ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
FACULTY OF TECHNOLOGY
DEPARTMENT OF MECHANICAL ENGINEERING

TRNSYS Modeling and Simulation of Solar Water Heating System for Addis Ababa University Technology Faculty Students Residence Hall

By

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A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for the Degree of Masters of Science in Mechanical Engineering (Thermal Engineering Stream)

Advisor

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Faculty of Technology

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ABSTRACT

In this study, the transient performance of direct open-loop circulation active solar water heating system is computed using TRNSYS modeling and simulation software for flat-plate collector from the input of average annual climatic data of Addis Ababa and collector parameters.

Typical daily hot water consumption for about 1000 students of Addis Ababa University, Technology Faculty was considered. The hot-water demand temperature (60 °C) is controlled by a conventional electrical/fuel auxiliary heater.

The thesis focuses on simulation of solar water heating system and its economic analysis. The various design parameters are taken from the manufacturers and dealer companies of solar water heaters in Ethiopia and also from the world experience. The meteorological data for simulation was taken from SEWERA website found in a text and TMY format.

The TRNSYS modeling and simulation are used to determine the outlet temperature of the solar collector and the daily contribution of the solar and the auxiliary heating system to the heating load.

From the annual contribution of solar energy to the heating load and the estimated investment cost, the payback period of the heating system using two backup systems (i.e. fossil fuel or electricity auxiliary heating) was compared.

The results obtained indicate that the payback period of the solar water heating system using furnace oil as backup heater is less than that of electricity, almost by half.

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Finally, all the thanks in the world go to my beloved mother and father. They endured so much to see this day, and the happiness it will bring to their heart is invaluable. I will always be in debt to them for all their sacrifice and love. It is to them that I dedicate this thesis.

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NOMENCLATURE

I_{ext}	Extraterrestrials radiation normal to the radiation, [W/m^2]
I_{sc}	Solar constant [W/m^2]
N	Day of the year, 1 for 1st January, 2 for 2nd January
$\overline{H}$	Monthly average daily radiation on horizontal surface [Wh/m^2.day]
$\overline{H}_0$	Monthly average radiation outside of the atmosphere for the same location [Wh/m^2.day]
a, b	Empirical constants
$\bar{n}_s$	Monthly average daily hours of bright sunshine [hr]
$\overline{N}_s$	Monthly average of the maximum possible daily hours of bright sunshine [hr]
I_N	Solar radiation energy incident on the collector surface [Wh/m^2]
G_r	Global radiation [Wh/m^2]
D_r	Diffuse radiation [Wh/m^2]
R_b	Beam radiation factor [$-$]
I_c	Flux collected per unit time [Wh/m^2]
V_s	Volume of Storage Tank [m^3]
C_{pw}	Heat Capacity of water [kJ/kg.k]
$\dot{Q}_u$	Useful energy gain [W]
$\dot{Q}_{Loss}$	Energy loss [W]
$\dot{Q}_{Load}$	Energy delivered to the Load [W]
$\dot{m}_w$	Mass flow rate of water [kg/s]
T_{wo}	Out let water temperature [^{0}C]
T_{wi}	Inlet water temperature [^{0}C]

A_s	Surface area of the storage tank [m^2]
D_i	Internal diameter of the storage tank [m]
D_o	External diameter of the storage tank [m]
t	Insulation thickness of the storage tank [m]
h	Height of the storage tank [m]
U_{LS}	Heat transfer coefficient of the storage tank [W/m^2-K]
DWC	Total daily hot water consumption [m^3]
PP(j)	Fraction of daily hot water consumption [-]
T_{ws}	Temperature of supply water [^{0}C]
T_1	Temperature of water in the tank [^{0}C]
T_a	Ambient temperature [^{0}C]
h_0	Convective heat transfer coefficient of ambient air [W/m^2-K]
K	Thermal conductivity of insulation [W/m.k]
$\dot{V}$	Volume flow rate [m^3/s]
k_f	Pressure loss factor [-]
V_1	Average velocity in the tube up stream of the fitting [m/s]
C_{pf}	Specific heat of collector fluid [kJ/kg-K]
T_a	Ambient (air) temperature [°C]
A	Total collector array aperture or gross area [m^2]
I_T	Global radiation incident on the solar collector (Tilted surface) [kJ/h-m^2]
F_R	Overall collector heat removal efficiency factor [-]
U_L	Overall thermal loss coefficient of the collector per unit area [kJ/h-m^2-K]
$U_{L/T}$	Thermal loss coefficient dependency on T [kJ/h-m^2-K]
a_0	Intercept (maximum) of the collector efficiency [-]

a_1	Negative of the first-order coefficient in collector efficiency equation [kJ/h-m^2-K]
a_2	Negative of the second-order coefficient in collector efficiency equation [kJ/h-m^2-k]
b_0	Negative of the 1st-order coefficient in the Incident Angle Modifier curve fit [-]
b_1	Negative of the 2nd-order coefficient in the IAM curve fit [-]
$\dot{P}_{rated}$	Rated power of the pump [kJ/hr]
$\dot{P}$	Power drawn by the pump at the current time [kJ/hr]
a_0, a_1, a_2, a_3	Polynomial coefficients in the pump power curve [-]
$\dot{Q}_{aux}$	Required heating rate including efficiency effects [kJ/hr]
C_{pf}	Fluid specific heat [kJ/kg.K]
$\dot{m}_i$	Inlet fluid mass flow rate [kg/hr]
$\dot{m}_0$	Outlet fluid mass flow rate [kg/hr]
$\dot{Q}_{fluid}$	Rate of heat addition to fluid stream [kJ/hr]
$\dot{Q}_{loss}$	Rate of thermal losses from heater to environment [kJ/hr]
$\dot{Q}_{max}$	Maximum heating rate of heater [kJ/hr]
T_{env}	Temperature of heater surroundings for loss calculations [°C]
T_{set}	Set temperature of heater internal thermostat [°C]
UA	Overall loss coefficient between the heater and its surroundings during operation [kJ/hr]
$Q_{a,solar}$	Annual contribution of solar energy to the heating load [kJ/hr]
f_a	Annual fraction of contribution of solar energy to the heating load [-]

ACRONYMS

SDHW	Solar domestic hot water
SHW	Solar hot water
SWH	Solar water heating
PV	Photovoltaic
FEP	Fluorinated Ethylene Propylene
ABS	Acrylonitrile-Butadiene-Styrene
UV	Ultraviolent
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl chloride
DNI	Direct Normal Irradiance
DIF	Diffuse Horizontal Irradiance
TRNSYS	Transient Systems Simulation Program
FORTRAN	FORmula TRANslation
SF	Solar fraction
RETs	Renewable and energy-efficient technologies
GHG	Greenhouse gas
LCC	Life cycle costing
REDI	Renewable Energy Deployment Initiative

GREEK LETTERS

$\emptyset$	Latitude angle [^{o}]
δ	Declination angle [^{o}]
ω	Hour angle [^{o}]
ω_s	Sunset hour angle [^{o}]

ρ	Ground reflectivity factor ,
γ	Pump control signal [0…1]
ρ_w	Density of water [kg/m^3]
μ_w	Dynamic viscosity of water [kg/m.s]
η_c	Collector efficiency [-]
α	Short-wave absorptance of the absorber plate [-]
τ	Short-wave transmittance of the collector cover(s) [-]
$\tau\alpha)_n$	($\tau\alpha$) at normal incidence [-]
β	Collector slope above the horizontal plane [°]
θ	Incidence angle for beam radiation [°]
ρ_g	Ground reflectance [-]
$(\tau\alpha)_b$	($\tau\alpha$) for beam radiation (depends on the incidence angle θ) [-]
$(\tau\alpha)_n$	($\tau\alpha$) at normal incidence [-]
$(\tau\alpha)_g$	($\tau\alpha$) for ground reflected radiation [-]
η_{htr}	Efficiency of auxiliary heater [-]
η_{motor}	Pump motor efficiency
$\eta_{Overall}$	Overall pump efficiency (motor efficiency * pumping efficiency)
$\eta_{Pumping}$	Efficiency of pumping the fluid

CHAPTER ONE

INTRODUCTION

Water heating accounts for a substantial portion of energy use at many residential, commercial, institutional and federal facilities. A solar water heating system is a substantial but rewarding investment. It can reduce the monthly heating bill while helping to protect our environment. Solar water heating systems, sometimes called solar domestic hot water (SDHW) systems which uses the sun's energy rather than electricity or gas to heat water, can efficiently provide up to 80% of the hot water needs of a family at tropical areas without fuel cost or pollution and with minimal operation and maintenance expense.

The amount of hot water that solar energy will provide depends on the type and size of the system, the climate, and the quality of the site in terms of solar access. A back-up heating system for water will be necessary during times when solar radiation is insufficient to meet hot water demands.

Solar water heating systems are generally composed of solar thermal collectors, a water storage tank or another point of usage, interconnecting pipes and a fluid system to move the heat from the collector to the tank.

A solar water heating system may use electricity for pumping the fluid, and have a reservoir or tank for heat storage and subsequent use. The water can be heated for a wide variety of uses, including home, business and industrial uses. Heating swimming pools, under floor heating or energy input for space heating or cooling are common examples of solar water heating.

Most commercial and institutional establishments use hot or warm water. The specific requirements vary in total volume, flow rate, duration of peak load period, and temperature.

The aim of this stage of the research is to develop a model of a solar water heater that can be used to predict the long-term performance of the system. Detailed system simulation has been performed using a transient simulation program, TRNSYS. This paper outlines the modeling procedure of each component of the solar water heater in the TRNSYS for system simulation.

1.1. Problem Background of the Study

Energy and the environment are two of the biggest problems that mankind face this century. Energy is one of the crucial inputs for socio-economic development. The rate at which energy is being consumed by a nation often reflects the level of prosperity that it could achieve.

Total energy consumption has increased along with economic and population growth and, at the same time, various environmental problems associated with human activities have become increasingly serious. In order to achieve the goals of sustainable development, it is essential to minimize the consumption of finite natural resources and to mitigate the environmental burden to within nature's restorative capacity.

The world energy demand increases time to time, so energy crises occurs now a-days. In addition to an increase in price of petroleum products, petroleum resources will be exhausted in a relatively short period of time and use of fossil fuel resources are affecting worldwide economic and social development.

To ensure a sustainable energy future, it is necessary to identify, develop and establish a variety of alternative energy solutions, some of which should be based on renewable forms of energy.

The impact of energy crises is particularly felt in less developed countries where a high percentage of national budgets for development must be diverted to the purchase of petroleum products. To reduce the dependant on imported fuels with high price, most countries have initiated programs to develop alternative energy sources based on domestic renewable resources.

The sun is our greatest domestic renewable energy resource. And we can use it for free. A great deal of research has been carried out on solar energy alternatives to heating by conventional means. The conclusion of a great part of this research is that solar energy is a viable, clean and sustainable source. Solar water heaters, or solar thermal systems, provide environmentally friendly heat for household water, space heating, and swimming pools.

Solar water heaters, sometimes called solar domestic hot water (SDHW) systems, use the sun to heat either water or a heat-transfer fluid, such as a water-glycol antifreeze mixture, in collectors generally mounted on a roof. The heated water is then stored in a tank similar to a conventional electric water tank. Solar hot water (SHW) systems use solar energy either to replace or supplement conventional, such a gas or electric, hot water heating units.

Reduced demand for fossil fuels will improve the environment by reducing air and water pollution as well as the heat-trapping gases that cause global warming. And though they cost a little bit more up front to install, a carbon free Solar Water Heating system will save consumers money in the long run as the fuel source (the sun's energy) will always be free.

1.2. Objectives of the Study

The general objective of this study is to model and simulate solar water heating system in students' residence hall of Addis Ababa university, technology faculty as an alternative method for heating water rather than using fossil fuel and electric power.

The specific objectives of this thesis are, therefore,

- Modeling of solar water heating system using TRNSYS
- Simulation of solar water heating system using TRNSYS
- Estimation of the daily hot water consumption needed and solar water heating system component sizing to cover the energy demand for heating water.
- Making cost and financial analysis

1.3. Methodology

The methods employed to achieve the objectives of the research are:

- Literature review of relevant materials on solar water heating systems
- Necessary Solar data for the analysis are collected from available sources

- Modeling and simulation of solar water heating system using TRNSYS simulation software
- Analysis and interpretation of the simulation results
- Financial analysis using RETScreen software
- Finally conclusions and recommendations are made

1.4. Thesis Organization

A brief introduction on the contents of the thesis report is outlined as follows:

- **Chapter one** gives the detail about an introduction to the topic. It also lays down the problem background of the study, the objectives of the thesis and elaborates the methodologies followed to meet the objectives.
- **Chapter two** gives the necessary literature review of solar water heating system in brief: various SDHW configurations, benefits and types of solar water heating systems.
- **Chapter three** focuses on the types of solar collectors used for solar water heating system with special attention given to flat plate collectors.
- **Chapter four** discusses the estimation of solar radiation and the collector energy for liquid flat plate solar collector used in simulation of solar water heating system.
- **Chapter five** discusses the hot water consumption pattern and component sizing of Addis Ababa University, Technology Faculty students’ residence hall hot water system.
- **Chapter six** discusses the TRNSYS modeling and simulation of the solar water heating system. It also comprises the simulation results of the solar water heating system and their discussions.
- **Chapter seven** discuses the economic analysis of the solar water heating system.
- **Chapter eight** discuses the conclusions and recommendations for the future work.

CHAPTER TWO

LITERATURE REVIEW

2.1. Solar Water Heating Systems Overview

Solar hot water systems use the sun's energy to heat water in liquid-based solar collectors; they are almost always used along with conventional water heaters.

Solar Water Heating technologies are simple, reliable, and cost-effective harnessing the sun's energy to provide for the solar thermal energy needs of homes and businesses.

The solar water heating system offsets the use of fossil fuel or electricity by preheating water before the conventional domestic hot water system.

Solar water heaters are cost competitive in many applications when we account for the total energy costs over the life of the system. Although the initial cost of solar water heaters is higher than that of conventional water heaters, the fuel (sunshine) is free. Plus, they are environmentally friendly. To take advantage of these heaters, we must have an unshaded, south-facing location (a roof, for example) on our property.

Nearly all of the SHW systems designed to date make use of solar thermal collectors. In these designs, solar energy is converted to thermal energy in a fluid which is circulated either actively (by use of a circulating pump) or passively (by natural convection) through one or more collectors exposed to the sun. In a typical system, potable water is circulated from the bottom of a hot water storage tank and passed through the collectors when adequate solar energy is available. The heated water is returned to the top of the storage tank for later use. In cases in which freezing is a concern, a heat exchanger might be employed to transfer heat from an antifreeze solution circulated through the collectors to potable water drawn from the storage tank.

The Performance of solar water heaters varies depending on how much energy is available and how cold the water is coming into the system.

The type and complexity of a solar water heating system is mostly determined by:

- The changes in ambient temperature during the day-night cycle.
- Changes in ambient temperature and solar radiation between summer and winter.
- The temperature of the water required from the system.

The amount of hot water a solar water heater produces depends on:

- The type and size of the system,
- The solar radiation intensity available at the site,
- Proper installation, and
- The tilt angle and orientation of the collectors.

Solar water heaters are made up of collectors, storage tanks, and depending on the system, pumps and controllers.

Solar water heating systems almost always require a backup system for cloudy days and times of increased demand. Conventional storage water heaters usually provide backup and may already be part of the solar system package. A backup system may also be part of the solar collector, such as rooftop tanks with thermosyphon systems. Solar Systems may also use a modulating type demand (tank less or instantaneous) water heater for backup.

2.2. Benefits of Solar Water Heating

It is a fact that most of the houses build today choose electric water heaters. The main reason is because they are easy to install and inexpensive. However, research has shown that in an average household with electric water heater spends about 25% of its home energy costs on heating water. According to the Florida Solar Energy Centre [4], it was found that U.S.A homes using solar water heaters can save as much as 50-85% annually on the utility bills over the cost of an electric water heater.

A solar water heater is a long-term investment that will save money and energy for many years. Like other renewable energy systems, solar water heaters minimize the environmental effects of enjoying a comfortable, modern lifestyle. In addition, they provide insurance against energy price increases, help reduce our dependence on imported oil, and are investments in everyone's future. Some of the advantages of solar water heating system are listed below:

Solar water heaters work in every climate

Today's solar hot water technologies can be operated efficiently and affordably in any climate. Systems are specifically designed for various climatic and geographical areas of the country.

Reduce energy costs

By installing a solar water heating system, a typical household can meet 50 to 80 percent of their hot water needs [4]. In southern climates, a SWH unit can meet nearly 100 percent of a household's hot water needs.

Proven efficient technology

Currently there are more than 300,000 Solar Water Heater units installed across the United States (excluding swimming pool applications) and because these systems have been proven efficient and reliable, the number of installations continues to grow by the thousands every year [4].

Improved environment

Solar energy is inherently nonpolluting, provides substantial freedom from the effects of fuel price increases, and saves valuable fossil fuels. Reduced demand for fossil fuels will improve the environment by reducing air and water pollution as well as the heat-trapping gases that cause global warming. And though they cost a little bit more up front to install, a carbon free Solar Water Heating system will save consumers money in the long run as the fuel source (the sun's energy) will always be free. Solar water heaters do not pollute because they avoid carbon dioxide, nitrogen oxides, sulphur dioxide and the other air pollution and wastes. When a solar water heater replaces an electric water heater, the electricity displaced over 20 years represents more than 50 tons of avoided carbon dioxide emissions [5].

2.3. Application Areas of Solar Water Heating Systems

The main application areas of solar water heating systems are as follows:

Residential applications:

- Excellent for home and condo
- Can be installed on almost any residence as a retrofit
- Remote locations where electricity is not available
- Anywhere green technology is desired

Commercial applications:

- Condominium, hotel, nursing home
- Resort, marina, cabins, sports complex
- University, research facility
- Park and recreational site, summer camp
- Factory and Industrial site
- Farm and agricultural site
- Laundry facilities
- Remote and off grid location
- Anywhere specified by building or engineering codes

2.4. Types of Solar Water Heating (SWH) Systems

There are two main categories of solar water heating systems. They can be either active or passive, but the most common are active systems. Active systems rely on circulating pump to move the liquid between the collector and the storage tank and some type of temperature control, while passive systems do not have any moving parts and rely on gravity and the tendency for water to naturally circulate as it is heated.

Solar water heaters are also characterized as open loop (also called "direct") or closed loop (also called "indirect"). An open-loop system circulates household water through the collector. A closed-loop system uses a heat-transfer fluid to collect heat and a heat exchanger to transfer the heat to household water.

2.4.1. Passive Solar Water Heating Systems

Passive systems move household water or a heat-transfer fluid through the system without pumps. Passive systems have the advantage that electricity outage and electric pump breakdown are not issues. This makes passive systems generally more reliable, easier to maintain, and possibly longer lasting than active systems [6, 7, and 8]. Passive systems are often less expensive than active systems, but are also generally less efficient due to slower water flow rates through the system.

There are two basic types of passive systems:

- Thermosiphon Systems and
- Batch collector-storage system

Passive systems that circulate water through thermosiphoning action are called Thermosiphon system and passive systems, whose collector and storage is one and the same, are called Batch Heater.

2.4.1.1. Thermosiphon Systems

The relatively simple, passive system and the most popular solar water heater worldwide is the thermosyphon. A thermosiphon system relies on warm water rising, a phenomenon known as natural convection, to circulate water through the solar absorber and to the tank. In an open-loop system (for nonfreezing climates only), potable water enters the bottom of the collector and rises to the tank as it warms. In colder climates, an antifreeze solution, such as propylene glycol, is used in the closed solar loop, and freeze-tolerant piping, such as cross-linked polyethylene (PEX), is used for the potable water lines in the attic and on the roof.

Several international manufacturers make thermosyphon systems. The following illustration (Figure 2-1) includes the primary components of any thermosyphon system.

