Analysis of the Impact of Solar Thermal Water Heaters on the Electrical Distribution Load

Terry Bruno Jesudhason Maria Therasammal

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree

Master of Science
in
Electrical Engineering

Saifur Rahman
Manisa Pipattanasomporn
Yue J. Wang

September 23, 2011
Arlington, Virginia

Keywords: Solar thermal water heater, Flat plate collector, Glass tube collector, electric water heater, electrical distribution load

Analysis of the Impact of Solar Thermal Water Heaters on the Electrical Distribution Load

Terry Bruno Jesudhason Maria Therasammal

Abstract

In this research, the impact of solar thermal water heaters on the electric water heating load curve in a residential distribution circuit is analyzed with realistic hot water draw profiles. For this purpose, the electric and solar thermal water heater models are developed in MATLAB and validated with results from GridLAB-D and TRNSYS respectively. The solar thermal water heater model is developed for two types of collectors namely the flat plate and evacuated glass tube collector. Simulations are performed with the climate data from two cities - Madison, WI and Tampa, FL - which belong to two very different climate zones in the United States. Minute-by-minute electric energy consumptions in all three configurations of water heaters are modeled for a single water heater as well as a residential distribution circuit with 100 water heaters for daily as well as monthly time frames.

The research findings include:

1) The electric energy saving potential of a solar thermal water heater powered by auxiliary electric element is in the range of 40-80% as compared to an all-electric water heater depending on the site conditions such as ambient temperature, sunshine and wind speed. The simulation results indicate that the energy saving potential of a solar thermal water heater is in the range of 40-70% during winter and 60-80% during summer.
2) Solar thermal water heaters aid in reducing the peak demand for electric water heating in a distribution feeder during sunshine hours when ambient temperatures are higher. The simulation results indicate that the peak reduction potential of solar thermal water heaters in a residential distribution feeder is in the range of 25-40% during winter and 40-60% during summer.
3) The evacuated glass tube collectors save an additional 7-10% electric energy compared to the flat plate collectors with one glass pane during winter and around 10-15% during

summer. The additional savings result from the capability of glass tube collectors to absorb ground reflected radiation and diffuse as well as direct beam radiation for a wider range of incidence angles. Also, the evacuated glass tube structure helps in reducing wind convective losses.

4) From the simulations performed for Madison, WI and Tampa, FL, it is observed that Tampa, FL experiences more energy savings in winter than Madison, WI, while the energy savings are almost the same in summer. This is due to the fact that Tampa, FL has warmer winters with higher ambient temperatures and longer sunshine hours during the day compared to Madison, WI while the summer temperatures and sunshine hours are almost the same for the two cities.
5) As expected, the simulation results prove the fact that lowering the hot water temperature set point will result in the reduction of electricity consumption. For a temperature reduction from 120 deg. F to 110 deg. F, electric water heaters save about 25-35% electric energy whereas solar thermal water heaters save about 30-40% auxiliary electric energy for the same temperature reduction.
6) For the flat plate collectors, glass panes play an important role in auxiliary electric energy consumption. Flat plate collectors with two glass panes save about 10-15% auxiliary electric energy compared to those with no glass panes and about 3-5% energy saving compared to collectors with one glass pane. This is because there are reduced wind convective losses with glass panes. However, there are also transmittance losses from glass panes and there are upper limits on how many glass panes can be used.

Results and findings from this research provide valuable insight into the benefits of solar thermal water heaters in a residential distribution feeder, which include the energy savings and peak demand reduction.

To My Loving Husband

Jimmycartor Berkmans

Acknowledgment

Firstly, I would like to thank God for immensely blessing and providing me with everything needed to achieve all that I have accomplished.

I am grateful to the invaluable assistance and guidance of my advisor, Dr. Saifur Rahman. Through your exemplary dedication to work and technical knowledge, you have always been a source of inspiration. Thank you, Dr. Rahman, for your advice, guidance and support.

I would like to express my special thanks to Dr. Manisa Pipattanasomporn for her precious comments on my work, her motivation and support throughout my stay at ARI.

I would also like to thank Dr. Joseph Wang for his time and effort.

Finally, I would like to acknowledge and thank my husband, my parents, in-laws and sisters for their prayers and provision throughout my life.

Table of Contents

List of Figures

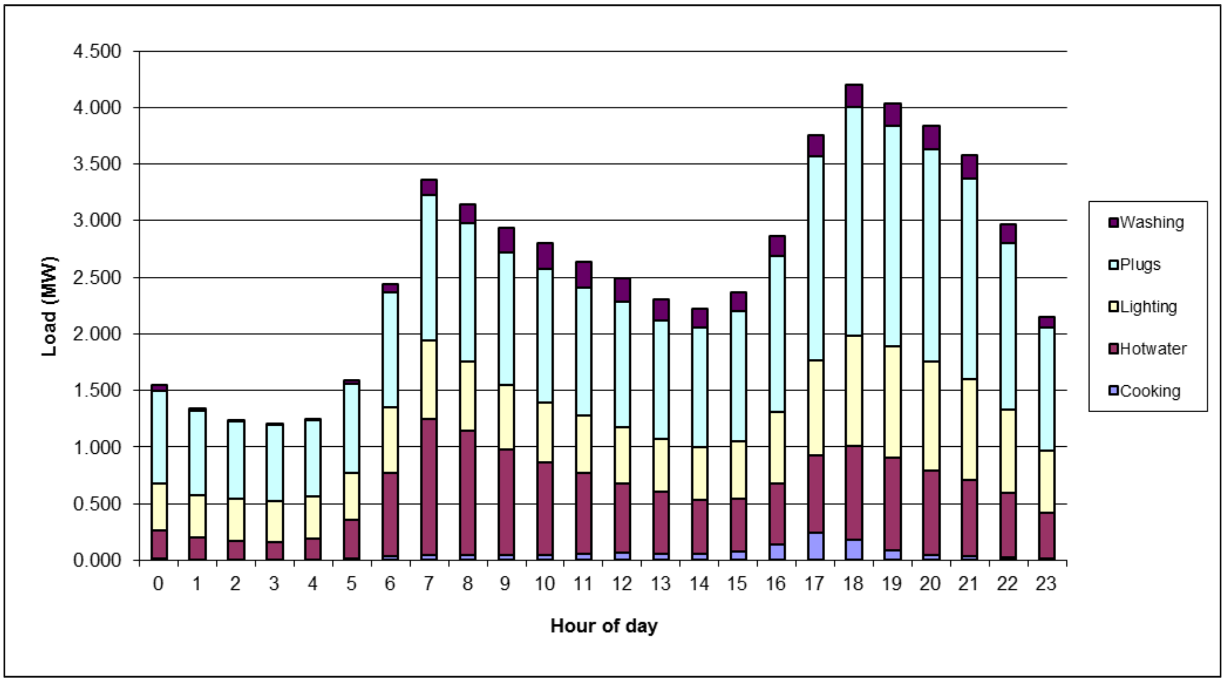
List of Tables

Chapter 1

Introduction

1.1 Background & Problem Statement

Residential Electric water heating is considered the second most energy-intensive activity which accounts for approximately 15% of a home's energy consumption, after HVAC [1]. This fraction could be as high as 30% for residents in winter dominated parts of the world [2]. Figure 1.1 shows an actual 24-hour load profile in kW (top) of a residential distribution circuit located in Los Angeles, CA composed of 500 single family homes and 20 multifamily homes, obtained from GridLAB-D [3]. The hot water load as a percentage of the total system load as shown in Figure 1.1 (bottom) varies between 15% during off-peak hours to 35% during system peak hours. The data represents a typical weekday in winter. The climatic conditions are referred from the TMY (Typical Meteorological Year) data of NREL (National Renewable Energy Laboratory).



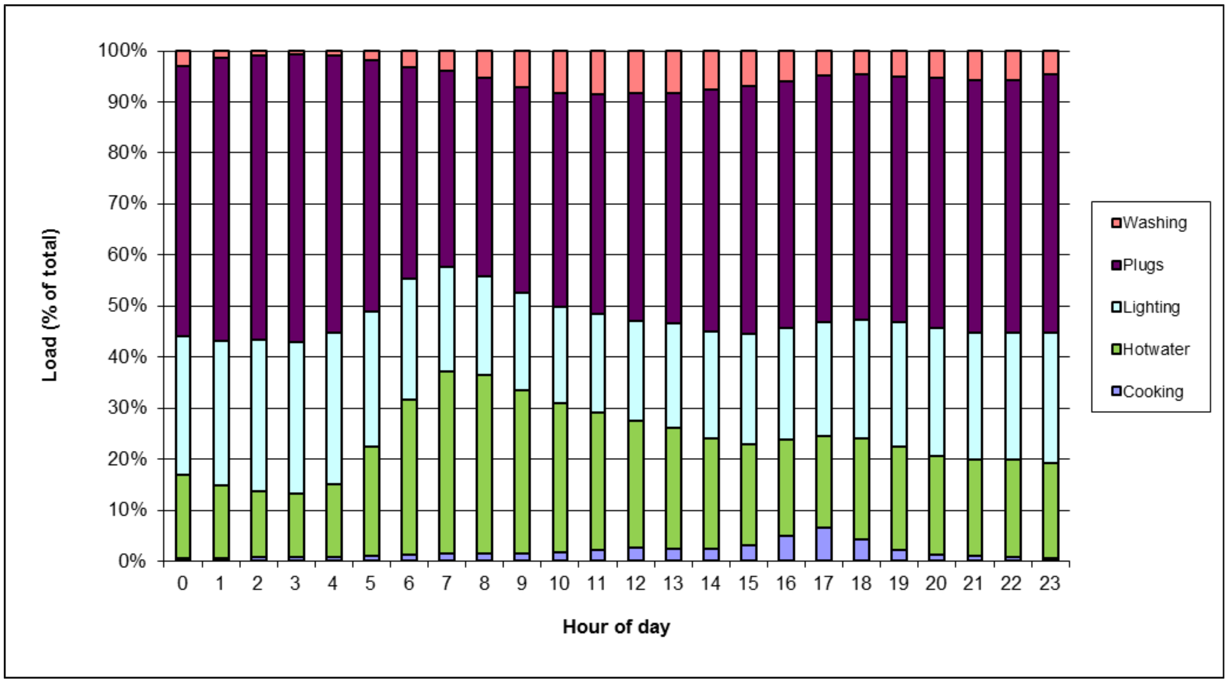


Figure 1.1 Composition of Energy consumption in a residential distribution circuit with 500 single family homes and 20 multifamily homes obtained through GridLAB-D (on top). Individual percentages of total power composition by each load type (bottom).

Since the daily hot water load in a typical residential circuit follows the overall load curve and water heaters have energy storage capabilities, water heating is one of the ideal candidates considered for load factor improvement and peak load shaving.

Solar Thermal water heating systems which utilize solar energy to produce hot water can be easily retrofitted into existing electric/gas water heating systems. Solar domestic hot water systems have been widely adopted since they use solar radiation which is free of cost, despite the changes that need to be incorporated to existing systems – such as installation of solar collectors, preheat tanks, internal or external heat exchangers, and circulation control and piping systems [4, 5]. According to [6, 7], the number of solar water heater installations in the United States has crossed 1.5 million as of 2010 in the residential and business sectors and more than 94% of customers are happy with this good investment, which lasts for a lifetime of 20 years and thereby avoiding more than 50 tons of CO_2 and greenhouse gas emissions.

A solar hot water system consists of a solar collector, storage tank for the potable hot water, heat transfer medium – liquid (water or glycol-water solution) or air, heat exchanger, circulation system and piping. Currently, solar collectors come in the form of flat plate collectors, integral collector-storage systems and evacuated glass tube collectors. Based on whether the collector tubes carry potable water or water-alcohol solution, the solar hot water systems can be classified as open loop and closed loop systems respectively. In an open loop system, potable water circulates in the collector to serve as the heat transfer medium, whereas in a closed loop system, an antifreeze solution of glycol and water flows through the collector tubes. Also, based on circulation of collector fluid, the systems are classified into active and passive types. In an active system, a pump forces the fluid in the collector, whereas in a passive system, the liquid raises in the collector by natural convection, e.g., thermo syphon systems.

Simulation programs such as TRNSYS, RETScreen, Energy Gauge USA and PREVIS have been developed in the past to design and analyze the thermal performance of domestic as well as large-scale solar water heaters. Short-term as well as long-term thermal performances of solar water heaters along with the auxiliary power consumption (in case of electric back up) can be determined with the help of these programs. A tool which helps with the analysis of solar thermal water heater impacts on the distribution level water heating load profile with realistic hot water draw events is still a necessity for utilities or ISOs.

1.2 Objectives

The goal of this thesis is to analyze the impact of solar thermal water heaters on electric water heating energy consumption in the residential distribution feeder level. To achieve this objective, the following tasks are performed:

1) Simulation models that represent an electric water heater and a solar thermal water heater with flat plate and evacuated glass tube collectors are developed in MATLAB.
2) Electric water heater model is validated with simulation outputs from GridLAB-D and the solar thermal water heaters with the flat plate and evacuated glass tube collectors are validated with simulation outputs from TRNSYS.
3) The developed water heater models are used to compare the electric energy savings potential of solar water heaters compared to electric water for a single home and for a residential distribution circuit that comprises of 100 homes. The aggregation of the water

heater loads is performed by randomly distributing the parameters such as the storage tank volume, collector area, hot water draw events, electric element power ratings, etc.,

For a single water heater, the following analyses are performed:

1) The energy savings potential of a solar thermal water heater powered by auxiliary electric element compared to an all-electric water heater is presented for the four different seasons (Winter, Spring, Summer and Fall) as prevailing in the United States.
2) The effect of outlet temperature set point on the electric energy consumption is studied on the three configurations of the water heaters mentioned above.
3) The effect of the number of glass panes on the auxiliary power consumption of solar thermal water heaters with flat plate collectors is also analyzed.

For a residential distribution feeder with 100 water heaters,

1) The energy savings potential of solar thermal water heaters powered by auxiliary electric elements compared to all-electric water heaters is presented for the four different seasons.
2) The peak demand reduction achieved by using solar thermal water heaters powered by auxiliary electric elements compared to all-electric water heaters is presented for the four different seasons.

Chapter 2

Literature Review

2.1 Previous Work

Solar thermal water heaters have been manufactured and used domestically since the 60’s of the 19th century. Initially, the flat plate collectors with thermo syphon storage tanks placed on top of the collector were the typically used solar hot water systems. Auxiliary heat was supplied with immersion electric heaters during periods of low insolation. Continuous research in the past has led the way to the advent of forced circulation systems with anti-freeze systems and in-tank auxiliary heaters. Initially, though the motivation for use of solar thermal water heaters was in the benefit of reduction in electric/auxiliary energy usage with free solar energy, in the recent past, the environmental benefits such as reduction in COX, NOX, SOX emissions are also playing an important inspiring role.

Several researchers have modeled and investigated the thermal performance of thermo syphon flat plate collectors based on heat balance equations to find the storage tank temperature. Duffie & Beckman [8] present the details of the solar radiation model and flat plate collectors which has been used in the model presented for this thesis. The Authors in [9] and [10] present the thermal and electrical performances of thermo syphon flat plate collectors modeled in MATLAB and validated with installations in China and Iran respectively. Authors in [11] and [12] provide the modeling and results of a thermo syphon solar hot water system with practical hot water draw off events built in TRNSYS.

B.S. Swanson and J.H. Fletcher [13] investigate the effects of solar thermal water heaters (includes the integral collector storage and active drain-back open loop systems) on peak demand. This report presents the details of the studies on household water usage and solar thermal performance. Though the results suggest that the system is able to reduce the power consumption during peak hours, details on thermal (as in TRNSYS) and electrical (reduction of electrical energy consumption) performance are missing here.

Kalogirou et al [14] present a simple validation method for a thermosyphon solar water heating system built in TRNSYS with actual weather and tank temperature data for an installation in Cyprus. Here, the tank temperature (collector fluid is outlet to the storage tank) has been used as a parameter for validation. The model built for this thesis is validated against TRNSYS model, using the collector fluid temperature at outlet and solar gain as parameters.

More work has been performed beyond modeling for thermal and electrical performances of solar thermal water heaters such as optimization of the system parameters for increasing the efficiency of heat collection and transfer. Jinling Cao, Zunfeng Yang [15] present an estimation approach to measure the solar heat gain based on its proportional relationship with the water heating rate. The results and measurement data show that the solar heat gain for solar water heater systems decays with increasing water temperature at tank outlet and hence can be used to decide on the minimal water temperature at outlet for intelligent solar water heater control. This thesis also verifies this fact with simulations of the model with different temperature set points.

D. Salcines, C. Estébanez and V. Herrero [16] present the results of modeling and dynamic simulation of a solar domestic hot water system in Spain for a family of four. The mathematical model validated against an installation has been used to show that the solar heat gain is higher with larger tank volumes.

Also, integration of newer computation techniques to improve calculation and data processing times has been of interest in the recent times. For example, [17] and [18] present the formula and results to use ANN (Artificial Neural Networks) to determine the efficiency of flat plate solar collectors. The results prove the advantages of using ANN such as speed and simplicity of calculations. Also, [19] uses fuzzy logic to prove the prediction accuracy and simplicity for the thermo syphon type of solar water heaters.

For the purpose of reducing energy consumption further with solar thermal water heaters, [20] presents a method to calculate the outlet temperature of the storage tank in a solar domestic hot water system with a flat plate collector driven by a PV (Photo voltaic) pump. Efficiency equations of a flat plate collector are used to compute the temperature for a low flow (smaller hot water draw) system in this study.

In [21] the authors have studied the effect of outlet temperature on the annual efficiency and solar fraction of a thermo syphon solar system with an in-tank auxiliary electric element, built with the TRNSYS program. Ayompe et al [22] present the results of a validated TRNSYS model for forced circulation solar hot water system using flat plate collector as well as heat pipe evacuated tube collectors. Authors in [23] show the results of the flat plate collector model with glass tube. Authors in [24] and [25] show the simulation results for the thermal performance of an all glass evacuated tubes collector and prove that all glass evacuated tubes are more efficient compared to flat plate collectors. In [26], the authors compare the energy savings in boiler and gas water heating system after installation of a solar hot water system is compared with that before the installation. Simulation results show the annual savings in energy though details of hot water draw events and daily or hourly energy reductions are missing in this study.

2.2 Knowledge Gaps

It is learnt from previous work that a solar thermal water heater model needs to be developed which reflects realistic hot water draw profiles. A comparison of daily energy consumption profiles of electric and solar auxiliary electric water heaters helps to understand the impact of solar thermal water heaters on electrical demand reduction as well as electric energy savings. Also, aggregation of solar thermal water heaters in a residential distribution setting will provide an insight into the reduction in peak demand and energy consumption by introducing solar thermal water heaters at various penetration levels. This thesis combines the knowledge from the literature cited in the last few pages to fix the missing parts as mentioned in this section.

2.3 Contributions

In this thesis, the impact of solar thermal water heaters on the residential electrical distribution load is studied. For this purpose, MATLAB is used to develop simulation models of an electric water heater and a solar thermal water heater with two configurations for heat collection – flat plate collector and all-glass evacuated tube collector. The energy savings in a residential distribution feeder is studied by aggregating the electric and solar water heaters by randomizing the hot water draw events, tank and collector parameters. From the simulation results, it is observed that solar thermal water heaters with flat plate collectors save around 40-60% electrical energy during winter and about 60-80% energy during summer, while those with glass tube collectors saves an additional 10-15% electrical energy. This additional savings results from the fact that the glass tube collector can absorb reflected radiation as well as direct and diffuse radiation for a wider range of incidence angles compared to the flat plate collector. Simulations can be performed for different geographic locations with the developed model. In this thesis, two extremely different climate zones in the Unites states namely Madison, WI and Tampa, FL are selected to show the effect of weather conditions on energy savings and peak demand reduction.

Chapter 3

Electric Water Heater

3.1 Overview

Electric water heaters contain two heating elements immersed in a water tank which is usually sized between 20 and 80 gallons for residential hot water usage. The elements along with their thermostats are placed one set at the top, near three fourths the height of the tank and other set near the bottom of the tank as seen in Figure 3.1. The lower element works most of the time to heat the tank water, while the upper element turns on only when the water layer near the upper thermostat is chill enough. Though the two elements are controlled by independent thermostats, only one element can be turned on at a time, since if both are on, the circuit breakers would blow up due to overcurrent [30]. This type of design allows for faster heating of the volume of water above the top element which is smaller compared to the tank volume, as soon as hot water is drawn.

Generally, a residential electric water heater with a tank for hot water storage is set to heat water at the outlet to a setting point of value T_{set}, with a T_{delta} dead band [31, 32]. As soon as hot water is drawn, an equal amount of cold water replenishes the tank at the same flow rate. When the mixed water temperature at the outlet drops below the lower bound, i.e. $T_{tank} < T_{set}-T_{delta}$, the heating elements are turned on to work at rated power till the outlet hot water temperature attains the set point value, i.e. $T_{set}+T_{delta}$. Water heaters with storage tanks are not free of the standby loss, unlike the tank less water heaters. The heating elements are turned off unless the outlet temperature is not within the range of the dead band, i.e. $T_{set}-T_{delta} <= T_{tank} <= T_{set}+T_{delta}$.

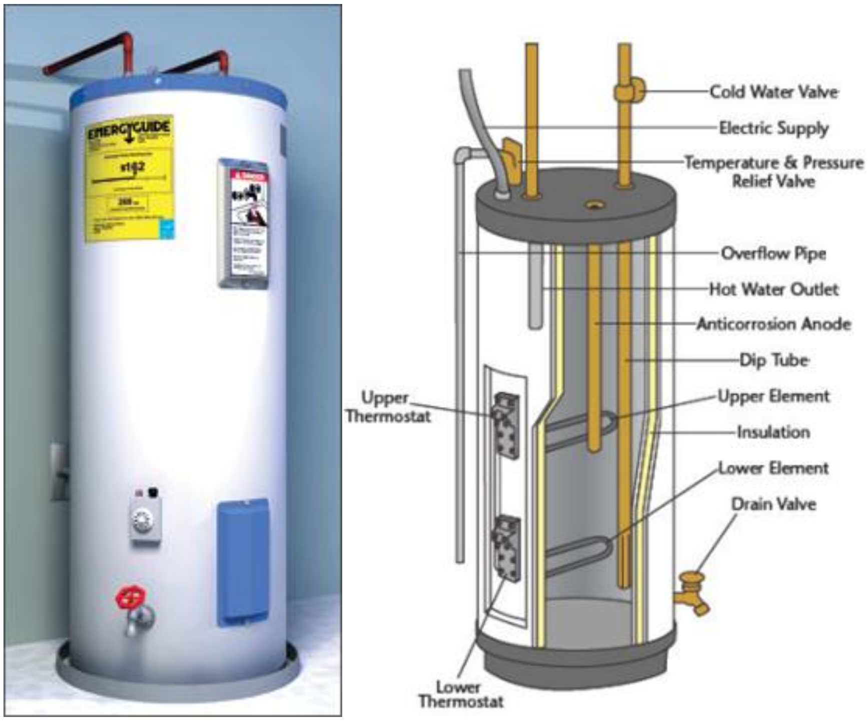


Figure 3.1 Picture of a commercially available residential Electric water heater (Left), Electric water heater parts – labeled (Right). (Courtesy: NREL, EERE)

This chapter presents the mathematical model of the electric water heater developed in MATLAB. Section 3.2 presents the information flow through the model followed by the assumptions made for the MATLAB model of the electric water heater, the thermal stratification of the storage tank, calculations for the mains water supply temperature, the tank outlet temperature and energy consumption are presented followed by a description of the hot water draw events and results and output validation against GridLAB-D.

3.2 Information Flow through the Electric Water Heater Model

Figure 3.2 shows the schematic of the information flow through the developed MATLAB model of the electric water heater. The inputs to the model are the storage tank parameters - volume, power rating of electric element, R-value of insulation jacket and hot water draw events from IEA SHC (International Energy Agency – Solar Heating and Cooling program) task 26. The hot water draw rates are distributed in one minute intervals. The output from the model is the electric energy consumption profiles of the electric water heater. For a single electric water heater model, the tank temperature profile is also presented in the results.

