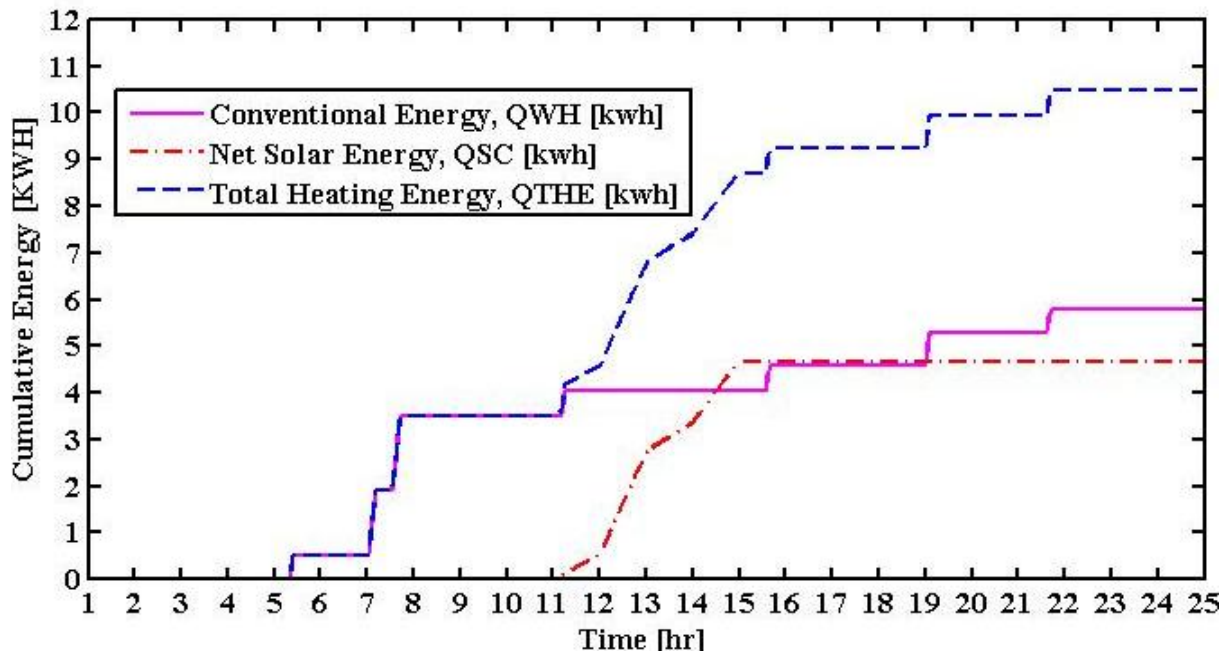


Figure 7.12 Daily cumulative heating energy generated, solar contribution and conventional energy contribution of configuration I for load profile 2LD in Williams Lake on day 16.

7.3 Performance Results of Configuration II

Figure 7.13 and Figure 7.14 illustrate the system energy factor between option A and option B of configuration II applying the 2LD load profile in Victoria. As indicated by the figures, option B has a higher system performance than option A for all load scenarios. Table-7.6 and Table-7.7 summarize the simulation results of day 228 and 16 in Victoria.

The DWHR Fraction column indicates the ratio of the daily recovered heating energy to the overall daily heating energy delivered (including both the conventional and recovered heating energy); DWHR/Shower indicates the ratio of the daily recovered heating energy relative to the energy delivered only to the shower. In general, both option A and option B have better system performance in the selected winter day than the summer day. This is due to the fact that the

temperature of the cold make-up water to the system is lower for the winter day (assumed to be 4°C for Victoria) than in the summer day (assumed to be 10°C for Victoria) resulting in more waste energy being recovered in the winter time. From the results shown in Table-7.6 and Table-7.7, there is no direct relationship between the total daily demand hot water consumption and the system's efficiency or the recovered energy ratio. This is because the drain water heat exchanger only recovers the waste energy from shower drain.

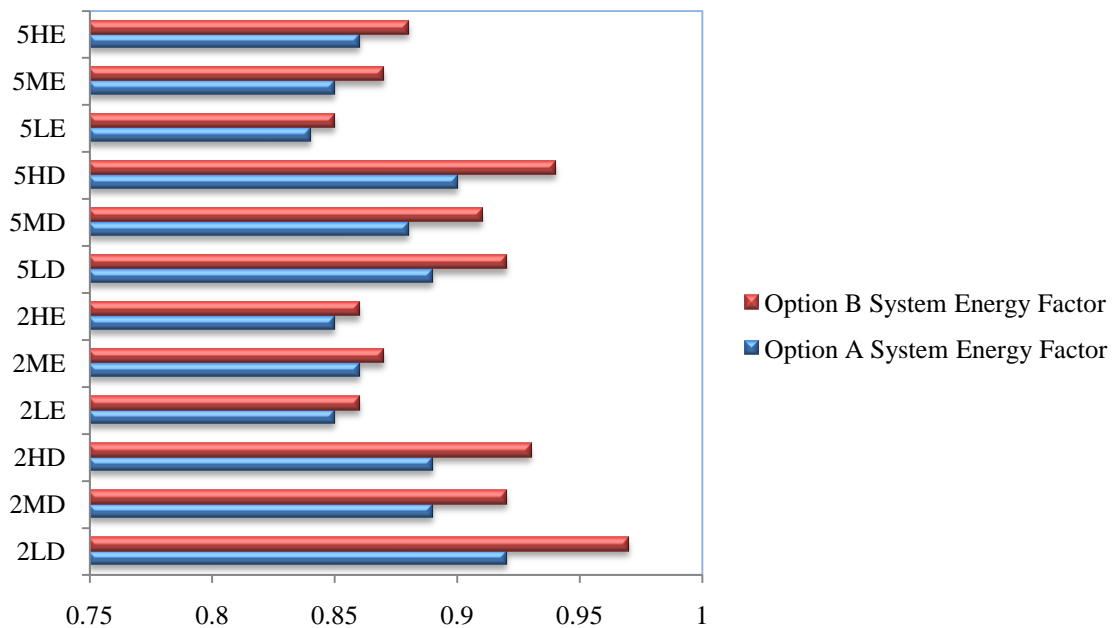


Figure 7.13 System energy factor comparison between option A and option B for day 228 simulation based on all the load profiles in Victoria, B.C.