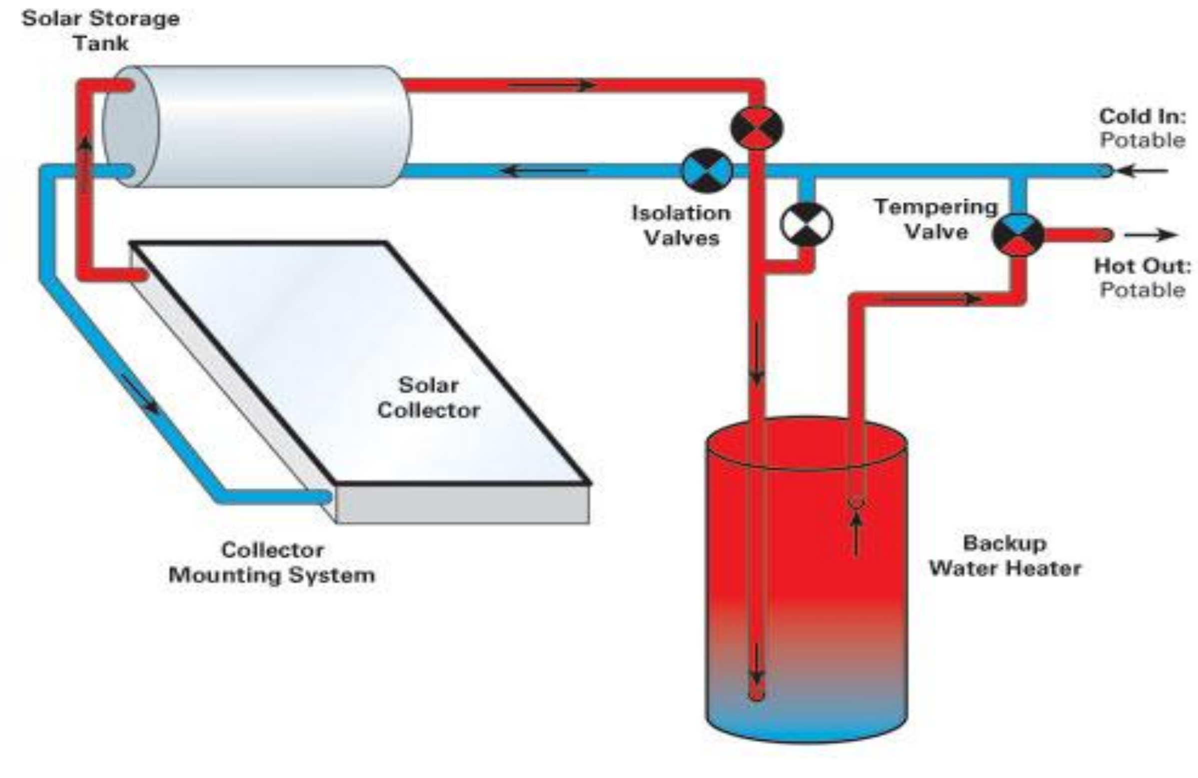


Figure 2-1: Thermosiphon System [3]

As the sun shines on the collector, the water inside the collector flow-tubes is heated. As it heats, this water expands slightly and becomes lighter than the cold water in the solar storage tank mounted above the collector. Gravity then pulls heavier, cold water down from the tank and into the collector inlet. The cold water pushes the heated water through the collector outlet and into the top of the tank, thus heating the water in the tank [6, 8].

A thermosiphon system requires neither pump nor controller. Cold water from the city water line flows directly to the tank on the roof. Solar heated water flows from the rooftop tank to the auxiliary tank installed at ground level whenever water is used within the residence.

Thermosyphon systems can be equipped with either evacuated tubes collectors or flat-plate collectors, which gives them the possibility of responding satisfactorily to different needs and climates. That's an advantage.

Thermosyphon systems are cheap, and since there are no pumps or controls they are reliable systems without technical or maintenance problems.

Relatively to the batch systems, thermosyphon systems allow a much higher flexibility: since the hot water is stored in a well-insulated tank - instead of being kept in the collector itself, like in batch systems – it can be used many hours after, without the problem of nighttime losses.

The big disadvantage or limitation of thermosyphon systems is that they depend deeply on air temperatures. To be more precise, they will stop working if temperatures drop below the freezing point and stay there for long. In that case the system needs to be drained or warmed. To overcome this limitation, in cold climates, some manufacturers equip their thermosyphon systems with small circulating pumps - pumps that are turned on in very cold weather conditions to move water and to prevent the one in the collector from freezing. Only in this case, thermosyphon systems are truly an all-climate solution.

Another possible disadvantage of this system – when installed on a roof – is their high weight. A tank full of water weights many liters, and that may require the reinforcement of roof structures.

2.4.1.2. Batch Collector- Storage Systems

Batch heaters are simple passive system consisting of one or more storage tanks placed in an insulated box that has a glazed side facing the sun.

In the integral collector storage solar system, the hot water storage system is the collector. Cold water flows progressively through the collector where it is heated by the sun. Hot water is drawn from the top, which is the hottest, and replacement water flows into the bottom [7, 8]. Some batch heaters use "selective" surfaces on the tank(s). These surfaces absorb sun well but inhibit radiative loss.

This system is simple because pumps and controllers are not required. On demand, cold water from the house flows into the collector and hot water from the collector flows to a standard hot water auxiliary tank within the house. Figure 2-2 shows the Batch collector-storage systems.

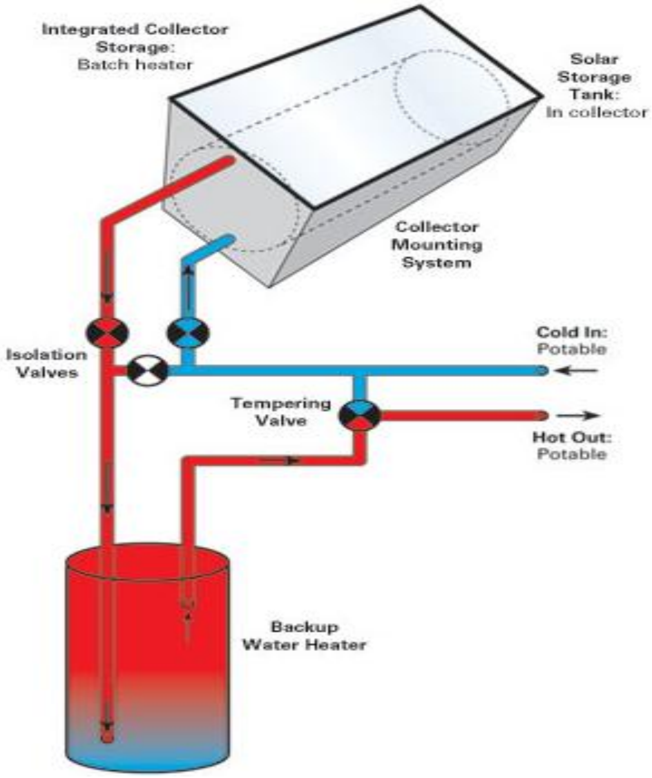


Figure 2-2: Batch Collector-Storage System [3]

2.4.2. Active Solar Water Heating Systems

Active systems use electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors. They are usually more expensive than passive systems but generally more efficient. Active systems are often easier to retrofit than passive systems because their storage tanks do not need to be installed above or close to the collectors. If installed using a PV panel to operate the pump, an active system can operate even during a power outage. But because they use electricity for pumping, they will not function in a power outage.

Active systems all function basically the same; however, there are different configurations depending on the climate zone.

There are two types of active solar water heating systems:

- Direct open loop circulation systems and
- Indirect closed loop circulation systems

2.4.2.1. Direct Open-Loop Circulation Systems

This is the simplest of the active type solar water heating systems. Direct Open-loop active circulation systems use pumps to circulate potable water through the collectors. This design is efficient and lowers operating costs but is not appropriate if water is hard or acidic because scale and corrosion will gradually disable the system. Open-loop active systems are popular in regions that do not experiences subzero temperatures (tropical and sub-tropical climates where temperatures do not often go below 0°C) [6, 7, and 8]. Flat plate open-loop systems should never be installed in climates that experience sustained periods of subzero temperatures. The basic components of an open loop system are listed below:

- Direct storage tank
- Circulating pump
- Differential control unit

- Temperature sensor
- Isolation valve
- Drain valve

A solar collector, typically mounted on the roof of the structure where the water is to be used, heats the water. The hot water is stored in a storage tank. The storage tank is typically installed in the basement, garage and is well insulated. The following illustration (Figure 2-2) includes the primary components of any open-loop direct system.

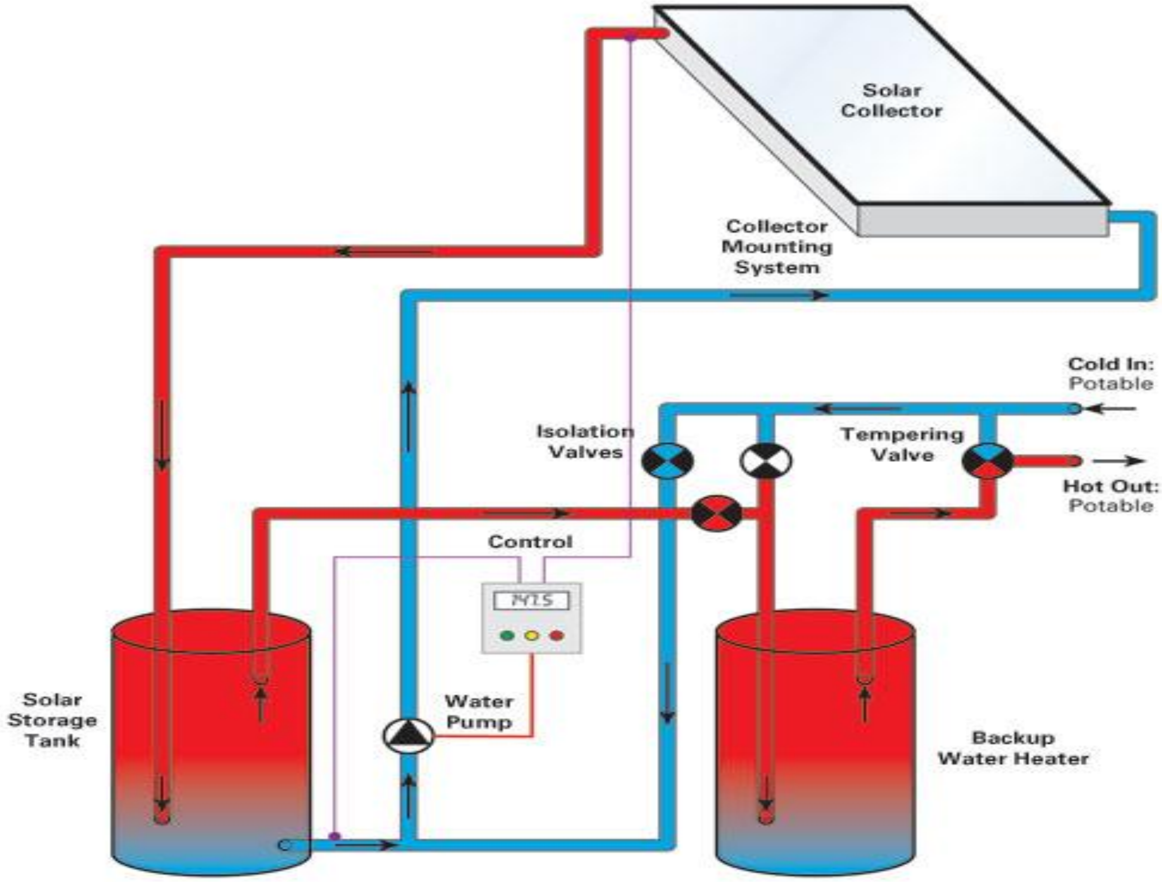


Figure 2-3: Active Direct Open Loop SWH System [3]

Sensors are used to monitor the temperatures of the water in the system. A differential control unit attached to the sensors is used to control a circulating pump. If the temperature at the collector is 5-7°C greater than the temperature at the bottom of the storage tank the water in the system is circulated. When the differential of the water temperature is 5°C the pump is turned off. In this way the water in the system is always being heated when the sun is shining. When required, a thermally operated valve, installed at the collector, is used to circulate the warm water into the collector as temperatures approach freezing.

Recirculation Systems

These are a specific type of open-loop system that provides freeze protection. They use the system pump to circulate warm water from storage tanks through collectors and exposed piping when temperatures approach freezing [6].

Photovoltaic Operated Systems

This type of solar water heaters is not much different to the ones discussed above. The main difference comes from the fact that the energy to power the pump is provided by a photovoltaic (PV) panel. The PV panel converts the sunlight into electricity, which then drives the pump. In this way water flows through the collector when the sun is shining.

The pump and the PV panel have to be suitable matched in order to ensure optimum performance of the system. The pump starts when there is sufficient solar radiation available to heat the solar collector.

Timers also used in order to control solar system operation. Most of them have a battery backup in case of power failure. The timers operate during the day when solar radiation is available to heat water. In order to avoid loss of energy from the tank during cloudy days, the collector lines are connected to the bottom of the storage tank with a special valve [6, 8].

2.4.2.3. Indirect Closed-Loop Circulation Systems

In this active, closed-loop system, incoming potable water is routed to the solar storage tank, but never into the collectors. These systems pump heat-transfer fluids (usually a glycol-water antifreeze mixture) from the collectors through a coil of pipe in the solar tank, and then pump back through the collectors. Heat exchangers transfer the heat from the fluid to the water that is stored in tanks. Double-walled heat exchangers or twin coil solar tanks prevent contamination of household water. Some standards require double walls when the heat-transfer fluid is anything other than household water. Closed-loop glycol systems are popular in areas subject to extended subzero temperatures because they offer good freeze protection. However, glycol antifreeze systems are more expensive to purchase and install and the glycol must be checked each year and changed every few years, depending on glycol quality and system temperatures.

Closed-loop active systems are designed for use in climates where freezing weather can occur more frequently. These systems, also known as closed loop systems, are the most commonly used in cold climates where temperatures often go below 0°c. A solar collector, filled with an anti-freeze solution (heat-transfer fluids), is used to collect the thermal energy in sunlight.

These systems require an expansion tank and a few other auxiliary components for filling, venting, and maintaining the system. A definite advantage to antifreeze systems is that the collectors can be mounted anywhere.

Typically a propylene glycol or ethylene glycol and water mixture is used [6, 7 and 8]. The following illustration (Figure 2-3) includes the primary components of any pressurized glycol system.

A pump circulates the solution through the collector and into a storage tank where a heat exchanger is fitted. The heat exchanger transfers the heat into the water stored in the tank.

The tube is designed to transfer the heat into the coldest water in the tank. The heat exchanger is a coil of tubing that wraps around inside the perimeter of the storage tank.

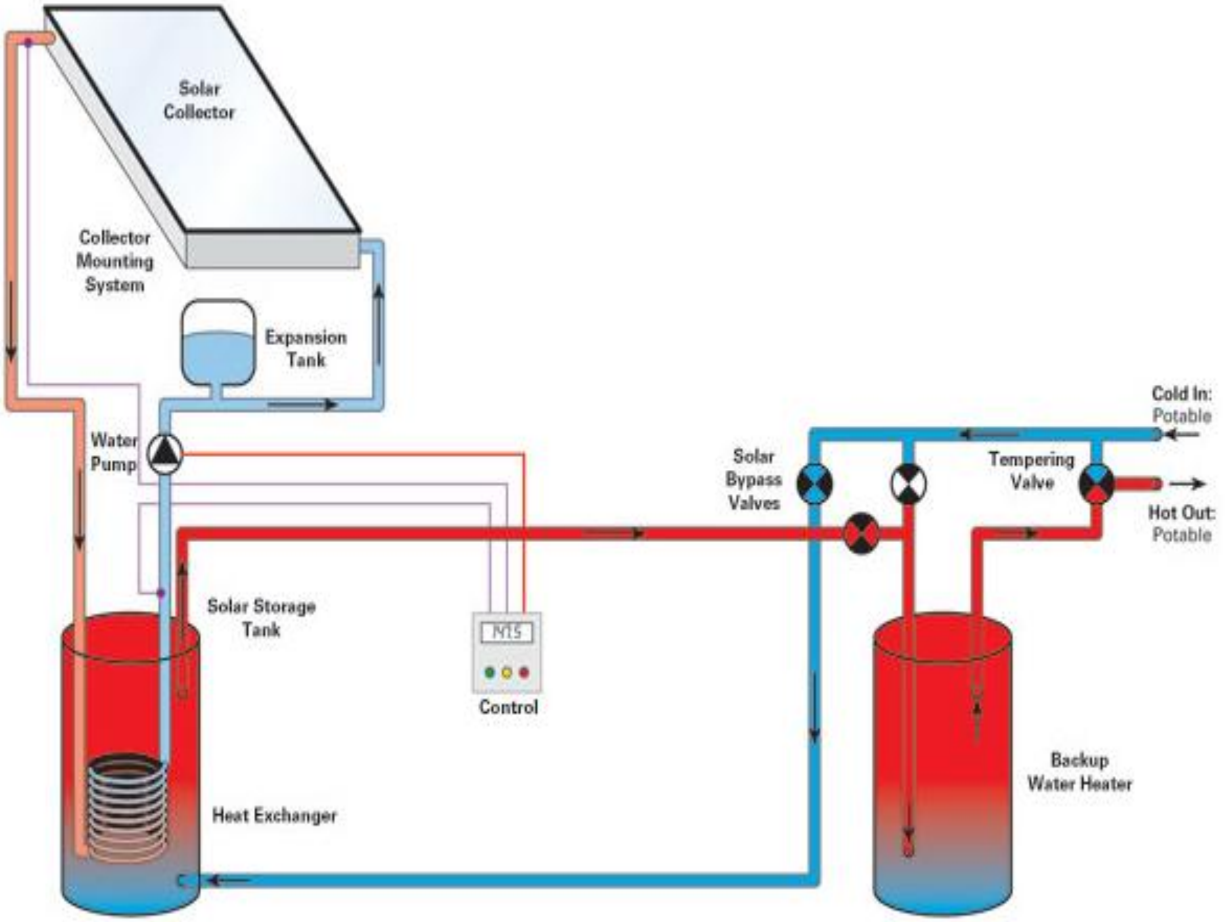


Figure 2-4: Active Indirect Closed- Loop SWH System [3]

2.4.2.4. Closed-Loop Drain Back Systems

The closed-loop drainback system requires perhaps the least routine service of any active system. Drain back systems are an indirect closed loop system that uses water as the heat-transfer fluid in the collector loop. There is no contact between the heat transfer liquid and the water in the system.

When the pump turns on, the distilled water is circulated from the reservoir back through the collector and heat exchanger, passing heat to the potable water in the solar tank. When the pump shuts off again, the distilled water drains back into the reservoir. The collector must therefore always be higher than the storage tank, and there must be sufficient continuous slope in the piping to ensure against freezing.

Drainback systems are effective and reliable. They work great, even on the hottest and coldest days of the year, and can operate twenty years without needing service. The only downside is that larger pumps usually have to be used, especially if you´re pumping water two stories or more, since the drainback pump has to lift the distilled water to the height of the solar collectors.

One way around the height problem is to place the reservoir in the attic, reducing the height the pump has to lift. However, if it´s located in a place where the pipes going to and from the reservoir could freeze, glycol must be added. This is also done when long, horizontal pipe runs do not allow drainback to occur quickly.

The following illustration (Figure 2-4) includes the primary components of any closed-loop drainback system.

The basic components of a drain back system are listed below:

- Indirect storage tank
- Reservoir tank
- Circulating pump
- Differential control unit
- Temperature sensor
- Gate valve
- Drain valve

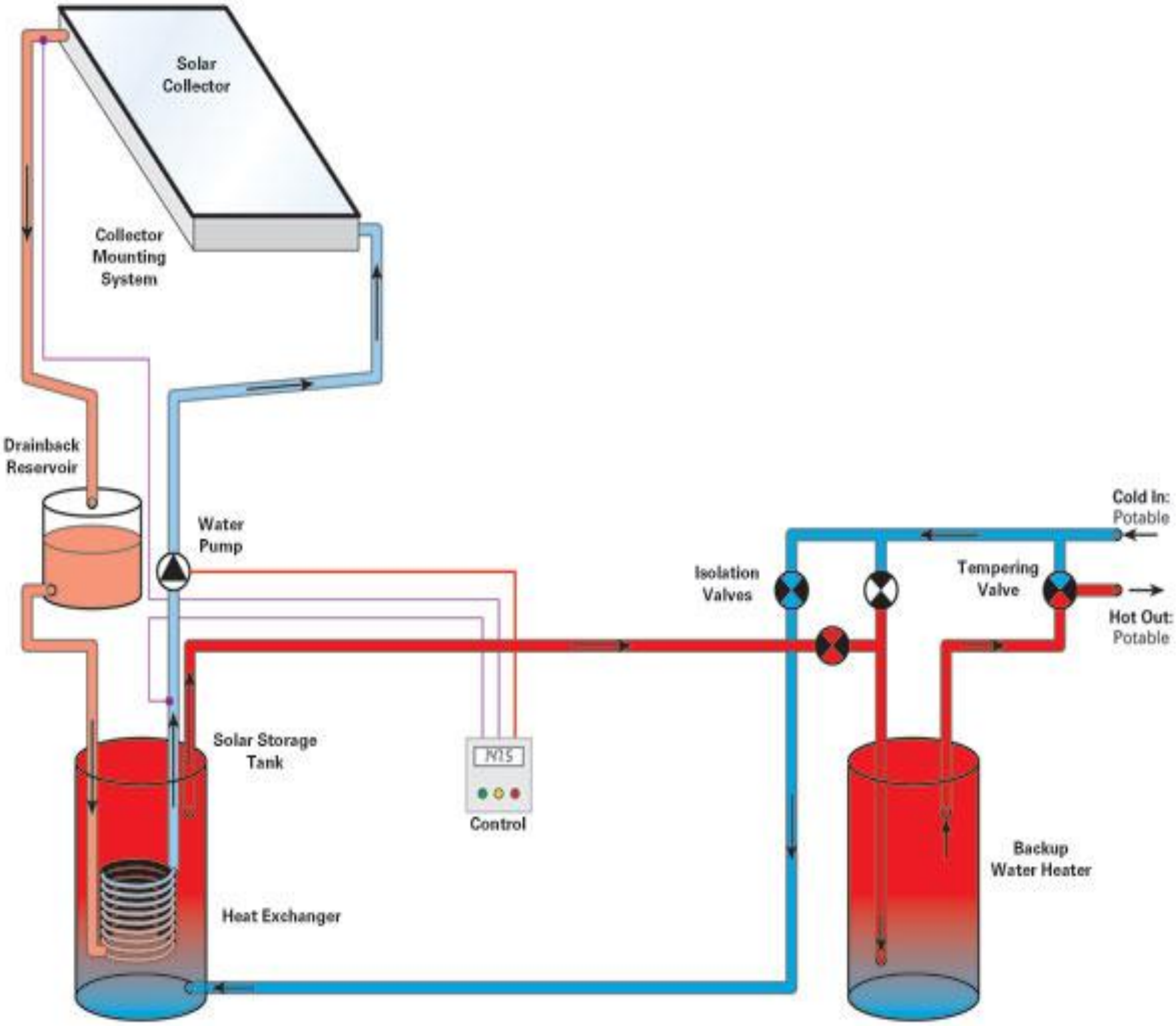


Figure 2-5: Closed-Loop Drainback SWH System **[3]**

CHAPTER THREE

SOLAR COLLECTORS

3.1. Types of Solar Collectors

Solar thermal energy refers to the capture of solar irradiation as usable thermal energy. Solar ‘collectors’ perform the task of capturing this energy. Solar collectors are the heart of most solar systems. The main task of the collector is to absorb the energy of the sun and to convert it to heat energy. According to the type of fluid they handle solar collectors can be divided into two main categories:

a) Liquid collectors: these types of solar collectors are mainly used for water heating in houses and swimming pools. The most common liquid used is water or antifreeze solutions in cold climates.

b) Air collectors: They are basically used for indoor spaces and to regenerate drying material in a drying cooling system.