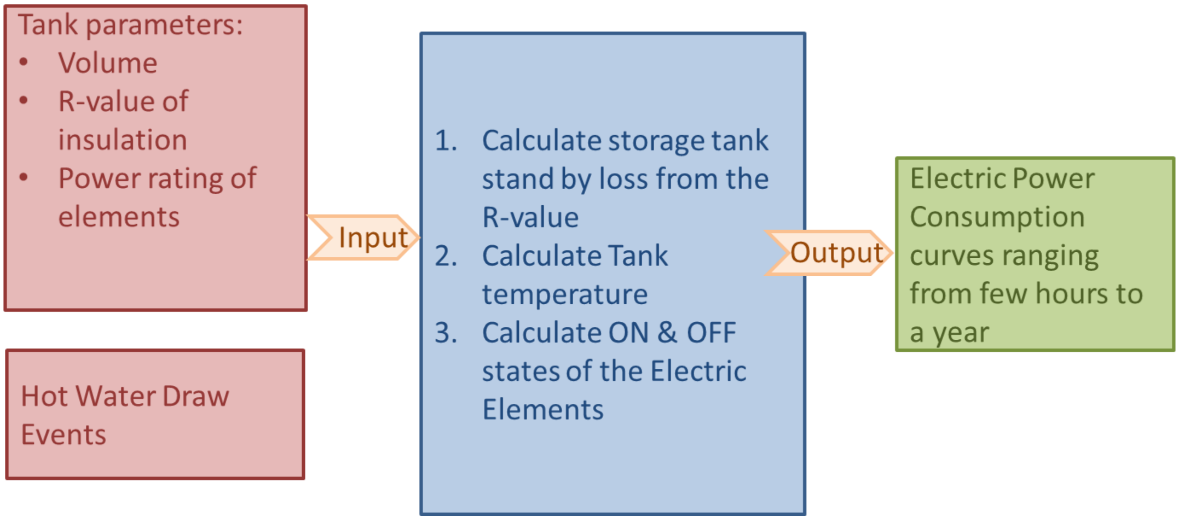


Figure 3.2 Flow of information through the MATLAB electric water heater model

3.3 Assumptions

Following are the assumptions taken into account while developing the electric water heater model in MATLAB:

- There are two electric elements of equal power rating in the hot water tank.
- The tank is thermally stratified based on the displacement mixing model into seven zones. The top element heats the top two layers and the bottom element heats the next three layers in the bottom while the bottom most two layers contain cold water which is not completely mixed with the top hot layers. The thermal stratification is further explained in Section 3.4.
- The outlet temperature of the tank is the hot water temperature before mixing takes place.

3.4 Thermal Stratification of the Hot Water Tank

This model uses the one-dimensional displacement mixing model for the temperature stratification of the hot water along the height of the tank [33, 34]. As shown in Figure 3.3, the cold water from inlet is uniformly distributed among the bottom layers and this cold volume pushes the top layers above whenever there is a hot water draw event. There are ‘m’ bottom layers which contain cold water that is not completely mixed with the top hot water layers. The energy balance applied to the layers of the tank yields the following temperature equations:

For $i<=m$,

$$T(i, n)= \{V(i)*T(i, n-1) + (\Delta V/m)* T_{mains} +(i-1)* (\Delta V/m)* T(i-1, n-1)\}/\{ V(i)+ (\Delta V/m)*i\}$$

For $i>m$,

$$T(i, n)= \{(V(i)- \Delta V)* T(i, n-1)+ (T(i-1, n-1)* \Delta V)\}/ V(i)$$

Where,

$T(0, 0)$: T_{mains} – Inlet water temperature (deg. C)
$T(i, n)$: temperature of layer ‘i’ at time ‘n’ (deg. C)
i : current layer whose temperature is computed
ΔV : volume of cold water flowing in which is equal to the hot water used at time ‘n’ (liters)
$V(i)$: volume of layer ‘i’ (liters)
T_{mains} : temperature of supply inlet water (deg. C)
m : number of bottom cold layers
n : number of stratified layers in the tank

Also, this model assumes that the specific heat and density of the hot water inside the tank are constant.

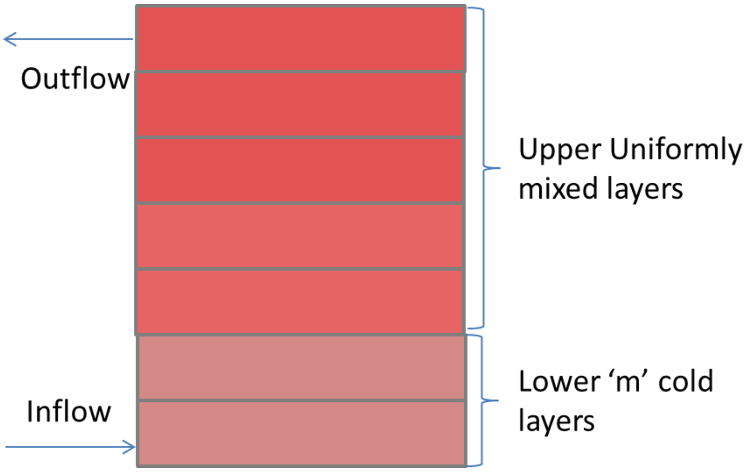


Figure 3.3 Thermal Stratification of the hot water tank

3.5 Inlet Temperature & Ambient Temperature

The inlet cold water temperature is usually the same as the soil temperature since the pipes are buried underground. Assuming the tanks are placed inside the house, the ambient temperature is assumed to be the AC set point. In previous work on electric water heater, inlet temperature is assumed to be constant [4, 5]. The developed MATLAB model uses the mains supply temperature calculation as used by Building America Program [35].

$$T_{mains} = (T_{amb,avg} + T_{offset}) + ratio * (\Delta T_{amb,max} / 2) * \sin(0.986 * (day\# - 15 - T_{lag}) - 90),$$

Where,

T_{mains} : Mains (supply) temperature to domestic hot water tank (°F)

$T_{amb,avg}$: Annual average ambient air temperature (°F)

$\Delta T_{amb,max}$: Maximum difference between monthly average ambient temperatures (°F)

day# : Julian day of the year (1 to 365)

T_{lag} : $35 - 1.0\ (T_{amb,avg} - 44)$

T_{offset} : 6 °F

ratio : $0.4 + 0.01\ (T_{amb,avg} - 44)$

3.6 Governing Equations

3.6.1 Energy Consumption

The input heat energy [36] in kWmin in each time duration ‘t’ is given by:

$E_{input}(t)=E_{WH}*Status(t)$, where

E_{WH} is the thermal energy that the heating coils can provide during the time duration (one minute) at rated power P_{WH}.

$E_{WH}=P_{WH}*\Delta t*\eta$;

Where,

P_{WH} : rated power of the water heater (kW)
E_{WH} : energy input to tank in one minute (kWmin)
η : efficiency factor
Δt : time interval (minutes)

Status(t) is the ON or OFF state of the water heater;

$$Status(t) = \begin{cases} 0 \; ; T_{tank}(t) >= T_{set} \\ Status(t-1); \; T_{set} - T_{delta} <= T_{tank}(t) <= T_{set}+T_{delta} \\ 1; \; T_{tank}(t) <= T_{set}-T_{delta} \end{cases}$$

0 corresponds to the OFF state and 1 corresponds to the ON state. Status(t-1) corresponds to the previous state where Status(t) is the current state.

3.6.2 Stand-by Heat Loss

The stand-by heat loss of the tank is given by:

$SL_{wh}(t) = A_{tank}* (T_{tank}(t) - T_{amb})/R_{tank}$

Where,

SL_{wh} : stand-by heat loss in each time duration ‘t’ (W)
A_{tank} : surface area of the tank (sq.m) , calculated as:

$$A_{tank} = 0.5*\pi* D_{tank}^2 + \left((4* V_{tank}* .001)/D_{tank}\right)$$

V_{tank} : volume of the tank (liters)

D_{tank} : diameter of the tank on the bottom (meters)

$T_{tank}(t)$: tank temperature in time duration ‘t’ (℃)

T_{amb} : room temperature, assumed to be equal to the AC setting point for the house T_{setAC} (℃)

R_{tank} : heat resistance of the tank (m².°C/W)

3.6.3 Tank temperature

The water temperature in the tank is:

$$T_{tank}(t+1) = \left((T_{tank}(t)*(V_{tank}-V_{hot}(t)*\Delta t))+(T_{mains}*V_{hot}(t)*\Delta t)+(E_{input}(t)*1000- SL_{wh}(t)*\Delta t\right)/V_{tank}$$

Where,

T_{mains} : temperature of inlet water into the water heater (℃), equal to the soil temperature

$V_{hot}(t)$: hot water flow rate in time slot ‘t’ (liters per minute)

3.7 Hot Water Usage

The status of the water heater’s elements is mainly driven by the hot water draw events. The more the hot water is drawn, the more the electric energy consumption. The hot water flow rate for domestic purposes in this model is obtained from the IEA’s (International Energy Administration) Solar Heating and Cooling Program - Task 26 [37] which provides realistic hot water draw profiles for US, Canada and a few European countries. From the profiles available in 1 hour, 15 minutes, 5 minutes and 1 minute intervals, the 1 minute interval profile has been chosen. This is to account for the real time events like hand washing in a sink which last only for a minute or less [38]. The profile for a 200liters/day hot water usage for a family of four in the Unites States has been chosen for developing the single water heater model. For aggregation purposes when considering a residential distribution load, the profiles for 100liters/day, 200liters/day and 300liters/day have been used to diversify the population’s hot water usage. Figure 3.2 shows the annual average weekday and weekend hot water consumption profiles as published by the IEA- task26.

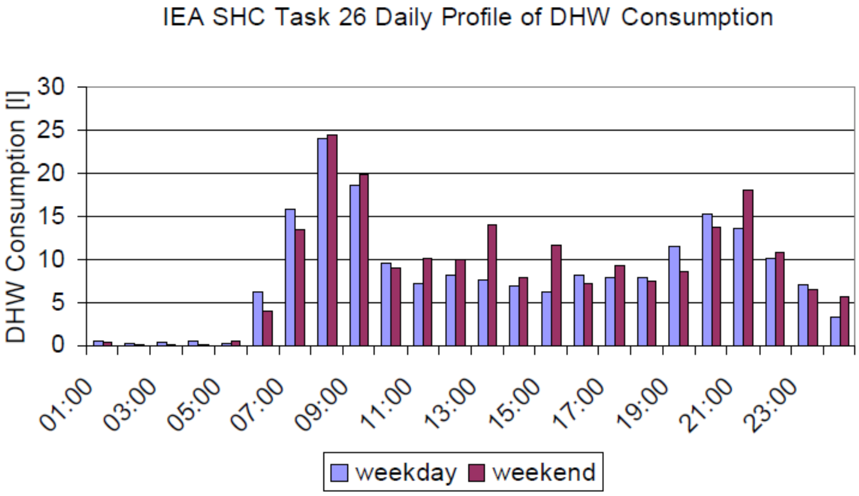


Figure 3.4 IEA Daily Hot water profile (Courtesy: IEA SHC Task 26)

3.8 Hot Water Usage in a Single home

Figure 3.5 shows the details of the hot water draw events obtained from IEA task 26, in a family of four in the United States, used for the individual water heater model used for this thesis. The snapshot of the hot water draw for a single home shows the durations for some of the events: first event in the morning (a brushing event) – for a duration of 2 minutes. The heavy draw events in the later hours span a duration of 4 minutes and 6 minutes as shown on the right hand side of Figure 3.5.

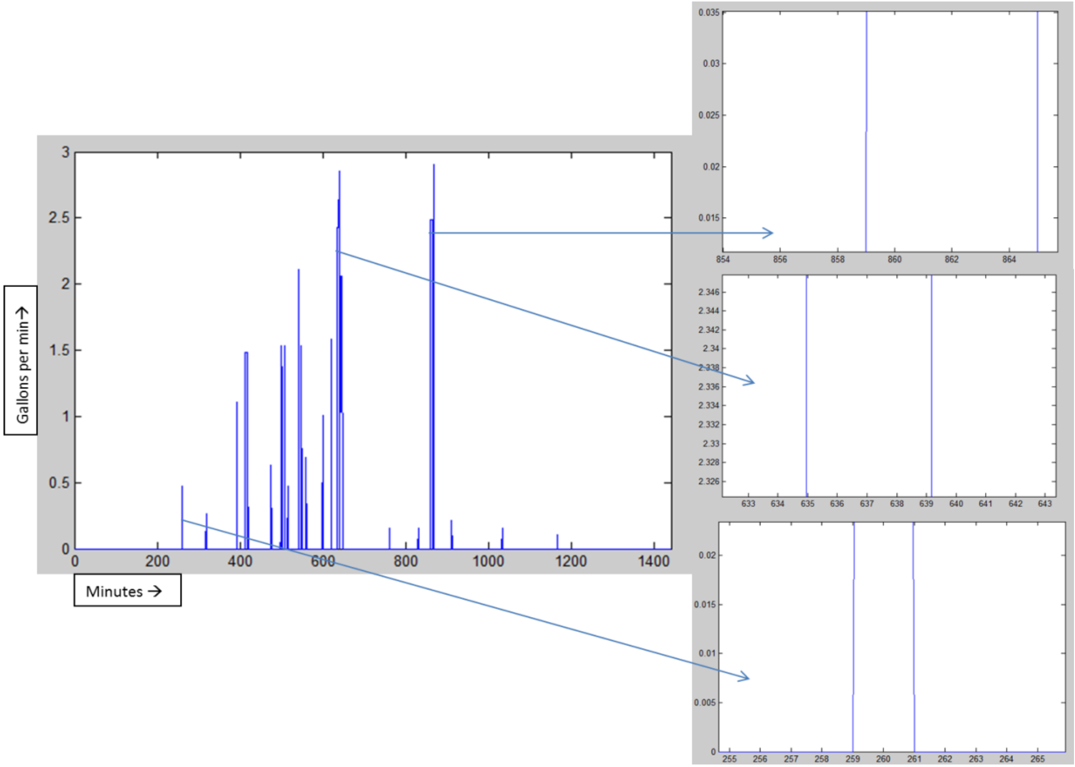


Figure 3.5 Details of Hot Water Draw in a four person family - data obtained from IEA Hot Water Draw Profiles

3.9 Model Outputs and Validation

The electric water heater model developed in MATLAB is validated against the electric water heater model in GridLAB-D. GridLAB-D is a new power distribution system simulation tool, developed by the US DOE at the Pacific Northwest National Laboratory (PNNL). The existing release files can be found here: http://www.gridlabd.org/. The tool is now free for download as open source software which allows interested developers to add new modules to the existing models. Both of these water heater models are provided with the same hot water draw event schedules and the energy consumption is recorded. Two types of days are chosen for validation: a winter weekday and a summer weekend.

The parameters used to validate the results are:

- Hot water draw event schedules for typical winter weekday and summer weekend obtained from IEA task 26.

- Power rating of water heater coil - 4.75 KW
- Storage tank size of 200 liters
- R-Value of 2.5 m²°C/W.
- T_{mains} – 15°C
- $T_{AMB} = T_{setAC}$ - 24°C
- Diameter of tank - 0.45 meters

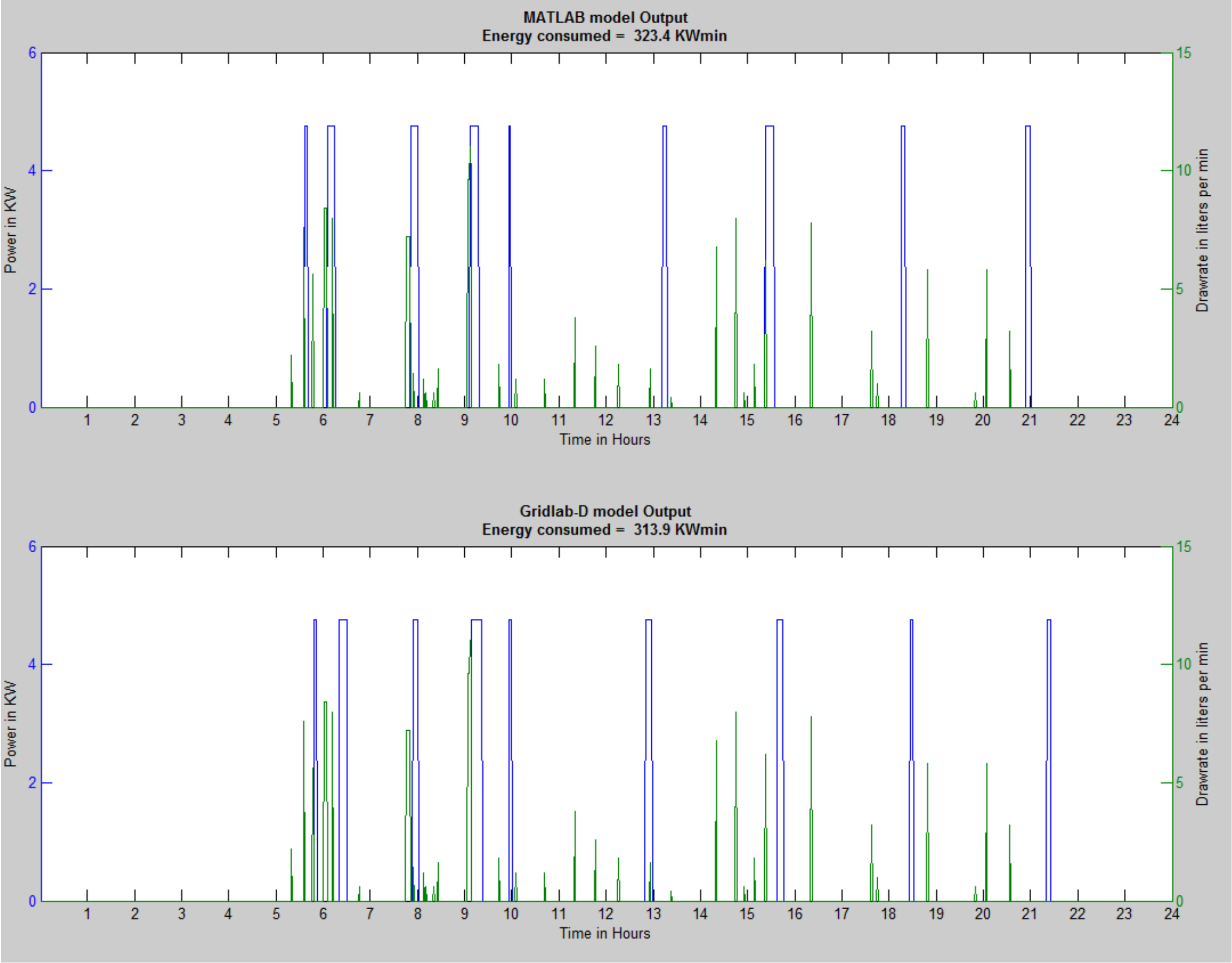


Figure 3.6 Comparison of MATLAB and GridLAB-D model outputs for electric energy consumption using a winter weekday hot water draw profile

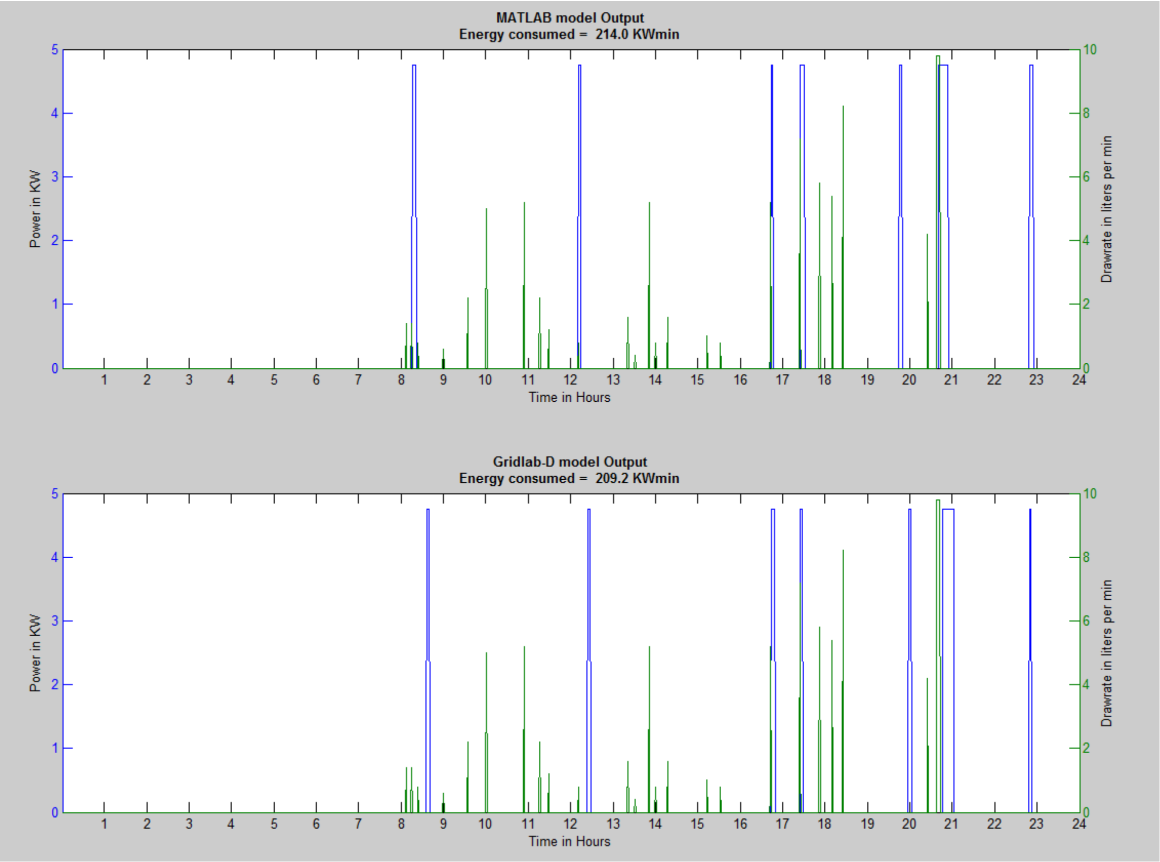


Figure 3.7 Comparison of MATLAB and GridLAB-D model outputs for electric energy consumption using a summer weekend hot water draw profile

The hot water draws and power consumption for a winter weekday and summer weekend are presented in Figures 3.6 and 3.7. The blue lines represent water heater ‘ON’ status and green lines represent the hot water draw events.

As can be seen from Figures 3.6 and 3.7, both of the electric water heaters are turned on almost at the same time with small deviations in the timing. The mean difference in energy consumption is within 3%. The small variation in the energy consumption of the GridLAB-D and MATLAB electric water heater models is accounted for in the difference in assumptions in both of these models. The models follow each other closely and hence the MATLAB model of the electric water heater is considered valid and is being used for further analysis.

Chapter 4

Solar Thermal Water Heater

4.1 Introduction

4.1.1 Overview of Flat Plate Collector

Flat plate collectors consist of a dark painted-metal absorber plate which absorbs the incident beam and diffuse radiation and heats the liquid in the metal tubes which are attached/embedded to the absorber plate as shown in Figure 4.2. The plate and the tubes are encased in an insulated box covered on top by a glass pane. The protective glass panes are usually coated with low iron glass which promotes light and heat absorption while avoiding reflection.

Flat plate collectors absorb the direct beam and diffuse solar radiation and are suitable for applications requiring moderate temperatures in the range of 50-100 °C above ambient temperature. They are fixed usually at an angle equal to the latitude of the location and the mechanical structures are simple since tracking is not required which again translates to little or no maintenance [8]. This thesis uses the governing equations for the flat plate collector model from Duffie & Beckman's Solar Engineering of Thermal Processes [8].

Figure 4.1 Top Frontal view of a commercially available flat plate collector (Courtesy: US DoE EERE)

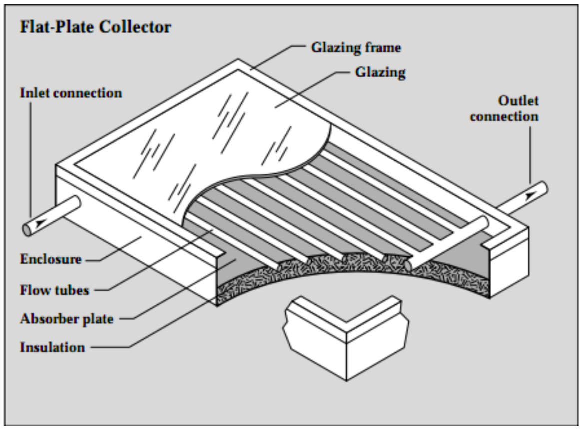


Figure 4.2 Cross sectional view of a flat plate collector (Courtesy: NREL)

4.1.2 Overview of Evacuated Glass Tubular Collector

Evacuated glass tube collectors consist of rows of concentric glass tubes separated by vacuum, where the inner glass tube is coated with absorber material or encloses a copper heat pipe, and carries the heat transfer medium, as shown in Figure 4.3. The vacuum between the glass tubes helps reduce losses due to convection and radiation [39]. Evacuated glass tube collectors can absorb solar radiation for a longer duration as compared to flat plate collectors. The glass tubes absorb solar radiation from all possible directions in form of direct beam, diffused and reflected radiation and even for lower solar angles in the early morning and late afternoon hours [40]. Evacuated tube solar collectors can maintain fluid temperatures in the range 75-175°C.

Figure 4.3 Top frontal view of a commercially available evacuated glass tube collector

This chapter presents the mathematical models of the flat plate and evacuated glass tube collector models for the solar thermal water heater developed in MATLAB. Section 4.2 presents the information flow in the model followed by the assumptions for the developed models, governing equations and results.

4.2 Information Flow through the Solar Thermal Water Heater Models

Figure 4.4 shows the schematic of the information flow through the solar thermal water heater models developed in MATLAB. The flat plate and the evacuated glass tube collectors share the same information flow. The inputs to the model are the climate data from NREL in the TMY3[29] (Typical Meteorological Year) format, hot water draw events from IEA SHC (International Energy Agency – Solar Heating and Cooling Program) task 26 and the solar collector, heat exchanger and tank parameters. These inputs along with the initial guesses for the solar collector performance parameters like the heat removal factor, heat loss coefficient and collector efficiency factor are used to obtain the collector surface mean temperature as well as the useful collector energy output. These values are then used to output the electric energy consumption profiles of the different configurations of the solar thermal water heaters, here the flat plate and glass tube collectors.