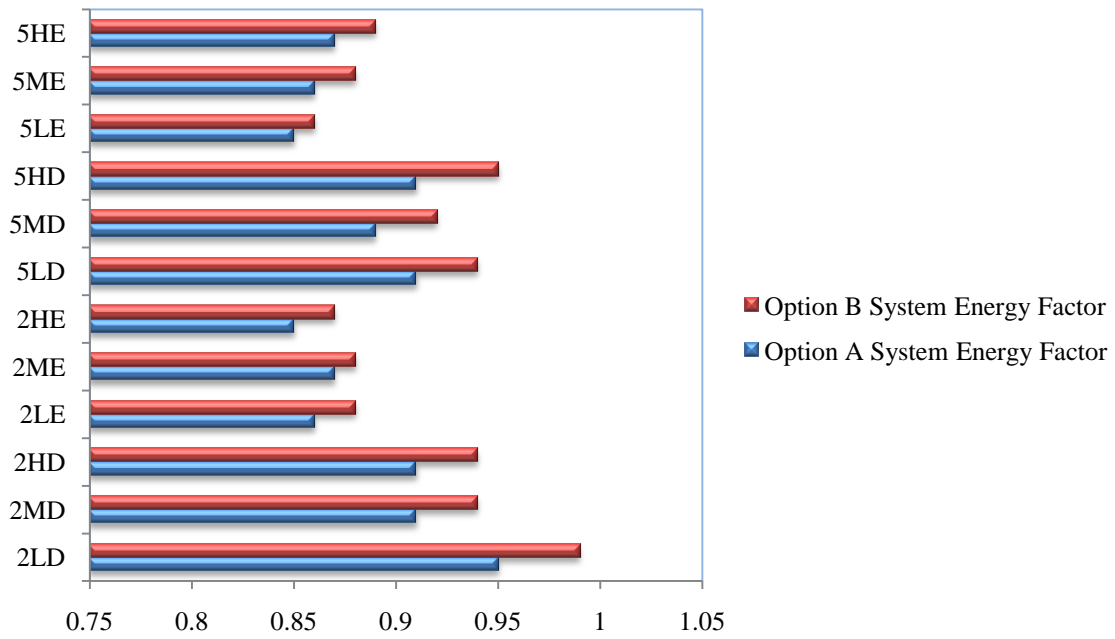


Figure 7.14 System energy factor comparison between option A and option B for day 16 simulation based on 2LD load profile in Victoria, B.C.

Table-7.3 Drain water heat recovery unit performance summary for day 228 in Victoria, B.C.

Victoria, B.C. Day 228							
Load Profile	Demand Hot Water Consumption [L/Day]	Option A			Option B		
		DWHR Fraction [%]	DWHR/ Shower [%]	System Energy Factor (SEF)	DWHR Fraction [%]	DWHR/ Shower [%]	System Energy Factor (SEF)
2LD	174	9.6	27.1	0.9	13.2	44.9	1.0
2MD	232	7.8	27.2	0.9	10.7	45.1	0.9
2HD	293	7.9	27.5	0.9	10.9	45.9	0.9
2LE	221	4.3	27.4	0.9	5.8	44.8	0.9
2ME	296	3.4	27.6	0.9	4.5	44.7	0.9
2HE	369	3.9	27.6	0.9	5.4	46.2	0.9
5LD	279	6.7	27.2	0.9	9.1	44.7	0.9
5MD	373	5.9	27.3	0.9	8.1	45.3	0.9
5HD	468	8.1	27.5	0.9	11.3	45.9	0.9
5LE	353	3.0	27.4	0.8	4.0	44.8	0.9
5ME	474	4.4	27.3	0.9	6.0	44.9	0.9
5HE	592	5.3	28.0	0.9	7.2	46.0	0.9

Table-7.4 Drain water heat recovery unit performance summary for day 16 in Victoria, B.C.

Victoria, B.C. Day 16							
Load Profile	Demand Hot Water Consumption [L/Day]	Option A			Option B		
		DWHR Fraction [%]	DWHR/ Shower [%]	System Energy Factor (SEF)	DWHR Fraction [%]	DWHR/ Shower [%]	System Energy Factor (SEF)
2LD	174	11.4	30.1	1.0	14.5	45.5	1.0
2MD	232	9.2	30.2	0.9	11.7	45.6	0.9
2HD	293	9.2	30.5	0.9	11.8	46.6	0.9
2LE	221	5.1	30.5	0.9	6.4	45.5	0.9
2ME	296	3.9	30.6	0.9	4.9	45.4	0.9
2HE	369	4.5	30.7	0.9	5.8	47.0	0.9
5LD	279	7.7	30.1	0.9	9.8	45.5	0.9
5MD	373	6.8	30.3	0.9	8.7	46.1	0.9
5HD	468	9.3	30.6	0.9	11.9	46.4	1.0
5LE	353	3.4	30.4	0.9	4.3	45.6	0.9
5ME	474	5.1	30.3	0.9	6.4	45.4	0.9
5HE	592	6.0	30.9	0.9	7.7	46.8	0.9