According to the type of concentrations solar collectors fall into two general categories: non-concentrating and concentrating. In the non-concentrating type (i.e. Flat plate and evacuated tube solar collectors), the collector area (i.e. the area that intercepts the solar radiation) is the same as the absorber area (i.e., the area absorbing the radiation). In these types the whole solar panel absorbs the light.

There are basically three types of collectors used for water heating system:

- Flat plate,
- Evacuated-tube, and
- Concentrating.

3.1.1. Flat Plate Solar Collectors

Flat-plate collectors are most suitable for low temperature applications such as domestic hot water and space heating. They collect both direct and diffuse radiation. It is not required that they track the sun, thus initial cost and maintenance are minimized. A properly designed flat-plate collector has a life expectancy of 10 to 25 years, or sometimes longer. All copper and glass systems currently exhibit the longest lives. Using softened water will help. Tubes should be 1/2 inch in diameter or greater for low pressure drop and longer life. The better the attachment of tube-to- plate (such as by soldering), the better the heat transfer, but the greater the manufacturing cost.

Flat plate collectors (Figure 3-1) are the most common collectors for water heating (liquid type) and for space heating installations (air type), air conditioning, industrial process heat, drying of agricultural products and also it is simple and effective means of collecting solar energy for applications that require heat at temperatures below about 100 ^{o}c. In simple words a flat plate collector is an insulated metal box with either glass or plastic cover, which is called “glazing”. The dark color plate is called the “absorber plate” because it absorbs the sun radiation. The glazing can be “transparent” or “translucent” [8]. Flat-plate collectors have the following main components: (1) a dark flat-plate absorber of solar energy, normally metallic or with a black surface, although a wide variety of other materials can be used. (2) a transparent cover that allows solar energy to pass through but reduces heat losses, (3) a heat-transport fluid (air, antifreeze or water) flowing through tubes to remove heat from the absorber, these are tubes, fins, passages or channels connected to the collector absorber plate, (4) a heat insulating backing, which should be provided at the back and sides to minimize the heat losses, and (5) The casing or container, which encloses the other components and protects them from the weather. The absorber consists of a thin absorber sheet (of thermally stable polymers, aluminum, steel or copper, to which a black or selective coating is applied) backed by a grid or coil of fluid tubing placed in an insulated casing with a glass or polycarbonate cover. Fluid is circulated through the tubing to transfer heat from the absorber to an insulated water tank. This may be achieved directly or through a heat exchanger.

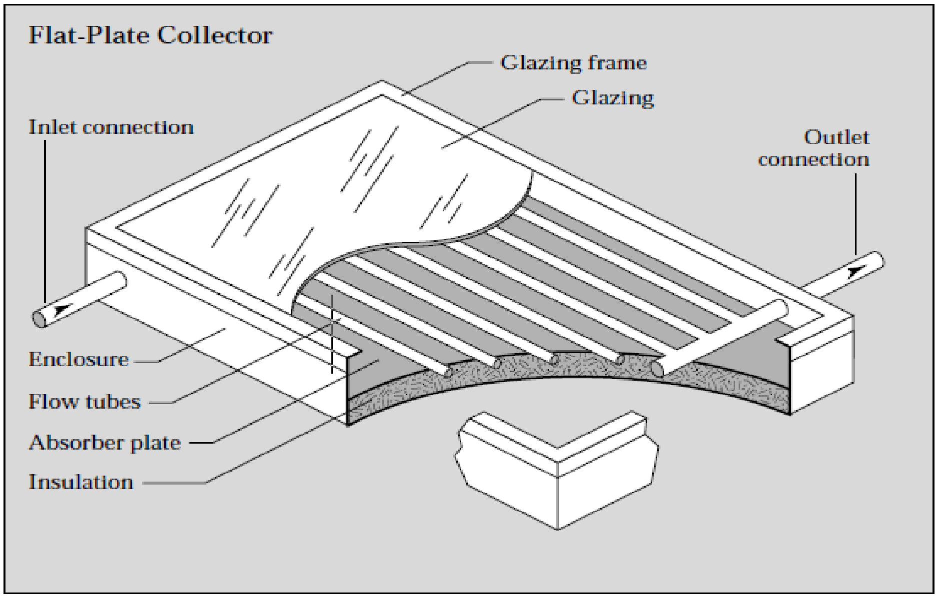


Figure 3-1: Flat Plate Solar Collector [27]

Translucent (transmitting light only), low iron glass is a common glazing material for flat-plate collectors because low iron glass transmits a high percentage of the available solar energy.

The roles of glazing in a solar collector are:

- To transmit as much solar energy as possible to the absorber plate;
- To minimize heat loss from the absorber plate to the environment;
- To shield the absorber plate from direct exposure to weathering.

Usually the sides and the bottom of the plate are insulated to minimize the heat losses.

The absorber plate is usually black. The reason is that dark colours absorb a higher percentage of sunlight than light colours.

The working principles of flat plate collector is, the sunlight passes through the glazing and strikes the absorber plate. The absorber plate then starts to heat up concentrating solar radiation into heat energy. The heat then is transferred to the water passing through the flow tubes [8]. Flat plate collectors are divided into two categories, a) liquid collectors and b) air collectors. Both of them can be either glazed or unglazed.

3.1.1.1. Liquid Collectors

In a liquid collector solar energy heats the liquid as it flows through the tubes in or adjacent to the absorber plate. The flow tubes are attached to absorber plate so the heat absorbed by the plate is transferred to the liquid. The simplest liquid systems use potable household water, which is heated as it passes directly through the collector and then flows to the house. There are two types of liquid collectors

a) The “Z” array (Figure 3-2) where the flow tubes are placed in parallel.

b) The “U” array (Figure 3-3)

The most common is the “Z” array. However, the “U” array has an extra advantage. First of all it eliminates the possibility of leaks and ensures uniform flow. The disadvantage is that the system cannot be drained completely in order to avoid freezing [9.10,11].

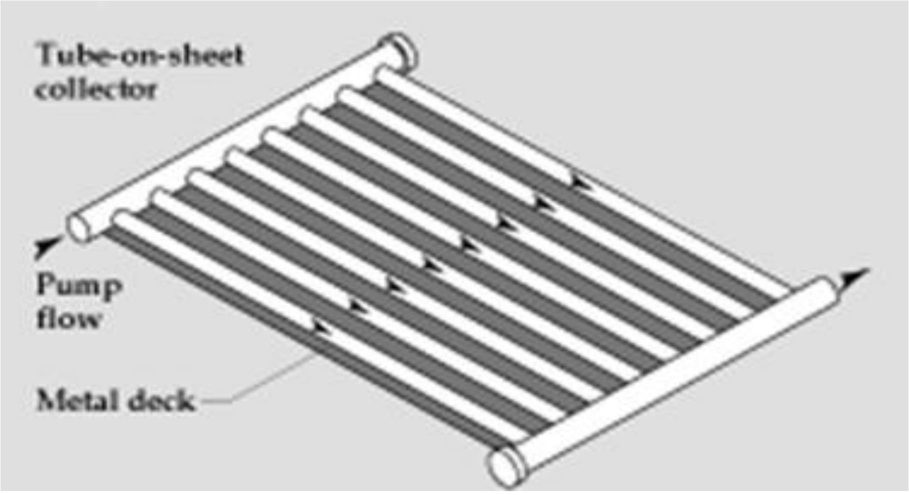


Figure 3-2: “Z” Array Liquid Collector [27]

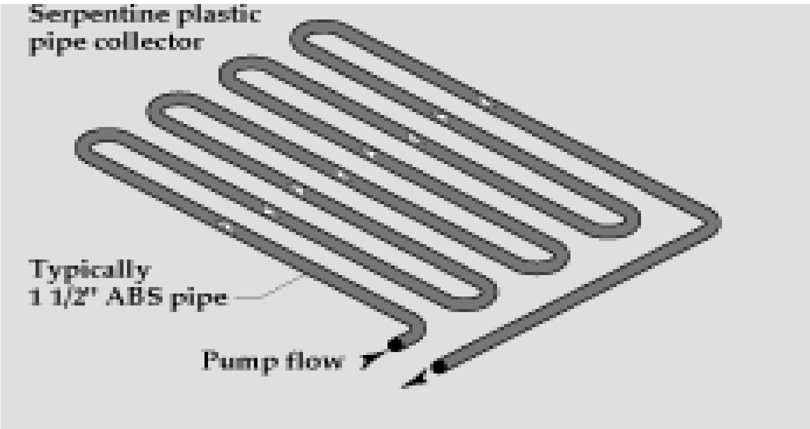


Figure 3-3: “U” Array Liquid Collector [27]

3.1.1.2. Air Collectors

Air flat plate collectors (Figure 3-4) are used mostly for solar space heating and drying crops. The absorber plate can be metal sheet or non-metallic materials. The air flows past the absorber plate placed by natural convection or forced by a fan. A disadvantage of air collectors compared to liquid is that less heat is transferred between the air and the absorber plate [12, 13].

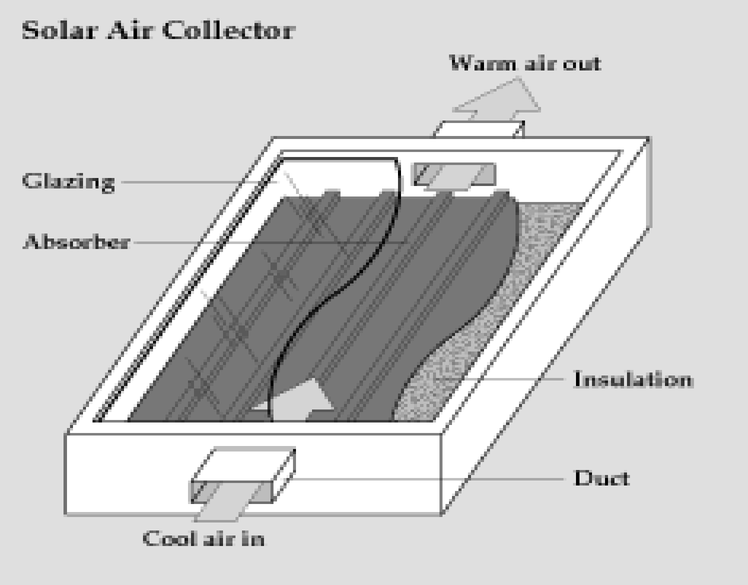


Figure 3-4: Solar Air Collector [27]

In some air collectors, fins on the absorbers are used to heat transfer. The disadvantage of this configuration comes from the fact that it increases the power needed for circulating fans and thus increases the systems operating cost.

The advantage of air system is they eliminate the problems associated with liquid collectors (e.g. freezing). Leaks can cause less troubles compared to liquid systems. They also use less expensive materials such as plastic [9, 13].

3.1.2. Evacuated Tube Solar Collectors

This type of collector uses a vacuum between the absorber and the glass outer tube to significantly reduce convection and conduction heat losses.

Evacuated-tube collectors operate essentially the same as flat-plate collectors. Solar radiation passes through the outer glass tube and is absorbed by the coated absorber. Heat energy is transferred to fluid flowing through the absorber.

Evacuated-tube solar collectors are not the most popular method for heating water, but they can be far more effective than some more popular systems in the right environment. For example, flat-plate solar collectors are the most used solar water heaters, but an evacuated tube collector can produce far more heat and absorbs more light. Evacuated-tube collectors can achieve extremely high temperatures (77^0C to 177°C), making them more appropriate for cooling applications and commercial and industrial application. However, evacuated-tube collectors are more expensive than flat-plate collectors, with unit area costs about twice that of flat-plate collectors.

Evacuated tube collectors are mostly used to heat water in residential applications that require higher temperatures. Sunlight enters through the outer glass tube and strikes the absorber tube(s) and changes to heat. The heat is transferred to the liquid flowing through the absorber tube. The collector consists of rows of parallel transparent glass (Figure 3-5) each tube contains an absorber tube with selective coating. In such type of solar collectors, tubes can be either added or removed [8].

The tubes are designed in such a way that air is evacuated from the space between the two tubes forming a vacuum. Conductive and convective heat losses are eliminated because there is no air to conduct heat nor to circulate and cause convective losses.

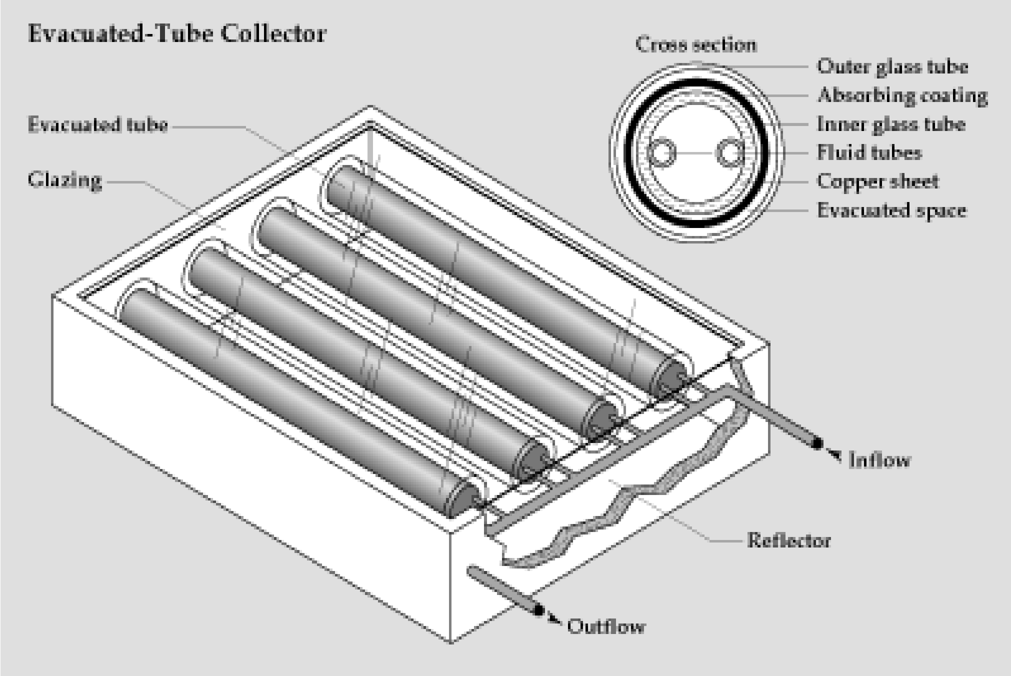


Figure 3-5: Evacuated Tube Collector [27]

Evacuated tube collectors are available in a number of designs. Some of them use a third glass tube inside the absorber tube or other configurations of heat transfer fins and fluid tubes. For additional sunlight it is possible to place reflectors behind the evacuated tubes. This makes the collector more efficient, offering the advantage of performing better in both diffuse and beam radiation, making the collectors useful in cold climate areas. Another positive fact is due to its shape. The circular shape absorbs the sunlight perpendicularly for most of the day. However the disadvantage of such collectors is that are more expensive compared to flat plate [9, 14].

They may not be as efficient as flat-plate collectors at low-temperature applications such as domestic water heating and space heating. For these applications, evacuated tube collectors should be judged on a cost per Btu basis to determine their effectiveness. Maintenance costs may be higher and heat dissipation coils may be required.

3.1.3. Concentrating Collectors

Concentrating or focusing collectors intercept direct radiation over a large area and focus it onto a very small absorber area. Concentrating collectors use mirror surfaces to collect sunlight on an absorber called receiver. These collectors can provide very high temperatures more efficiently than flat-plate collectors, since the absorption surface area is much smaller. However they can only focus direct solar radiation, which affects the performance of the collectors especially in cloudy days [8]; diffuse sky radiation cannot be focused onto the absorber. Most concentrating collectors require mechanical equipment which constantly orients the collectors towards the sun and keeps the absorber at the point of focus.

Concentrating collectors can be designed in two methods. In one, which is the most advantageous, the sun’s energy is concentrated along a thin line called the “focal line” (Figure 3-6). The second method is to concentrate the sun’s energy onto a “focal point” [2, 9].

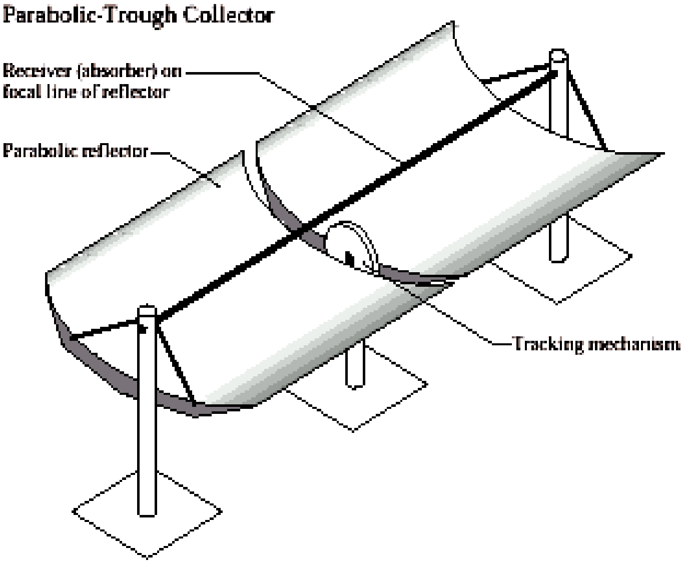


Figure 3-6: Concentrating Solar Collector (Parabolic Trough Type) [27]

There are many types of concentrating collectors. The most popular types are the parabolic trough, the power tower system, parabolic dish and linear Fresnel lens concentrators.

Concentrators are mostly used in commercial applications due to high cost and frequent maintenance of tracking mechanisms. For residential applications the most common type is the parabolic through collector with simple tracking mechanisms, which are less expensive than dual axis, for either hot water or space heating [15].

3.2. Selection of Collector

Evacuated tube type collectors are designed to heat the heat transfer fluid to high temperatures, in the order of 149º C (300º F). They are more suitable for applications that in addition to domestic hot water heating require space heating and or absorption cooling. Flat plate collectors are more cost effective for applications where the predominant load is domestic hot water heating. Since flat plate solar water heaters are most suitable for a temperature below 100^{o}C and are simple to assemble; low cost; simple in design and fabrication; durable; do not require sun-tracking; can work on cloudy days; and require minimum maintenance, in this research paper liquid – collector type flat-plate solar collector is chosen for solar water heating system of the residence hall. Therefore, this document provides further details on the flat plate collectors only.

3.3. Materials for Collector Components

The materials selected for one component will affect the possible choices of other components of the system. Therefore, it is important to consider all components whether they play a major role in the system or not. Thus the selection of the optimum materials and manufacturing processes is of vital importance of solar collectors and more specifically solar systems. As the project deals with a flat plate solar collector, this part gives an analytical overview of the appropriate materials and their specifications.

To design and construct solar collectors for water heating, detailed knowledge of the properties of the materials and the characteristics of the various components is necessary to predict the performance and durability of the collector.

Needed property data can generally be classified into three categories:

- Thermo physical

- Physical, and
- Environmental properties

Thermo physical properties: - include thermal conductivity, heat capacity and radiant heat transfer characteristics.

Physical properties: - include density, tensile strength, melting point, and modulus of elasticity.

Environmental properties: - include resistance to ultraviolet degradation, moisture penetration and degradability due to pollutants in the atmosphere.

Different components of the Flat-plate collector are discussed below:

3.3.1. Absorber Plate

The absorber is the central component of the solar collector. The collector absorber plate should have high thermal conductivity, adequate tensile and comprehensive strength, and good corrosion resistance. Metals such as Copper, Aluminium, Steel and Stainless steel are commonly used for absorber materials. Since these are not strongly absorbing a coating is provided which absorbs the solar radiation.