For this model of the solar water heater, the hot water draw events and tank stratification are similar to those of the electric water heater discussed in Sections 3.4 and 3.7 respectively. The essential difference in the flat plate and glass tube collector models is the set of equations governing the models, discussed in Section 4.5. Both of these collector models use the same hot water draw, climate data and sky models, discussed in Sections 4.4, 4.6 and 4.7.

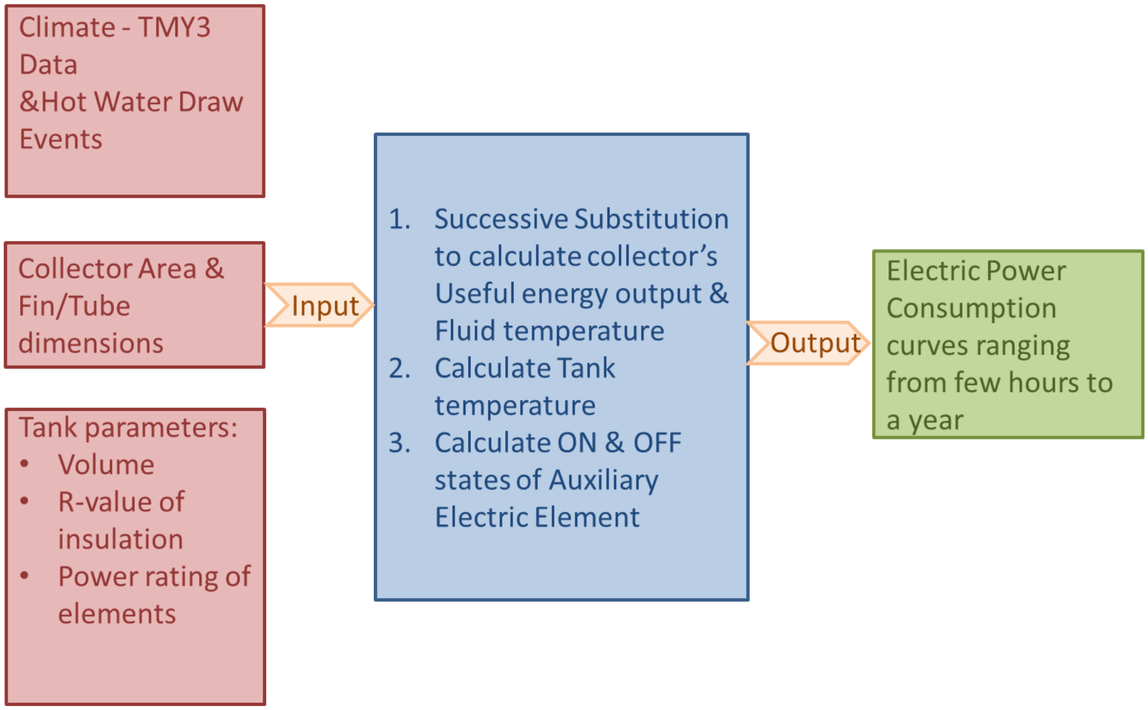


Figure 4.4 Flow of information through the MATLAB solar thermal water heater models

4.3 Assumptions for the Solar Water Heater models

The following are the assumptions made for the developed flat plate and evacuated glass tube collector models in MATLAB:

- The flat plate and glass tube collector and heat exchanger of the solar water heater operate in steady state and hence, the specific heat and density of the collector and tank fluids are constant
- The piping, collector plate and tubes, glass panes have a negligible temperature stratification or gradient across them [41]
- The flat plate collector may have no glass pane or one to two glass panes. This parameter is variable in this model (An Analysis in Section 5.5 follows further to show the difference in power consumption on varying the number of panes in flat plate collector – solar water heater with electric backup.)
- The collector is free of shadowing from trees or buildings. Hence the shadow factor is not analyzed here.

4.4 Climate Data

This model uses the TMY3 version of the weather data from NREL. TMY or Typical Meteorological Year is defined as a year which summarizes all the climatic information that is characteristic of a period as long as the mean life of the system. The TMY is considered as a representative year for the location. TMY3 data is available in hourly intervals. The following parameters from the TMY3 data set are used as weather input for this MATLAB model:

- Dry bulb temperature – for ambient temperature
- Beam and diffuse solar radiation (from which radiation for any slope and orientation of surface can be calculated)
- Wind speed
- Latitude of the Location

4.5 Governing Equations

4.5.1 Flat Plate Collector

Under steady state as assumed, the useful energy output from the collector is,

$Q_{useful} = [A_{coll} * \{Q_{solar} - U_L*(T_{pm}-T_{ambient})\}]^+$

Where,

A_{coll} : Area of Collector (sq. m)

Q_{solar} : Solar radiation absorbed by the collector per unit area (W/m^2)

$= Q_{direct} + Q_{diffuse}$

$Q_{direct} = I_{beam}R_b$, where $R_b = \cos\theta/\cos\theta_z$

Here, θ is the incidence angle and θ_z is the zenith angle mentioned in Section 4.6.

$Q_{diffuse} = I_{diffuse}(1+\cos\beta)/2$

For flat plate collector model in MATLAB, the reflected radiation is negligible.

U_L : Heat loss coefficient due to convection, conduction and radiation (W/m^2 deg. C)

T_{pm} : Absorber plate mean temperature (deg. C)

$T_{ambient}$: Ambient temperature (deg. C)

The positive superscript for the right hand side of the above equation implies that only when the solar energy absorbed is greater than the heat losses due to radiation, conduction and convection, useful heat energy to provide hot water is produced.

This model uses the following equation of heat loss coefficient from Duffie & Beckman [7]:

$$
\begin{aligned}
U_L = &\left[\frac{N_g}{\left\{\left(\frac{C}{T_{pm}}\right)\left[\frac{T_{pm} - T_{ambient}}{N_g + f}\right]^{e}\right\}} + h_w^{-1}\right]^{-1} \\
&+ \Bigg[\sigma * \left(T_{pm} + T_{ambient}\right) \\
&* \frac{{T_{pm}}^{2} + {T_{ambient}}^{2}}{\left\{\left[\varepsilon_p + .00591 N_g h_w\right] - 1 + \frac{\left[2N_g + f - 1 + .133\,\varepsilon_p\right]}{\varepsilon_g} - N_g\right\}}\Bigg]
\end{aligned}
$$

Where,

N_g : Number of glass panes

f : $(1+.089h_w-.1166h_w\,\varepsilon_p)(1+.07866\,N_g)$

C : $520(1-.000051\beta^2)$, for $0° < \beta < 70°$. Using $\beta = 70°$, for $70° < \beta < 90°$

e : $.43[1-(100/T_{pm})]$

β : Collector tilt angle (degrees)

ε_p : absorber plate emissivity – a dimensionless number

ε_g : glass emissivity – a dimensionless number

h_w : Wind heat transfer coefficient ($W/m^2.°C$) = $2.8+3V_{wind}$

V_{wind} : wind speed (m/s)

T_{pm} : Absorber plate mean temperature (deg. K)

$T_{ambient}$: Ambient temperature (deg. K)

4.5.1.1 Collector Fluid & Absorber Plate Mean Temperature

In order to find the mean plate temperature of the absorber surface in the collector, the following factors are calculated.

The collector efficiency factor, $F' = \frac{\frac{1}{U_L}}{\left\{W\left[\left(U_L(D+(W-D)F)\right)+\frac{1}{C_b}+\frac{1}{\pi D_i h_{fi}}\right]\right\}}$

Here,

W : distance between the collector tubes (m)
D : tube outer diameter (m)
D_i : tube inner diameter (m)
C_b : bond conductance (W/m.°C)
h_{fi} : Heat transfer coefficient between tube surface and collector fluid (W/m^2 .°C)

F is called the fin efficiency factor given by $F = \frac{\tanh\left(\frac{m(W-D)}{2}\right)}{\left(\frac{m(W-D)}{2}\right)}$

Here, $m = \sqrt{\left(\frac{U_L}{k\delta}\right)}$

Where,

K : insulation conductivity (W/m. °C)
δ : plate thickness (m)

The collector heat removal factor, $F_R = \left(\frac{f_{coll}C_p}{A_{coll}U_L}\right)\left[1 - e^{\left(-\frac{A_{coll}U_L F'}{f_{coll}C_p}\right)}\right]$

Where,

f_{coll} : total collector flow rate (kg per hour)
A_{coll} : Area of Collector (sq. m)
C_p : Specific heat of collector fluid (Joule/kg.°C)

Assuming, the absorber plate is initially at the collector fluid temperature and attains higher temperatures by absorbing the solar radiation minus the optical and thermal losses, the mean collector fluid temperature is given by the following equation [8],

$$\mathrm{T_{fm}} = \mathrm{T_{ci}} + \left(\frac{\frac{\mathrm{Q_{useful}}}{\mathrm{A_{coll}}}}{\mathrm{F_R U_L}}\right)(1 - \mathrm{F''})$$

Where,

F” = F_R/F' – a dimensionless number

And the absorber plate mean temperature is given by

$$\mathrm{T_{pm}} = \mathrm{T_{ci}} + \left(\frac{\frac{\mathrm{Q_{useful}}}{\mathrm{A_{coll}}}}{\mathrm{F_R U_L}}\right)(1 - \mathrm{F_R})$$

Where,

T_{ci} : collector fluid inlet temperature in °C

4.5.1.2 Successive Substitution for calculation of plate temperature

Since, Q_{useful} is derived using plate mean temperature, the equation for plate mean temperature is solved by applying an initial guess and then iterating until a steady state value is obtained. This model uses the successive substitution method to calculate the value of T_{pm}. The initial guess is about T_{ci} + 10°C. With this guess, the values of U_L, F’, F_R, F’’ and hence T_{pm} is arrived at. This process is repeated until the difference between consecutive values of T_{pm} at an interval of one minute, is not higher than a tolerance value set to be say ε=0.1°C.

The flowchart in Figure 4.5 below shows the successive substitution method as applied to the absorber plate’s mean temperature calculations.

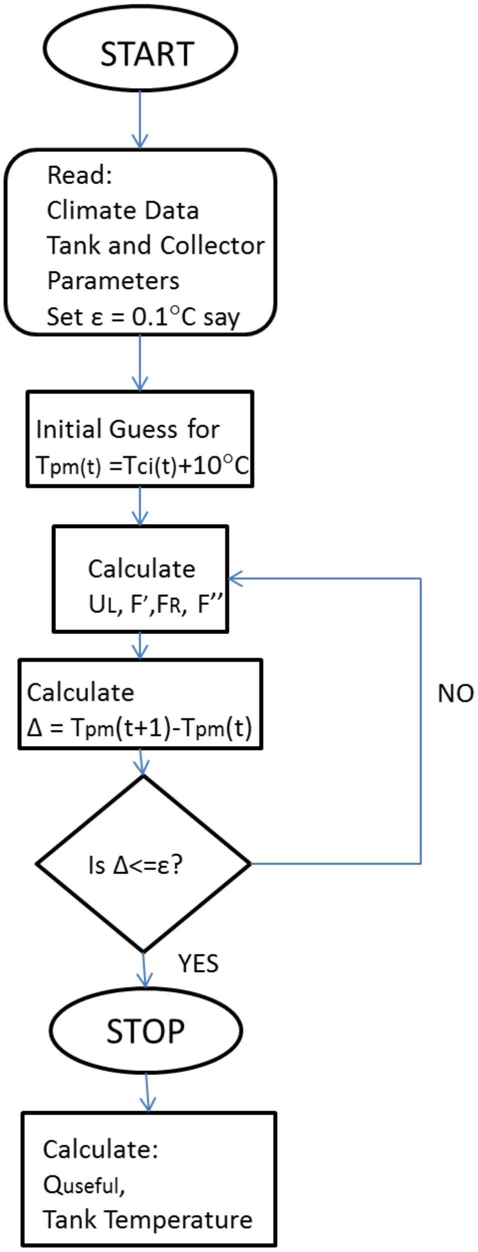


Figure 4.5 Flowchart of the successive substitution method for calculation of mean plate temperature

4.5.2 Glass Tube Collector

For the MATLAB model developed for this thesis, the glass tube collector's performance and useful output are obtained by integrating the flat plat collector's performance equations throughout the circumference of the tubes [46, 47] and effect of shading from other tubes during early morning and evening hours are neglected [48]. Figure 4.6 shows the cross sectional view of the individual glass tube comprising the evacuated glass tube collector.

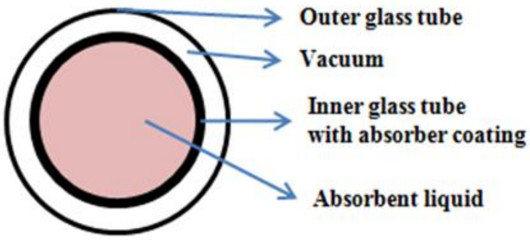


Figure 4.6 Cross sectional view of the glass tubes in the evacuated glass tube collector

The useful energy output from the collector tubes is given by the following heat balance equations [46, 47]:

$Q_{useful} = Q_{beam} + Q_{diffuse} + Q_{reflect} - Q_{loss}$

The tube absorber area as seen from the top is, $A_{abs} = L_{abs} * R_{abs}$ in sq. m

The thermal loss from the tubes if obtained by integrating the absorber area through the tube circumference,

$$Q_{loss} = \int_{-\pi}^{\pi} A_{abs} U_L (T_{fm} - T_{ambient}) d\emptyset$$

The energy absorbed from direct beam radiation is given as:

$$Q_{beam} = \int_{-\pi}^{\pi} A_{abs} (K_\theta F_R G_{beam} \alpha\tau) VF \, d\emptyset$$

Where,

VF : view factor of the absorber tubes from the sky
$VF = \int_{-\pi}^{\pi} (1 + \cos\omega)/2 \, d\omega$ = 0.5 (If shadowing is accounted for, this factor will still be reduced)

A_{abs} : Area of the absorber tube (sq. m)

G_{beam} : Direct beam solar radiation (Watt per sq. m)

K_θ : Incident angle modifier constant (a dimensionless number) for the beam direct radiation, ratio of radiation on tilted to horizontal surface same as R_b

F_R : heat removal factor from the absorber (a dimensionless number)

$\alpha\tau$: absorptance transmittance product for efficiency (a dimensionless number)

The energy absorbed from diffuse radiation is given as:

$$Q_{diffuse} = \int_{-\pi}^{\pi} A_{abs}\left(K_{\theta,d} F_R G_{diffuse} \alpha\tau\right) VF \, d\emptyset$$

Where,

$K_{\theta,d}$: incident angle modifier for the diffuse radiation (a dimensionless number) = $(1 + \cos \beta)/2$

$G_{diffuse}$: Diffuse solar radiation (Watt per sq. m)

The energy absorbed from reflected radiation is given as:

$$Q_{reflect} = \int_{-\pi}^{\pi} A_{abs}\left(K_{\theta,r} F_R G_{reflect} \alpha\tau\right) VF \, d\emptyset$$

Where,

$K_{\theta,r}$: incident angle modifier for the reflected radiation (a dimensionless number) = $(1 - \cos \beta)/2$

$G_{reflect}$: Reflected solar radiation (Watt per sq. m) = $\rho_{r*}(G_{diffuse} + G_{beam})$

ρ_r : reflectance of surface (a dimensionless number)

4.6 Sky model and Angles

The isotropic diffuse sky model for the solar radiation calculations are used in this MATLAB model. The incident angle relation with other angle such as latitude, collector slope, surface azimuth angle, hour angle is given below [8]:

$$\cos\theta = \sin\delta \sin\emptyset \cos\beta - \sin\delta \cos\emptyset \sin\beta \cos\gamma + \cos\delta \cos\emptyset \cos\beta \cos\omega$$
$$+ \cos\delta \sin\emptyset \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega$$

Where,

δ : Declination angle = 23.45 sin [360 (N + 284) / 365;
where N : Julian day

$\emptyset$: Latitude of location

β : Collector slope (degrees)

γ : Surface azimuth angle – varies between -180°(east of prime meridian) and +180°(west of prime meridian)

ω : Hour angle = 15° * (hour of the day - 12). Negative for AM hours and Positive for PM hours.

The zenith angle needed to account for the sloped collector surfaces as mentioned in Section 4.5.1 and 4.5.2 is given by,

$$\cos\theta_z = \cos\delta \cos\emptyset \cos\omega + \sin\emptyset \sin\delta$$

4.7 Heat Exchange & Fluid Circulation

Solar thermal water heater installations come with a solar control station, which comprises of the thermostat to sense the difference between collector fluid and heat exchanger fluid temperatures and control the pump which is usually about 100 W [42]. The circulation pump is turned on whenever the collector fluid temperature is at least 5°C above the cold fluid's temperature at the heat exchanger's outlet. The hot collector fluid which has absorbed the thermal energy from the solar radiation is pumped out to the heat exchanger which transfers the heat to the potable water in the storage tank. The heat exchanger can be internal or external to the tank. When it is internal, the solar heat exchanger can be directly used to heat the stored water or used to preheat the water before it reaches the actual storage tank equipped with electric heater elements. In all these cases, the storage tank is equipped with an auxiliary electric heater element which supplies for the deficit heat to match the outlet temperature during cloudy or colder days.

Figures 4.7 and 4.8 are the courtesy of www.renewedbytheson.com, which display the commercially available solar storage tank with external and internal heat exchangers respectively. The storage tank is fitted with the internal heat exchanger while the solar control station and expansion units are placed outside the tank.

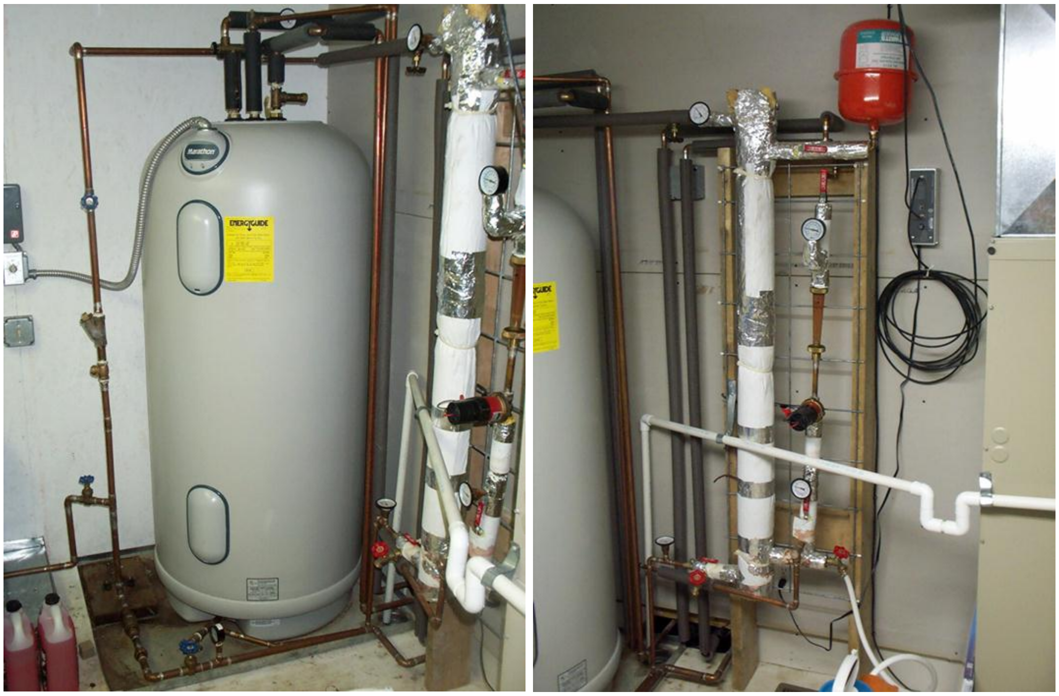


Figure 4.7 Photo of a solar water heater tank with external heat exchanger in white on the right side of the tank (Courtesy: www.renewedbytheson.com)

This MATLAB model has been developed with propylene glycol as the collector fluid for heat exchange. A mixture of 60% propylene glycol and 40% water does not freeze until temperatures below -50 °C, though propylene glycol in its purest form freezes at about -12°C [43]. This property allows for propylene glycol to be used for antifreeze circulation systems in automobiles and solar water heating systems in the coldest parts of the world where freezing ambient temperatures are very usual. Although ethylene glycol has very similar properties as propylene glycol, the latter has been proved to be non-toxic and can be used in potable hot water systems [44].

Figure 4.8 Photo of a solar water heater with internal heat exchanger and solar control station attached to the storage tank (Courtesy: www.renewedbytheson.com)

4.8 Storage Tank Temperature

In this model, the lower main element in the electric water heater tank is replaced with the solar heat exchanger. The upper electric element is still present to supply for temperature matching in case of solar energy deficit, which is called the auxiliary electric heater element. The useful solar energy gain in the collector (Q_{useful}) is calculated from the plate mean temperature in the case of flat plate collector and as in Section 4.5.2 for glass tube collector, from which the tank temperature is calculated as follows [8]:

$$T_{tank}(t+1) = T_{tank}(t) + \left(\frac{\Delta t}{V_{tank}C_{ptank}}\right)\left\{Q_{useful} - SL_{wh} - \varepsilon_{h}\left(V_{hot}(t)C_{pcoll}\right)\left(T_{tank}(t) - T_{mains}\right)\right\}$$

Where,

ε_h : heat exchanger effectiveness

C_{ptank} : Specific heat of tank fluid (water)

C_{pcoll} : Specific heat of collector fluid (glycol-water solution)

Δt : simulation interval

4.9 Auxiliary Power Consumption

The auxiliary electric element is turned on whenever the tank temperature is below the set point for the tank temperature. This set up is done to match for the outlet temperature in times of solar energy deficiency. The auxiliary element in this model is the upper electric element as in the electric water heater, which heats up the upper layers quickly in case of a faster hot water draw accompanied by temperature drop in the lower layers.

4.10 Model Outputs and Validation

4.10.1 Flat Plate Collector

This section presents the results from the MATLAB model of the flat plate collector which is validated with results from the flat plate collector model in TRNSYS. TRNSYS is a transient systems simulation program which can be used to model thermal and electrical energy systems in a modular fashion with detailed mathematical and behavioral analyses [45]. The solar hot water model built in TRNSYS has been widely accepted and hence is chosen as a benchmark to validate this MATLAB model.

Simulations are performed for two types of days: a summer day and a winter day for the location – Virginia Tech airport, VA with results shown in Figures 4.9 and 4.10 respectively.