7.4 System Performance of Configuration III and IV For Victoria

Table-7.5 and 7.6 indicate the unmet load and the corresponding system energy factor for both of configuration III and IV employing a 151.6 liter main hot water storage tank for Victoria on Day 228 and day 16, respectively. Both configurations have higher system energy factor in

the selected summer day than the winter day. Furthermore, configuration III has the higher system energy efficiency; however, an unmet load exists which indicates the temperature of the delivered hot water is lower than the demand temperature for a specific plumbing fixture at some time in the day. Figure 7.15 and Figure 7.16 illustrate the daily temperature profile of the plumbing fixtures being used and the delivered hot water for the selected summer day in Victoria applying 2LD and 5HE load profiles. In the 2LD scenario, the delivered hot water temperature curve (bold black line type curve) is always higher than any plumbing fixture demand temperature. In the 5HD load profile scenario, there are points where the delivered hot water does not meet demand resulting in an unmet load. The lower delivered water temperature provided by the heat pump combined with the higher hot water consumption cause the unmet load situation. This result shows that a system can not be assessed purely by the system energy factor. Even though the unmet load is small relative to the total load, it may not be acceptable to the consumer.

Table-7.5 System performance comparison between configuration III and IV of day 228 in Victoria.

Load Profile Victoria, BC 151.6 Liter Tank	Demand Hot Water Consumption [l/day]	Configuration III on Day 228		Configuration IV on Day 228	
		Unmet Load [kWh]	SEF	Unmet Load [kWh]	SEF
2LD	174	0	2.8	0	1.2
2MD	232	0.2	3.0	0	1.4
2HD	293	0.3	3.1	0	1.6
2LE	221	0.1	3.0	0	1.3
2ME	296	0.3	3.1	0	1.5
2HE	369	0.3	3.1	0	1.6
5LD	279	0.1	3.0	0	1.5
5MD	373	0.3	3.1	0	1.6
5HD	468	0.4	3.2	0	1.7
5LE	353	0.4	3.1	0	1.5
5ME	474	0.7	3.2	0	1.7
5HE	592	0.8	3.2	0	1.8

Table-7.6 System performance comparison between configuration III and IV of Day 16 in Victoria.

Load Profile Victoria, BC 151.63 Liter Tank	Demand Hot Water Consumption [l/day]	Configuration III on Day 16		Configuration IV on Day 16	
		Unmet Load [kWh]	SEF	Unmet Load [kWh]	SEF
2LD	174	0	2.9	0	1.3
2MD	232	0.3	3.1	0	1.5
2HD	293	0.5	3.2	0	1.7
2LE	221	0.2	3.1	0	1.4
2ME	296	0.4	3.1	0	1.6
2HE	369	0.5	3.2	0	1.7
5LD	279	0.2	3.1	0	1.6
5MD	373	0.6	3.2	0	1.7
5HD	468	0.9	3.3	0	1.8
5LE	353	0.8	3.2	0	1.7
5ME	474	1.4	3.3	0	1.8
5HE	592	1.4	3.3	0	1.9