Heat transfer to the fluid depends on the thermal conductivity of the plate material and on the distance between fluid passageways. Thermal conductivities of absorber plate materials are given in Table 3-1. High thermal conductivities such as Copper and Aluminium can be economically used in plate and tubes, where heat conduction takes place along the plate. The passageways are most of the time closed spaces with medium conductivity materials, such as steel or stainless steel or copper and aluminium. Novel forming techniques such as super plastic forming and integral rolling are used to provide good mechanical bond between the absorber plate and the passageways.

Table 3-1: Thermal Conductivities of Absorber Materials

Material	Thermal Conductivity ($Wm^{-1}K^{-1}$)
Copper	376
Aluminium	205
Mild Steel	50
Stainless Steel	24
Acrylic	0.2
Polyethylene	0.30-0.44
Polypropylene	0.20
PVC (Polyvinyl Formal)	0.16

Absorber Coating

Some collectors are manufactured with a black coating which absorbs the high frequency incoming solar radiation very well and which emits low frequency infrared radiation poorly. This is a highly desirable combination of properties for a collector. In current solar collector constructions, the absorber is generally made from a material with poor absorbing properties (e.g. copper, aluminium, steel). A coating, which is highly absorbent of solar radiation, is generally applied to the upper surface. Two basic types of coatings are available. These are non-selective and selective coatings. Non-selective coatings have a high absorptance of solar radiation and a high emittance of thermal radiation, at high operating temperatures. Selective coatings have high absorptance of solar radiation but the emittance is low [16]. The absorptance should be 0.9 or higher and emittance may be 0.1 or lower. Such coatings are approximately equal in effect to one cover glass. Thus, a selective coating plus one cover glass may be expected to be about equal in efficiency to a collector with two cover glasses and a flat black painted surface.

The materials used for non-selective surfaces include matt-black paint based on polyester acrylic and epoxy resins. Common pigments are carbon black iron oxide, amorphous graphite, bone black and asphalt bases. Aluminium black paints can be used in concentrating collectors. For selective surfaces black chrome coatings have been investigated and show that there is a little change in optical properties after long time at high temperatures. Black nickel coatings are less stable and degrade with exposure to temperature and to humidity. Copper cobalt and zinc oxide show significant deterioration with exposure and stain less steel conversion coatings show a little decrease in absorptivity [16].

3.3.2. Glazing

The role of glazing in a solar collector is to reduce heat losses by trapping infrared radiation. The glazing also protects the absorber from the environment and may reduce radiative heat losses by reflective thermal radiation emitted by the absorber. But the most important property is the higher amount of transmittance of solar radiation. Any loss of transmittance will have direct effect of the collector's efficiency [16].

The important properties are transmission of solar radiation (up to 2μm), which must be as high as possible, and transmission of thermal radiation (greater than 2μm), which is more preferably should to be low. Glass, acrylic, polycarbonate and glass-reinforced polyester all have good optical properties. PVF and FEP (Fluorinated Ethylene Propylene) have better transmission of solar radiation but low transmission of thermal radiation. Metal oxide semiconducting films such as tin oxide and indium oxide are applied increasing the reflectance of thermal radiation to 75-80% [16].

Glass is highly resistant to weathering compared to some polymers, which are susceptible to solar radiation. Acrylic has also good resistance to weathering. PVT's are also resistible and are used to protect the less durable glassing. Other polymers such as GRP and polycarbonate are deteriorated by ultra violet radiation but can be stabilized by addition of fillers. The main disadvantage in this case is the high cost of fillers [16].

3.3.3. Casing

The choice of the material for casing is largely one of cost. Of the metallic materials, stainless steel and aluminium have good mechanical and weather properties. Coated mild steel has also good mechanical properties is cheaper but the weathering properties are poor. Mild steel has the advantage of little maintenance of solar collectors for at least 20 years, except in dry environments [16].

Cheaper casings are produced using polymeric materials. GRP is suitable for the outdoor environment although it cost nearly as much as aluminium or stainless steel. Other useful materials are extruded polypropylene or PVC molded thermoplastics and vacuum formed thermoplastic such as polypropylene or ABS (Acrylonitrile-Butadiene-Styrene). Filled polypropylene appears to be the lowest cost option. Some potential properties with polymeric casings are UV degradation, high thermal expansion coefficients and fire properties. Wood is also cheaper than plastics, but it is not used so often because it requires maintenance [16].

3.3.4. Collector Gaskets and Sealants

Gaskets and sealants must be carefully selected if a collector is to have a long life. Generally, the housing and the glazing have different rates of thermal expansion. Gaskets and sealants form the flexible interface between the two components and seal out moisture and other contaminants; if they fail, moisture will fog the glazing and may possibly damage the absorber coating and the insulation. These problems can drastically reduce the thermal performance of the collector.

The gaskets provide flexible support and the primary weather sealant insures against moisture leakage. Desiccants are sometimes placed between the two glazings to absorb any moisture that may remain after cover installation. When selecting collector gaskets and sealants, certain material requirements must be kept in mind. The gaskets and seals must:

1. Withstand significant expansion and contraction without destruction.
2. Adhere effectively to all surfaces.
3. Resist ultraviolet degradation.
4. Resist outdoor weathering.
5. Not harden or become brittle.
6. Withstand temperature cycling from -30 deg. to 400 deg. F.
7. Not outgas at high temperatures.

Both EPDM and silicone rubbers have been found adequate for use as gasket materials. Silicone sealants have exceptional weathering resistance and have received widespread use for many years. Neoprene and butyl rubbers are sometimes used. The sealing material is applied in solid form. In this case it is known as a seal. Also it can be applied in a butyl form [16]. The important properties of sealing materials are their temperature resistance, mechanical properties and weathering resistance. Some properties of the most appropriate materials are presented in Table 3-2 below.

An important consideration is that sealing materials must withstand low ambient temperatures, which may be as low as -15°C. Seals must also withstand the high temperatures encountered under stagnation conditions, which can be in excess of 100°C [16].

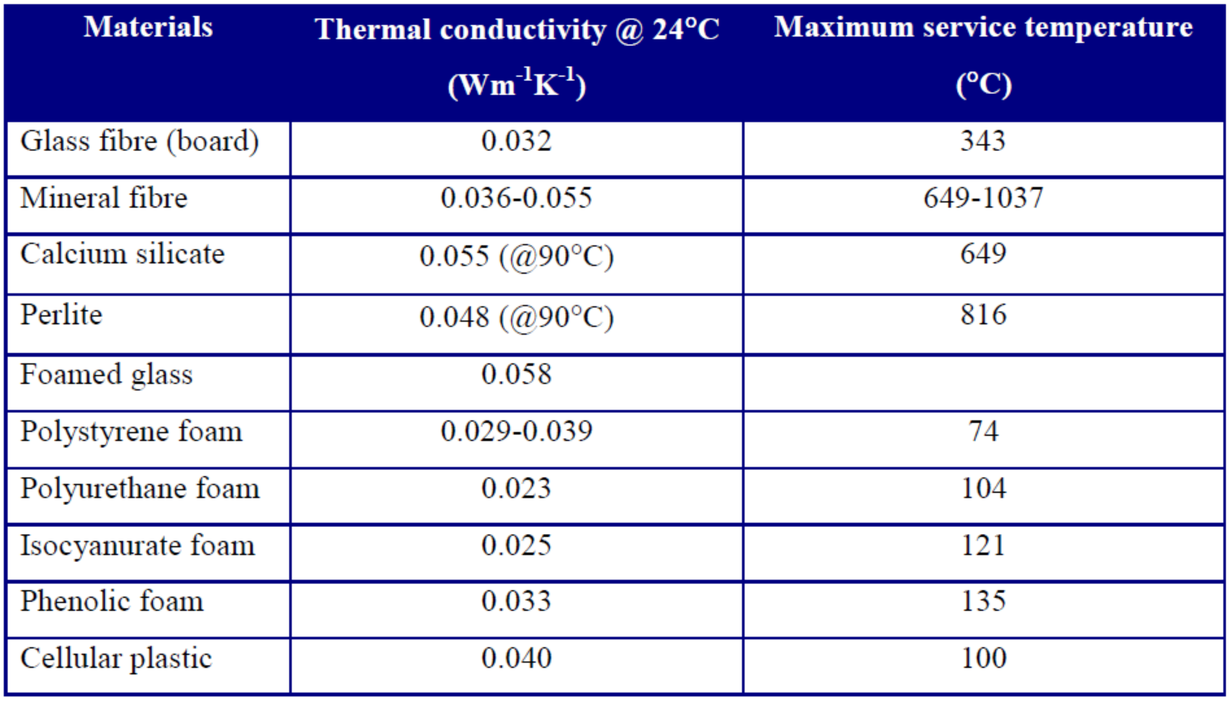
Table 3-2: Properties of Sealing Materials (4=excellent, 3=good, 2=fair, 1=poor)

Materials	**Working temp. Range (^{0}C)**		**Elongation to failure (%)**	**Resistance to compression set**	**Resista-nce to creep**	**Resistance to weathering**	**Resistance to water**
	Min	Max					
Acrylic	-40	130	400	3	2	4	1
Butyl	-50	125	800	2-3	2	4	2-4
Chloroprene (neoprene)	-20	130	600	3-4	2-3	4	3
Chlorosulphonated polyethylene	-40	120	500	1-2	2	4	3-4
EPDM	-40	120	600	3-4	2	4	4
Fluroelastomers	-40	230	300	3-4	3	4	4
Silicone	-60	230	700	2-4	3	4	3-4
Urethanes	-50	100	700	1-4	3	4	1-2

3.3.5. Absorber Insulation

A layer of insulating material can reduce conduction heat losses from the back and edge of an absorber. Insulation materials are commonly cellular, fibrous or granular [16]. Usually, this insulation consists of 1-6 inches of high-temperature fiberglass batting or semi-rigid board or even mineral wool. Styrofoam and urethane foams are usually not used because they may deform at high temperatures or give off gases (which may be toxic). Some properties of insulation materials are presented in Table 3-3. The common insulating materials such as glass fiber, mineral fiber, polystyrene foam, polyisocyanurate foam and polyethene foam, all have compatible thermal conductivities.

Table 3-3: Properties of Insulation Materials



Materials	Thermal conductivity @ 24°C ($Wm^{-1}K^{-1}$)	Maximum service temperature (°C)
Glass fibre (board)	0.032	343
Mineral fibre	0.036-0.055	649-1037
Calcium silicate	0.055 (@90°C)	649
Perlite	0.048 (@90°C)	816
Foamed glass	0.058	
Polystyrene foam	0.029-0.039	74
Polyurethane foam	0.023	104
Isocyanurate foam	0.025	121
Phenolic foam	0.033	135
Cellular plastic	0.040	100

The insulation material in a solar collector is generally in contact with the absorber. Therefore, it should be able to withstand the collector stagnation temperatures. Inorganic materials such as glass, fiber, mineral fiber, calcium silicate and perlite can withstand high temperatures.

Mineral fiber is selected for the back and edge of absorber plate insulation because it presents no fire hazards compared to other polymeric foams and can resist the high collector stagnation temperature.

3.4. Materials for Heat Management and Storage

The heat management and storage system consists of the pipework, the storage vessel (i.e. as the project deals with hot water system) and the control system. It is necessary that the particular conditions to consider for a solar water heating system. The materials aspects of these components are considered in this section.

3.4.1. Pipes and Connection

The pipework in a solar system must be able to withstand circulating fluid at temperatures up to 100°C without corroding. The most commonly used material is copper. Copper has good corrosion resistance. Stainless steel has also excellent corrosion resistance but it is more expensive than copper. It has several advantages like lower thermal conductivity (leading to lower heat losses) lower thermal expansion coefficient and higher strength to mass ratio allowing the use of thinner sections. Some other metals are cheaper than mild steel and copper but the oxidization rate is higher [16].

3.4.2. Storage Vessels

The primary task of the storage vessels is to contain the hot heat transfer fluid without corroding, and must withstand the pressures involved. Copper is the most commonly used material used for storage vessels because of its high thermal conductivity. The corrosion resistance of the copper is good but its disadvantage lies in its high thermal conductivity leading to heat losses.

Stainless steel and galvanized steel are used as storage vessel materials. Stainless steel has much better corrosion resistance but is more expensive. The thermal conductivity of steel is lower than copper and therefore less insulation material is required.

Polymeric such as polypropylene and GRP can be used for storage vessels. Corrosion and degradation resistance are adequate and the polymeric have the major advantage of thermal conductivity values reducing the need for insulation. The price for GRP is close to copper [16].

3.4.3. Control System

The control circuit contains several components and depending on the system design it may include a central control unit, temperature and pressure sensors, pumps flow meters.

The temperature and pressure sensors and the wiring in the collector box must be able to withstand the temperatures reached during stagnation conditions. The cable insulation is mostly from a material PTFE (Polytetrafluoroethylene), which have good high temperature properties compared to the commonly used PVC (polyvinyl chloride).

Pump components, valves are generally made from cast iron, brass, bronze, and stainless steel and for certain components polymeric such as acetal and nylon [16].

3.4.4. Collector Fluids

The choice of which collector fluid to use is important because this is the life-blood of the system. The cheapest, most readily obtainable, and thermally efficient fluid to use is ordinary water. However, water suffers from two serious drawbacks - it freezes and it can cause corrosion. Therefore, the choice of collector fluid is closely linked to the type of solar system, the choice of components, future maintenance, and several other factors. Implicit in this discussion is the use of a fluid other than air as the collector fluid.

If there is no danger of freezing and the collector loop consists of all copper flow passages, then ordinary water would be the choice for collector fluid.

Since in Ethiopia specifically in Addis Ababa there is no danger of freezing and the collector loop can all consists of copper flow passages, ordinary water is the choice for the collector fluid.

CHAPTER FOUR

SOLAR RADIATION AND ENERGY HARNESSED BY FLAT PLATE SOLAR COLLECTOR

4.1. Introduction

The prediction of collector performance requires knowledge of the absorbed solar energy by the collector absorber plate. Hence, an accurate knowledge of solar radiation distribution at a particular geographical location is of vital importance for the development of solar energy devices and for estimates of their performances.

The global solar radiation on horizontal surface at the location of interest is the most critical input parameter employed in the design and prediction of the performance of a solar energy device. The total solar radiation or global radiation, that is, the sum of the diffuse and beam solar radiation on a surface, is important for the design of flat-plate collectors.

The design of a solar water heating system requires precise knowledge regarding the availability of global solar radiation and its components at the location of interest. Therefore, knowledge of the local global solar radiation is required to simulate the solar water heater. Since the solar radiation reaching the earth's surface depends upon climatic conditions of the place, a study of solar radiation under local climatic conditions is essential.

Unfortunately, for many developing countries such as Ethiopia, solar radiation measurements are not easily available for not being able to afford the measurement equipment and techniques involved. Therefore, it is rather important to elaborate methods to estimate the solar radiation on the basis of more readily meteorological data.

In the absence and scarcity of trustworthy solar radiation data, the use of an empirical model to predict and estimate solar radiation seems inevitable. These models use climatological parameters of the location under study. Among all such parameters, sunshine hours are the most widely and commonly used. Hence the solar radiations used in TRNSYS are estimated from the average monthly sunshine hours available.

4.2. Extraterrestrial Radiation

Solar radiation outside of the earth's atmosphere is called extraterrestrial solar radiation. The extra-terrestrial radiation is the radiation that would be received from the sun on a horizontal surface with no atmosphere present.

The intensity of extraterrestrial radiation I_{ext} measured on a plane normal to a surface on the N^{th} day of the year is given in terms of solar constant (I_{sc}) as follows [1]:

$$I_{ext} = I_0 = I_{sc}\left[1 + 0.33\cos\left(\frac{360N}{365}\right)\right] \tag{4.1}$$

Where: I_{ext} = Extraterrestrials radiation normal to the radiation, [W/m^2]

I_{sc} = solar constant, given by I_{sc} = 1367 W/m^2

N = day of the year, 1 for 1st January, 2 for 2nd January,

The extraterrestrial radiation incident on a horizontal plane outside the atmosphere is given by:

$$I_0 = I_{sc}\left[1 + 0.33\cos\left(\frac{360N}{365}\right)\right] cos\theta_z \tag{4.2}$$

Where: θ_z is the zenith angle given by:

$$cos\theta_z = sin\delta\, sin\emptyset + cos\delta\, cos\omega\, cos\emptyset \tag{4.3}$$

$\emptyset$, **latitude**, is the angular location of the area north or south of the equator, north positive.

δ, **declination**, is the angular position of the sun at solar noon given by:

$$\delta = 23.45^0 \times \sin[\frac{360^0}{365} \times (284 + N)] \tag{4.4}$$

ω, **hour angle**, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15^0 per hour, morning negative, afternoon positive [1].

$\omega = (\mathrm{ST} - 12) \times 15^0$, Where, ST is solar time

By integrating equation (4.2) from sunrise to sunset we can obtain the daily extraterrestrial radiation on a horizontal surface, $\overline{\mathrm{H}}_0$:

$$\overline{\mathrm{H}}_0 = \left[\frac{24\times3600}{\pi}\mathrm{I_{sc}}\right]\left[1.0 + 0.033\cos\left(\frac{360\mathrm{N}}{365}\right)\right]\left[\cos\emptyset\cos\delta\sin\omega_s + \frac{\pi}{180}\omega_s\sin\delta\sin\emptyset\right] \tag{4.5}$$

Where: ω_s is the sunset hour angle given by

$$\omega_s = \cos^{-1}(-\tan\emptyset\tan\delta) \tag{4.6}$$

$\mathrm{I_{sc}} = 1367W/m^2, (solar\ constant)$

4.3. Solar Radiation on a Horizontal Surface

The radiation reaching the earth's surface can be represented in a number of different ways. Global Horizontal Irradiance is the total amount of shortwave radiation received from above by a surface horizontal to the ground. This value includes both Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DIF).

DNI is solar radiation that comes in a straight line from the direction of the sun at its current position in the sky. DIF is solar radiation that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere and comes equally from all directions.

4.3.1. Monthly Average Daily Global Radiation on a Horizontal Surface

The Angstrom regression equation related monthly average daily radiation to clear day radiation at the location in question and average fraction of possible sunshine hours is**:**

$$\frac{\overline{\mathrm{H}}}{\overline{\mathrm{H}}_0} = \mathrm{a} + \mathrm{b}\frac{\overline{\mathrm{n}}_\mathrm{s}}{\overline{\mathrm{N}}_\mathrm{s}} \tag{4.7}$$

The regression parameters ‘a’ and ‘b’ can be determined from:

$$a = -0.110 + 0.235 cos\emptyset + 0.323\left[\frac{\bar{n}_s}{\bar{N}_s}\right] \tag{4.8}$$

$$b = 1.449 - 0.533 cos\emptyset - 0.694\left[\frac{\bar{n}_s}{\bar{N}_s}\right] \tag{4.9}$$

The length of sun shine hours ($\bar{N}_s$) are computed from Cooper's formula:

$$\bar{N}_s = \frac{2}{15}\omega_s \tag{4.10}$$

4.3.2. Monthly Average Daily Diffuse Radiation on a Horizontal Surface

The monthly average daily diffuse radiation on a horizontal surface can be determined from the monthly average daily global radiation on a horizontal surface and the number of bright sunshine hours [1].

$$\frac{\bar{H}_d}{\bar{H}} = 0.931 - 0.814\left[\frac{\bar{n}_s}{\bar{N}_s}\right] \tag{4.11}$$

4.3.3. Monthly Average Hourly Global Radiation on a Horizontal Surface

The monthly average hourly global radiation on a horizontal surface can be calculated from the knowledge of the monthly average daily global radiation on a horizontal surface [1].

$$\frac{\bar{I}}{\bar{H}} = \frac{\pi}{24}(a + b cos\omega)\frac{cos\omega - cos\,\omega_s}{sin\,\omega_s - \frac{\pi}{180}\omega_s cos\,\omega_s} \tag{4.12}$$

Where: $a = 0.409 + 0.5016 sin(\omega_s - 60)$ (4.13)

$$b = 0.6609 - 0.4767 \sin(\omega_s - 60) \tag{4.14}$$

4.3.4. Monthly Average Hourly Diffuse Radiation on a Horizontal Surface

The monthly average hourly diffuse radiation on a horizontal surface can be calculated from the knowledge of the monthly average daily diffuse radiation on a horizontal surface [1].

$$\frac{\bar{I}_d}{\bar{H}_d} = \frac{\pi}{24}\frac{cos\omega - cos\,\omega_s}{sin\,\omega_s - \frac{\pi}{180}\omega_s cos\,\omega_s} \tag{4.15}$$

4.4. Energy Harnessed by Collector

In the flat-plate collector shown in Figure 4-1, the blackened absorber plate absorbs solar radiation and transfers heat to the water in the tube. The transparent cover which is opaque to infrared radiation and the insulation at the back trap the collected energy from being lost by radiation and convection.