Given below are the parameters used for the results of the MATLAB model:

Area Of Collector – 5 m^2

Storage tank volume – 300 liters

Location – Virginia Tech Airport, VA, USA – TMY3 code: 724113TY

Collector flow rate – 0.5 kg per hour

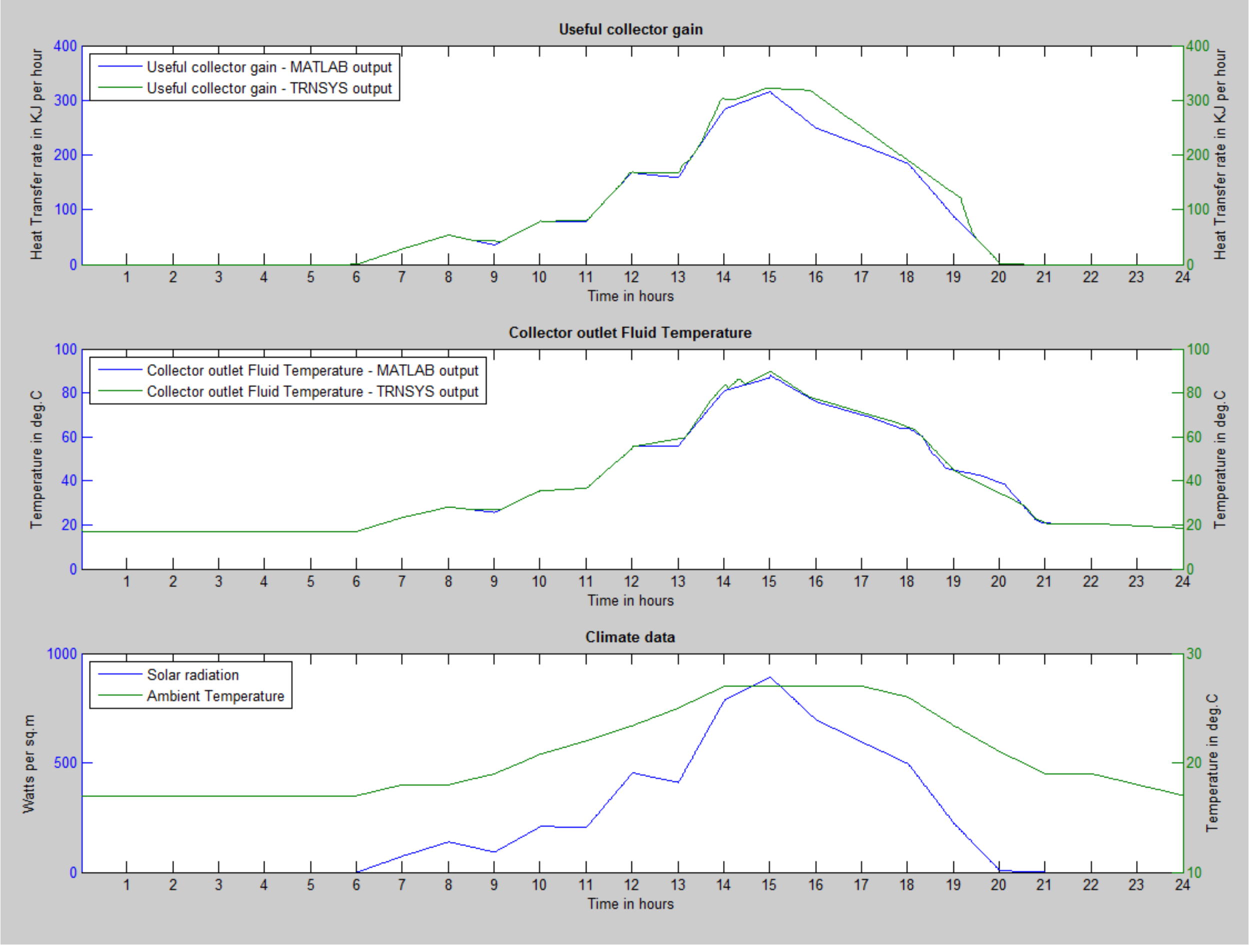


Figure 4.9 Comparison of Useful collector gain and collector fluid temperature from MATLAB and TRNSYS – flat plate collector model, Location used – Virginia Tech airport, VA on a summer day

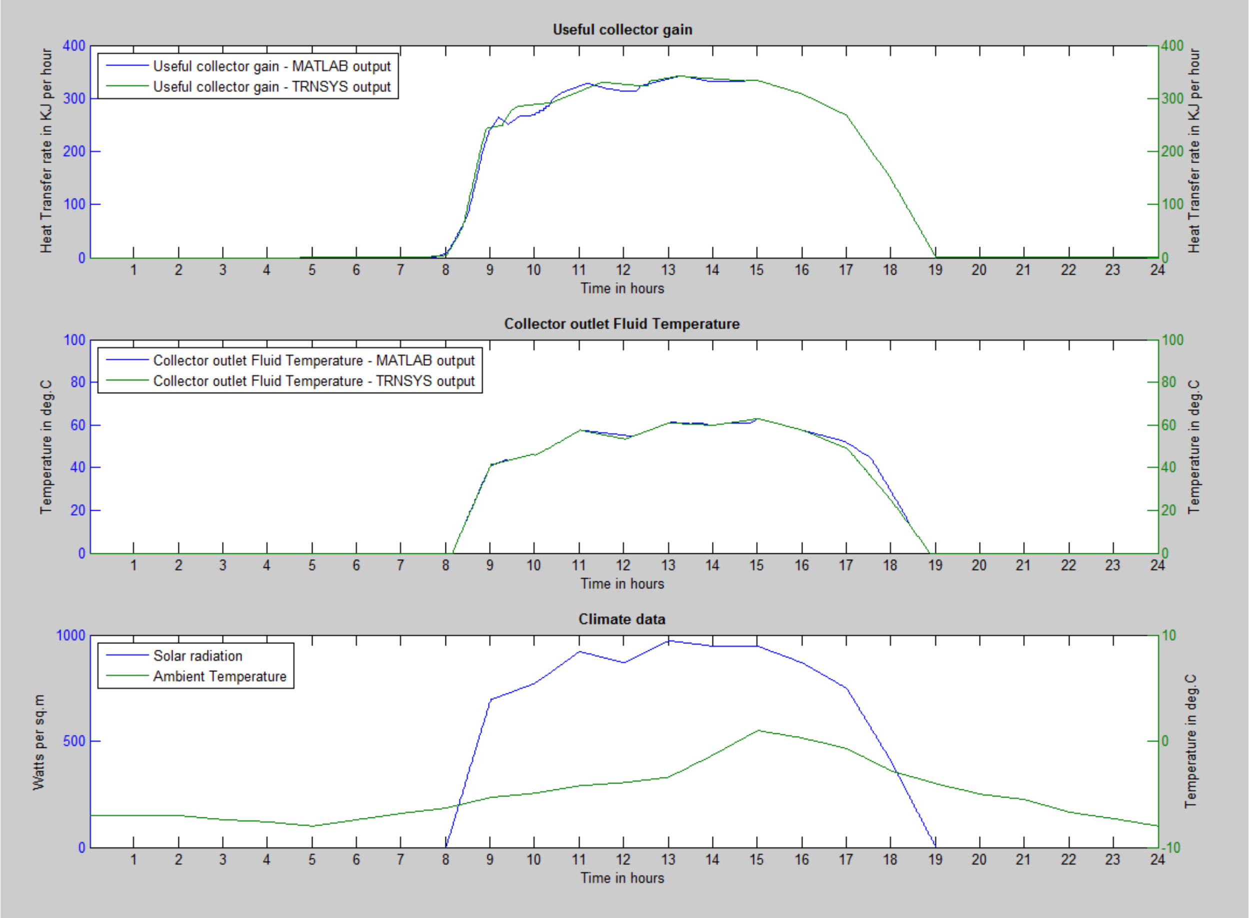


Figure 4.10 Comparison of Useful collector gain and collector fluid temperature from MATLAB and TRNSYS – flat plate collector model, Location used – Virginia Tech airport, VA on a winter day

The first and second plots in Figures 4.9 and 4.10 show the results of collector fluid outlet temperature and the useful collector energy gain obtained from the MATLAB (shown in blue) model and TRNSYS (shown in green) built-in model respectively. The third plot in both these figures represents the climate data: solar radiation (W/m^2) in blue and ambient temperature (deg. C) in green. The mean difference in fluid temperature is about 1.5 deg. C (around 2.5%) and the mean difference in useful energy gain is about 10 KJ per hour (around 3%) and the peaks are synchronous in both of these models. Since the two models follow closely, the MATLAB model is considered valid, and used further for analysis.

4.10.2 Glass Tube Collector

This section presents the results from the MATLAB model of the evacuated glass tube collector which is validated with results from the evacuated tube collector model in TRNSYS. Simulations are performed for two types of days: a winter day and a summer day for the location – Virginia Tech airport, VA with results shown in Figures 4.11 and 4.12 respectively.

Given below are the parameters used for the results of the MATLAB and TRNSYS model:

Effective Area of Collector – 5 m^2

Number of glass tubes - 15

Storage tank volume – 300 liters

Location – Virginia Tech airport, VA, USA – TMY3 code: 724113TY

Collector flow rate – .75 kg per hour

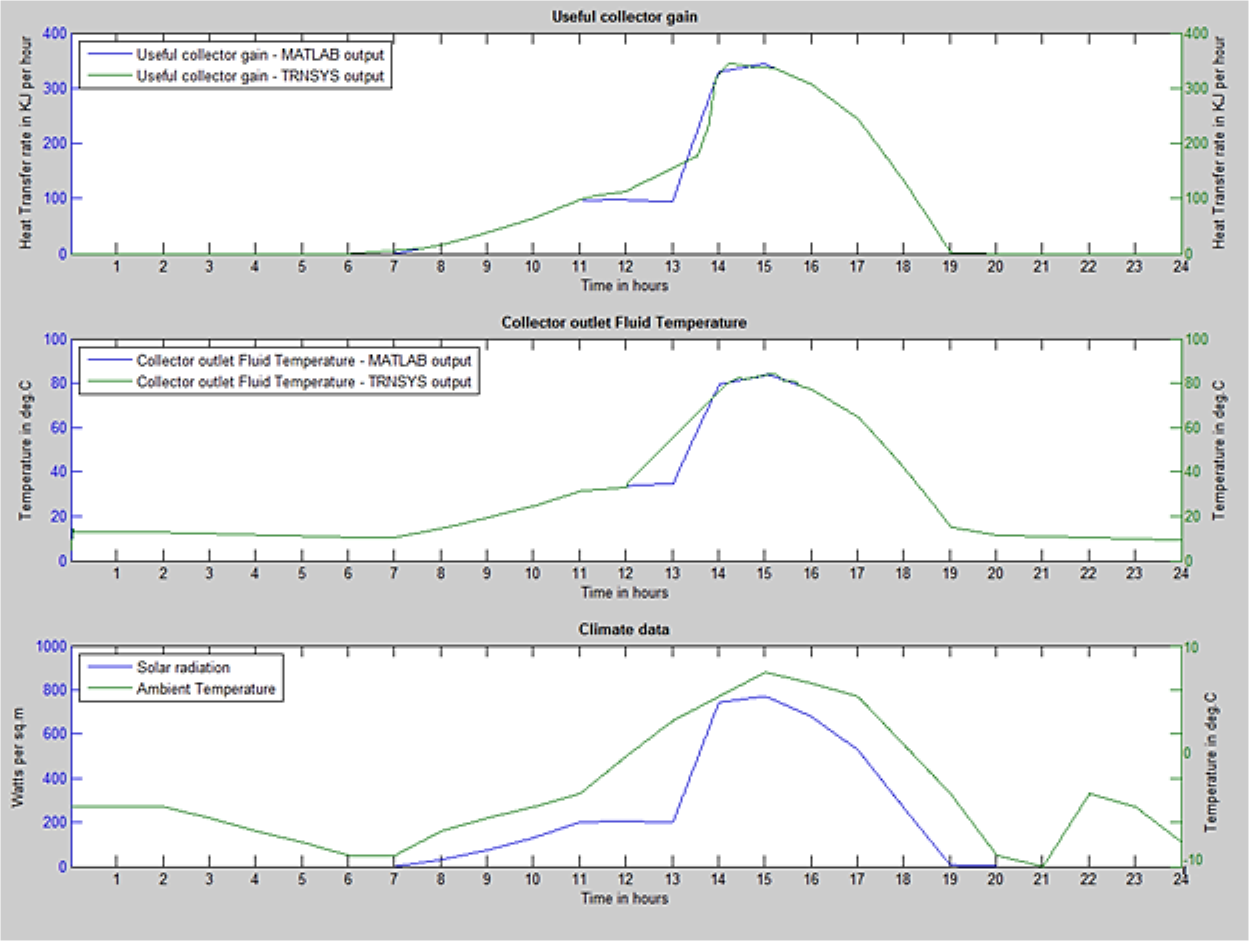


Figure 4.11 Comparison of Useful collector gain and collector fluid temperature from MATLAB and TRNSYS – evacuated glass tube collector model, Location used – Virginia Tech airport, VA on a winter day

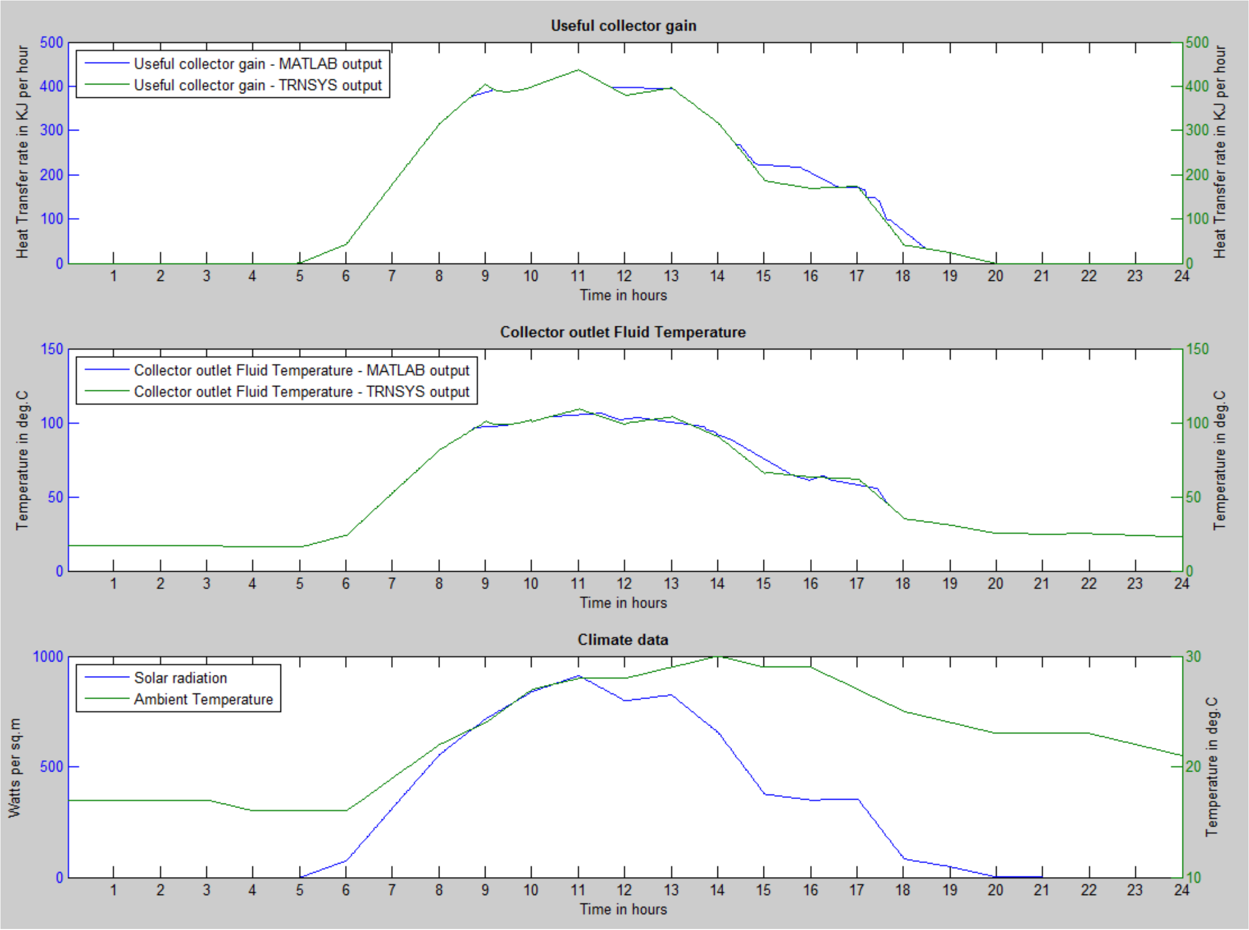


Figure 4.12 Comparison of Useful collector gain and collector fluid temperature from MATLAB and TRNSYS – glass tube collector model, Location used – Virginia Tech airport, VA on a summer day

The first and second plots in Figures 4.11 and 4.12 show the results of collector fluid outlet temperature and the useful collector energy gain obtained from the MATLAB (shown in blue) model and TRNSYS (shown in green) built-in model respectively. The third plot in both these figures represents the climate data: Solar radiation (W/m^2) in blue and ambient temperature (deg. C) in green. The mean difference in fluid temperature is about 2 deg. C (around 2%) and the mean difference in useful energy gain is about 15 KJ per hour (around 3.5%) and the peaks are synchronous in the two models. Since the MATLAB and TRNSYS models follow closely in the results, the MATLAB model is considered valid, and used further for analysis.

Chapter 5

Power Consumption Analysis Case Studies

This chapter presents the simulation results and energy savings comparison for a single water heater as well as for a residential distribution feeder with 100 water heaters for the three configurations namely the electric water heater, the solar thermal water heater with flat plate collector and solar water heater with evacuated glass tube collector. The simulations are extended for two seasons – summer and winter in the case of the residential distribution feeder to analyze the energy savings as well as peak demand reduction. This is followed by the case studies to analyze the effect of outlet temperature in all three configurations of water heaters and the effect on glass panes in flat plate collectors on electric energy consumption.

5.1 Justification for the Use of Consecutive Days in Simulations

5.1.1 Simulation for a single day for a single water heater

In this section, all three configurations of water heaters namely, an electric water heater, a solar thermal water heater with flat plate collector and a solar water heater with evacuated glass tube collector are simulated in MATLAB for one summer day for Virginia Tech airport, VA.

The MATLAB model simulation is performed with the following parameters:

- Temperature set point – 110 deg. F – 43.34 deg. C
- Volume of storage tank – 200 liters
- HVAC set point – 74 F
- Effective area of collectors – 4 m^2

The first three plots in Figure 5.1 shows the water heater temperature (in green) and the electric power consumption (in blue) of the electric water heater and the solar thermal water heaters with flat plate collector and glass tube collector. The fourth plot presents the solar radiation (in green) and the hot water draw events (in blue). The fifth plot shows the wind speed (in blue) and the ambient temperature (in green). As can be seen in Figure 5.1, the glass tube collector is very efficient and hence the associated storage tank temperature is higher compared to the others. Therefore, the auxiliary electric energy consumption is lower than that of the solar water heater with flat plate collector.

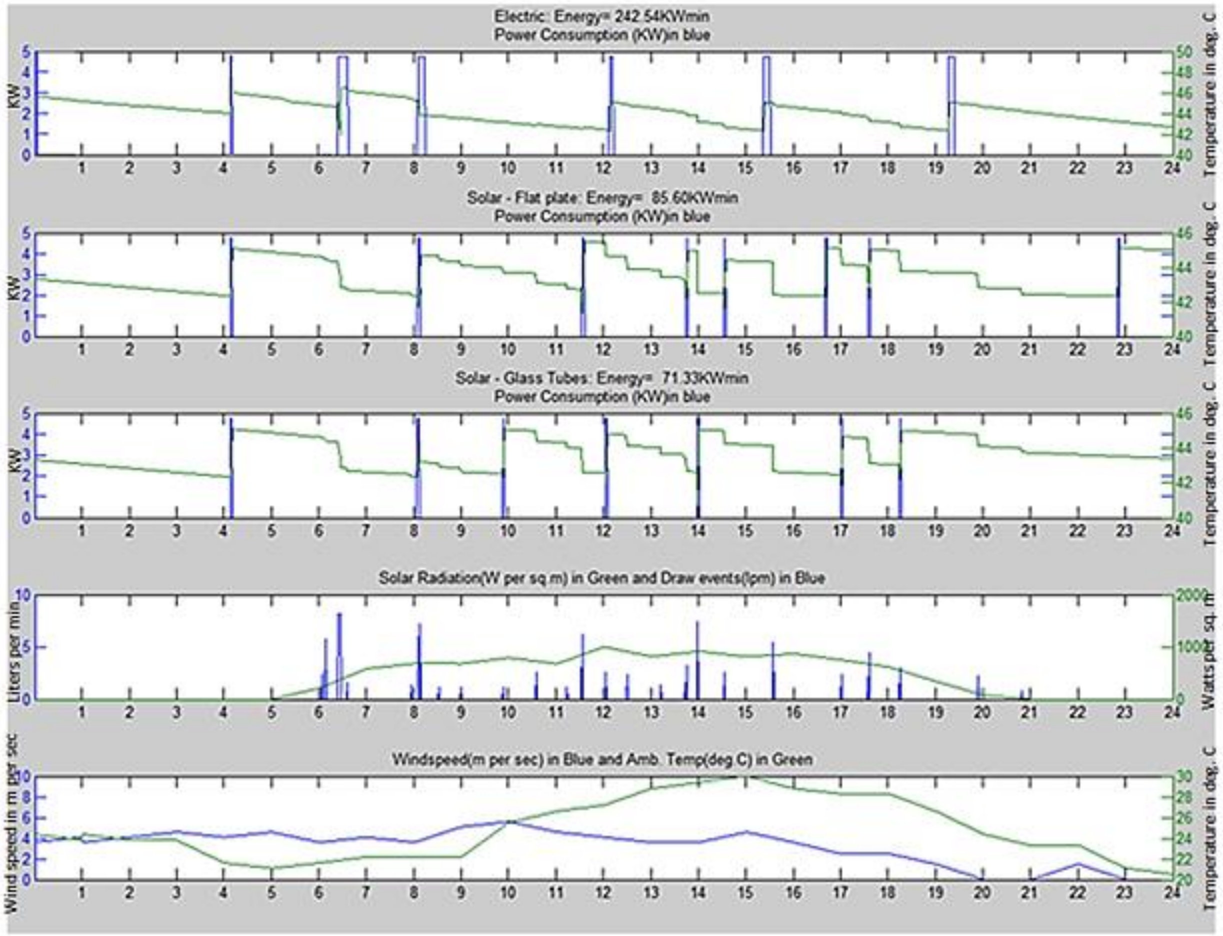


Figure 5.1 Electric Energy consumptions of single water heaters with 3 different configurations: Electric only, flat plate and glass tube collectors with auxiliary electric elements in a summer day, Location used – VA Tech airport, VA.

Figure 5.1 illustrates the fact that the thermal energy in the storage tank is rolled forward to the next day and hence the electric element in the heater tanks will get turned on only on the next day when the temperature reaches the lower limit. To account for this residual effect, the simulations in this thesis are performed for five consecutive days to record the savings in energy and reduction in peak demand from the electric water heaters.

5.1.2 Simulation for Consecutive Days for a Single Water Heater

As discussed in Section 5.1.1, the residual effect of thermal energy stored in the water tank, the simulation performed for five consecutive days is shown in Figure 5.2. The simulation parameters are the same as in Section 5.1.1. The first three plots in Figure 5.2 shows the water heater temperatures (in green) and the electric power consumption (in blue) of the electric water heater and the solar thermal water heaters with flat plate collector and glass tube collector for five consecutive days. The fourth plot presents the solar radiation (in green) and hot water draw events (in blue). The fifth plot shows the wind speed (in blue) and the ambient temperature (in green).

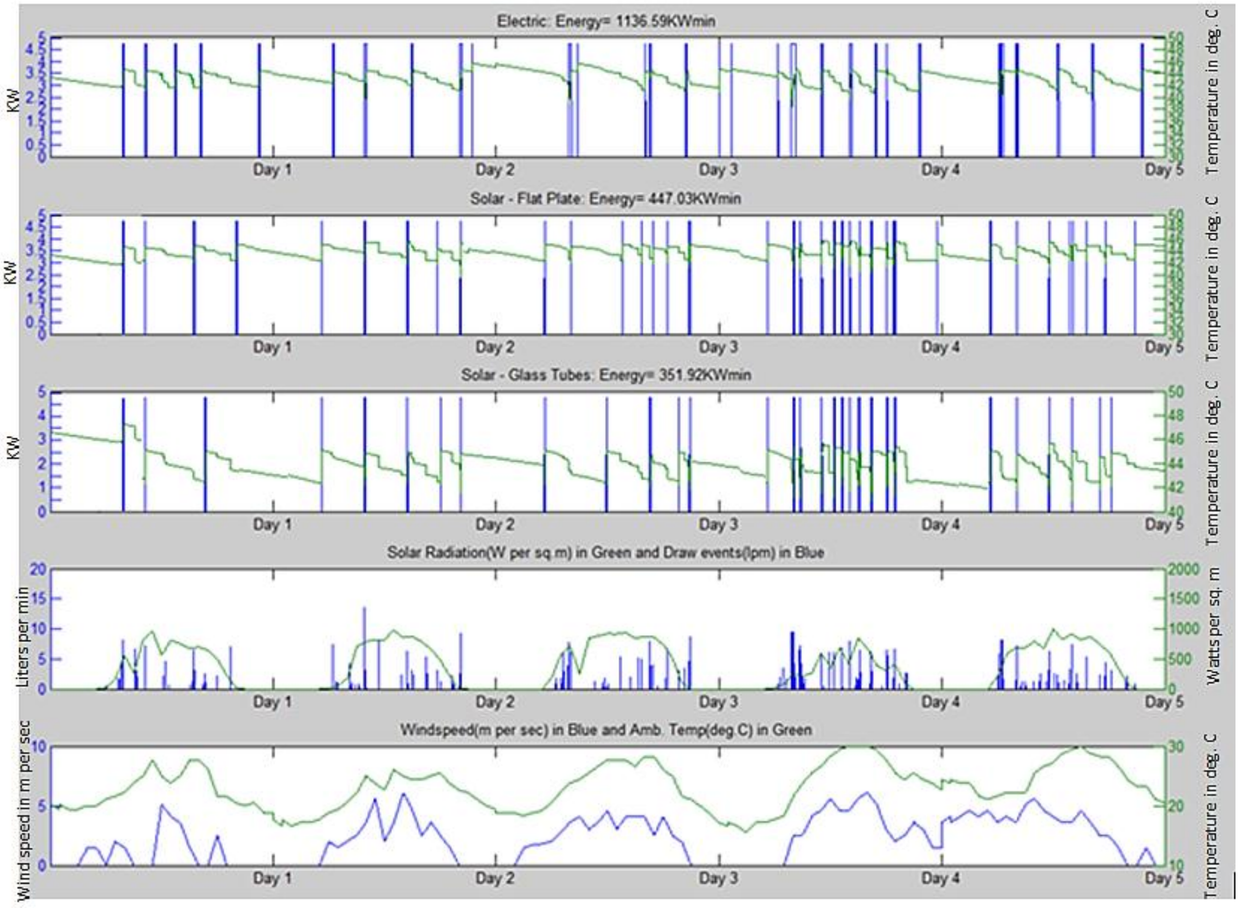


Figure 5.2 Electric Energy consumptions of single water heaters with 3 different configurations: Electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer days, Location used – VA Tech airport, VA.

The insulated water tank acts like a hydro thermal battery which stores thermal energy. The thermal energy stored from one day is rolled forward to the next day and hence the electric elements are not turned on until the next day when the temperature drops to the lower limit. To account for this energy rollover, this MATLAB model is simulated for five consecutive days to compare the energy savings on typical summer and winter - sunny and cloudy days in the United States, the results of which are presented in Section 5.2. Figure 5.2 shows the rollover effect of the thermal energy in the storage tank.