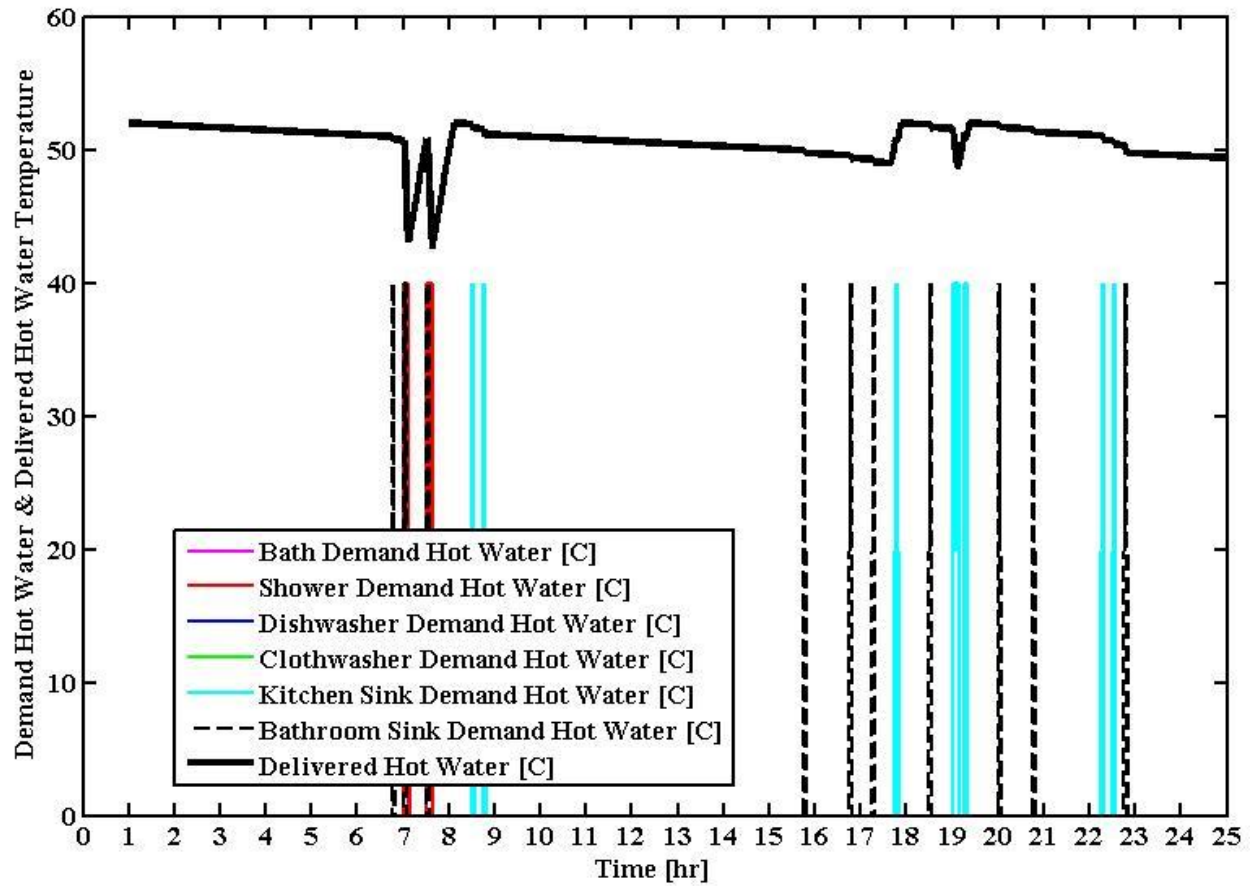


Figure 7.15 Daily main hot water tank temperature profile, demand hot water temperature profile of Victoria for 2LD load profile on day 228 (Configuration III) .

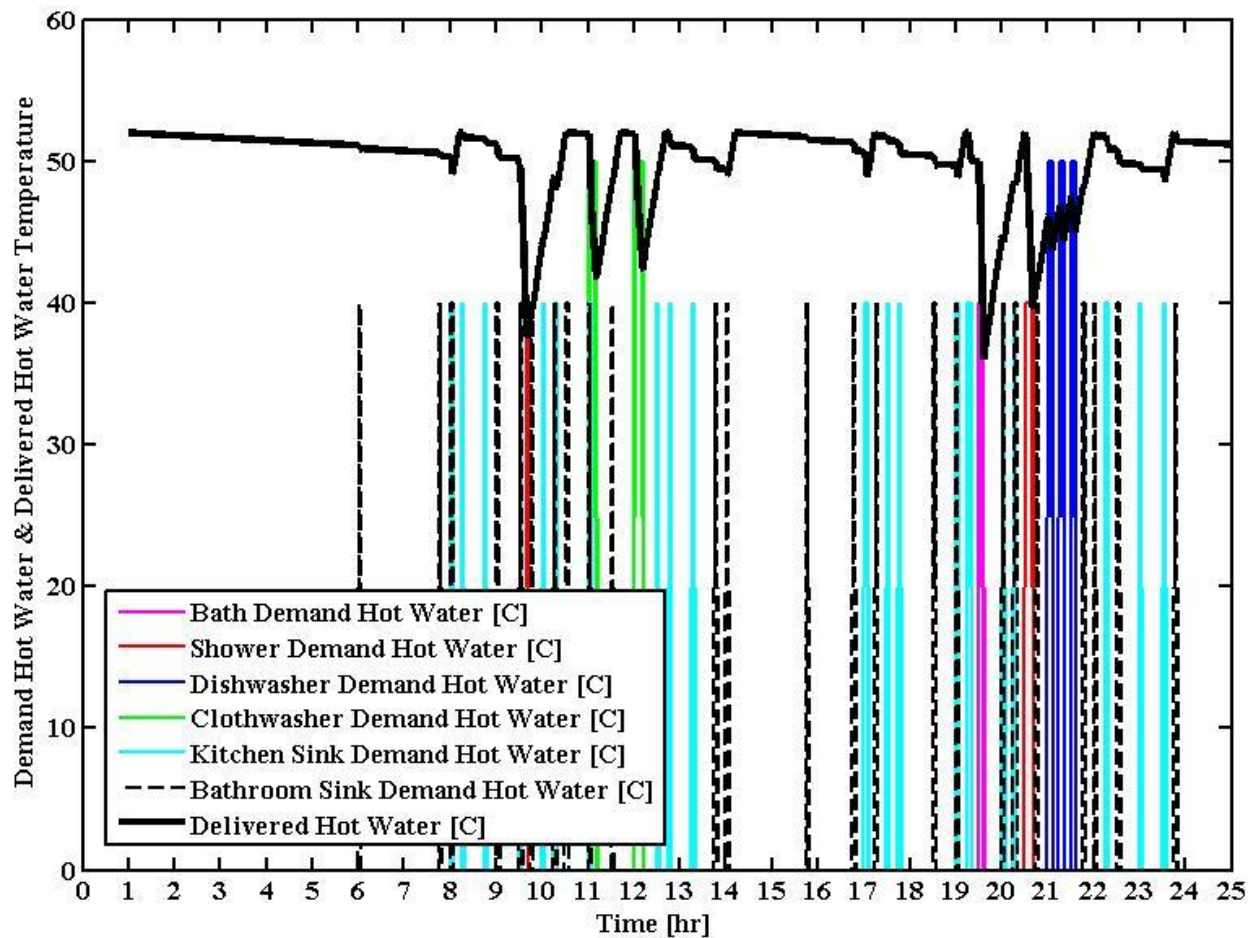


Figure 7.16 Daily main hot water tank temperature profile, demand hot water temperature profile of Victoria for 5HE load profile on day 228 (Configuration III).

7.5 Configuration I Performance Using a Lower Hot Water Tank Set Point

An obvious way to decrease energy requirements is to decrease the set-point temperature for the main hot water tank. Table-7.7 summarizes the system solar fraction and the corresponding unmet load of Victoria based on lower hot water tank set-points. When the set-point is adjusted from 60°C to 55°C, depending on the load profile, the corresponding solar fraction increases 2.4% - 5.2%. Also, the solar fraction increases when the set-point is adjusted

from 55°C to 50°C; however, at the lowest setting, an unmet load appears for most of the load profiles.