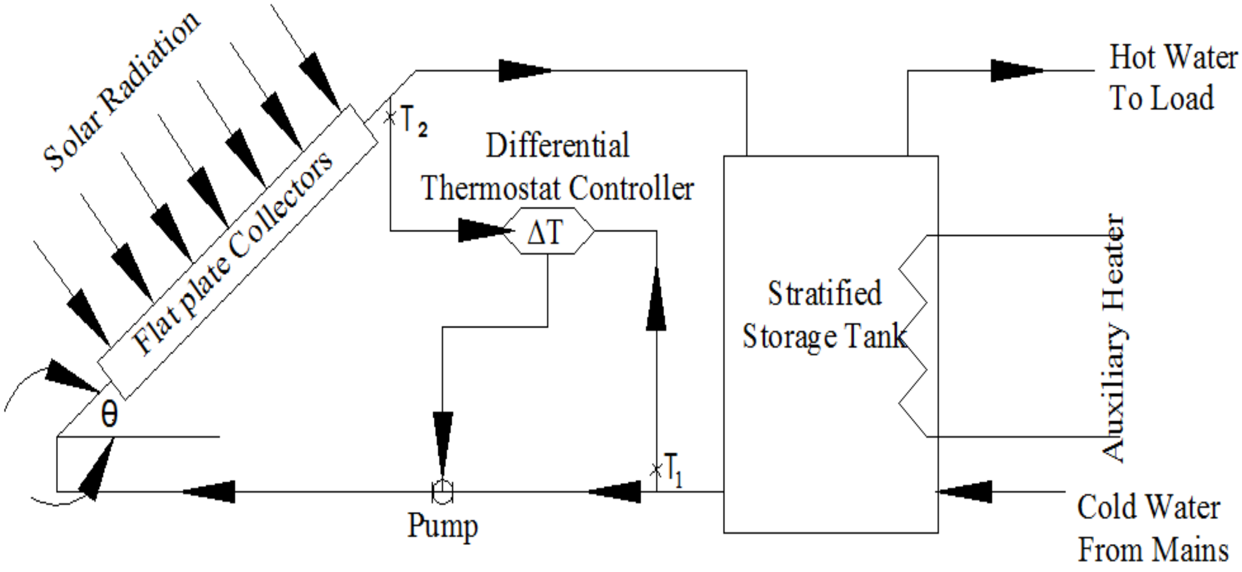


Figure 4-1: Schematic Representation of Active Direct Water Heating System with a Flat-Plate Collector

The solar radiation energy I_N incident on the blackened collector surface which is inclined at an angle θ to the horizontal, defined in terms of the global radiation G_r, the diffuse radiation D_r, the beam radiation factor R_b and the ground reflectivity factor ρ, is given by [1]:

$$I_N = R_b(G_r - D_r) + 0.5(1 + \cos\theta)D_r + 0.5\rho(1 - \cos\theta)G_r \tag{4.16}$$

The beam radiation factor R_b is dependent on hour angle, latitude, azimuth, solar declination, and collector slope.

Where: $R_b = \frac{\cos\theta_i}{\cos\theta_Z}$, $\theta_i = Angle\ of\ Incident, and\ \theta_Z = Zenith\ angle$

$$\cos\theta_i = (\cos\emptyset\cos\beta + \sin\emptyset\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma + \sin\delta\sin\emptyset\cos\beta - \sin\beta\cos\emptyset\cos\gamma \quad (4.17)$$

$$\cos\theta_Z = sin\delta\ sin\emptyset\ +\ cos\delta\ cos\omega\ cos\emptyset \quad (4.18)$$

The flux collected per unit time depends on the transmissivity τ of the glass cover (glazing) and the absorbtivity α of the absorber plate and is given as [1]:

$$I_c = I_N(\tau\alpha) \quad (4.19)$$

While most of the energy is transferred to the water, the rest is:

- Transferred to the surrounding across the glazing and insulation, and
- Stored in the absorber plate and glazing.

4.5. Efficiency of Collector

The thermal efficiency of the solar collector is a measure of the thermal performance of the collector and can be evaluated from energy balance that determines the portion of the incoming radiation delivered as useful energy to the working fluid.

$$\eta_C = \frac{Q_u}{Q_{in}} = \frac{\dot{m}_w C_{pw}\,\Delta T}{A_C I_C} \quad (4.20)$$

$$where: \Delta T = T_{wo} - T_{wi}$$

4.6. Energy Balance of Storage Tank

The heat balance in the storage tank for the model shown in the figure (4.1) is given by the following expression:

$$\rho_w V_s C_{pw}\,\frac{dT_s}{dt} = \dot{Q}_u - \dot{Q}_{Loss} - \dot{Q}_{Load} \quad (4.21)$$

Where the left-hand side term corresponds to the heat energy stored in the tank and the three terms on the right-hand side of the above expression represent the rate of the net solar energy gain, the rate of heat loss from the storage tank and the rate of heating Load required respectively.

- The net solar useful heat gain is given by:

$$\dot{Q}_u = \left(\dot{m}C_p\right)_w (T_{wo} - T_{wi}) \tag{4.22}$$

- The storage tank heat loss is given by:

$$\dot{Q}_{Loss} = A_s U_{LS}(T_s - T_a) \tag{4.23}$$

Hot water supply rate is given by:

$$\dot{Q}_{Load} = ALOAD(T_s - T_{ws}) \tag{4.24}$$

Where: $ALOAD = \left(\rho C_p\right)_w DWC \times PP(j)$

CHAPTER FIVE

ESTIMATION OF HOT WATER CONSUMPTION AND SOLAR WATER HEATING SYSTEM COMPONENT SIZING

5.1. Introduction

As already discussed, the study area of this thesis is considering a solar energy system to supplement or replace the service hot water load of Addis Ababa University, Technology Faculty Students' Residence Hall.

The analysis of the hot water consumption is an indispensable part that comes before the choice of solar water heating equipments size and capacity.

Hot water requirements for college dormitories generally include showers, lavatories, service sinks, clothes washers, dish washers, food preparation, cleaning pots, pans and floors. Peak demand usually results from the use of showers.

In this study, the hot water consumption areas include:

- Showers,
- Service sinks,
- Dish washing,
- Food preparation and
- Cleaning pots and pans.

When choosing a solar system for hot water we must first determine our needs for hot water, in quantity as well as in preferred temperature of consumption. The typical calculation for the temperature of consumption is 60^0C, but for the calculation of required quantity we must take into account the daily needs.

5.2. Preliminary Load Estimate

To size the collectors and storage tank it is necessary to estimate or measure the hot water consumption of the facility or building. Therefore, either historical records of service hot water usage or real-time data collection would be used to estimate the service hot water load**.** In this study, these methods were not available for use. The load is estimated based on the ASHRAE 1999 Systems Handbook guidelines for hot water demand.

The dormitory contains:

- 88 rooms with the capacity of ten students per room,
- 2 rooms with the capacity of eighteen students per room, and
- 2 rooms with the capacity of sixteen students per room.

Therefore, the total capacity of the residence hall is 948, say 1000 students using some safety factor.

The requirement of hot water varies from person to person. However, the estimated average hot water requirement per student per day is considered in this study.

The daily consumption of hot water is a very important parameter for the choice of dimension of the solar plant. According to ASHRAE Systems Handbook guidelines for hot water demand, as a preliminary estimate, the average hot water demand for dormitories is 49.5 L/student per day [21].

Therefore, the total daily hot water requirement of the students' residence hall is:
$1000\ \text{students}\ \times 49.5\ \text{L per students per day} = 49{,}500\ \text{L per day} \approx \mathbf{50}\ \text{m}^3$per day with some contingency.

This daily hot water consumption pattern can be approximately distributed over the day as 5 % from 1am up to 5 am, 20% from 6am up to 8am, 40% from 9am up to 4pm, 30% from 5pm up to 9pm, and 5% from 10pm up to 12am assuming most students take shower afternoon from 7pm up to 12am since most of the day time is occupied by classes and reading. This distribution pattern is seen in Figure 5-1 below.

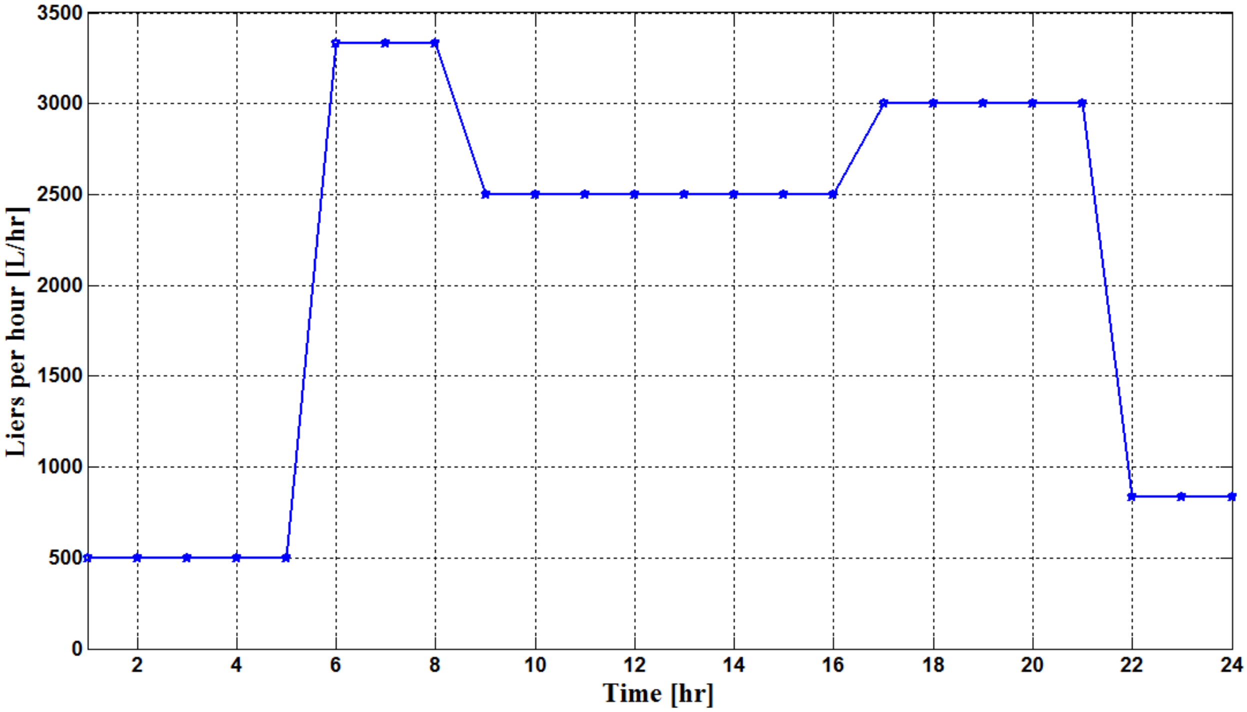


Figure 5-1: Estimated Daily Hot Water Consumption Pattern of the Students' Hall

N.B:- The above water consumption pattern is not taken from the real measured data of water consumption pattern as there is not any documented measured data. But it is just an assumption to show the minimum and maximum daily hot water consumption (load) flow rate. From the assumption the minimum hot water consumption flow rate is 500 L/hr and the maximum hot water consumption flow rate is about 3330 L/hr. The average daily hot water flow rate is about 1915 L/hr.

5.3. Hot Water Supply Temperature

Domestic hot water supply systems using solar energy require an auxiliary source of energy, for the following reasons:

- Maintaining the required water temperature for the hot water needed,
- Maintaining the required water temperature in order to avoid bacteria, particularly legionellas in dishwashing system.

In order to limit the development of these bacteria, water stagnation in dead-end piping should be avoided. Hence, the temperature of the hot water needed to avoid the bacteria should be at least 60°C. Therefore, the temperature of the system we need is 60°C. In addition, the auxiliary heater is used on cloudy days and at night time to supplement the solar system and maintain the temperature required.

5.4. Component Sizing of Solar Water Heating System

It is extremely important to select the correct size of the solar water heater system. The solar water heater sizing needs to be done based on the hot water requirements and the hot water use habits of the students. The basic idea of having a solar water heater is to reduce electricity or fuel consumption for water heating. An under-sized system is insufficient to meet the hot water requirement, and an over sized system will result in overheating of the water. As back-up system is required for cloudy days and night time, it may be possible to manage with marginal back up use in extreme weather to optimize the size of the system for use in the rest of the year.

The main components of the solar water heater to be considered for sizing are the collector, pump and the storage tank.

5.4.1. Storage Tank Sizing

Storage tank is one of the major components in solar water heating systems. The storage tank holds the water that has been heated in the collector by the sun. The water can be stored in any vessel suitable for high temperatures. The tanks can be pressure rated depending on the application and whether or not a back-up heating system is used. Depending on the system design, solar tanks may be vertical or horizontal. Storage tank is used in most solar systems to provide a thermal inertia or capacitance effect. This thermal capacitance is required to damp out fluctuations of energy collection and demand in solar system. The amount of thermal storage is usually subjected to economic constraint, since very large storage, which could produce a nearly uniform system output, is generally very expensive. They are designed to encourage temperature stratification so that when water is drawn for service, it is supplied from the hottest stratum in the tank at the top. To further encourage stratification of cold and hot water in the storage tank, the cold supply water inlet is located at the bottom of the tank.

The shapes of the storage tanks used in this research are a vertical right circular cylinder with height to diameter ratio of 2:1.

For the climatic condition of Addis Ababa city the volume of storage tank for a single collector is assumed to be 0.1 m^3 and the daily heating capacity of a single collector is assumed 0.125 m^3 [13, 22]. Therefore, the total volume of storage tank needed for the total daily hot water consumption is:

$$\text{Total volume of storage tank needed} = \text{Daily Hot Water Consumption} \times \left(\frac{\text{Assumed volume of storage tank for one collector}}{\text{Assumed volume of water heated by one collector per day}}\right) \tag{5.1}$$

As already discussed, the total amount of water required per day is 50 m^3. Therefore, the total storage tank volume required is:

$$\text{Total volume of storage tank needed} = 50\text{m}^3 \times \frac{0.1\text{m}^3}{0.125\text{m}^3} = 40\text{m}^3$$

For, $\frac{h}{D_i} = 2$, Volume of a single storage tank is:

$$V_s = \pi \frac{D^2{}_i}{4} h = \pi \frac{D^3{}_i}{2} \tag{5.2}$$

Surface area of the storage tank is:

$$A_s = \pi D_i h + 2(\pi \frac{D^2{}_i}{4}) = \frac{5}{2}\pi D^2{}_i \tag{5.3}$$

5.4.1.1. Storage Tank Insulation Thickness Determination

The exterior of a storage tank should be well insulated to retain heat. Heat losses from the storage tank have great impact on the economic utilization of the system as a whole. For this reason thickness of insulation should be determined by considering it as one part of the storage tank design. The determination of the storage tank insulation can be made by using different consideration. In one case for example, the insulation thickness is taken as an utilizable parameter and then determined by considering the economic trade-off between the cost of the added insulation and the benefit gained from the saved solar heat.

The other way of calculating the insulation thickness is as follows: The overall heat transfer coefficient U across the storage tank is assumed first. Then, the thickness of the insulation is determined. For simplification of the problem, the second method is used for the determination of the required insulation thickness for some assumed value of the overall heat transfer coefficient U. Neglecting the effect of the storage tank material on heat transfer, the temperature difference across the insulation is taken as ΔT.

The rate of heat loss from the tank is then given by:

$$\dot{Q} = \frac{2\pi h(T_1 - T_a)}{{}^{2}/_{D_0 h_0} + {}^{1}/_{k} \ln\left(\frac{D_o}{D_i}\right)} \tag{5.4}$$

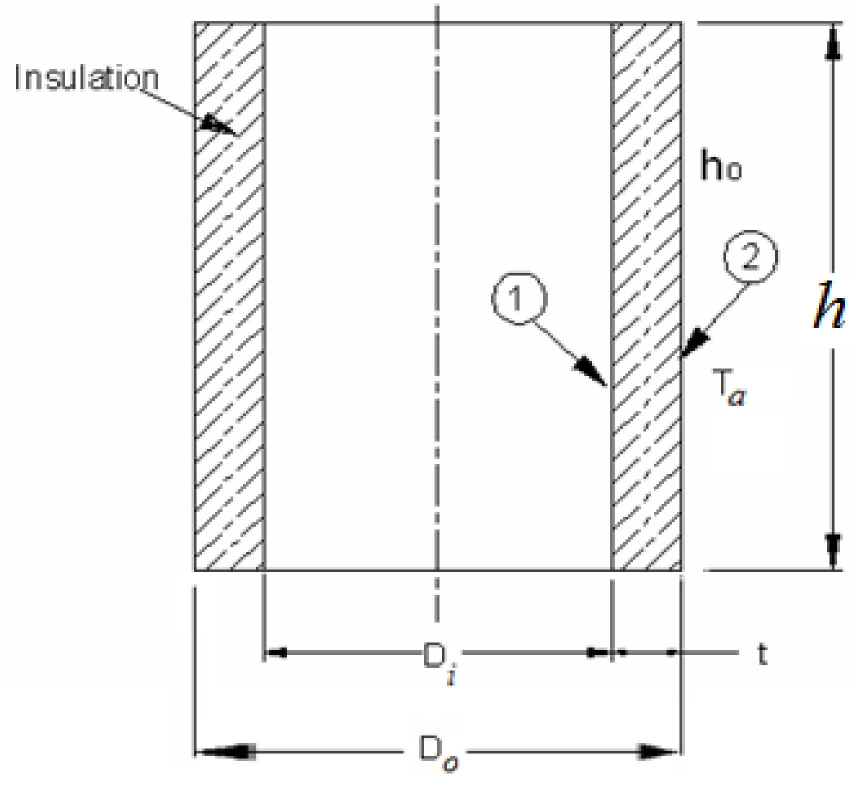


Figure 5-2: Side Insulation of the Storage Tank

The outside diameter D_0 is given by:

$$D_0 = D_i + 2t \tag{5.5}$$

The rate of heat transfer can also be given by:

$$\dot{Q} = UA\Delta T \tag{5.6}$$

Where: $\Delta T = T_1 - T_a$

Equating and simplifying equation (5.1) and (5.3) gives:

$$D_0 = D_i \times \exp\left[\frac{2k\left(\frac{1}{U}-\frac{1}{h_0}\right)}{D_0}\right] \tag{5.7}$$

Taking: k = 0.032 W/m.k (for Glass fiber)

U [W/m^2.k] (Assumed)

h_0 = 12 W/m^{2}k

Substituting equation (5.2) into equation (5.3) gives:

$$t = 0.5\left[D_i \times exp\left[\frac{2k}{D_i+2t}\left(\frac{1}{U}-\frac{1}{h_0}\right)\right] - D_i\right] \tag{5.8}$$

Considering the tank plate thickness of 2mm and insulation cover plate thickness of 1mm, the outside storage tank diameter is:

$$D_o = D_i + 2t + 2 \times 0.002 + 2 \times 0.001 \tag{5.9}$$

Table 5-1 shows the selection and specification of technical data for the storage tank.

Table 5-1: Technical Data of Storage Tank

Parameter	**Amount**
Daily hot water consumption	50 m^3
Storage tank capacity needed	40 m^3
Number of storage tanks	4

Single storage tank volume, V_s	10 m^3
Internal surface area, A_s	26.97 m^2
Height, h	3.706 m
Inside diameter, D_i	1.853 m
Outside diameter, D_o	2.053 m
Insulation material	Glass fiber (k=0.032 w/m.k)
Insulation thickness, t	0.097 m
Mild steel plate thickness (internal cover)	2 mm
Galvanized pre painted steel jacket (outer cover)	1 mm

5.4.2. Collector Sizing

The geographical location and climate where the solar water heater is located will determine the size and number of collectors we will need. A heater located in tropical climates will need less collector area because the sun heats more water faster.

In America Contractors usually follow a guideline of around 20 square feet (2 square meters) of collector area for each of the first two family members for domestic hot water consumption. For every additional person, they add 8 square feet (0.74 square meters) for those at Sun Belt.

The daily heating capacity of a single collector area of $2m^2$ is assumed to be 0.125 m^3 for the climatic condition of Addis Ababa city [22]. Taking this general assumption in our calculation, we get the total number of collectors in parallel we need as:

$$\text{Total number of collector} = \frac{50\,m^3}{0.125\,m^3} = 400 \text{ Collectors}$$

Therefore, the total collector area needed for the system is 800 m^2.

5.4.3. Collector System Design Parameters Selection

There are manufacturers and dealers of flat plate solar water heaters in Ethiopia [22]. Among these are:

- **Vonal.Com** – Manufacturer of solar water heater in Ethiopia.
- **GPG Solar** – Dealer of solar water heater in Ethiopia (Manufacturer: Israel).

There are also Canada manufacturers (**S-Series** and **G-Series** – Canada standard type solar water heaters) with different design parameters which we used to compare with **Vonal.Com and GPG Solar** and select the best design parameters for our flat plate collector. Table 5-2 below shows the collector parameters and important properties of fluids from manufacturers' catalogue [22].