5.2 Power Consumption Analysis of a Single Water heater

In this section, the simulation results for the 3 configurations of the water heaters: electric only, flat plate collector solar water heater and glass tube collector solar water heater are presented for two different locations - Tampa, FL and Madison, WI. These locations represent two extremely different climate zones in the United States and hence will be helpful in comparison of energy savings. Four different day types are chosen: summer sunny and cloudy days, winter sunny and cloudy days. The weekday and weekend profiles are differentiated through the hot water draw events. The energy savings comparison is presented in Section 5.2.1.

5.2.1 Simulation Results for a Single Water Heater

Figures 5.3 through 5.10 present the simulation results as mentioned above with the following parameters:

- Temperature set point – 115 deg. F – 46 deg. C
- Volume of storage tank – 200 liters
- HVAC set point – 74 deg. F
- Effective area of flat plate and glass tube collectors – 4 m^2

As can be seen from Figure 5.3 through 5.10, the glass tube collector -equipped solar water heater is turned on less frequently compared to the flat plate collector – solar water heater, since evacuated glass tube construction helps reduce wind convective losses as well as absorb direct beam, diffuse and reflected radiation from the ground, whereas the flat plate collector absorbs only direct beam and diffuse solar radiation. Also, glass tubes help in absorbing solar radiation for a wider range of incidence angles compared to the flat plate collector.

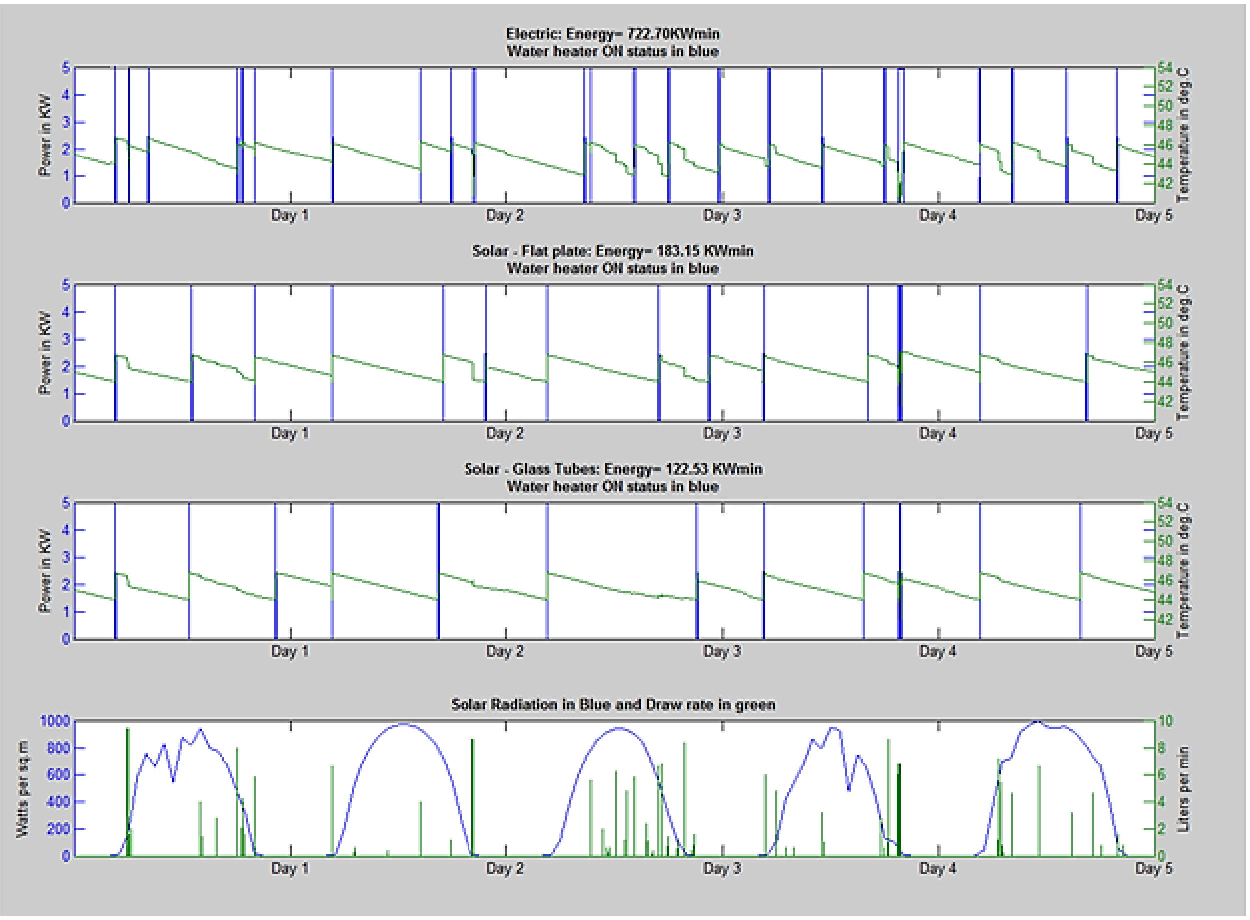


Figure 5.3 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer sunny days, Location used – Madison, WI.

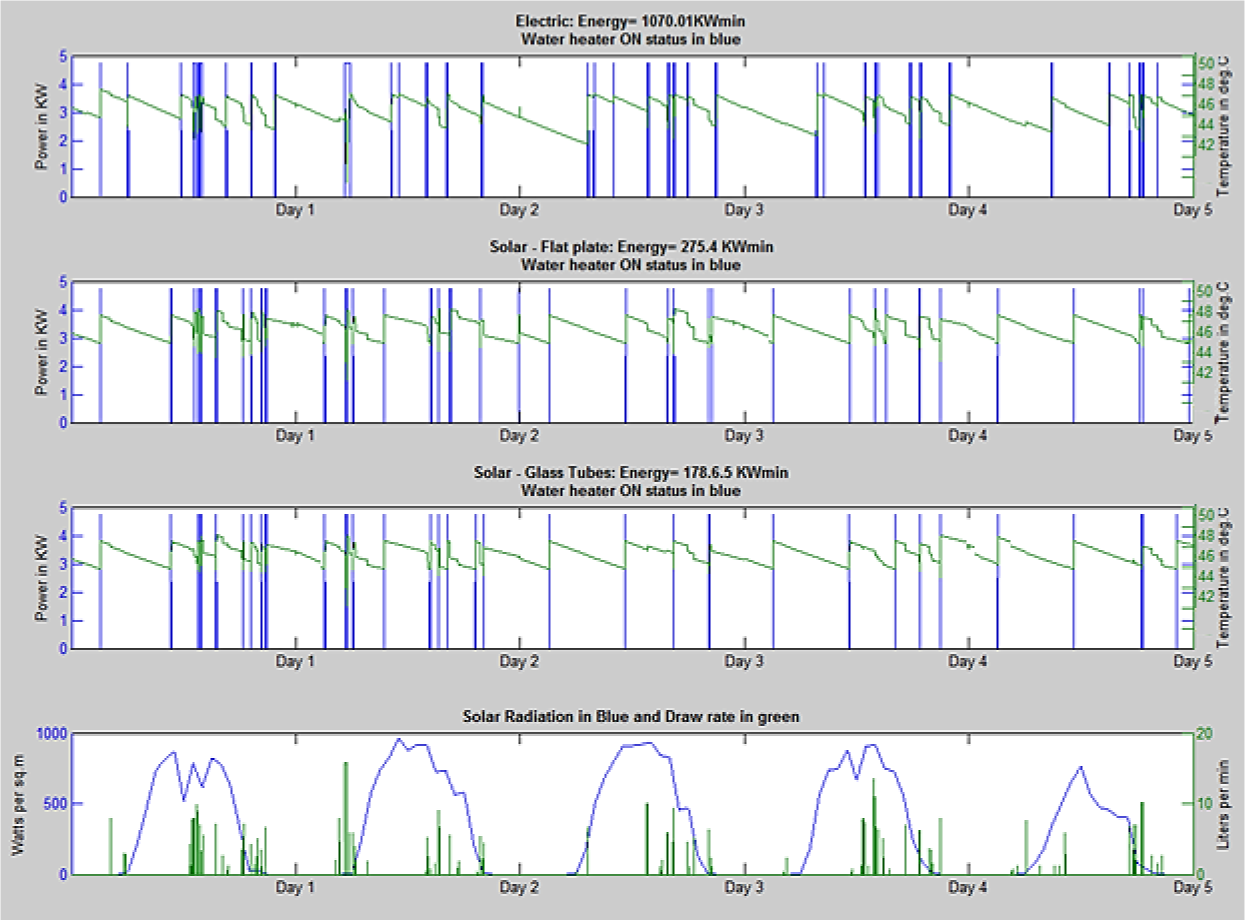


Figure 5.4 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer sunny days, Location used – Tampa, FL.

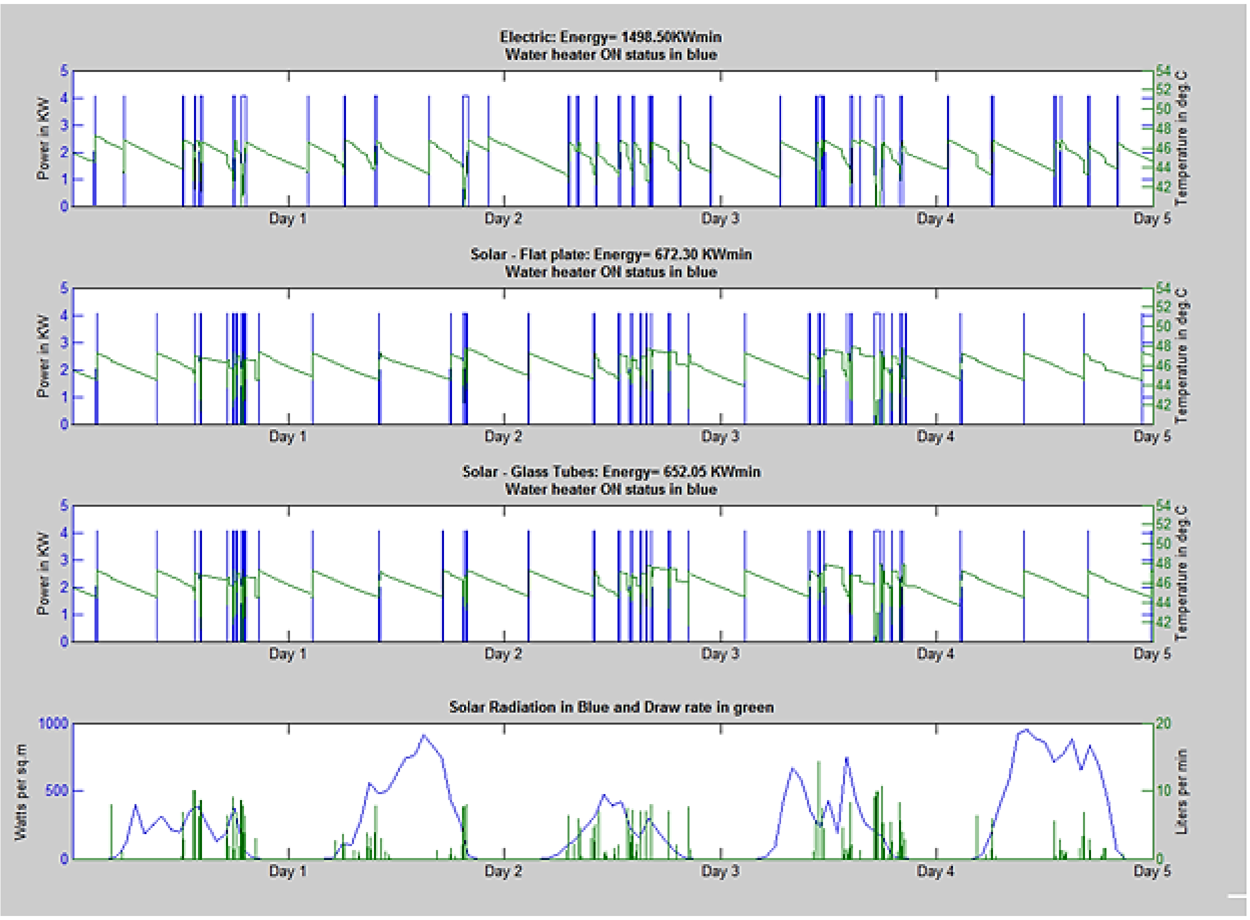


Figure 5.5 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer cloudy days, Location used – Madison, WI.

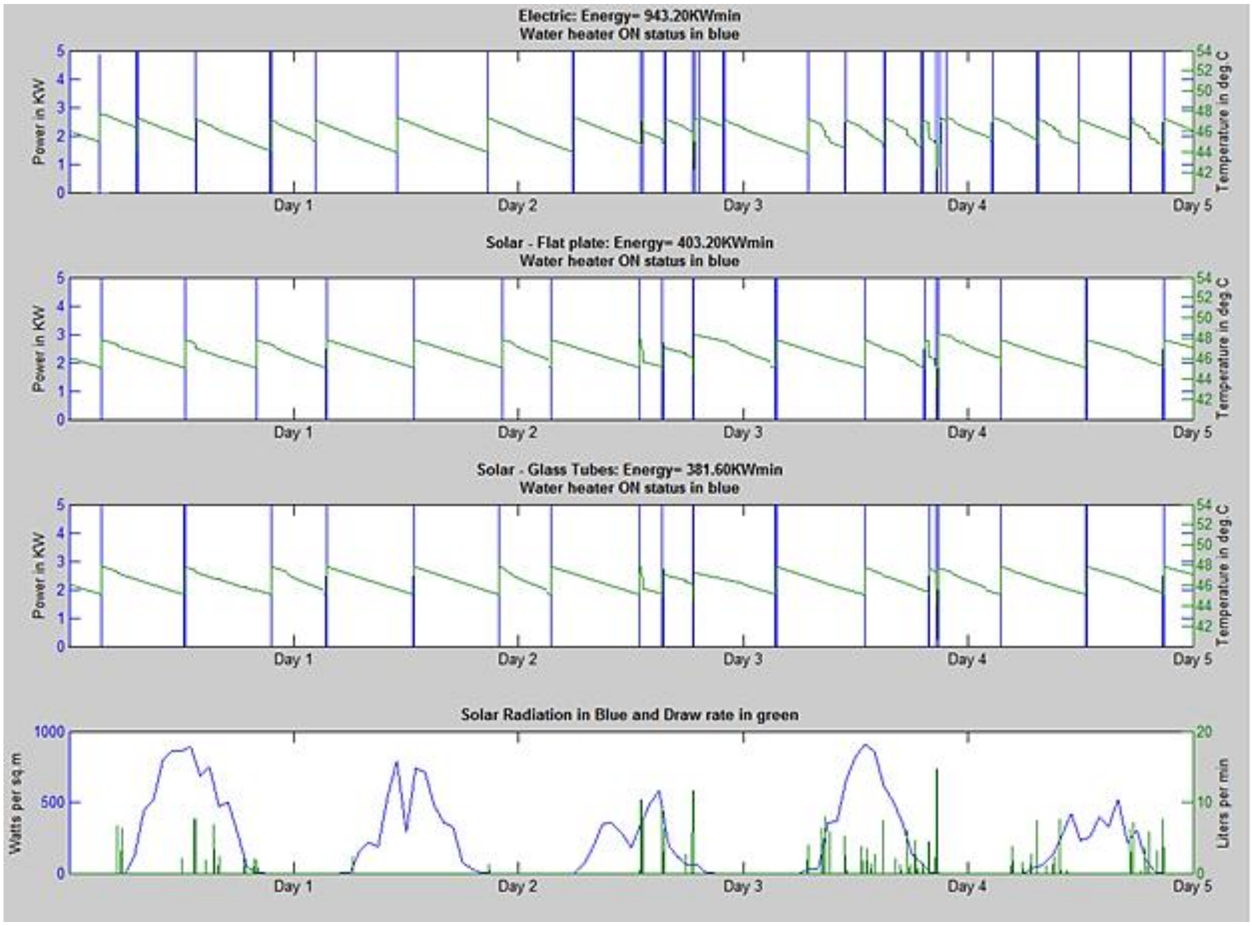


Figure 5.6 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer cloudy days, Location used – Tampa, FL.

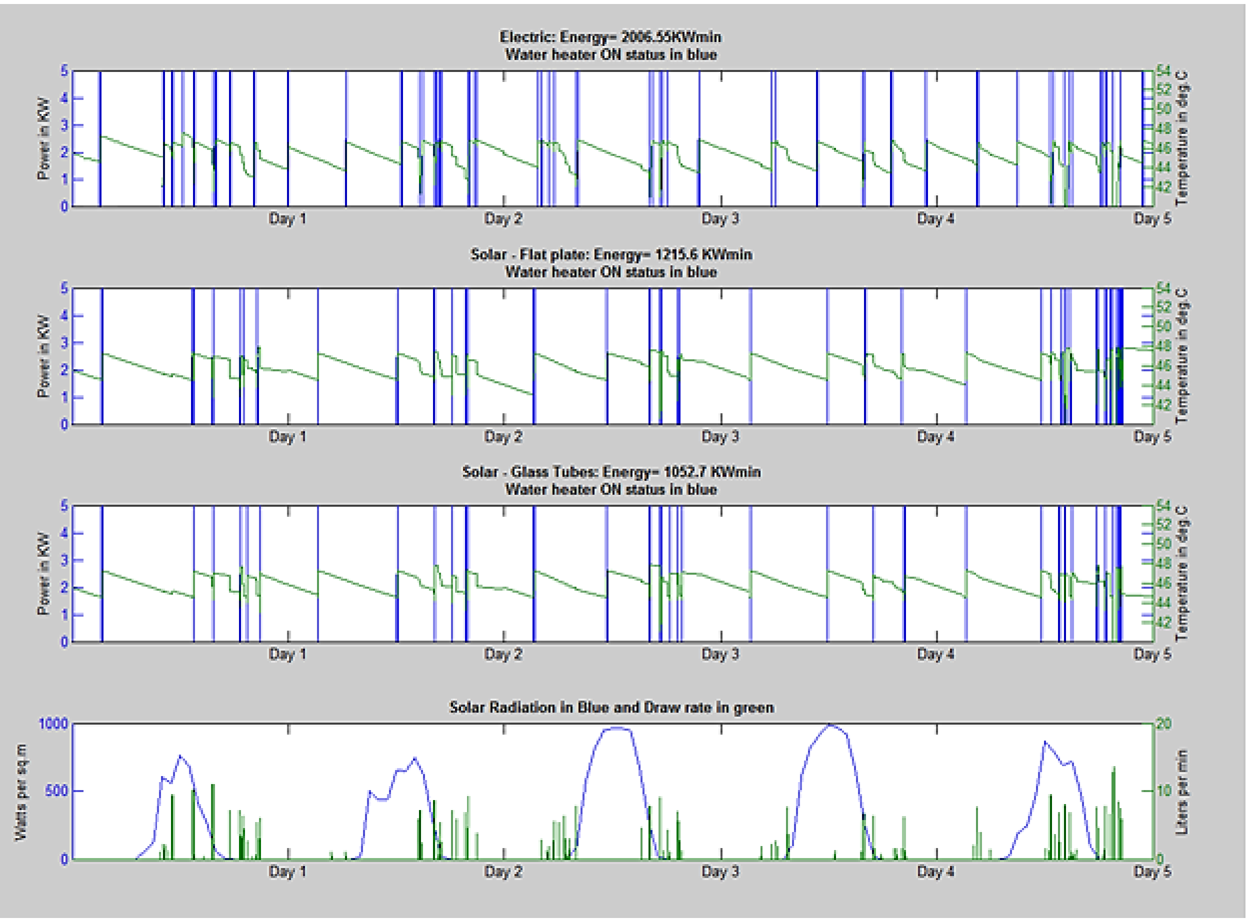


Figure 5.7 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter sunny days, Location used – Madison, WI.

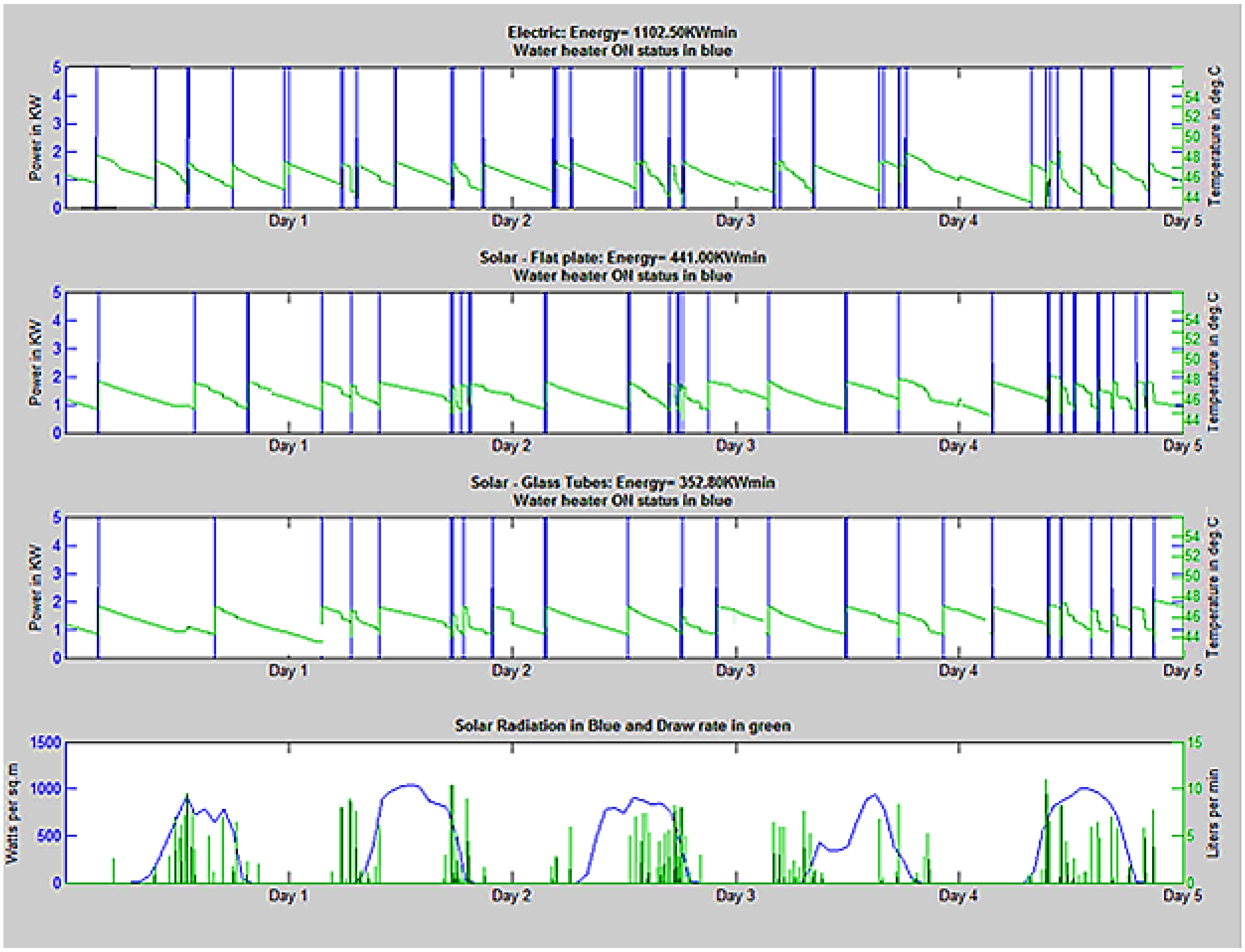


Figure 5.8 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter sunny days, Location used – Tampa, FL.