Table-7.7 Configuration I system performance of day 228 for Victoria simulation based on different main hot water tank set- point

Victoria, BC, Day 228						
Load Profile	60°C		55°C		50°C	
	Solar Fraction [%]	Unmet Load [kWh]	Solar Fraction [%]	Unmet Load [kWh]	Solar Fraction [%]	Unmet Load [kWh]
2LD	65.6	0	73.4	0	80.2	0
2MD	61.8	0	68.1	0	75.7	0.1
2HD	60.4	0	66.2	0	73.8	0.1
2LE	66.9	0	71.0	0	79.3	0
2ME	64.6	0	72.0	0	80.0	0.0
2HE	62.2	0	68.8	0	75.8	0.1
5LD	61.7	0	69.5	0	75.8	0
5MD	60.0	0	65.1	0	72.0	0.1
5HD	53.4	0	58.4	0	66.4	0.2
5LE	62.3	0	70.0	0	77.6	0
5ME	57.8	0	63.0	0	72.3	0.1
5HE	54.1	0	59.3	0	65.3	0.3

7.6 Discussion

Based on the previous model results, when compared to a conventional DHW system (base configuration), the energy saving technologies all resulted in lower conventional energy consumption and CO₂ emissions. For example, from Table-7.1, during the selected summer day

in Victoria with a high demand load profile, the system's energy factor is improved from 0.67 to up to 1.69, and the corresponding conventional energy consumption and CO₂ emissions decrease from 22.90 kWh to 8.95 kWh, and 4.1 kg/day to 0.3 kg/day, respectively.

One reason for results varying with season is because the cold water make-up temperature changes. Usually, this temperature can be estimated knowing the maximum and minimum soil temperature. For reasons of simplicity, two fixed water make-up temperatures (10°C and 4°C) are assumed for the summer and winter seasons in all three locations where the summer season is defined from May to September, and the winter season is defined from October to April. Moreover, the results only reflect the system's performance for the selected summer or winter day not the whole summer or winter season. For example, even though results show that configuration I has low performance in Williams Lake on the selected summer day, that doesn't necessarily mean solar assisted technology should not be applied in that area during the summer time. It only means the solar system has lower performance on the day selected. To evaluate the impact of solar in a specific area, the system's long-term (yearly) performance should be investigated and analyzed.

As shown in Table-7.2B, in Williams Lake, the system energy factor of the selected summer day for all the hot water usage profiles seem low. The reason for this is there is insufficient solar energy for Williams Lake on Day 228. In addition, the assumed initial pre-heating water temperature of 60°C causes a considerable amount of thermal loss even though the pre-heating tank water temperature keeps decreasing during that day as indicated in Figure-7.5. Combined low solar energy and the thermal loss through the pre-heating water tank cause the unexpected low system energy factor.

The drain water heat recovery unit in configuration II (as shown in Figure-3.2 and 3.3) is connected between the shower drain and the cold water make-up piping. This means only energy from the shower is recoverable. This configuration is examined because hot water consumed by the shower can be 40-45% of total household consumption [5]. These units are meant to be installed at the main drainage riser so that heating energy can be recovered from the drain water of each plumbing fixture being used. Also, the heat recovery device must be installed vertically so that a larger wetted perimeter can be formed when drain water flows through the drain stack resulting in larger heat transfer area. The results indicate option B of configuration II in Table-7.3 has a better system performance than option A.

In some scenarios, an unmet load is seen for configuration III. The reason this happens is not because of the undersized heat pump, but due, instead, to the limited delivered hot water temperature of 52°C provided by the add-on heat pump water heater. When the required demand temperature is high or the plumbing fixture being used draws a lot of water, the cold water make-up can cause a large drop in the temperature of the main hot water storage tank in very short time. In addition, the supplemental water heater inside the main hot water storage tank is only activated when the temperature is out of the working range specified by the manufacturer which means even though the delivered hot water temperature is much lower than the tank's set point the system relies on the heat pump water heater only. Configuration IV employs the same technology as III, but because a separate main storage tank and heater is used, does not have the same unmet load. The add-on heat pump provides pre-heating to the incoming cold water make-up. When the system calls for hot water with a higher temperature or for a longer period, the electric heater can be activated to provide supplemental heating to maintain the appropriate delivered hot water temperature. However, since conventional energy is used to quickly respond

to a temperature drop in configuration IV, the corresponding conventional energy consumption is increased resulting in a relatively lower system energy factor and more CO₂ emissions. By comparing the simulation results shown in Table-7.5 and Table-7.6, for each group of hot water load profiles, the system energy factor is seen to increase with respect to the hot water consumption. One reason is that the loss become relatively smaller compared to demand. Another reason is because a higher load means more cold water make-up and a relatively lower tank temperature, thereby resulting in a higher heat pump COP value. This is also the reason why configuration III and IV have better system performance in the selected winter day than the selected summer day.

The simulation models for configuration III and IV assume that the ambient temperature of the space where the heat pump is installed is 18°C which is within the required working ambient temperature range specified by the manufacturer; however, in reality, this type of heat pump is usually installed in the garage in which the temperature might be much higher in the summer time and much lower in the winter time in some areas of Canada. Once the heat pump ambient temperature is out of the working ambient temperature range within which the heat pump can work properly, the heating mode will be automatically switched from the heat pump heating to the conventional electric resistance heating resulting in lower system energy factor and more CO₂ emissions than the simulation results shown in Chapter 7. Also, when the heat pump heats the water with its condenser, the evaporator will produce a cooling load which needs to be dumped to either the outside or some indoor space. When inside the house, this might help the air conditioning system in the summer; however, in the winter time, it could be another heating load to be served by the building heating systems. Further research regarding how

heating load will be compromised in the winter time for a residential house in different locations of Canada is necessary.