Table 5-2: Collector Parameters and Important Properties of Fluids [22]

Parameter	Vonal.Com	GPG Solar	S-Series	G-Series
Collector Area (width*length) [m^2]	2*	2.09	2.53	2.53
Collector Perimeter [m]	6*	6	6.8	6.8
Back Insulation Thickness[m]	0.05*	0.05	0.025	0.025
Edge Insulation Thickness[m]	0.025*	0.025	0.025	0.025
Depth of the Collector [m]	0.095*	0.09	0.086	0.086
Depth of the Edge [m]	0.054*			
Emissivity of the Panel [-]	0.1*	0.1	0.29 painted 0.15 selective	0.25 painted 0.15 selective
Absorptivity of the Panel [-]	0.90	0.96 coated with black chrome*	0.95 painted 0.92 selective	0.95 painted 0.92 selective
Emissivity of the Glass [-]	0.88*	0.88	0.88	0.88
Transmissivity of the Glass [-]	0.9*	0.9	0.898	0.898
Number of Glass Cover	1*	1	1	1
Insulation Material	Mineral wool*	Mineral wool	Fiber glass AF530	Fiber glass AF530
Conductivity of Insulation	0.045*	0.045	0.036	0.036

Material [w/m.K]				
Panel Material	Steel*	Copper	Aluminium	Aluminium
Panel Height [m]	2*	1.9	2.3	2.3
Panel Width [m]	1*	1.1	1.1	1.1
Thickness of the Panel [m]	0.002*	0.0004	0.0005	0.0005
Tube Material	Copper*	Copper	Aluminium	Aluminium
No. of Tubes per m of Panel Width	8*	7	8	8
Tube Diameter (outer/inner) [m]	0.022 (circular)*	0.016 (circular)	0.008 (rhombus)	0.012 (rhombus)
Space b/n Collector Panel & Glass [m]	0.05*	0.05	0.02-0.025	0.02-0.025
Thermal Conductivity of the Absorber [W/m.K]	386*	386	205	205
Other selected properties of the collector and the fluid [22]				
Mass*Sp. Heat of the Panel [J/K]		14112.0*		
Mass*Sp. Heat of the Glass [J/K]		18417.067*		
Wind Velocity[m/s]		3.0*		
Average Density of Water [kg/m^3]		994.74*		
Sp. Heat of water [J/kg.k]		4178*		
Thermal Conductivity of Water [W/m.k]		0.625*		
Thermal Conductivity of Air [W/m.k]		0.026*		
Specific mass flow Rate, $\dot{m}$ [kg/s.m^2]		0.003*		
Sealing Material		EPDM*		

<u>Remark</u>: - The superscript * indicates parameters of flat plate solar water heater selected for this research paper.

5.4.4. Selection of Pump

Pumps are mechanical devices that add mechanical energy to liquids. An active domestic hot water systems use electrically driven pumps and valves to control the circulation of the heat absorbing liquid and to move this heat absorbing fluid between the storage tanks and collectors.

In pressurized systems, the system is full of fluid and a circulator is used to move hot water or heat transfer fluid from the collector to the tank.

Pumps are sized to overcome static and head pressure requirements in order to meet specific system design and performance flow rates.

When the sun is shining, the control valve is activated and the pump circulates water through the pressurized solar loop.

Most active solar systems use centrifugal pumps. Pump selection depends on the following factors:

- System type (direct or indirect).
- Heat collection fluid.
- Operating temperatures.
- Required fluid flow rates.
- Head or vertical lift requirements.
- Friction losses.

The most common pump (circulator) used in solar systems is the “wet rotor” type in which the moving part of the pump, the rotor, is surrounded by liquid. The liquid acts as a lubricant during pump operation, negating the need for manual lubrication.

Because the circulation pump had to overcome the total pressure drop of the system caused by the different components at the determined flow rate, the overall pressure drop of the system had to be determined before the appropriate circulation pump could be selected.

5.4.4.1. Pressure Drop in the System

Flow balance through the collector array depends on the relative pressure drop associated with the different piping branches of the array. The change in pressure along any flow path is a measure of the resistance to flow. Of interest to the solar system designer are the pressure losses across the collector risers, along manifolds, and along linear uninterrupted pipe. The pressure drop calculation of the system is used to select the correct pump to circulate the water between the solar collector arrays and the storage tank. Figure 5-3 shows the schematic representation of the solar collector-storage layout of the system.

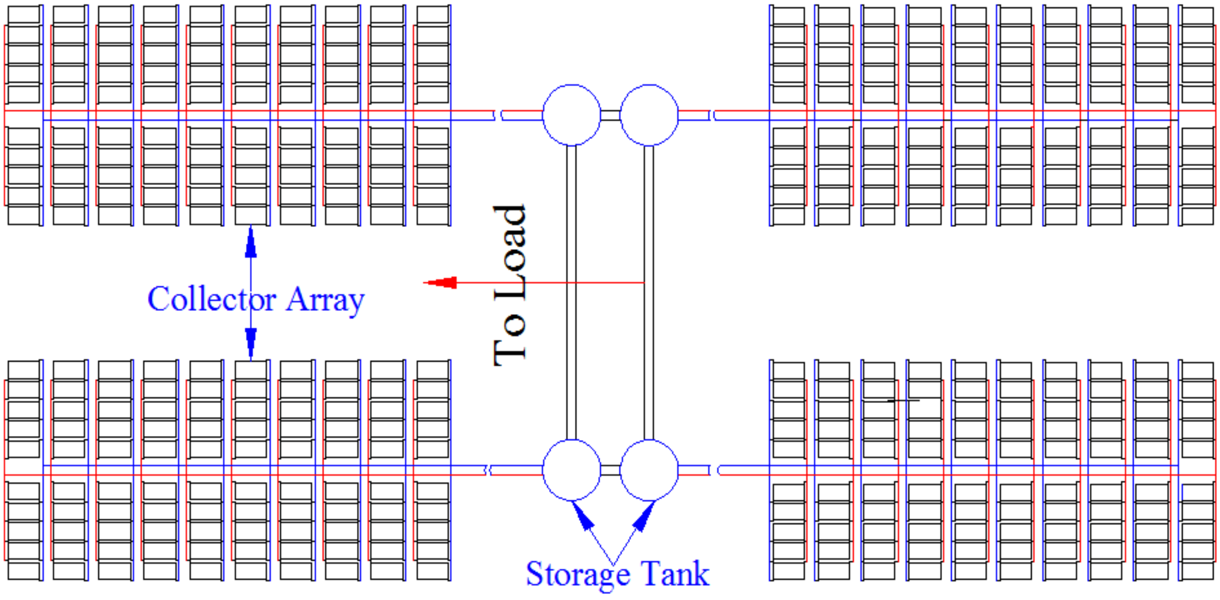


Figure 5-3: Schematic Representation of the Collector-Storage Layout of the System

a. Pressure Drop in the Collector

A piping system is the sum of pipes, fittings, valves and other restrictions which impose a pressure drop that has to be counter forced by the pump.

Based on the designed diameter of tube, number of riser tubes, mass flow rate and flow pattern the pressure drop inside the collector can be calculated with the help of the schematic diagram shown in Figure 5-4 below.

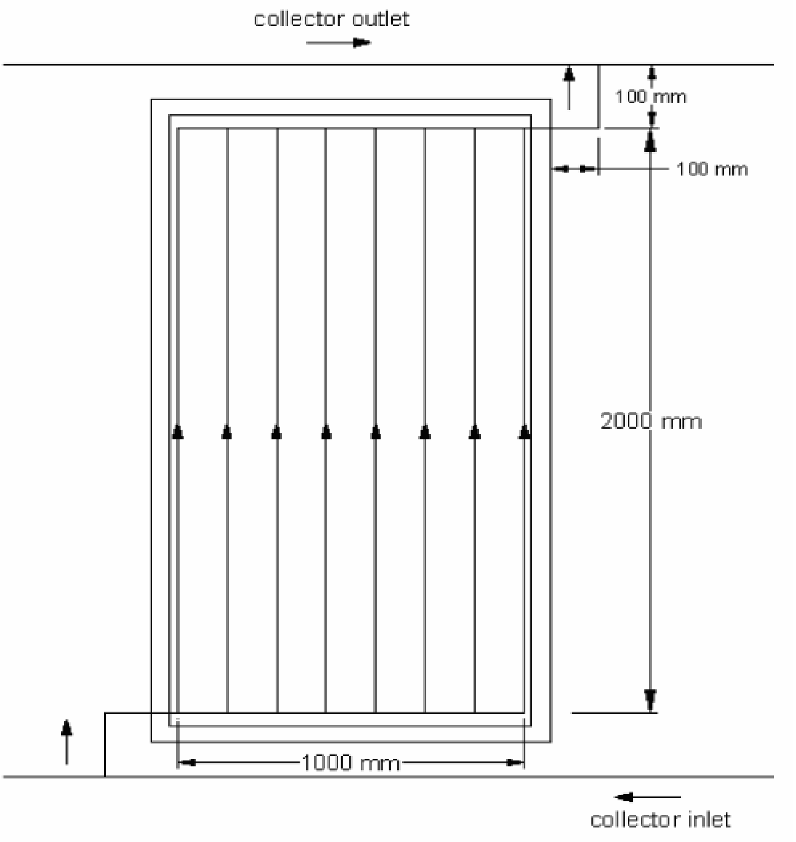


Figure 5-4: Schematic Representation of the Flow in the Collector

The mass flow rate of water through a single collector is:

$$\dot{m} = 0.003\ \frac{kg}{s.m^2} \times 2\ m^2 = 0.006\ \frac{kg}{s}$$

At average temperature of 40^0C the property of water is:

$$\rho_w = 992.3\ kg/m^3\ ;\ \mu_w = 6.53 \times 10^{-4} kg/m.s$$

Therefore, the volume flow rate is:

$$\dot{V} = \frac{\dot{m}}{\rho_w} = 6.05 \times 10^{-6}\ {m^3}/{s}$$

i) Pressure drop inside the risers

Assuming uniform flow rate in each risers the volume flow rate per riser is:

$\dot{\mathrm{Q}}_{\mathrm{i}} = \frac{\dot{\mathrm{Q}}}{\mathrm{N}} = 7.57 \times 10^{-7}\, \mathrm{m}^3/_{\mathrm{s}}$; Where N is the number of risers.

Average velocity in a riser: $V_{avr} = \frac{\dot{\mathrm{Q}}_{\mathrm{i}}}{A_r} = 0.002 m/s$

Reynolds Number: $R_e = \frac{\rho v_{avr} D}{\mu} = 66.6$

Since the Re < 2300 it is laminar flow

For laminar flow: $\Delta P_r = f \frac{L}{D} \frac{\rho v^2{}_{avr}}{2}, \; f = \frac{64}{R_e}$

$$\Delta P_r = 0.173 Pa$$

ii) Pressure drop inside the header

Taking the average volume flow rate:

$$\dot{Q}_{avg} = \frac{\dot{Q}}{2} = 3.025 \times 10^{-6}\, \mathrm{m}^3/_{\mathrm{s}}$$

Average velocity in the header:

$$V_{avh} = \frac{\dot{\mathrm{Q}}_{\mathrm{avg}}}{A_h} = 0.0062 m/s$$

Reynolds Number: $R_e = \frac{\rho v_{avh} D}{\mu} = 234.1$

Since the Re < 2300 it is laminar flow

For laminar flow: $\Delta P_h = f \frac{L}{D} \frac{\rho v^2{}_{avh}}{2}, \; f = \frac{64}{R_e} = 0.273$

$$\Delta P_h = 0.208 Pa$$

For the two headers, $\Delta P_H = 2 \times \Delta P_h = 0.416 Pa$

iii) Pressure drop inside the fittings

Based on figure (5-4) there are 20 bends.

Pressure loss in the fitting, $\Delta P_f = k_f \frac{\rho {V_1}^2}{2}$

Where: k_f = pressure loss factor

V_1 = average velocity in the tube up stream of the fitting.

For 90° bend, laminar flow k_f = 0.9

$$\Delta P_f = 0.150 Pa$$

iv) Pressure drop inside the connection pipes

The total connection pipes length for a single collector is L = 0.45m

Pressure drop in the connection pipe is given by:

$$\Delta P_c = f \frac{L}{D} \frac{\rho {V_{avh}}^2}{2} = 0.094 Pa$$

The total pressure loss due to viscous effect of the fluid in a single collector is the sum of all the above losses.

$$\Delta P_{Tc} = \Delta P_r + \Delta P_h + \Delta P_f + \Delta P_c = 0.833\text{Pa}$$

b) Pressure drop on the line from the storage tank up to solar collectors' inlet and from collector's outlet back to Storage tank

Approximating the length of the pipe line from the storage tank up to collectors and from collectors outlet back to Storage tank as 60m, the total volume flow rate is equal to the amount that flows through all the solar collectors and given by:

$$\dot{V}_{S-C} = 100 \times \dot{V} = 6.05 \times 10^{-4} \ {m^3}/{s}$$

Taking 52 mm diameter pipe, the average velocity is:

$$v_{av} = \dot{V}_{S-c}/A = 0.3 \ m/s$$

Therefore, the Reynolds number is:

$$R_e = \frac{\rho v_{av} D}{\mu} = 28{,}716.9$$, the flow is turbulent.

For the tube material of galvanized steel the equivalent roughness is, $\varepsilon = 0.15mm$

Therefore, $\frac{\varepsilon}{D} = 0.0029$ and from the Moody Chart or by using the explicit Haaland formula with the corresponding Reynolds number $f = 0.03$

Therefore, the pressure drop due to friction in the pipe is:

$$\Delta P_{f\,(s-c)} = f \frac{L}{D} \frac{\rho {v^2}_{av}}{2} = 1530Pa$$

c) Pressure drop in the main manifold connecting all arrays together

Average flow rate in the manifold is:

$$\dot{V}_{av} = 100 \times \left(\frac{\dot{V}}{2}\right) = 3.025 \times 10^{-4} m^3/s$$

With 41 mm manifold diameter, the average velocity is:

$$v_{av} = \dot{V}_{av}/A = 0.23\ m/s$$

Therefore, the Reynolds number is:

$$R_e = \frac{\rho v_{av} D}{\mu} = 14275.2$$, the flow is turbulent.

For the tube material of galvanized steel the equivalent roughness is, $\varepsilon = 0.15mm$

Therefore, $\frac{\varepsilon}{D} = 0.00366$ and from the Moody Chart or by using the explicit Haaland formula with the corresponding Reynolds number $f = 0.034$.

i. The pressure drops in the supply main manifolds

For collector array with 5 collectors and 10 arrays in parallel to each other as shown in Figure 5-3, the length of the manifold leaving a space of 0.5 m between two arrays for easy maintenance is L=22.5m. Therefore, the pressure drop is:

$$\Delta P_{f(mm-1)} = f\frac{L}{D}\frac{\rho {v^2}_{av}}{2} = 489.72 \text{ Pa}$$

ii. The pressure drops in the return main manifolds

The length of the return main manifold leaving a space of 0.5 m between two arrays for easy maintenance is L=24.5m. Therefore, the pressure drop is:

$$\Delta P_{f(mm-2)} = f\frac{L}{D}\frac{\rho {v^2}_{av}}{2} = 533.25 \text{ Pa}$$

iii.Pressure drop in the bend

Based on the layout there are 2 bends on the main manifolds.

Pressure loss in bends is given by, $\Delta P_b = k_f \frac{\rho {v^2}_1}{2}$

Where: k_f = pressure loss factor

v_1 = average velocity in the tube up stream of the fitting.

For 90º standard elbow, k_f = 0.9

Therefore, $\Delta P_b = k_f \frac{\rho {v^2}_1}{2} = 94.4\ Pa$

d) Pressure drop in the array manifold

i. Pressure drop in the supply array manifold

The length of the supply array manifold leaving a space of 0.25 m between two collectors for easy maintenance and taking 0.5m from main supply manifold up to first collector is L=6.5m.

Average flow rate in the manifold is:

$$\dot{V}_{av} = 5 \times \left(\frac{\dot{V}}{2}\right) = 1.5125 \times 10^{-5} m^3/s$$

With 25mm manifold diameter, the average velocity is:

$$v_{av} = \dot{V}_{av}/A = 0.031\, m/s$$

Therefore, the Reynolds number is:

$R_e = \frac{\rho v_{av} D}{\mu} = 1170.5$, Since the Re < 2300 it is laminar flow

For laminar flow: $\Delta P_r = f \frac{L}{D} \frac{\rho {v^2}_{avr}}{2}$, $f = \frac{64}{R_e}$ = 0.0547

Therefore, the pressure drop in the supply manifold is:

$$\Delta P_{f(sm-1)} = 6.78\text{Pa}$$

ii. Pressure drop in the return manifold of array

The length of the return array manifold leaving a space of 0.25 m between two collectors for easy maintenance and taking 0.5m from main supply manifold up to first collector is L= 5.5m.

Therefore, the pressure drop in the supply manifold is:

$$\Delta P_{f(sm-2)} = f \frac{L}{D} \frac{\rho {v^2}_{av}}{2} = 5.74\text{Pa}$$

e) Pressure drop due to the inclination of the collector to the horizontal

Assuming the inclination of the collectors is equal to 20^0, the pressure drop is:

$$\Delta P_I = \rho g h = 6{,}659 \text{ Pa}$$

f) Pressure drop due to the lift up of water to the top of the Building

Taking the total height of the building to which the water is to be lifted is about 20m:

$$\Delta P_L = \rho g h = 194689.26\, Pa$$

g) Total pressure drop of the system

The total pressure drop of the system is the sum of all the pressure drops:

$$\Delta P_T = \Delta P_{TC} + \Delta P_{f(s-C)} + \Delta P_{f(mm-1)} + \Delta P_{f(mm-2)} + \Delta P_b + \Delta P_{f(sm-1)} + \Delta P_{f(sm-2)} + \Delta P_I + \Delta P_L =$$

204008.983Pa ≈ 205000 Pa

Hence, the total pumping pressure needed for the system design is the above pressure drop.

Total specific work is: $Y = \frac{\Delta P_T}{\rho} \approx 210\ m^2/s^2$

Total Head $H = \frac{Y}{g} \approx 22m$

The total volume flow rate for the pump is:

$$\dot{V}_T = 100 \times \dot{V} = 6 \times 10^{-4}\ m^3/s = 2.16\ m^3/hr$$

The proper centrifugal electric drive pump specification satisfying the requirement of water Head of 22m and flow rate of 2.16 m^3/hr is as follows.

Table 5-3: Pump Selection Data

Type	**Caprari Electric Drive Pump**
Model	MEC-A 01/30B
The proper motor data	
Frequency	50 Hz
Normal Speed	1450 rpm
Rated Voltage	400 V
Shaft Power	0.17kW
Rated power	0.2 kW
Efficiency	63%
Motor Type	3~

5.5. Control Element

Controls for solar heating systems are usually more complex than those of a conventional heating system, because they have to analyze more signals and control more devices (including the conventional, backup heating system). Solar controls use sensors, switches, and/or motors to operate the system. The system uses other controls to prevent freezing or extremely high temperatures in the collectors.

The heart of the control system is a differential thermostat, which measures the difference in temperature between the collectors and storage unit.

The operation of the pump should be designed only when solar collection is feasible. To determine whether solar collection is feasible or not, measuring collector temperature and comparing it with the storage tank bottom temperature is necessary. If the energy obtained from solar collection is not relatively greater than the pumping cost, the pump should be off until sufficient energy is obtained, and on elsewhere. This can be done by the use of differential controller.

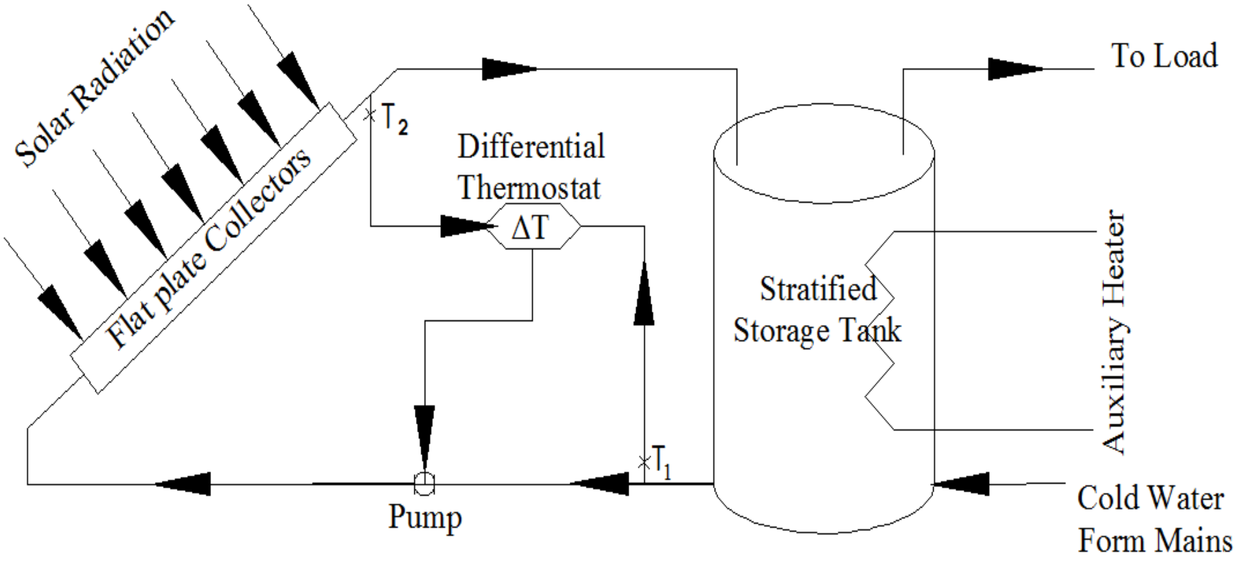


Figure 5-5: Positioning of Differential Controller

A thermostat whose electrical resistance varies with temperature messages the differential temperature at a two specified points. The differential thermostat which is pre-set for maximum and minimum temperature difference closes or opens the electric pump circuit.