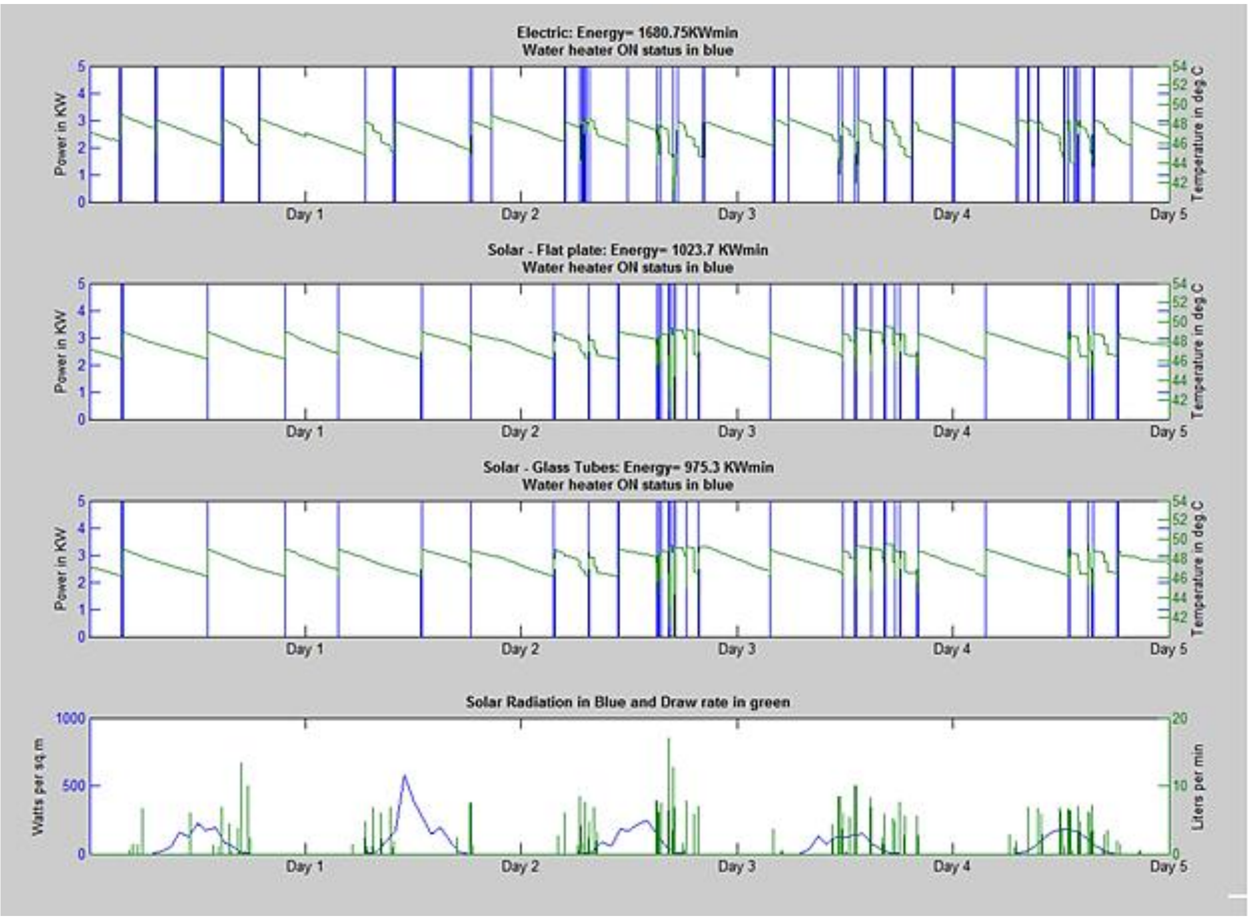


Figure 5.9 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter cloudy days, Location used – Madison, WI.

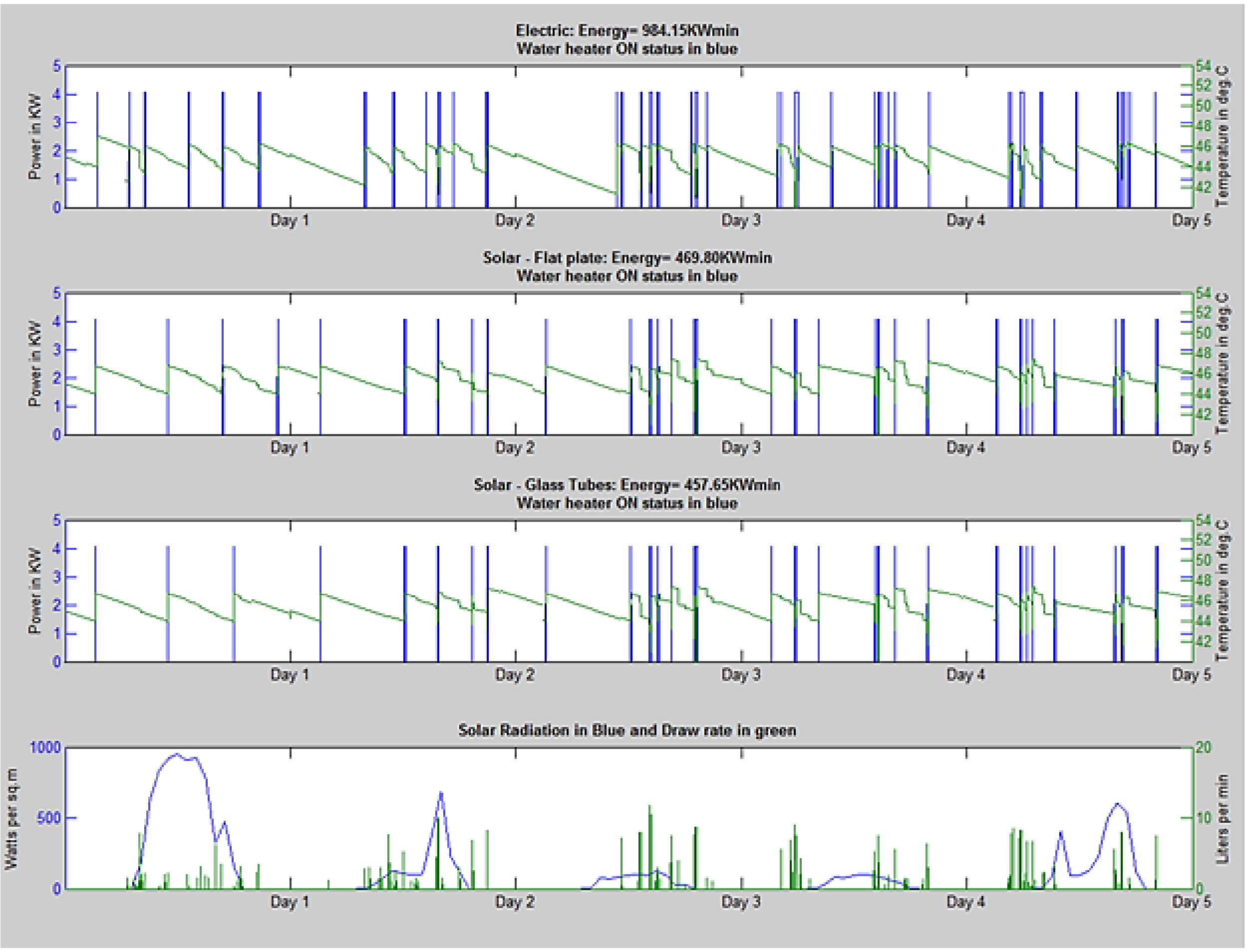


Figure 5.10 Electric energy consumptions of single water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter cloudy days, Location used – Tampa, FL.

5.2.2 Comparison of Energy Savings of a Single Water Heater

Table 5.1 summarizes the energy savings from using solar thermal water heaters against electric water heaters during 5 consecutive days, as presented in Section 5.2.1. The glass tube collectors result in higher savings compared to the flat plate collectors. These savings result from the fact that a glass tube collector absorbs reflected radiation as well as diffuse and direct beam radiation for a wider range of incidence angles compared to a flat plate collector which absorbs only direct beam and diffuse solar radiation.

Table 5.1 Comparison of savings in the electric energy consumptions of a single water heater with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	Electric Elements only Energy in kWmin	Flat Plate Collector Energy in kWmin	% energy savings with FPC	Glass Tubes Collector Energy in kWmin	% energy savings with GTC
Madison WI	Summer Sunny	722.7	183.15	74.65	122.53	83.04
	Summer Cloudy	1498.5	672.3	55.13	652.05	56.48
	Winter Sunny	2006.55	1215.6	39.45	1052.7	47.53
	Winter Cloudy	1680.75	1023.7	38.89	975.3	41.97
Tampa, FL	Summer Sunny	1070.1	275.4	74.26	178.6	83.3
	Summer Cloudy	943.2	403.2	57.25	381.6	59.54
	Winter Sunny	1102.5	441.5	59.95	352.8	68
	Winter Cloudy	984.15	469.8	52.26	457.65	53.5

The electric energy savings with solar thermal water heaters are almost the same for the two locations Tampa, FL and Madison, WI during summer, though during winter, the savings are higher in Tampa, FL due to the city's warmer winter compared to Madison, WI. For Madison, WI, the difference between sunny and cloudy days in summer is higher compared to that during winter. This result follows from the fact that this city's frigid winters with freezing temperatures present an obstacle to the heat collection capability of both flat plate and glass tube collectors.

Also, glass tube collectors are more efficient than flat plate collectors during sunny as well as cloudy days during summer and winter which is due to the fact that glass tubes absorb solar radiation for a wider range of incidence angles as well as absorb reflected radiation from ground.

Further, the sunny days experience more savings compared to the cloudy days in summer as well as winter for both these cities, which is directly related to higher solar radiation and thereby higher heat collection.

5.3 Power Consumption Analysis of Water Heaters in a Residential Distribution Circuit

In this section, the methodology for aggregation of electric and solar water heaters is discussed. This is followed by the simulation results for a residential distribution feeder with 100 homes in Madison, WI and Tampa, FL during summer and winter for sunny and cloudy day types. A comparison of the energy savings and peak reduction for the simulation results is also presented.

5.3.1 Aggregation of Electric Water Heaters

To aggregate the power consumption of electric water heaters in a residential distribution feeder, the individual heaters are differentiated from one another by the following influential parameters [50, 51]:

- Water heater element power ratings
- Hot water usage pattern
- Storage volume which affect the duration of 'ON' times
- Tank temperature set point

This MATLAB model uses the above parameters to randomize the behavior of individual electric water heaters in addition to the following parameters:

- Ambient temperature set point for the home
- R-value of the tank's insulation.

Table 5.2 shows the parameter distributions used to diversify the properties of the individual water heaters and their respective boundary values. These parameters are used to simulate a residential distribution feeder with 100 electric water heaters.

Table 5.2 Parameters used in simulations for a residential distribution feeder.

Parameter	**Distribution Type**	**Minimum**	**Maximum**	**Units**
Volume of tank	Uniform	150	300	Liters
R value of tank	Uniform	12	19	Deg. F* sq. ft.*hours/Btu
Temp. set for WH	Uniform	110	120	Deg. F
Temp. set for HVAC	Uniform	74	78	Deg. F
Daily Hot water Usage	100 liters/day, 200 liters/day and 300 liters/day profiles are used from IEA.			

5.3.2 Aggregation of Solar Water Heaters

The solar water heaters follow the same distribution of parameters for aggregation purposes as the electric water heaters as mentioned in Section 5.3.1, except the volume of the water tank and the area of the collectors. This thesis uses recommendations from PREVIS [52] for these parameter distributions. PREVIS is one of the SHW system modeling softwares which allows the users to optimally size a solar hot water system's parameters.

Based on the system parameters already used in the electric water heater aggregation model, the following parameters are calculated for the solar water heaters:

- Area of Collectors is such that $60 < \text{Daily consumption in Kg/Area}_{coll} < 100$
- Storage tank volume [53] is such that $.8 < \text{Daily consumption in Kg/Volume} < 1.2$

5.3.3 Simulation Results for a Residential Distribution Feeder

In this section, the electric energy consumption profiles of 100 electric water heaters are presented for summer and winter with sunny and cloudy day. This Section will help in learning the impact of solar thermal water heaters on electric energy savings and electric water heater peak demand reduction against electric water heaters in a residential distribution circuit. The simulations are performed with the parameters mentioned in Sections 5.3.1 and 5.3.2.

A comparison of the energy savings is presented following this Section in Section 5.3.4 for the simulation results shown in Figures 5.11 through 5.18. In Figures 5.11 through 5.18 the first three plots show the power consumption in a residential distribution feeder with all-electric water heaters, solar thermal water heaters with flat plate collectors and solar water heater with evacuated glass tube collectors in the same order. The fourth plot shows the solar radiation (in blue) and ambient temperature for the location (in green). It is evident from these figures that the solar thermal water heaters collect more heat during the warm sunshine hours occurring in the afternoon which results in more peak shaving during the latter part of a day than during morning hours.

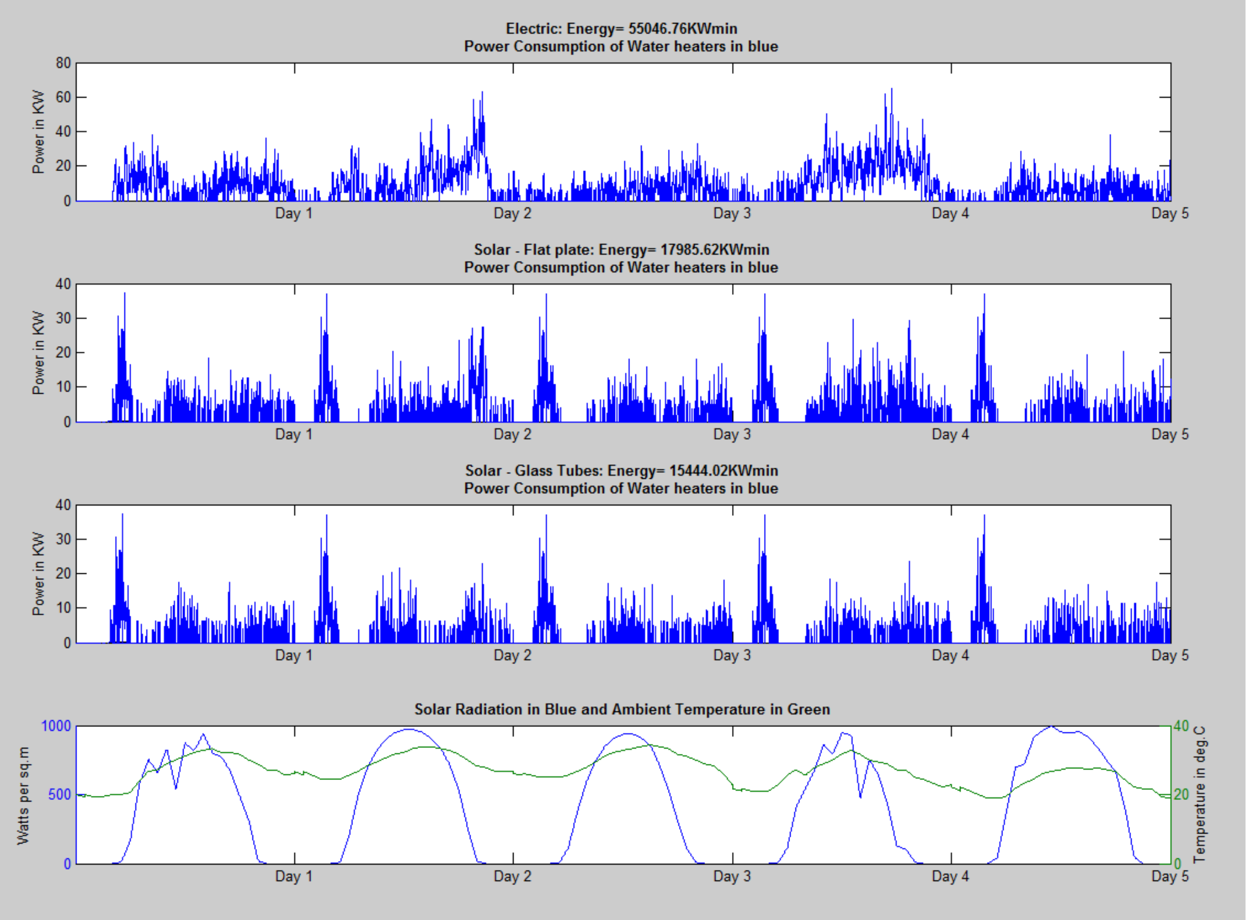


Figure 5.11 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer sunny days, Location used – Madison, WI.

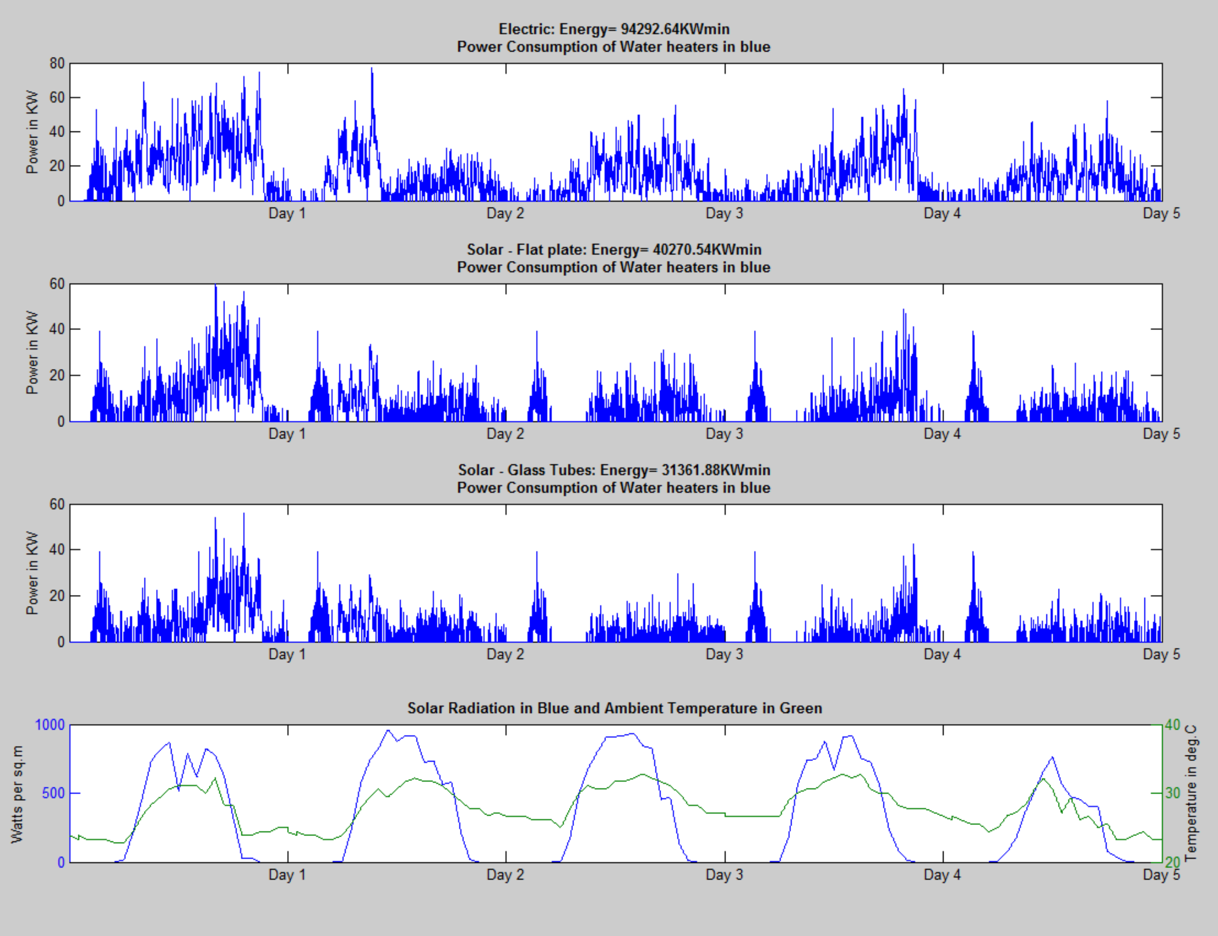


Figure 5.12 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer sunny days, Location used – Tampa, FL.

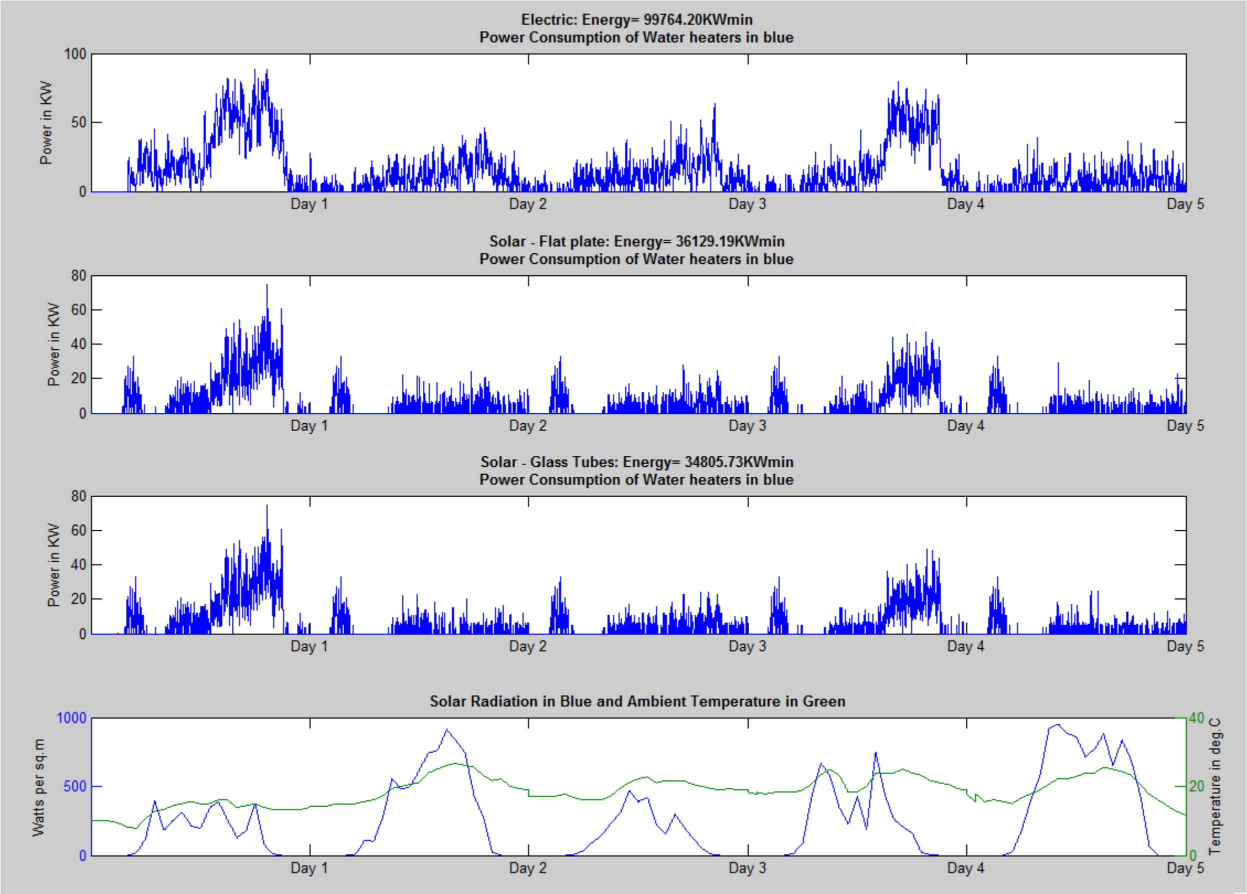


Figure 5.13 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer cloudy days, Location used – Madison, WI.

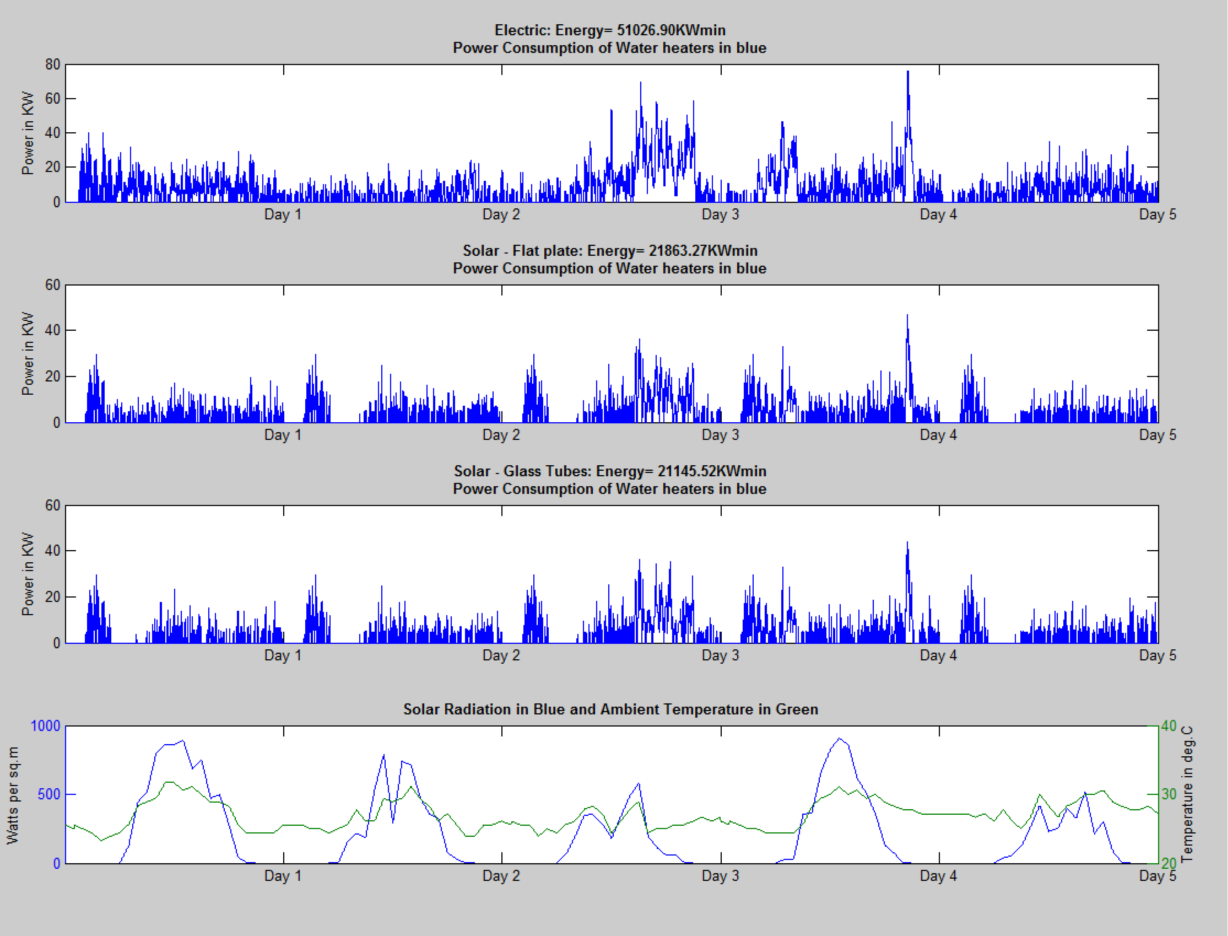


Figure 5.14 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive summer cloudy days, Location used – Tampa, FL.