As can be seen from the results shown in Table-7.7, decreasing the main hot water storage tank set-point to provides a longer time for the solar heat to service to load. This can result in a higher solar fraction, lower conventional energy consumption, and lower CO₂ emission; however, if set point is too low, an unmet load situation can result. Determining the appropriate hot water storage tank set point is important for all configurations.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The results and key findings of this thesis are described in the following section.

A numerical tool simulating three unconventional hot water system components (flat-plate solar collector, drain water heat exchanger, and heat pump water heater) was developed to study domestic hot water systems. The Simulink model uses a time-step of one minute with Excel spreadsheets listing load profiles, water tank specifications, and location-dependent resource and weather data. Actual gas or electric tanks can be modeled, or design studies can be performed where tank parameters are arbitrarily set. A variety of system performance parameters such as heat inputs, system thermal losses, delivered energy, fuel consumption, CO₂ emissions and overall system energy factors can be calculated and output. This tool can track unmet load events and cycling of the auxiliary heater to analyze the effects of under-sizing a system. Each component model was validated against known solutions of experimental data and system model was partially validated against a solar simulation code called Watsun. Good agreement was obtained. Watsun was found to give higher performance for the same solar system configuration; however, the model developed in this thesis has a more accurate representation of tank operation. This can explain why there is a small, but consistent difference between the two codes.

The performance of five hot water system configurations was analyzed and compared for three locations in British Columbia, Canada. Results show that:

- 1) Solar assisted configurations having higher system energy factors than the base case configuration (conventional domestic hot water system) in both summer and winter days.
- 2) Drain-water recovery is effective in increasing system energy factor over the base case configurations (~40%). Configuring the system to preheat the hot and cold water going to the shower fixtures provides better performance than just preheating water going to hot water shower fixture (~5%).
- 3) The lowest emissions resulted from the use of heat-pump assisted hot water tanks because heat pumps have higher co-efficiency of performance (>3.0). However, the heat-pump specifications used in the simulations have a maximum operating temperature that is lower than the normal hot water tank set-point range, resulting in unmet loads occurring for some of demand profiles.

The impacts of location arise due to differences in solar resource. In the three locations examined, solar assisted water heating was found to provide benefits to system energy factor over the base configuration. Solar pre-heating tanks have a significant impact on system performance. As the volume increases, the ability to carry-over absorbed radiation into other days also increases. This can make solar contribute more on a day with low radiation levels. Thus, unlike the other technologies examined, the accurate assessment of solar requires simulations over longer time periods. This is needed so that initial conditions in the solar pre-heating tank do not influence results and so that anomalies in weather data are properly accounted for.

8.2 Recommendations

After simulating and analyzing the results of various hot water system configurations, recommendations for future work and improved results are made.

Firstly, the cold make-up water temperature is assumed to be 4 °C and 10 °C for all three locations during the summer season (May to October) and winter season (November to April), respectively. In reality, the make-up water temperature varies in each month and is similar to the ground soil temperature monthly variation. The variation of make-up water temperature will affect performance metrics such as conventional energy consumption, delivered energy, water heater efficiency, and the overall system energy factor. Future studies might benefit from a more accurate representation of make-up water temperatures as a function of time and location. Further work on results sensitivity to make-up water temperature is recommended.

Secondly, the weather data used in this thesis for all three locations are referenced from WATSUN's weather database which reflects the average weather condition for the past 20 years. Long time-series weather data is available for many locations and can be statistically analyzed to determine the probability of a specific weather condition occurring in a selected day so that the corresponding probability of a desired system performance occurrence such as unmet load, system energy factor and so on can be determined from simulations. The probability for a specific system performance occurrence can help water heating system designers to determine the certainty that a load can be satisfied under certain design conditions. In addition, in the case of solar, simulations should be run for periods longer than one day.

Thirdly, in this thesis, unconventional heating systems utilizing single energy saving technologies were analyzed and compared. In practice, more than one technology could be used

simultaneously. However, although further increases in system efficiency may result, there will also be additional initial equipment costs. Thus, cost considerations should also be implemented.

Finally, hot water profiles used in this thesis do not reflect seasonal changes. In general, hot water usage patterns vary during different seasons. The variation of hot water usage will affect the system performance; therefore, updating the hot water usage scenario database to reflect seasonal variations will allow the tool developed in this thesis to more accurately predict system performance.

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Appendices

Appendix-A

Table-A1 Actual hourly-basis meteorological data on **day228** in **Victoria, B.C.**

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
228	1	0	14	0.2
	2	0	14	
	3	0	13	
	4	0	13	
	5	0	13	
	6	43	13	
	7	164	13	
	8	232	15	
	9	366	16	
	10	546	18	
	11	622	19	
	12	765	20	
	13	756	20	
	14	768	20	
	15	675	20	
	16	548	20	
	17	392	19	
	18	224	19	
	19	65	17	
	20	0	16	
	21	0	13	
	22	0	12	
	23	0	12	
	24	0	10	

Table-A2 Actual hourly-basis meteorological data on **day228** in **Kamloops**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
228	1	0	19	0.2
	2	0	18	
	3	0	16	
	4	0	15	
	5	0	14	
	6	68	15	
	7	197	17	
	8	366	17	
	9	407	18	
	10	523	19	
	11	667	20	
	12	499	23	
	13	506	25	
	14	572	27	
	15	482	30	
	16	315	31	
	17	286	31	
	18	172	31	
	19	31	28	
	20	0	26	
	21	0	22	
	22	0	21	
	23	0	21	
	24	0	22	