For this model one end of the thermistor sensors is placed at the bottom of the storage tank and the other end at the collector outlet pipe and set to start the pump when the water outlet temperature is 5ºC hotter than the storage medium. The pump will stop its operation when the temperature difference is below 5ºC. In order to avoid continuous off and on operation of the pump, 1 – 3 minutes delay increases the life of the motor.

CHAPTER SIX

TRNSYS MODELING AND SIMULATION OF FLAT PLATE SOLAR WATER HEATING SYSTEM

6.1. Introduction

A complete hot water system is modeled and simulated using a thermal systems simulation software package, TRNSYS [24]. The computer program TRNSYS (version **16)** is used to perform the computer modeling and simulations. TRNSYS is a transient system simulation program with a modular structure. The program is well suited to simulate the performance of systems, the behavior of which is a function of the passage of time. This is the case if outside conditions that influence the system behavior change, such as weather conditions, or if the system components themselves go through conditions that vary with time.

Modular simulation of a system requires the identification of components whose collective performance describes the performance of the system. Each component is formulated by mathematical equations that describe its physical behavior. The mathematical models for each component are coded in FORTRAN, so that they can be used within the TRNSYS program. Formulation of the components has to be in accordance with the required TRNSYS format. A basic principle in this format is the specification of parameters, inputs and outputs for each component. Parameters are constant values that are used to model a component. Inputs are time-dependent variables that can come from a user supplied data source such as weather data or from outputs of other components.

There can be several components of the same type specified in one simulation. The way this identification is accomplished is that each component is assigned an identifying type number that is component specific. A second number, the unit number is unique; one can only be used once in a simulation.

Different unit numbers can be associated with the same type number, although there are limitations on how many types of one kind can be used in one simulation. A system is set up in

TRNSYS by means of an input file, called a TRNSYS deck. This deck contains all the information that specifies the components and how the components interact. The system is set up by connecting all inputs and outputs in an appropriate way to simulate the real system. Once a system is set up in a TRNSYS deck, the program can be run over a user defined time interval. The time interval is divided into equal number of time steps. At each time step the program calls each component and solves all the mathematical equations that specify the component performance. The program iteratively calls the system component until a stationary state is reached. The stationary state is reached when all the calculated inputs to the components remain constant between two iterations. Naturally, in a numerical solution such as calculated by TRNSYS, there will always be a difference in results between two iterations. Therefore the user has to specify tolerances that define a stationary state.

TRNSYS is well known for its capability to handle many different system components and to solve for numerous heat transfer equations that describe the interaction of the components. Various components modeled by TRNSYS include solar collecting unit, auxiliary heating equipment, water storage tanks, pump, and control devices. Each of these components may be interconnected and/or controlled using equations or constants. The components may also be defined using specific characteristics such as heat transfer coefficient, length, or volume.

The model is constructed with the following components linked together to form a complete hot water system:

- Weather data reader and solar radiation processor
- A section of load input device (forcing function) representing the incoming water to the water heating equipment;
- Stratified water storage tank;
- Water pumps to circulate water through the solar collector and storage tank;
- Array of Flat plate solar collector
- Auxiliary water heating equipment
- Control devices; and
- Online plotters, Integrators and printers

A TRNSYS project is typically setup by connecting components graphically in the simulation Studio. Each Type of component is described by a mathematical model in the TRNSYS simulation engine and has a set of matching Proforma's in the Simulation Studio.

6.2. TRNSYS Modeling of the System

This section is devoted to describing the modeling of TRNSYS system and the parameters of the components used. A TRNSYS model is developed to determine and verify system parameters using the data acquired on the system during the clear and cloudy days of the year considered.

Individual components were selected from TRNSYS library and the out-input connection of components with each other as shown in Figure 6.1.

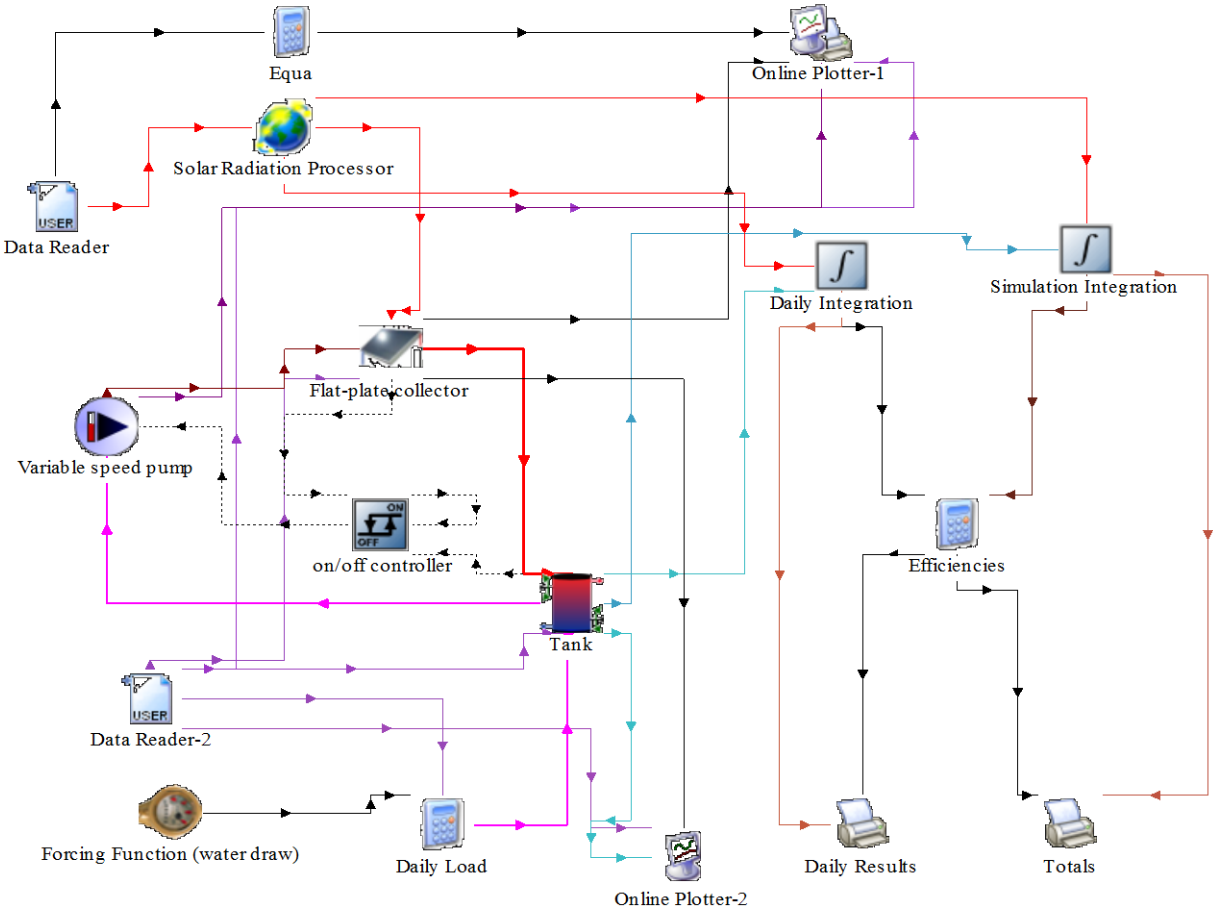


Figure 6-1: TRNSYS Components Model of the Solar Water Heating System

6.2.1. Flat Plate Collector (Type 1)

The flat plate collector (quadratic efficiency) Type 1b is selected from TRNSYS component libraries for this model. This component models the thermal performance of a flat plate solar collector. The total collector array may consist of collectors connected in series and in parallel. The number of modules in parallel and the characteristics of each module determine the thermal performance of the collector array.

A general equation for solar thermal collector efficiency can be obtained from the Hottel-Whillier equation [1, 24] as:

$$\eta_c = \frac{Q_u}{AI_T} = \frac{\dot{m}\, C_{pf}\, (T_{w0} - T_{wi})}{AI_T} = F_R(\tau\alpha)_n - F_R U_L \frac{(T_{wi} - T_a)}{I_T} \tag{6.1}$$

The loss coefficient U_L is not exactly constant, so a better expression is obtained by taking into account a linear dependency of U_L versus $(T_i - T_a)$ [1, 24]:

$$\eta_c = \frac{Q_u}{AI_T} = F_R(\tau\alpha)_n - F_R U_L \frac{(T_{wi} - T_a)}{I_T} - F_R U_{L/T} \frac{(T_{wi} - T_a)^2}{I_T} \tag{6.2}$$

Equation 6.2 can be rewritten as [24]:

$$\eta_c = a_0 - a_1 \frac{(\Delta T)}{I_T} - a_2 \frac{(\Delta T)^2}{I_T} \tag{6.3}$$

Which is the general solar collector thermal efficiency equation used in Type 1.

The thermal efficiency is defined by 3 parameters: a_0, a_1 and a_2. Those 3 parameters are available for collectors tested according to ASHRAE standards and rated by SRCC (ASHRAE, 2003; SRCC, 1995), as well as for collectors tested according to the recent European Standards on solar collectors (CEN, 2001).

6.2.1.1. Incidence angle modifier (IAM)

Collector tests are generally performed on clear days at normal incidence so that the transmittance - absorptance product (τα) is nearly the normal incidence value for beam radiation, $(\tau\alpha)_n$. The intercept efficiency, F_R $(\tau\alpha)_n$, is corrected for non-normal solar incidence by the factor $(\tau\alpha)/(\tau\alpha)_n$. By definition, $(\tau\alpha)/(\tau\alpha)_n$ is the ratio of the total absorbed radiation to the incident radiation. Thus, a general expression for $(\tau\alpha)/(\tau\alpha)_n$ is [24]:

$$\frac{(\tau\alpha)}{(\tau\alpha)_n} = \frac{I_{bT}\frac{(\tau\alpha)_b}{(\tau\alpha)_n} + I_d\left(\frac{1+\cos\,\beta}{2}\right)\frac{(\tau\alpha)_d}{(\tau\alpha)_n} + \rho_g I\left(\frac{1-\cos\,\beta}{2}\right)\frac{(\tau\alpha)_g}{(\tau\alpha)_n}}{I_T} \tag{6.4}$$

For flat-plate collectors, $(\tau\alpha)_b/(\tau\alpha)_n$ can be approximated from ASHRAE test results (ASHRAE, 2003) as [24]:

$$\frac{(\tau\alpha)_b}{(\tau\alpha)_n} = 1 - b_0\left(\frac{1}{\cos\,\theta} - 1\right) - b_1\left(\frac{1}{\cos\,\theta} - 1\right)^2 \tag{6.5}$$

TRNSYS models of solar collectors have different types of functions named parameters, inputs and outputs. A parameter value function is specifically related to the manufacturers. These values need to be input according to manufacturer specifications. An input value function has a value that depends upon the taste conditions, such as collector slope, orientation, etc. Some inputs and all outputs have a ‘linked’ value, which means that this function has values, which are linked to other components and will be determined by the real time flow. Table 6-1 shows the Parameters, Inputs, and Outputs characteristics of the solar collectors for the flat plate solar water heater.

Table 6-1: The Parameters, Inputs, and Outputs Characteristics of the Solar Collector

Parameter	Input	Output
Collector area	Inlet temperature	Outlet temperature
Fluid specific heat	Inlet flow rate	Outlet flow rate
Tested flow rate	Ambient temperature	Useful energy gain
Intercept efficiency	Collector slope	
Incident angle modifier	Incident radiation	
	Total horizontal radiation	
	Horizontal diffuse radiation	

6.2.2. Variable Speed Water Pump (Type 110)

Type110 models a variable speed pump that is able to maintain any outlet mass flow rate between zero and a rated value. The mass flow rate of the pump varies linearly with control signal setting. Pump power draw, however, is modeled using a polynomial. Pump starting and stopping characteristics are not modeled, nor are pressure drop effects. As with most pumps and fans in TRNSYS, Type110 takes mass flow rate as an input but ignores the value except in order to perform mass balance checks. Type110 sets the downstream flow rate based on its rated flow rate parameter and the current value of its control signal input.

If the pump is determined to be off due to its control signal being set equal to 0, the Type110 pump mass flow rate, power drawn, energy transferred from the pump to ambient and energy transferred from the pump to the fluid stream are all set to zero. The temperature of fluid exiting the pump under the OFF condition is set to the temperature of fluid at the pump inlet. If, however, the pump is determined to be ON (control signal greater than 0) then the power drawn by the pump is [24]:

$$\dot{P} = \dot{P}_{rated}\,(a_0 + a_1\gamma + a_2\gamma^2 + a_3\gamma^3 + \cdots) \tag{6.6}$$

Where: $\dot{P}_{rated}$ = Rated power of the pump [kJ/hr].

$\dot{P}$ = Power drawn by the pump at the current time [kJ/hr].

a_0, a_1, a_2, a_3 = Polynomial coefficients in the pump power curve [-]

γ = Pump control signal [0…1].

The mass flow rate of fluid exiting the pump is a linear function of the control signal with a control signal of 1 resulting in the pump delivering its rated mass flow.

The shaft power of the pump can now be calculated. The shaft power is the power required to perform the pumping operation, excluding the effects of motor inefficiency.

$$\dot{P}_{shaft} = \dot{P}\eta_{motor} \tag{6.7}$$

Energy transferred from the pump motor to the fluid stream is calculated as [24]:

$$\dot{Q}_{fluid} = \dot{P}_{shaft}\left(1 - \eta_{pumping}\right) + (\dot{P} - \dot{P}_{shaft})f_{motorloss} \qquad (6.8)$$

In which $\eta_{pumping}$ is the pumping process efficiency and $f_{motorloss}$ is a value between 0 and 1 that determines whether the pump motor inefficiencies cause a temperature rise in the fluid stream that passes through the pump or whether they cause a temperature rise in the ambient air surrounding the pump. The energy transferred from the pump motor to the ambient is given by [24]:

$$\dot{Q}_{ambient} = \left(\dot{P} - \dot{P}_{shaft}\right)(1 - f_{motorloss}) \qquad (6.9)$$

The temperature of fluid exiting the pump can now be calculated as:

$$T_{fwo} = T_{wi} + \frac{\dot{Q}_w}{\dot{m}_w c_{pw}} \qquad (6.10)$$

Table 6-3 shows the Parameters, Inputs, and Outputs characteristics of the pump.

Table 6-2: The Parameters, Inputs, and Outputs Characteristics of the water pump

Parameter	Input	Output
Rated flow rate	Inlet fluid temperature	Outlet fluid temperature
Fluid specific heat	Inlet fluid flow rate	Outlet flow rate
Rated power	Control signal	Power consumption
	Pump efficiency	Fluid heat transfer
	Motor efficiency	Environment heat transfer

6.2.3. Storage Tank (Type 4)

Water is stored in the stratified storage tank after it gets warmed up with the solar collectors. Type 4 models a stratified fluid storage tank (multi-node) with 2 optional internal auxiliary heaters. It is a robust model that provides a very good accuracy while keeping the parameter complexity and the computational effort reasonable. This is the most frequently used tank model in the standard library.

Type 4c is modeled from TRNSYS component library. This tank works based on thermosiphon principal, the hot water flows upward in the tank and then transferred to the load.

The load flow enters at the bottom of the tank and the hot source stream enters just below the auxiliary, if present or at the top of the tank if no auxiliary is specified. The heating elements are activated in this tank.

6.2.3.1. Internal Auxiliary Heaters

An auxiliary heater is modeled to elevate the temperature of a flow stream using either internal control, external control or a combination of both types of control. The heater is designed to add heat to the flow stream at a user-designated rate ($\dot{Q}_{max}$) whenever the external control input is equal to one and the heater outlet temperature is less than a user-specified maximum (T_{set}).

By providing a control function of zero or one from a thermostat or controller, this routine will perform like a furnace adding heat at a rate of $\dot{Q}_{max}$ but not exceeding an outlet temperature of T_{set}. In this application, a constant outlet temperature is sought and T_{set} may be thought of as a safety limit.

The model optionally includes two electric resistance heating elements, subject to temperature and/or time control. The control option allows the addition of electrical energy to the tank during selected periods of each day (e.g., off-peak hours). The electric resistance heaters may operate in one of two modes. The first mode, a master/slave relationship, allows the bottom heating element to be enabled only when the top element is satisfied. In this control mode, it is impossible for both electric heaters to be on simultaneously; only one heater may be on at any instant of time. However, it is possible for both heaters to be on during the same time step (upper heater may be on during first half of the time step and lower heater may be on during the second half of the time step). This is a common design in residential electric hot water tanks. In the second mode both heaters enabled: In this mode, both heaters may be on simultaneously. This allows for significantly quicker heating of the water, but at a much higher electrical demand.

The auxiliary heaters employ a temperature deadband (ΔT_{db}). The heater is enabled if the temperature of the node containing the thermostat is less than (T_{set} - ΔT_{db}) or if it was on for the previous interval and the thermostat temperature is less than T_{set}. If the lower heater meets these criteria and the master/slave relationship is employed, a check will be made to see if the upper electric heater is on before enabling the second heating element.

The maximum available energy transfer to the fluid stream will be the product of the maximum possible energy transfer and the conversion efficiency $\eta_{htr} * \dot{Q}_{max}$.

The Typical values of thermal conversion efficiency of the auxiliary heater are: Electric Heater = 1.0; Natural Gas = 0.79 [21]. The energy balance on the steady-state heater is:

$$T_0 = \frac{\dot{Q}_{max}\,\eta_{htr} + \dot{m}C_{pf}\,T_i + UAT_{env} - \frac{UA\,T_i}{2}}{\dot{m}\,C_{pf} + \frac{UA}{2}} \tag{6.11}$$

$$\dot{m}_0 = \dot{m}_i \tag{6.12}$$

$$\dot{Q}_{max} = \dot{Q}_{aux} \tag{6.13}$$

$$\dot{Q}_{fluid} = \dot{m}_0 C_{pf}(T_0 - T_i) \tag{6.14}$$

$$\bar{T} = \frac{(T_0 + T_i)}{2} \tag{6.15}$$

$$\dot{Q}_{loss} = UA(\bar{T} - T_{env}) + (1 + \eta_{htr})\dot{Q}_{max} \tag{6.16}$$

Unless $T_0 > T_{set}$, then $T_0 = T_{set}$,

$$\dot{Q}_{fluid} = \dot{m}_0 C_{pf}(T_{set} - T_i) \tag{6.17}$$

$$\bar{T} = \frac{(T_{set} + T_i)}{2} \tag{6.18}$$

$$\dot{Q}_{aux} = \frac{\dot{m}C_{pf}(T_{set} - T_i) + UA(\bar{T} - T_{env})}{\eta_{htr}} \tag{6.19}$$

Where: $\dot{Q}_{aux} = \dot{Q}_{loss} + \dot{Q}_{fluid}$

Table 6-3 shows the parameters, inputs, and outputs characteristics of the storage Tank

Table 6-4: Parameters, Inputs, and Outputs Characteristics of Storage Tank

Parameters	Inputs	Outputs
Tank volume	Hot side temperature	Temperature to heat source
Fluid specific heat	Hot side flow rate	Flow rate to heat source
Fluid density	Cold side temperature	Temperature to load
Tank loss coefficient	Cold side flow rate	Flow rate to load
Height of nodes	Environment temperature	Thermal losses
Auxiliary heater mode	Control signals for elements	Auxiliary heating rate
Set point temperatures		Average tank temperature
Maximum heating rates		Temperature of each nodes

6.2.4. Controller (Type 2)

There are two basic methods for controlling transient simulations of solar energy systems or components: energy rate control and temperature level control. Type 2 is most frequently used to control fluid flow through the solar collector loop on the basis of two Input temperatures.

The on/off differential controller generates a control function which can have a value of 1 or 0. The value of the control signal is chosen as a function of the difference between upper and lower temperatures T_H and T_L, compared with two dead band temperature differences. The new value of the control function depends on the value of the input control function at the previous time step. The controller is normally used with the input control signal connected to the output control signal, providing a hysteresis effect. However, control signals from different components may be used as the input control signal for this component if a more detailed form of hysteresis is desired.

For safety considerations, a high limit cut-out is included with this controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded. This controller is not restricted to sensing temperatures, even though temperature notation is used. This controller instance uses unit descriptions of ^{0}C so that it is readily usable as a thermostatic differential controller.

6.2.5. Forcing Function (Type 14)

The TYPE 14b forcing functions: In a transient simulation, it is sometimes convenient to employ a time dependent forcing function which has a behavior characterized by a repeated pattern. The pattern of the forcing function is established by a set of discrete data points indicating the value of the function at various times throughout one cycle.

6.2.6. Data Reader (Type 9)

This component serves the purpose of reading data at regular time intervals from a data file, converting it to a desired system of units, and making it available to other TRNSYS components as time-varying forcing functions. This component is very general in nature and can read many different types of files. The data from line to line must be at constant time intervals. Here, in this research work it is used to read the weather data of Addis Ababa and sends it to the solar radiation processor.