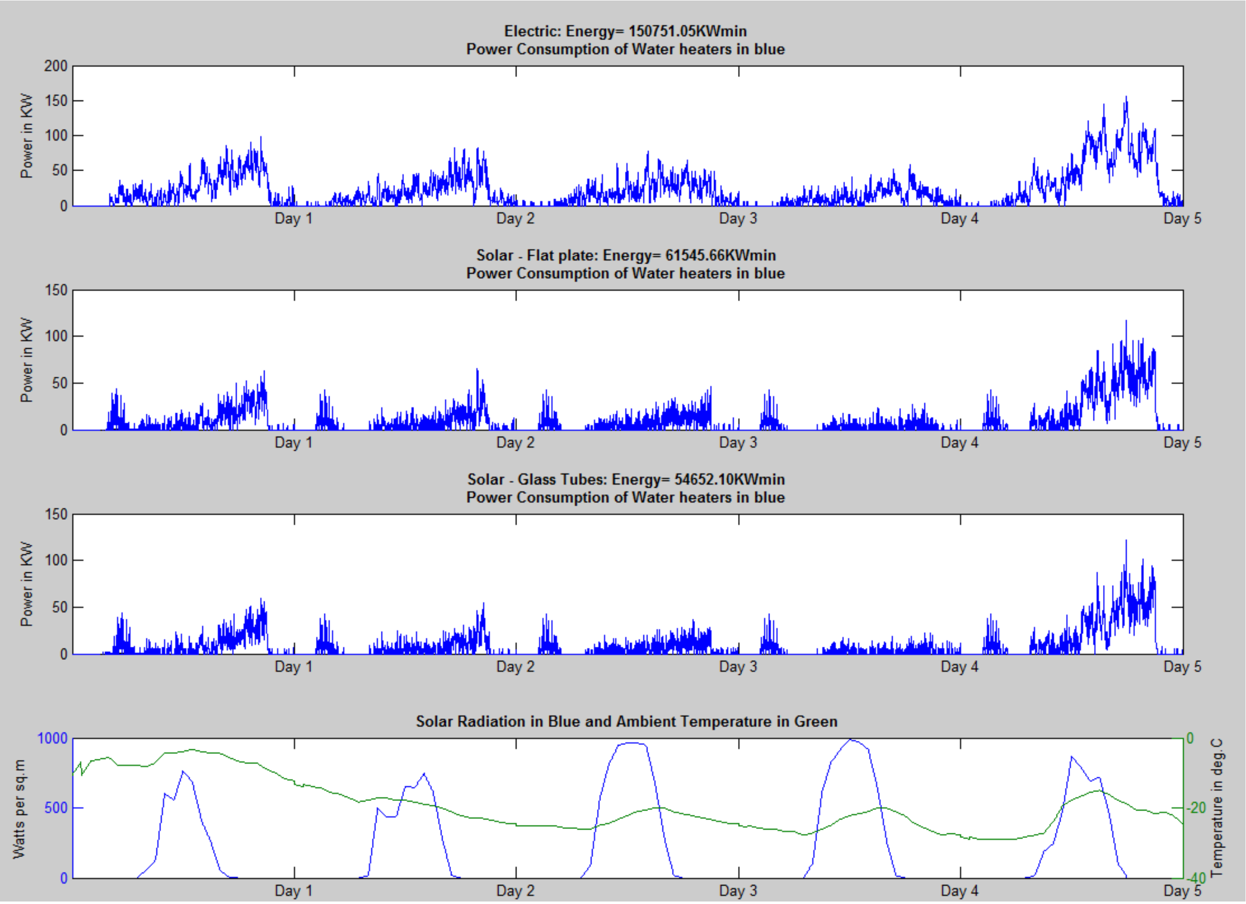


Figure 5.15 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter sunny days, Location used – Madison, WI.

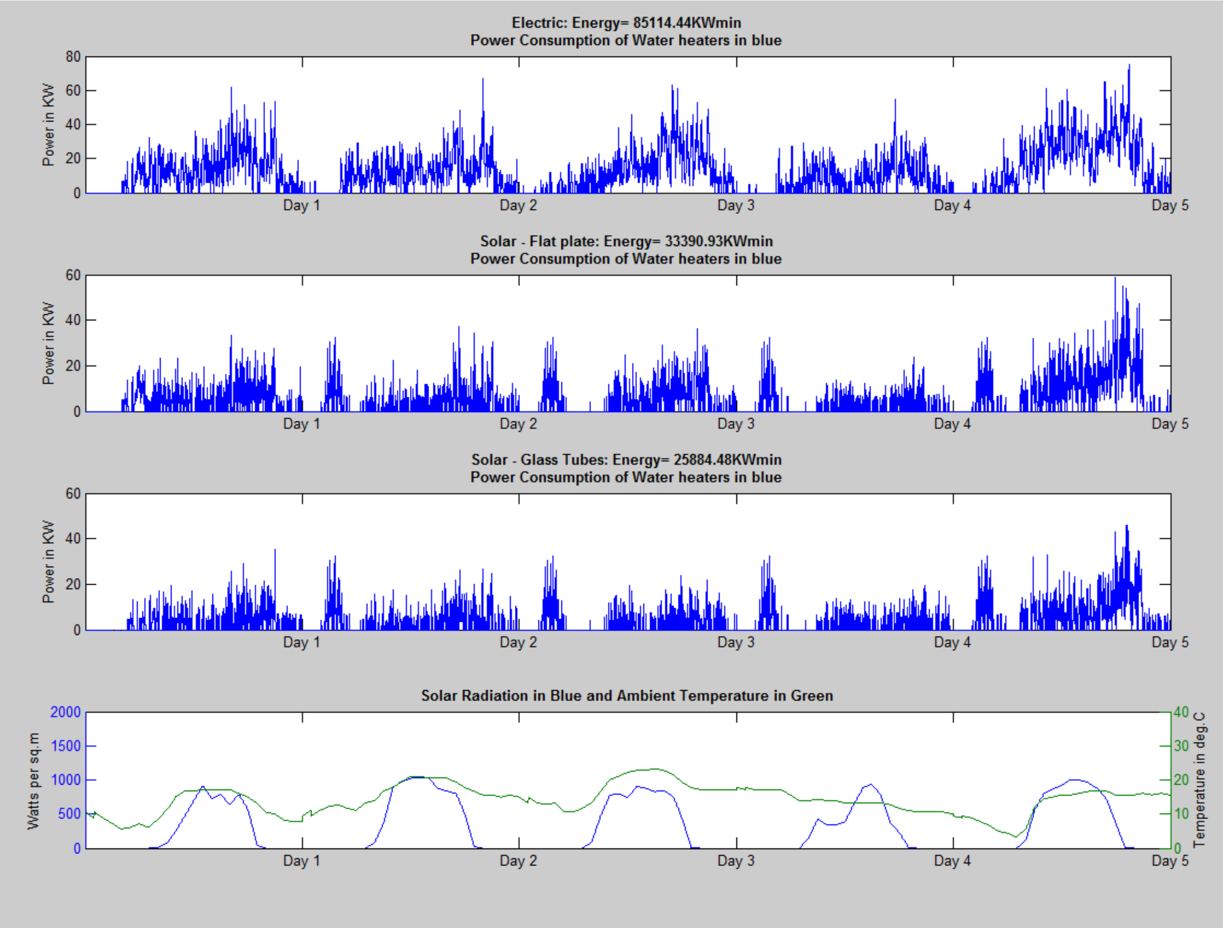


Figure 5.16 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter sunny days, Location used – Tampa, FL.

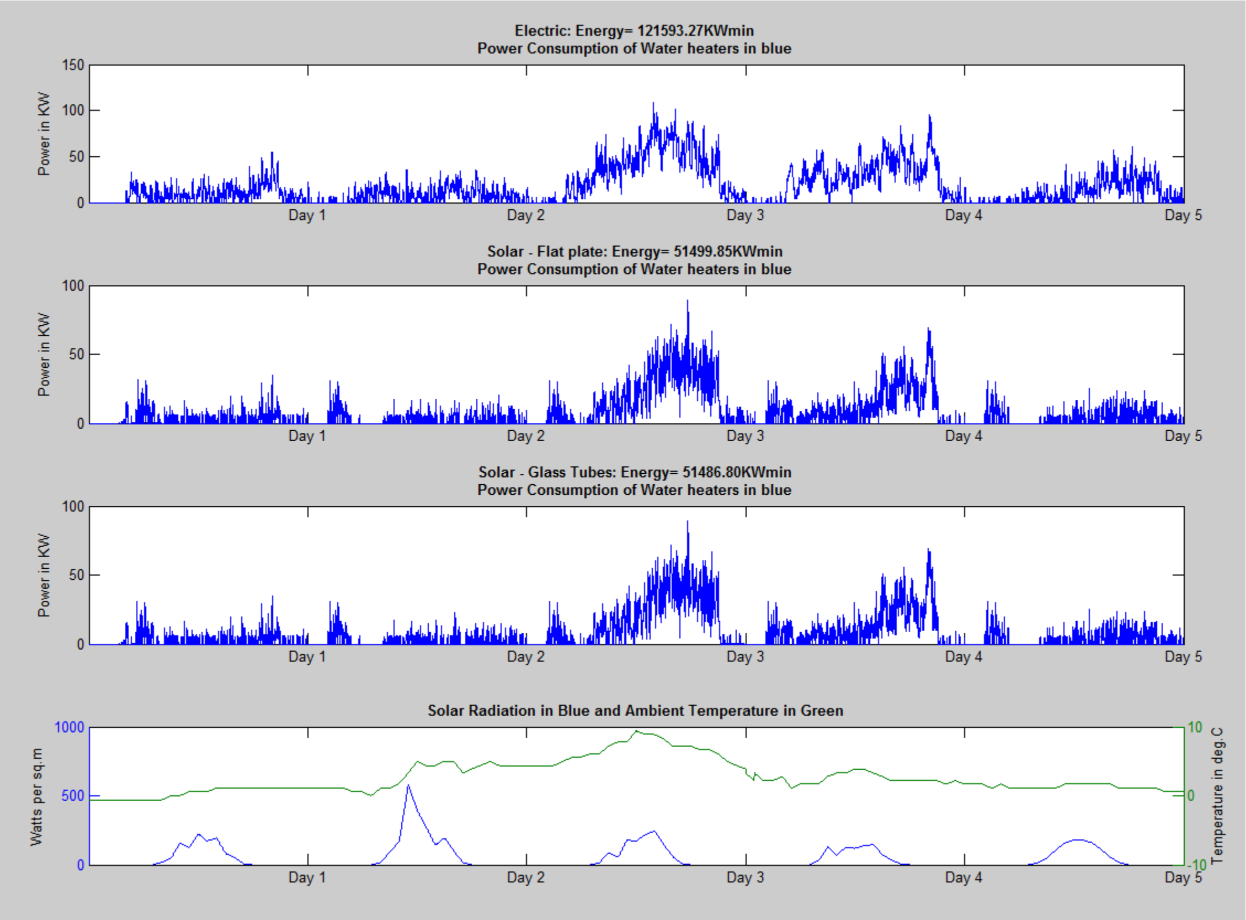


Figure 5.17 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter cloudy days, Location used – Madison, WI.

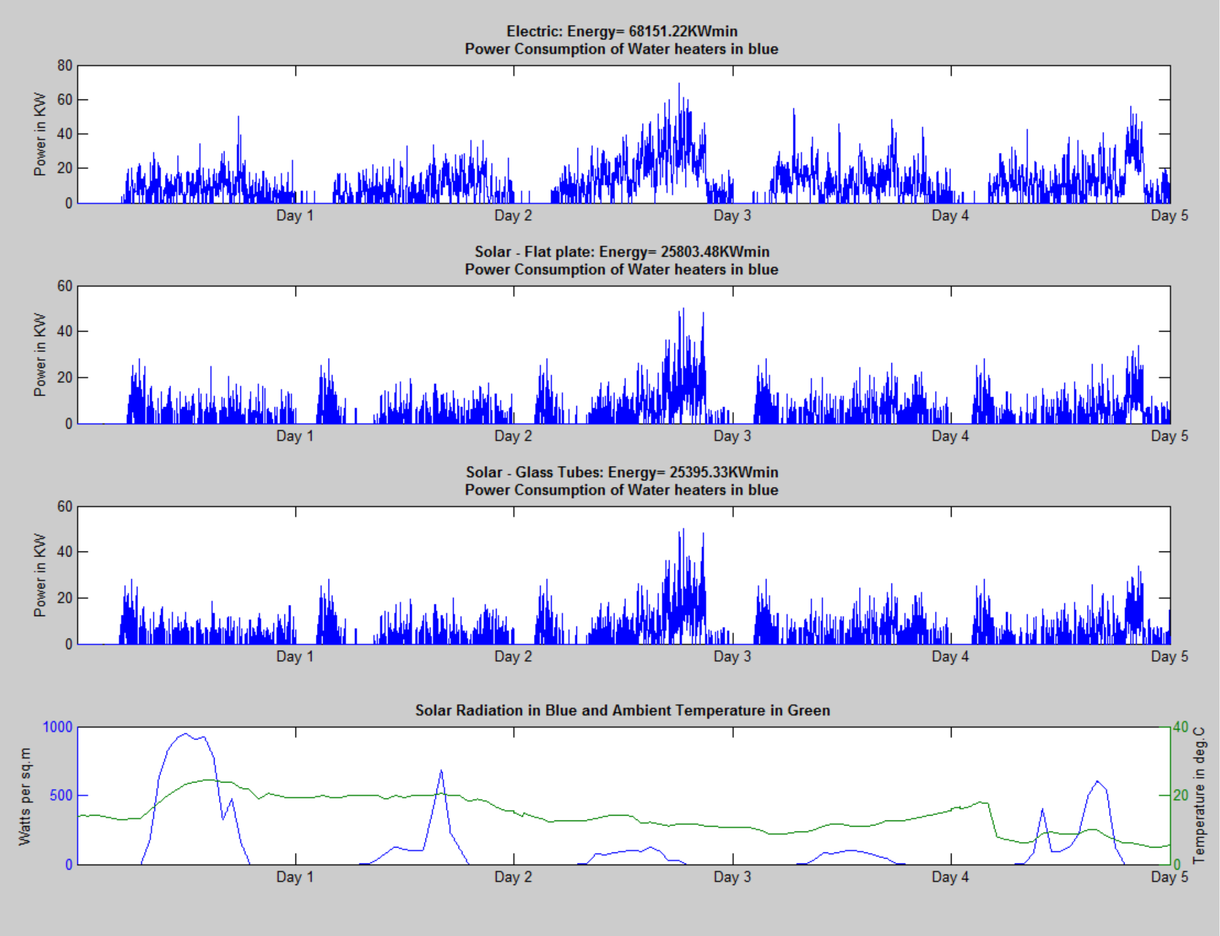


Figure 5.18 Electric energy consumptions of 100 water heaters with 3 different configurations: electric only, flat plate and glass tube collectors with auxiliary electric elements in 5 consecutive winter cloudy days, Location used – Tampa, FL.

5.3.4 Comparison of Energy Savings in a Residential Distribution Feeder

Table 5.3 summarizes the energy savings in a residential distribution feeder for the results presented in Section 5.3.3. As can be seen from Table 5.3, the distribution feeder with solar thermal water heaters can save between 60-80% of water heating energy during summer and 40-70% of water heating energy during winter. While, aggregating the water heaters, both the cities in FL and WI are fairly equal in energy savings during summer, though during winter, the energy savings in FL is higher than that of WI. The reason accounted for this result is that Florida experiences warmer winters with longer sunshine hours and higher ambient temperatures compared to Wisconsin which has frigid winters with lower sunshine periods and freezing ambient temperatures, though both these states enjoy similar climatic conditions in summer.

Table 5.3 Comparison of savings in the Electric Energy Consumptions of 100 water heaters in a residential distribution feeder with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	electricity consumed by all-electric	electricity consumed by FPC	% energy savings with FPC	electricity consumed by GTC	% energy savings with GTC
Madison WI	Summer Sunny	54346.76	14985.62	72.42	11454.02	78.92
	Summer Cloudy	92564.5	36129.9	60.97	34275.3	62.96
	Winter Sunny	153862	90696.26	41.05	84486.55	45.09
	Winter Cloudy	125193.48	76488.21	38.9	75129.23	39.98
Tampa, FL	Summer Sunny	95292.22	28600.55	69.98	19766.96	79.25
	Summer Cloudy	51027	21863	57.15	21145	58.56
	Winter Sunny	85144	33390	60.79	25884	69.59
	Winter Cloudy	68151	30503	55.34	29393	56.87

Also, the sunny days experience more savings compared to the cloudy days in summer as well as winter for both these cities, which is directly related to higher solar radiation and thereby higher heat collection. In Table 5.3, the electricity consumption on a winter sunny day is higher than that during a winter cloudy day. This anomaly is accounted to the randomness in the hot water usage profiles as well as the small population (100 homes) taken for aggregation. This trend is not seen in the second population of 100 homes analyzed in Table 5.4 where, the electricity consumption on winter sunny days is less than that on winter cloudy days.

The percentage of savings for the residential distribution feeder in Table 5.3 is different from that for a single home given in Table 5.1 as one would generally expect. This is due to the fact that the aggregation of water heaters follows a random uniform distribution for the temperature set point, which varies between 110 and 120 deg. F as shown in Table 5.2. Also, the volume and power rating of hot water tanks in each of these water heaters and hot water usage vary randomly.

5.3.4.1 Statistical Significance of the Results – Energy Savings

In this section, the statistical significance of the results obtained in Section 5.3.4 is explained. The hot water usage profiles used to arrive at the results are distributed in a random normal fashion and also the sample size of the population used for simulations is relatively small (100 as compared to 1000s of water heaters in a real distribution feeder). Hence a two-sample t-test will reveal the probability that the energy savings obtained are not purely coincidental or random, which implies the null hypothesis with a 0.05 level of significance. For this purpose, along with the results obtained in Table 5.3 for one population of 100 homes, another population of 100 homes (shown in Table 5.4) is compared to present the test for statistical significance. Also, this test is performed to show the level of confidence intervals for the results of energy savings obtained. The two populations use the same average hot water usage profiles obtained from IEA.

Table 5.4 Comparison of savings in the Electricity Consumption of 100 water heaters (Population II) in a residential distribution feeder with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	electricity consumed by all-electric	electricity consumed by FPC	% energy savings with FPC	electricity consumed by GTC	% energy savings with GTC
Madison WI	Summer Sunny	49786.3	14963.4	69.94	11964.3	75.97
	Summer Cloudy	97864.56	39457.23	59.68	35175.83	64.06
	Winter Sunny	149757.4	91268.6	39.06	82990	44.58
	Winter Cloudy	159327.64	97043.43	39.09	95457.42	40.09
Tampa, FL	Summer Sunny	87649.54	27659.32	68.44	21954.6	74.95
	Summer Cloudy	83456.23	36879.5	55.81	35605.78	57.34
	Winter Sunny	69874.54	28035.9	59.88	24987	64.24
	Winter Cloudy	79764.21	34987.6	56.14	34203.58	57.12

The two sample t-test for the energy savings with the null hypothesis that the results obtained from the random hot water profiles are also random gives a p-value of .027 and .046 for the flat plate and glass tube collectors respectively for the two tailed normal distribution, which is lower than the level chosen (0.05). Hence, the null hypothesis that the average savings obtained in the two sets of data is purely random is rejected and the results are statistically significant within the 95% confidence interval.

5.3.5 Peak Reduction Comparison in a Residential Distribution Feeder

Table 5.5 summarizes the peak reduction capacity of solar thermal water heaters available from the simulation results presented in Section 5.3.3. As can be seen from Table 5.5, the distribution feeder with solar thermal water heaters can help reduce peak water heating demand between 40-60% during summer and 25-40% during winter. When it comes to peak demand reduction Tampa, FL outperforms Madison, WI with higher percentages of peak shavings. The peak demand hours in a residential electrical distribution circuit occur between 10 am and 2 pm which coincides with the duration of higher sunshine and ambient temperatures in day. During this time period, the useful energy collected by the flat plate and glass tube collectors is generally higher than during the other hours in a day, which aids the peak reduction capability of solar thermal water heaters.

Table 5.5 Comparison of peak reductions in electric water heating demand with 100 water heaters in a residential distribution feeder with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	Electric Elements only Peak Demand in KW	Flat Plate Collector Peak Demand in KW	% Peak reduction with FPC	Glass Tubes Collector Peak Demand in KW	% Peak reduction with GTC
Madison WI	Summer Sunny	64.8	30.45	53.01	25.15	61.19
	Summer Cloudy	89.8	54.12	39.73	51.74	42.38
	Winter Sunny	155.4	101.79	34.5	96.46	37.93
	Winter Cloudy	121.6	88.2	27.47	83.38	31.43
Tampa, FL	Summer Sunny	77.3	34.83	54.94	28.9	62.61
	Summer Cloudy	79.3	47.3	40.35	42.4	46.53
	Winter Sunny	68.9	44.6	35.27	41.5	39.77
	Winter Cloudy	69.2	48.73	29.58	45.36	34.45

As evident from Table 5.5, glass tube collectors outperform flat plate collectors in lowering peak demand which is again accounted to the capability of the evacuated glass tube which prevents wind convective losses during higher sunshine hours which coincides with the peak demand hours.

5.3.5.1 Statistical Significance of the Results – Peak Demand Reduction

In this section, the statistical significance of the results of peak demand reduction obtained in Section 5.3.5 is explained. Since, the hot water usage profiles used to arrive at the results are distributed in a random normal fashion and also the sample size of the population used for simulations is relatively small, a two-sample t-test as performed in Section 5.3.4.1 will reveal the probability that the energy savings obtained are not purely coincidental or random, which implies the null hypothesis with a 0.05 level of significance. For this purpose, along with the results obtained in Table 5.5 for one population of 100 homes, another population of 100 homes (shown in Table 5.6) is compared to present the test for statistical significance.

Table 5.6 Comparison of peak reductions in electric water heating demand with 100 water heaters in a residential distribution feeder (population II) with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	Peak demand with all electric	Peak demand with FPC	% Peak reduction with FPC	Peak demand with GTC	% Peak reduction with GTC
Madison WI	Summer Sunny	70.6	33.2	52.97	27.9	60.48
	Summer Cloudy	90.67	55.72	38.55	52.89	41.67
	Winter Sunny	129.56	85.94	33.67	80.56	37.82
	Winter Cloudy	149.56	109.94	26.49	102.2	31.67
Tampa, FL	Summer Sunny	78.45	37.45	52.26	29.5	62.4
	Summer Cloudy	81.1	48.32	40.42	43.7	46.12
	Winter Sunny	65.34	42.67	34.7	39.89	38.95
	Winter Cloudy	70.4	49.7	29.4	46.21	34.36

The two sample t-test for the peak reductions with the null hypothesis that the results obtained from the random hot water profiles are also random gives a p-value of .036 and .032 for the flat plate and glass tube collectors respectively for the two tailed normal distribution, which is lower than the level chosen (0.05). Hence, the null hypothesis that the average savings obtained in the two sets of data is purely random is rejected and the results are statistically significant within the 95% confidence interval.

5.3.6 Comparison of Energy Savings in a Residential Distribution Feeder during Summer & Winter

In this section a long duration simulation for 3 months is performed for the two cities aforementioned, to compare the energy savings in summer and winter with parameters as mentioned in Sections 5.3.1 and 5.3.2. The simulation interval is 90 days long to show the typical summer and winter savings effect of using solar thermal water heaters on the electrical water heating load. The months chosen for summer are June, July and August and the months chosen for winter are December, January and February as prevailing in the United States.

Table 5.7 shows the percentage of energy savings with solar thermal water heaters during summer and winter. The summer savings are in the range from 70-80%, while the winter savings are between 35-45%. It is to be noted that the energy savings for winter is much higher in the case of simulation with five consecutive days, since winter comprises mostly cloudy days compared to summer. The glass tube collectors have an upper edge in savings even after aggregation. Energy savings in this seasonal simulation is not similar to that in Table 5.4 since the simulations for winter and summer in both these cities include the boundary climate days at the start and the end of the season as well as sunny and cloudy days.

Table 5.7 Comparison of Energy Savings in electric water heating during Summer and Winter with 100 water heaters in a residential distribution feeder with electric elements only, flat plate (with one glass pane) and glass tube collectors with auxiliary electric elements, Locations used – Madison, WI and Tampa, FL.

Locations	Day types	Electric Elements only Energy in KWHr	Flat Plate Collector Energy in KWhr	% energy savings with FPC	Glass Tubes Collector Energy in kWhr	% energy savings with GTC
Madison WI	Summer	15398.25	4594.84	70.16	3512.34	77.19
	Winter	43594.23	27412.05	37.12	26178.34	39.95
Tampa, FL	Summer	14457.65	4053.93	71.96	3218.27	77.74
	Winter	22142.78	13396.38	39.5	12849.46	41.97

Table 5.7, which summarizes the seasonal energy savings, re-emphasizes the fact that Tampa, FL in the warmer climate zone experiences more energy savings compared to Madison, WI which lies in the frigid northern climate zone in United States from the use of solar thermal water heaters.