Table-A3 Actual hourly-basis meteorological data on **day228** in **Williams Lake**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
228	1	0	12	0.2
	2	0	11	
	3	0	11	
	4	0	11	
	5	0	11	
	6	9	11	
	7	163	11	
	8	110	12	
	9	190	12	
	10	244	12	
	11	138	15	
	12	146	16	
	13	196	14	
	14	146	15	
	15	117	16	
	16	295	14	
	17	250	15	
	18	180	17	
	19	34	16	
	20	0	15	
	21	0	14	
	22	0	13	
	23	0	13	
	24	0	11	

Table-A4 Actual hourly-basis meteorological data on **day16** in **Victoria, B.C.**

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
16	1	0	2	0.4
	2	0	2	
	3	0	1	
	4	0	1	
	5	0	1	
	6	9	1	
	7	0	1	
	8	0	0	
	9	52	0	
	10	108	1	
	11	189	2	
	12	215	2	
	13	199	2	
	14	165	2	
	15	128	2	
	16	45	2	
	17	0	2	
	18	0	2	
	19	0	2	
	20	0	2	
	21	0	2	
	22	0	2	
	23	0	2	
	24	0	1	

Table-A5 Actual hourly-basis meteorological data on **day16** in **Kamloops**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
16	1	0	3	0.4
	2	0	4	
	3	0	6	
	4	0	5	
	5	0	5	
	6	9	4	
	7	0	4	
	8	0	3	
	9	40	3	
	10	114	3	
	11	199	3	
	12	236	4	
	13	255	5	
	14	201	6	
	15	131	6	
	16	49	5	
	17	0	4	
	18	0	2	
	19	0	1	
	20	0	1	
	21	0	-1	
	22	0	0	
	23	0	-1	
	24	0	-1	

Table-A6 Actual hourly-basis meteorological data on **Day16** in **Williams Lake**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Horizontal Surface, I [W/m ²]	Outdoor Air Temperature, T_a [°C]	Ground Reflectance, ρ_g
16	1	0	-1	0.4
	2	0	-1	
	3	0	-1	
	4	0	-1	
	5	0	-1	
	6	9	-1	
	7	0	-2	
	8	0	-2	
	9	40	-2	
	10	114	-2	
	11	199	-2	
	12	236	-2	
	13	255	-1	
	14	201	-1	
	15	131	1	
	16	49	0	
	17	0	-1	
	18	0	-2	
	19	0	-2	
	20	0	-2	
	21	0	-5	
	22	0	-5	
	23	0	-6	
	24	0	-9	

Table-A7 Calculated hourly-basis solar irradiation on tilted surface on **day228** in **Victoria**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
228	1	N/A	N/A	48.65
	2			
	3			
	4			
	5			
	6			
	7			
	8	12124	61	
	9	19875	47	
	10	32606	33	
	11	38815	20	
	12	52277	14	
	13	51972	20	
	14	52131	33	
	15	43822	47	
	16	32464	61	
	17	N/A	N/A	
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Table-A8 Calculated hourly-basis solar irradiation on tilted surface on **day228** in **Kamloops**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
228	1	N/A	N/A	50.7
	2			
	3			
	4			
	5			
	6			
	7			
	8	20259	60	
	9	22930	46	
	10	31510	32	
	11	44439	19	
	12	29282	12	
	13	30419	19	
	14	37667	32	
	15	30748	46	
	16	17986	60	
	17	N/A	N/A	
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Table-A9 Calculated hourly-basis solar irradiation on tilted surface on **day228** in **Williams Lake, B.C.**

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
228	1	N/A	N/A	52.18
	2			
	3			
	4			
	5			
	6			
	7			
	8	5710	60	
	9	9905	46	
	10	12777	31	
	11	7183	18	
	12	7603	10	
	13	10232	18	
	14	7606	31	
	15	6087	46	
	16	16800	60	
	17	N/A	N/A	
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Table-A10 Calculated hourly-basis solar irradiation on tilted surface on **day16** in **Victoria**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
16	1	N/A	N/A	48.65
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9	2949	49	
	10	6233	36	
	11	13550	25	
	12	17413	21	
	13	7857	25	
	14	5413	36	
	15	1578	49	
	16	555	62	
	17	N/A	N/A	
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Table-A11 Calculated hourly-basis solar irradiation on **day16** in **Kamloops**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
16	1	N/A	N/A	52.18
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9	1514	51	
	10	13691	39	
	11	34874	30	
	12	50797	26	
	13	3328	30	
	14	2724	39	
	15	1639	51	
	16	N/A	N/A	
	17			
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Table-A12 Calculated hourly-basis solar irradiation on **day16** in **Williams Lake**, B.C.

Day of Year	Hour of Day	Global Solar Irradiation on Tilted Surface, I_T [J/min. m ²]	Incidence Angle, θ [°]	Tilted Angle, β [°]
16	1	N/A	N/A	50.7
	2			
	3			
	4			
	5			
	6			
	7			
	8			
	9	2276	50	
	10	7095	37	
	11	17707	27	
	12	26026	23	
	13	38251	27	
	14	36429	37	
	15	32711	50	
	16	604	63	
	17	N/A	N/A	
	18			
	19			
	20			
	21			
	22			
	23			
	24			

Appendix-B

Appendix-B illustrates the derivation of the equations of $F'_R(\tau\alpha)'_n$ and $F'_R U'_L$ by knowing the ratio of $\frac{F'_R}{F_R}$ (shown in equation (5.6)), as well as $F_R(\tau\alpha)'_n$ and $F_R U'_L$, which take into account connecting pipes loss. This derivation is taken from Page 307 to 308 in [23] beginning with the following equations:

$$F_R(\tau\alpha)'_n = F_R(\tau\alpha)_{use} * \frac{(\tau\alpha)'}{(\tau\alpha)} \quad (B-1)$$

$$F_R U'_L = F_R U_{Luse} * \frac{U'_L}{U_L} \quad (B-2)$$

Where,

$$\frac{(\tau\alpha)'}{(\tau\alpha)} = \frac{1}{1 + \frac{U_p A_c}{(\dot{m} C_p)_c}} \quad (B-3)$$