This long term simulation gives a realistic picture of the seasonal energy savings in a residential distribution feeder, which will help utilities to estimate electrical water heating distribution load based on weather as well as plan ahead for load control activities. Further, all glass tube collectors which are more efficient than flat plate collectors can be recommended based on the savings in energy and peak demand reduction.

5.3.7 Energy Savings Comparison in a Residential Distribution Feeder for different SWH penetration levels

In this section, simulations are presented with different penetration levels of solar thermal water heaters in a residential distribution feeder with 100 homes. Figure 5.19 and Table 5.8 show the auxiliary energy consumption with different penetration levels of solar thermal water heaters in comparison with all-electric water heaters in a residential distribution feeder. The parameters used for simulations are mentioned in Sections 5.3.1 and 5.3.2. The months chosen for summer are June, July and August and the months chosen for winter are December, January and February as prevailing in the United States.

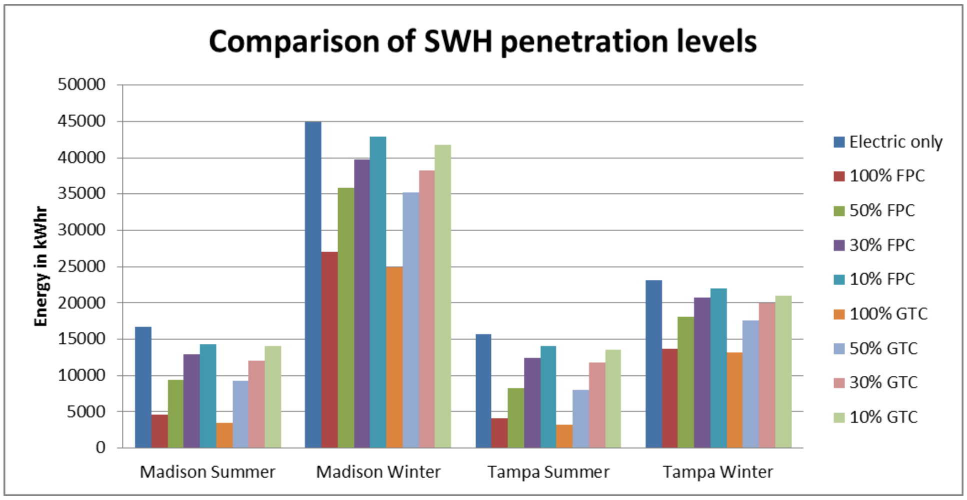


Figure 5.19 Comparison of electric energy consumption with different solar water heater penetration levels. The flat plate collector here has one glass pane, Locations used – Madison, WI and Tampa, FL.

Table 5.8 Comparison of electric energy consumption with different solar thermal water heater penetration levels. The flat plate collector here has one glass pane, Locations used – Madison, WI and Tampa, FL.

Location/ Day Types	Madison Summer		Madison Winter		Tampa Summer		Tampa Winter	
Configur-ation-->	Energy consumption in kWhr	% Energy savings compared to Electric only	Energy consumption in kWhr	% Energy savings compared to Electric only	Energy consumption in kWhr	% Energy savings compared to Electric only	Energy consumption in kWhr	% Energy savings compared to Electric only
Electric only	16738.93	-	44973.78	-	15735.56	-	23152.45	-
100% FPC	4659.53	72.16	26987.56	39.99	4135.87	73.72	13629.34	41.13
50% FPC	9429.3	43.67	35875.8	20.23	8271.74	47.43	18021.56	22.16
30% FPC	13278.54	20.67	39980.32	11.1	12053.21	23.4	20343.98	12.13
10% FPC	15029.45	10.21	43096.67	4.17	13952.78	11.33	21985.04	5.04
100% GTC	3498.65	79.1	25997.5	42.19	3256.54	79.3	13108.32	43.38
50% GTC	9233.45	44.84	35257.87	21.6	8034.56	48.94	17543.5	24.23
30% GTC	12753.5	23.81	38699.95	13.95	11774.68	25.17	19632.32	15.2
10% GTC	14278.43	14.7	41756.76	7.15	13203.23	16.09	20999.967	9.3

One would generally expect to see the savings to be proportionate to the level of penetration of solar thermal water heaters, though it is seen from the results that the savings is not proportionate to the penetration level since the hot water usages are realistic and random as in real life. Yet, the energy savings increase as the penetration of solar thermal water heaters increases.

Compared to Madison, WI, energy savings in Tampa, FL are higher with the different penetration levels of solar thermal water heaters due to the presence of Tampa in the warmer southern climate zone of the United States.

5.4 Effect of Outlet Temperature on Auxiliary Power Consumption

This section presents the results of energy savings associated with reduced temperature set points in a single water heater. Table 5.9 and Figure 5.20 show the comparison of the energy consumptions among the three configurations of water heaters with hot water temperature set point being 110°F and 120°F. The results are presented for four different seasons – winter, spring, summer and fall with hot water draw events considered for weekday as well as weekend. The simulation parameters are mentioned in Section 5.2.1 except temperature set points.

Table 5.9 Effect of outlet temperature set point on electric/auxiliary energy consumptions, Location used – VA Tech airport, VA. 'WE' refers to weekend and 'WD' refers to weekday.

Day Types	Setpoint=110 deg.F			Setpoint=120 deg.F		
	Electric Elements only Energy in Kwmin	Flat Plate Collector Energy in Kwmin	Glass Tubes Collector Energy in Kwmin	Electric Elements only Energy in Kwmin	Flat Plate Collector Energy in Kwmin	Glass Tubes Collector Energy in Kwmin
Winter WD	232.074	106.526	95.112	331.942	164.544	146.474
Winter WE	180.714	70.384	65.628	299.604	130.304	121.744
Spring WD	215.906	89.406	83.698	329.088	137.912	113.184
Spring WE	171.202	61.824	53.262	292.946	112.232	98.916
Summer WD	113.184	37.094	29.86	195.932	55.166	42.8
Summer WE	132.206	42.8	33	204.492	74.188	57.068
Fall WD	169.3	51.36	36.182	285.338	115.086	97.966
Fall WE	140.766	48.48	40.8	180.714	60.872	54.97

As seen in Table 5.9, the outlet temperature of water heater has an important role in energy consumption. As the outlet temperature increases, the energy required to heat the specified volume of water in the tank also increases. With 10 deg. F decrease in outlet temperature set point, the energy savings in electric water heaters range between 25-40% depending on the weather conditions. For solar water heaters, these savings is still higher which is due to higher fraction of solar energy being used to heat water with lower set point for outlet temperature. This implies that with solar thermal water heaters, hot water users benefit from additional savings by lowering the set point to the lowest possible temperature without compromising comfort.

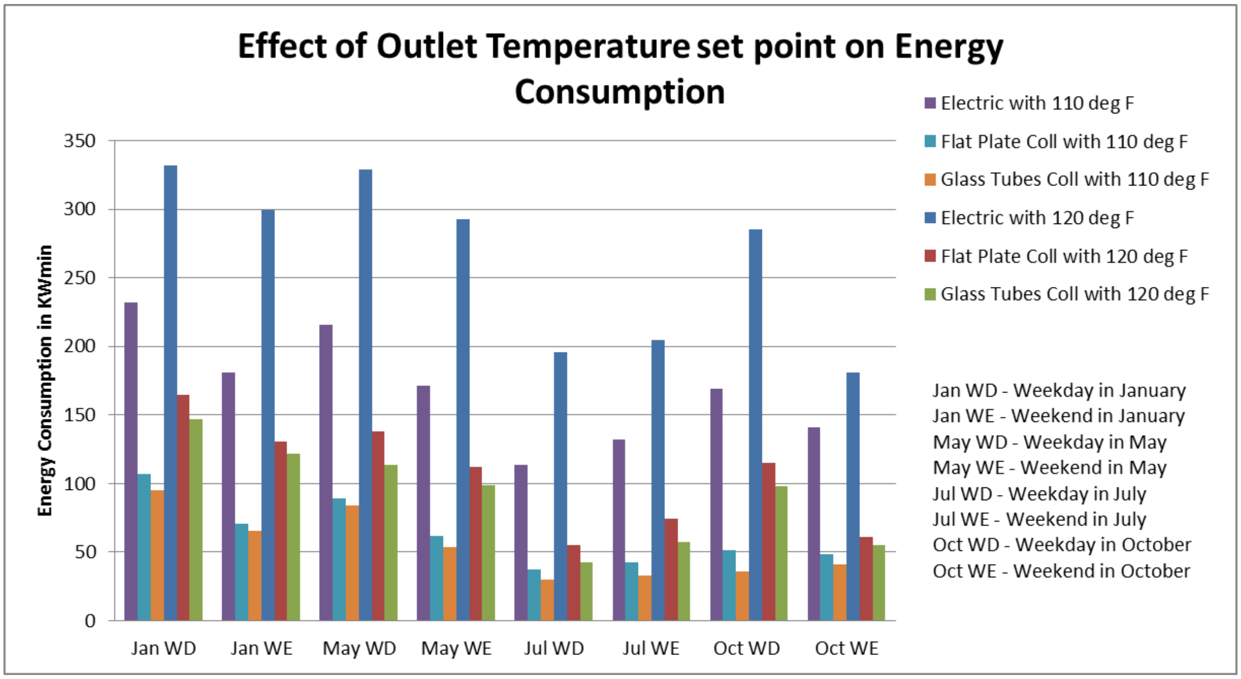


Figure 5.20 Comparison of the effect of outlet temperature on the electric energy consumption. The flat plate collector here has one glass pane, Location used – VA Tech airport, VA.

5.5 Effect of Glass Panes on Auxiliary Power Consumption

In this section, a single solar thermal water heater with flat plate collector is simulated for the number of glass panes Ng = 0, 1, 2 and the difference in auxiliary energy consumptions are compared. The simulation parameters for this comparison are the same as those used in Section 4.10.1 with the location set as Virginia Tech airport, VA, USA with TMY3 code: 724113TY. As seen in Figure 5.21, flat plate collectors with two glass panes save about 10-15% auxiliary electric energy compared to those with no glass panes and about 3-5% energy compared to collectors with one glass pane, which is accounted to the reduced wind convective losses with glass panes.

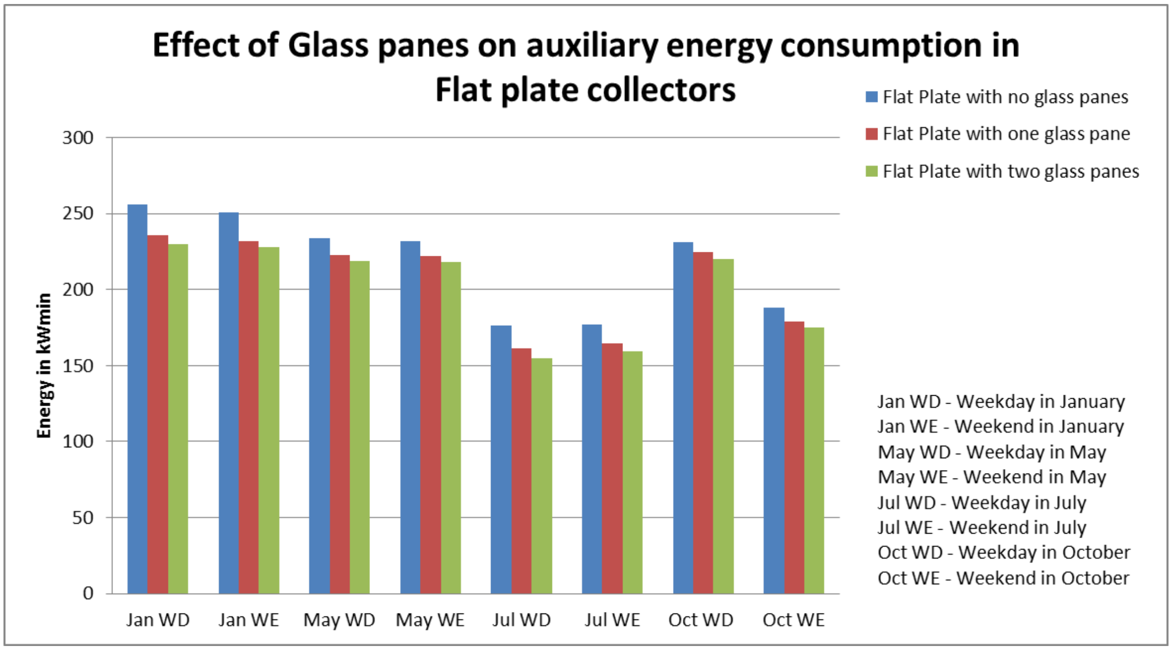


Figure 5.21 Comparison of auxiliary energy consumptions with 0, 1, 2 glass panes in a flat plate collector, Location used – VA Tech airport, VA.

The energy savings from flat plate collector with glass panes results from the fact that glass panes prevent convective losses from the absorber plate’s surface due to wind. Also, the lower face of the glass panes reflect back the long wavelength visible light reflected by the plate’s surface. As the number of glass panes on the flat plate collector increases the losses due to wind convection are reduced, though if the number of glass panes in higher than the optimal value, the absorption of the solar energy by the absorber plate itself is hindered by the combined transmittance effect of the glass panes.

The difference in the energy consumptions of single and double glass panes collectors is very minimal. Considering the high cost of glass panes, single glass pane collector is considered practical without compromising the savings in energy.

Chapter 6

Conclusions

In this research, the impact of solar thermal water heaters on the electric water heater load in a residential distribution circuit is analyzed. For this purpose, the electric water heater and solar thermal water heaters with both flat plate and evacuated glass tube collector are modeled in MATLAB. The model's inputs include the climate data from NREL in TMY3 hourly format, hot water draw events distributed in one-minute intervals and the solar collector and tank parameters. The output of the models is the electric energy consumption of all-electric and solar thermal water heaters with an auxiliary electric heating element.

Results obtained are statistically significant and show the energy saving and peak demand reduction potentials from solar thermal water heaters. The glass tube collector equipped solar water heater is more efficient than flat plate collectors with one glass pane. This efficiency results from the fact that the glass tube collector can absorb reflected radiation as well as direct and diffuse radiation for a wider range of incidence angles compared to the flat plate collector. Simulations can be performed for different geographic locations with the model presented. In this thesis, Madison, WI and Tampa, FL are chosen for simulations.

Also, the effect of the number of glass panes in a flat plate collector is analyzed. The flat plate collector equipped solar water heater consumes less electric energy with one or two glass panes compared to that with no panes. This results from the fact that glass panes prevent losses from the absorber plate due to wind convection. Further, the effect of the outlet temperature set point on the auxiliary energy consumption in both electric and solar thermal water heaters is noted.

It is expected that the model can serve as a tool for electric utilities and Independent System Operators (ISOs) to quantify the energy saving and peak demand reduction benefits obtained through the use of solar thermal water heaters at different penetration levels. It also helps home-owners to estimate their seasonal as well as daily electricity savings if using solar thermal water heaters.

Future Work

Efforts to improve scalability and computing speed can be helpful in obtaining useful results to perform large-scale analyses. Also, the electrical energy savings cited in this thesis can be translated into the actual financial savings with some light thrown on the economic aspects of solar thermal water heaters such as life-cycle cost calculations and electrical energy tariffs. Furthermore, the system reliability improvement with the introduction of solar thermal water heaters in a residential distribution circuit can be analyzed.

References

1. Liam Paull, Howard Li, Liuchen Chang. “A novel domestic electric water heater model for a multi-objective demand side management program”, Electric Power Systems Research 80 (2010) 1446–1451.
2. Søren Knudsen. “Consumers’ Influence On the Thermal Performance of Small Sdhw Systems—Theoretical Investigations”, Solar Energy Vol. 73, No. 1, pp. 33–42, 2002.
3. GridLAB-D Simulation Software [Online]. Available: http://www.gridlabd.org/
4. Soteris A. Kalogirou. “Solar thermal collectors and applications”, Progress in Energy and Combustion Science 30 (2004) pp. 231–295.
5. Renyuan Zhang, Huanlian Zhu, Hanbing Wen, Meicun L. “Performance Analysis of A Solar Glass Tube Collector”, Renewable Energy Vol. 3, No. 8. pp. 877- 883, 1993.
6. Benjamin S. Swanson, James H.Fletcher. “Analysis of Solar thermal water heaters on Peak demand”, Proceedings of ECTC 2008, 2008 ASME Technical conference, Oct 3-4, 2008.
7. DOE – Energy Efficiency & Renewable Energy – Solar water heaters – how they work [online]. Available: http://www.energysavers.gov/your_home/water_heating/index.cfm/mytopic=12850
8. John A. Duffie, William A. Beckman. “Solar Engineering of Thermal Processes”, Second Edition, 1980.
9. Runsheng Tang, Yanbin Cheng, Maogang Wu, Zhimin Li, Yamei Yu. “Experimental and modeling studies on thermosiphon domestic solar water heaters with flat-plate collectors at clear nights”, Energy Conversion and Management 51 (2010) 2548–2556.
10. H. Taherian, A. Rezania, S. Sadeghi, D.D. Ganji. “Experimental validation of dynamic simulation of the flat plate collector in a closed thermosyphon solar water heater”, Energy Conversion and Management 52 (2011) 301–307
11. W. A. Kamal. “Modelling The Thermosiphonic Solar Water Heater With Draw-Off”, Energy Conversion Mgmt Vol. 26, No. 3/4, pp. 329-335, 1986.

12. Afif Hasan. “Thermosyphon Solar Water Heaters: Effect Of Storage Tank Volume And Configuration On Efficiency”, Energy Conversion Mgmt Vol. 38. No. 9. pp. 847-854, 1997.
13. Benjamin S. Swanson, James H.Fletcher. “Analysis of Solar thermal water heaters on Peak demand”, Proceedings of ECTC 2008, 2008 ASME Technical conference, Oct 3-4, 2008.
14. Soteris Kalogirou and Christos Papamarcou. “Simple Validation Method of a TRNSYS Model for a Therrnosyphon Solar Water Heating System”, 10th Mediterranean Electrotechnical Conference, MEleCon 2000, Vol. III, IEEE.
15. Jinling Cao, Zunfeng Yang. “An Estimation Approach to Effective Solar Heat Gain Power”, 2010 International Conference on Computer Application and System Modeling (ICCASM 2010).
16. Delfín Silió Salcines, Carlos Renedo Estébanez and Valentín Castañera Herrero. “Simulation Of A Solar Domestic Water Heating System, With Different Collector Efficiences And Different Volumen Storage Tanks”.
17. Adnan Sozen, Tayfun Menlik, Sinan Unvar. “Determination of efficiency of flat-plate solar collectors using neural network approach”, Expert Systems with Applications 35 (2008) 1533–1539.
18. I. Farkas, P. Geczy-Vıg. “Neural network modelling of flat-plate solar collectors”, Computers and Electronics in Agriculture 40 (2003) 87/102.
19. Nand Kishor, Mihir Kr. Das, Anirudha Narain, Vibhaw Prakash Ranjan. “Fuzzy model representation of thermosyphon solar water heating system”, Solar Energy 84 (2010) 948–955.
20. T. Grassie, K. MacGregor, T. Muneer, J. Kubie “Design of a PV driven low flow solar domestic hot water system and modeling of the system collector outlet temperature”, Energy Conversion and Management 43 (2002) 1063–1078.
21. Adnan M. Shariah, A. Ecevit. “Effect of Hot Water Load Temperature On The Performance Of A Thermosyphon Solar Water Heater With Auxiliary Electric Heater”, Energy Conversion Mgmt Vol. 36, No. 5, pp. 289-296, 1995.

22. L.M. Ayompe, A. Duffy, S.J. McCormack, M. Conlon. "Validated TRNSYS model for forced circulation solar water heating systems with flat plate and heat pipe evacuated tube collectors", Applied Thermal Engineering 31 (2011) 1536-1542.

23. Renyuan Zhang, Huanlian Zhu, Hanbing Wen, Meicun L. "Performance Analysis of A Solar Glass Tube Collector", Renewable Energy Vol. 3, No. 8. pp. 877- 883, 1993.

24. Zhiyong Li, Chao Chen, Hailiang Luo, Ye Zhang, Yaning Xu. "All-glass vacuum tube collector heat transfer model used in forced-circulation solar water heating system", Solar Energy 84 (2010) 1413–142.

25. C. A. Estrada-Gasca, G. Alvarez-Garcia, T R. E. Cabanillas, P. K. Nair. "Theoretical analysis of the thermal performance of all-glass evacuated tube solar collectors with absorber coating on the outside or inside of the inner tube", Renewable Energy Vol. 2, No. 4/5, pp. 477-483, 1992.

26. Alexander Thur, Simon Furbo, Louise Jivan Shah. "Energy savings for solar heating systems", Solar Energy 80 (2006) 1463–1474.

27. National Renewable Energy Laboratory [Online]. Available: www.nrel.gov

28. Ian Knight, Nico Kreutzer, Hajo Ribberink. "European and Canadian non-HVAC Electric and DWH Load Profiles for use in Simulating the Performance of Residential Cogeneration Systems", Annex 42 of the International Energy Agency, May 2007.

29. Climate data in TMY3 format from NREL website [Online]. Available: http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

30. Water Heater University – Electric water heaters: How they work [Online]. Available: http://waterheateruniversity.com/electric-water-heater.html

31. Water heating tips from DOE – EERE [Online]. Available: http://www.energysavers.gov/tips/water_heating.cfm

32. ZT Taylor, K Gowri, S Katipamula. "GridLAB-D Technical Support Document: Residential End-Use Module Version 1.0", July 2008.

33. Shahab Alizadeh. "An Experimental and Numerical Study of Thermal Stratification in A Horizontal Cylindrical Solar Storage Tank", Solar Energy Vol. 66, No. 6, pp. 409–421, 1999 Elsevier Science Ltd.

34. Y.M. Han, R.Z. Wang, Y.J. Dai. "Thermal stratification within the water tank", Renewable and Sustainable Energy Reviews 13 (2009) 1014–1026.

35. Building America program tools at EERE website [Online]. Available: http://www1.eere.energy.gov/buildings/building_america/perf_analysis.html

36. Hot Water Tank Loss Calculation [Online]. Available: http://www.leaningpinesoftware.com/hot_water_heater_tank_insul.shtml

37. R. Hendron and J. Burch, "Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings", Conference Paper, NREL/CP-550-40874, August 2008.

38. Philip Fairey, Danny Parker. "A Review of Hot water draw Profiles used in Performance Analysis of Residential Hot Water Systems", July 20, 2004.

39. Introduction to evacuated tube collectors [Online]. Available: http://greenterrafirma.com/evacuated_tube_collector.html

40. Introduction to evacuated glass tube receivers [Online]. Available: http://www.gearsolar.com/GlassTubeReceivers.aspx

41. Jae-Mo Koo. "Development of a Flat-Plate Solar Collector Design Program", Master's Thesis, University of Wisconsin at Madison, 1999.

42. H.P.Garg. "Design and Performance of a Large size Solar Water Heater", Solar Energy 1973, Vol 14, pp 303-312.

43. Glycol Properties [Online]. Available: http://www.xydatasource.com/xy-showdatasetpage.php?datasetcode=234654&dsid=67&searchtext=glycol

44. Siegfried Rebsdat, Dieter Mayer. "Ullmann's Encyclopedia of Industrial Chemistry", JUN 2000, Wiley-VCH, Weinheim.

45. University of Wisconsin's TRNSYS software link [Online]. Available: http://sel.me.wisc.edu/trnsys/index.html

46. L.J. Shah, S. Furbo. "Vertical evacuated tubular-collectors utilizing solar radiation from all directions", Applied Energy 78 (2004) 371–395, Elsevier.

47. William A. Beckman, Lars Broman, Alex Fiksel, Sanford A. Klein, Eva Lindberg, Mattias Schuler, and Jeff Thornton. "TRNSYS - The most complete solar energy system modeling and simulation software", Renewable Energy, Vol.5, Part l, pp. 486-488, 1994.

48. C. A. Estrada-Gasca, G. Alvarez-Garcia, T R. E. Cabanillas, P. K. Nair. "Theoretical analysis of the thermal performance of all-glass evacuated tube solar collectors with

absorber coating on the outside or inside of the inner tube", Renewable Energy Vol. 2, No. 4/5, pp. 477-483, 1992.

49. Zhiyong Li, Chao Chen, Hailiang Luo, Ye Zhang, Yaning Xu. "All-glass vacuum tube collector heat transfer model used in forced-circulation solar water heating system", Solar Energy 84 (2010) 1413–142.

50. IE Lane, N Beute. "A Model of the Domestic Hot Water Load", IEEE Transactions on Power Systems, Vol. 11, No. 4, November 1996.

51. R. F. Bischke, R. A. Sella. "Design and Controlled Use Of Water Heater Load Management", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, No. 6, June 1985.

52. M. Ahachad, R. Dkiouak, M. Ajdour, M. El Metoui and R. Belarbi. "PREVIS 1.0: Easy software for simulation and sizing of solar water heating system", Revue des Energies Renouvelables Vol. 10 N°1 (2007) 67 – 74.

53. I.M. Michaelides and D.R. Wilson. "Optimum Design Criteria for Solar Hot Water Systems", WREC 1996.