And

$$\frac{U'_L}{U_L} = \frac{1 - \frac{U_p A_i}{(\dot{m} C_p)_c} + \frac{U_p (A_i + A_o)}{A_c F_R U_L}}{1 + \frac{U_p A_o}{(\dot{m} C_p)_c}} \quad (B-4)$$

In the equations shown above, U_p is the pipe heat loss coefficient, and can be calculated as

$$U_p = \frac{2k}{D_o \ln\left(\frac{D_o}{D_i}\right)} \quad (B-5)$$

A_o and A_i are the surface area of the inlet pipe and the outlet pipe between the solar collector and the solar heat exchanger, respectively. In this research, since the length of the inlet and outlet

pipe are the same, $U_p A_i = U_p A_o$. A_c is the solar collector's aperture area. $F_R(\tau\alpha)_{use}$ and $F_R U_{L_{use}}$ values under actual use conditions can be calculated using the corresponding $F_R(\tau\alpha)$ and $F_R U_L$ values under the test conditions and the ratio r

$$F_R(\tau\alpha)_{use} = F_R(\tau\alpha)_{test} * r \quad (B-6)$$

$$F_R U_{L_{use}} = F_R U_{L_{test}} * r \quad (B-7)$$

Where,

$$r = \frac{\frac{(\dot{m} C_p)_c [1 - \exp\left\{-\frac{A_c F_R U_L}{(\dot{m} C_p)_c}\right\}]_{use}}{A_c F_R U_L}}{\frac{(\dot{m} C_p)_c [1 - \exp\left\{-\frac{A_c F_R U_L}{(\dot{m} C_p)_c}\right\}]_{test}}{A_c F_R U_L}} \quad (B-8)$$

And

$$F_R U_L = -\frac{(\dot{m} C_p)_c}{A_c} \ln\left(1 - \frac{F_R U_L A_c}{(\dot{m} C_p)_c}\right) \quad (B-9)$$

As for $F_R(\tau\alpha)_{test}$ and $F_R U_{L_{test}}$ values under the test conditions, both of them can be found by the first order efficiency equation of the solar collector:

$$\eta = F_R(\tau\alpha) - F_R U_L (T_i - T_a) / G \quad (B-10)$$

which is provided in the technical specifications of the solar collector [25] (*Refer 5.1.1 for $F_R(\tau\alpha)_{test}$ and $F_R U_{L_{test}}$ values under the test conditions*).

Thus,

$$F_R'(\tau\alpha)_n = F_R(\tau\alpha)_n * \frac{F_R'}{F_R} \quad (B-11)$$

$$F'_R U'_L = F_R U'_L * \frac{F'_R}{F_R} \quad (B-12)$$

Then, by knowing the value of the parameters introduced above, the useful solar energy gathered by a glazed liquid flat plate solar collector can be calculated by Equation 5.3.

Appendix-C

Table-C1 Gas-fired domestic hot water tank specifications

Model	M-I-TW40L6BN	GS6 40YBVIT	HVN412 40P	M-4-5036FBN5	GS6 50YBVIT	HVN412 50P
Brand	Bradford White	State	Maytag	Bradford White	State	Maytag
Max. Heating Capacity	11.71kW	11.71kW	11.71kW	11.71kW	11.71kW	11.71kW
Tank Volume	0.151m ³	0.151m ³	0.151m ³	0.189m ³	0.189m ³	0.189m ³
Tank Set Point	60°C	60°C	60°C	60°C	60°C	60°C
Dead Band Setting	3°C	3°C	3°C	3°C	3°C	3°C
Insulation Thickness	0.025m	0.025m	0.05m	0.05m	0.025m	0.05m
RSI	1.408	1.408	2.816	2.816	1.408	2.816
Rated Efficiency	0.80	0.81	0.82	0.80	0.82	0.82
Rated E.F.	0.63	0.65	0.67	0.63	0.65	0.67
Tank Diameter	0.508m	0.470m	0.520m	0.559m	0.508m	0.558m
Tank Height	1.245m	1.400m	1.400m	1.448m	1.441m	1.441m

Table-C2 Electric domestic hot water tank specifications

Model	EPX 40 DXRT	ES6 40 DOCT	ES6 40 DORT	EPX 52 DXRT	ES6 52 DOCT	ES6 52 DORT
Brand	State	State	State	State	State	State
Max. Heating Capacity	4.5kW	4.5kW	4.5kW	4.5kW	4.5kW	4.5kW
Thank Volume	0.151m ³	0.151m ³	0.151m ³	0.189m ³	0.189m ³	0.189m ³
Tank Set Point	52°C/ 60°C	52°C/ 60°C	52°C/ 60°C	52°C/ 60°C	52°C/ 60°C	52°C/ 60°C
Dead Band Setting	3°C	3°C	3°C	3°C	3°C	3°C
Insulation Thickness	0.0762m	0.0653m	0.05m	0.0762	0.0653	0.05
RSI	4.224	3.52	2.816	4.224	3.52	2.816
Rated Efficiency	N/A	N/A	N/A	N/A	N/A	N/A
Rated E.F.	0.95	0.93	0.92	0.95	0.93	0.91
Tank Diameter	0.508m	0.483m	0.457m	0.572	0.546	0.521
Tank Height	1.540m	1.524m	1.511m	1.448m	1.435m	1.372m