6.2.7. Solar Radiation Processor (Type 16)

Solar Insolation data is generally taken at one hour intervals and on a horizontal surface. In most TRNSYS simulations, estimates of radiation at time intervals other than one hour are required. This component interpolates radiation data, calculates several quantities related to the position of the sun, and estimates Insolation on a number of surfaces of either fixed or variable orientation.

This instance of Type16 takes hourly integrated values of total horizontal and direct normal radiation as inputs. It can use various algorithms to compute radiation on tilted surfaces. Data can be entered in solar or in local time.

6.2.8. Integrator (Type 24)

This component integrates a series of quantities over a period of time. Each quantity integrator can have up to, but no more than 500 inputs. Type24 is able to reset periodically throughout the simulation either after a specified number of hours or after each month of the year. With the release of TRNSYS 16, Type24 was expanded so that the time between resets could be counted relative to the start time of the simulation or in absolute time.

6.2.9. Printer (Type 25)

The printer component is used to output (or print) selected system variables at specified (even) intervals of time. In this mode, TRNSYS supplied units descriptors (kJ/hr, deg C, W, etc.) if available, are printed to the output file along with each column heading. Output can be printed in even time intervals starting relative to the simulation start time or can be printed in absolute time. If relative printing is chosen with a one hour print interval and the simulation starts at time 0.5, values will be printed at times 0.5, 1.5, 2.5, etc. If absolute printing is selected, for the same simulation, values will be printed at times 0.5, 1.0, 2.0, 3.0, etc. Type25 is also able to print simulation information as a header to the output file (name of input file, and time of simulation run). It is further able to append new data to an existing file or can be set to overwrite the existing file.

6.3. TRNSYS Simulation Results and Discussion of the System

Once a system model has been established, running TRNSYS causes the program to step through all the system components evaluating output variables at each time step. Thus, weather data (solar radiation, ambient temperature, etc.) and all time dependent variables are determined and calculated every time step through the simulation time period. For a true thermal transient model, the transient equations in the modeled components are solved using TRNSYS analytical solutions.

A program such as TRNSYS has the capability of interconnecting system components in any desired manner. Once all of the components of the system have been identified and a mathematical description of each component is available, an information flow diagram for the system needs to be constructed. The purpose of the information flow diagram is to facilitate identification of the components and the flow of information between them. Each component is represented as a box, which requires a number of constant PARAMETERS and time-dependent

INPUTS and produces time-dependent OUTPUTS. An information flow diagram shows the manner in which all system components are interconnected. A given OUTPUT may be used as an INPUT to any number of other components. A simplified information flow diagram of the solar water heater plant under investigation is shown in Figure 6-2.

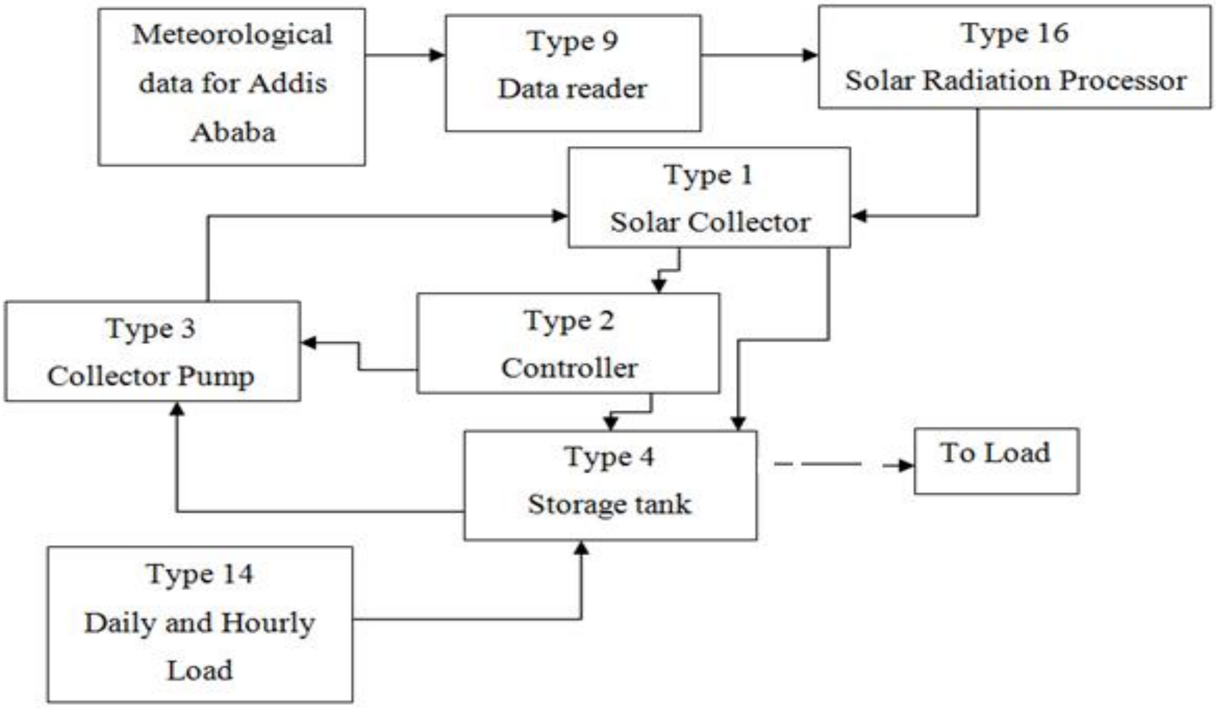


Figure 6-2: A simplified information flow diagram of the solar water heater plant under investigation

From the flow diagram a deck file has to be constructed containing information on all system components, weather data file and output format. Simulations generally require some components that are not ordinarily considered as part of the system. Such components are utility subroutines and output producing devices. The TYPE number of a component relates the component to a FORTRAN subroutine, which models that component. Each component has a unique TYPE number. The UNIT number is used to identify each component (which can be used more than once) in the deck file. Although two or more system components can have the same TYPE number, each must have a unique UNIT number.

6.3.1. TRNSYS Simulation Results

The result of TRNSYS simulation of the solar water heating system is briefly outlined in this section of the chapter. The reference values for this simulation are found from the daily hot water consumption pattern, system sizing and manufacturers catalogue. The goal is to create a detailed model that accurately predicts solar water heater plant behavior on short time scales (i.e. hours) and through transients. Consequently, the TRNSYS model input data are plotted on a daily, rather than monthly or annual basis. Results are shown for sunny and cloudy days in 2001 with solar-only operation and solar with auxiliary heating operation cases. Figure 6-3 shows the weather conditions at Addis Ababa for the year 2001.

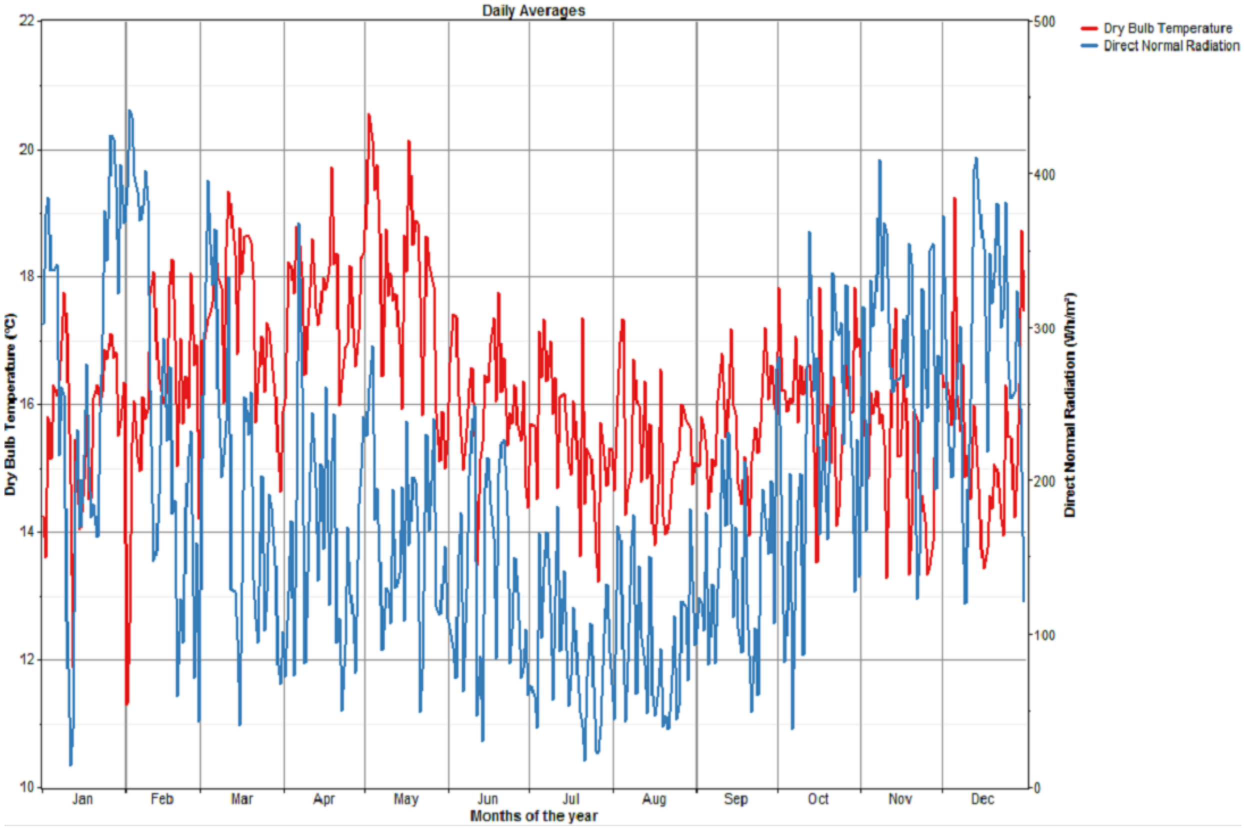


Figure 6-3: Daily Average Weather Conditions of Addis Ababa

The simulation is done for year 2001 G.C under Addis Ababa weather condition. The selection of the year is random. The weather data for Addis Ababa considered is found from SEWERA website [28] in a text and TMY formats.

From Figure 6.3 the maximum daily average DNI occurs on February 2nd (441.38Wh/m^2) and minimum daily average DNI on January 11th (13.46Wh/m^2). These days are, therefore, used as clear and cloudy day representatives respectively for the hot water system simulation.

6.3.1.1. Simulation Results for Clear Day

Clear day in this context is a representative day for occurrence of relatively higher daily average DNI from the days of the year considered. In this research, five days (January 31- February 4) two days before and two days after the day with maximum DNI are selected for clear day simulation.

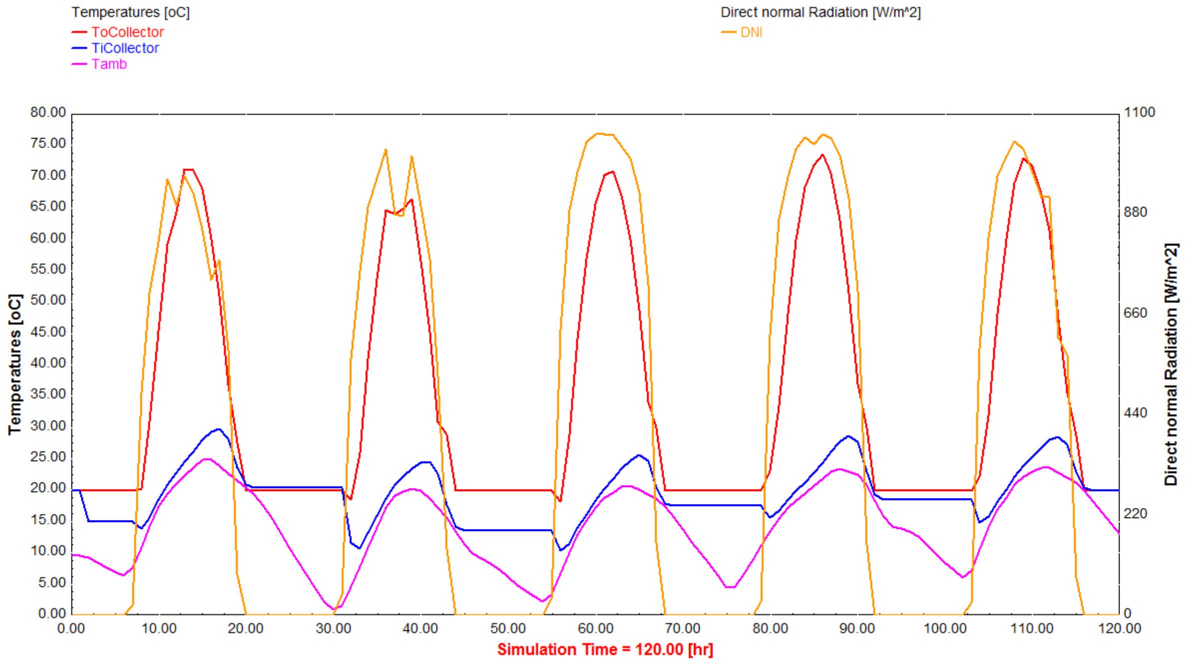


Figure 6-4: Plot of DNI, Ambient Temperature and Water Temperatures at Solar Collector Inlet and Outlet for January 31st - February 4th of the Year Considered without Auxiliary Heater

Figure 6.4 shows the variation of water temperatures at solar collector inlet and outlet with respect to the variations of Direct Normal Radiation (DNI) and ambient temperature for the clear days of the year considered. From this result we can see that for the days the temperature of the water reaches even above the required set point temperature. But there is a need of small amount of heat from another source to maintain the hot water delivery temperature of 60^0C throughout the day.

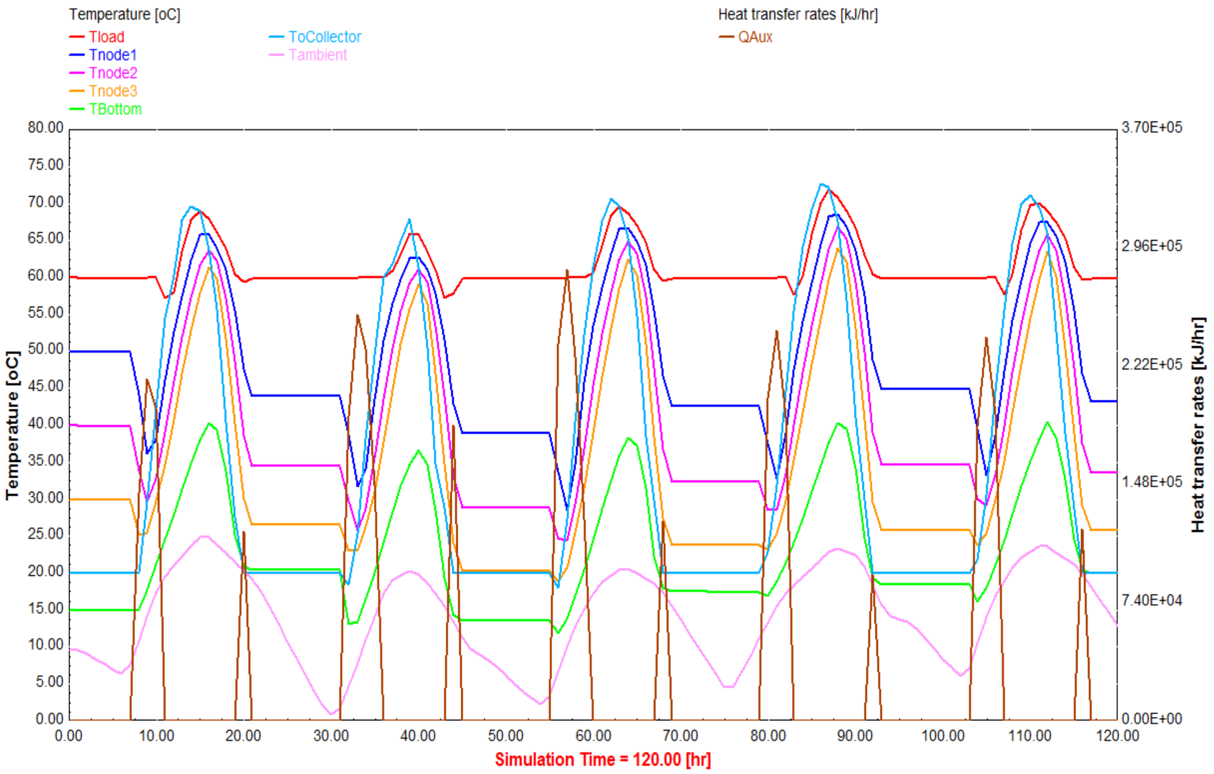


Figure 6-5: Plot of Temperature Distributions in the Storage tank, Load Temperature, Ambient Temperature and Auxiliary Heating Rates on Clear Days of the Year Considered

Figure 6.5 shows the output of the program which consists of the variation of water temperature in the stratified storage tank and temperature of the load with respect to the water temperature at the collector outlet, ambient temperature and the heat addition with auxiliary heater for the specified clear days of the year considered. From the figure we can seen that the temperature of the nodes of the stratified storage tank increases from bottom upwards which shows the thermal stratification effect. Most of the daily load is covered by the solar radiation and the contribution of auxiliary heater is very low for these days. For the clear day of February 2nd the contribution of solar energy to the heating load is 87.4% and the contribution of Auxiliary heater is only 12.6%.

6.3.1.2. Simulation Results for Cloudy Day

Cloudy day in this context is a representative day for occurrence of relatively lower daily average DNI from the days of the year considered. In this research, January 9th -13th is selected for cloudy day simulation.

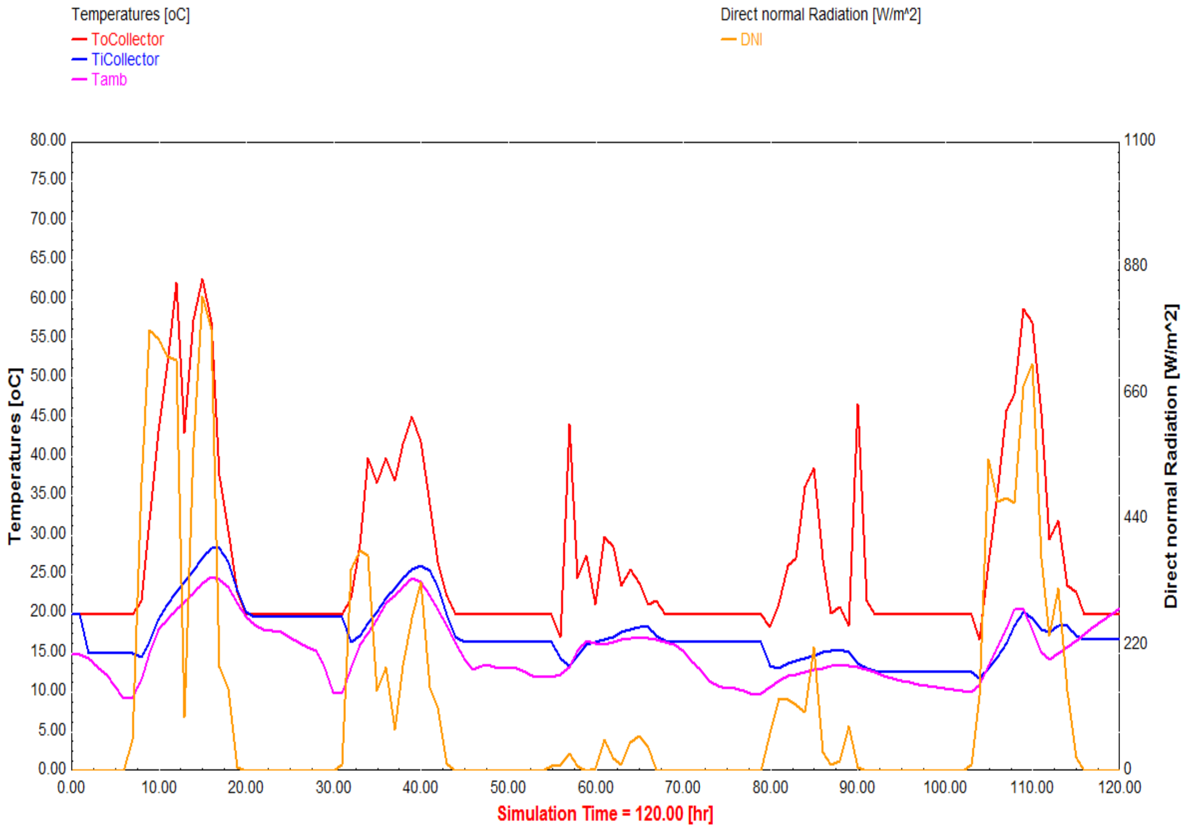


Figure 6-6: Plot of Solar Collector Input and Output, DNI and Ambient Temperature for January 9th - 13th of the Year Considered without Auxiliary Heater

Figure 6.6 shows the variation of water temperatures at solar collector inlet and outlet with respect to the variations of Direct Normal Radiation (DNI) and ambient temperature for the cloudy days of the year considered. From this result we can see that for the days the temperature of the water cannot reach the required set point temperature by the solar collectors only. Therefore, there is a need of much amount of heat from another source to maintain the hot water delivery temperature of 60^0C.

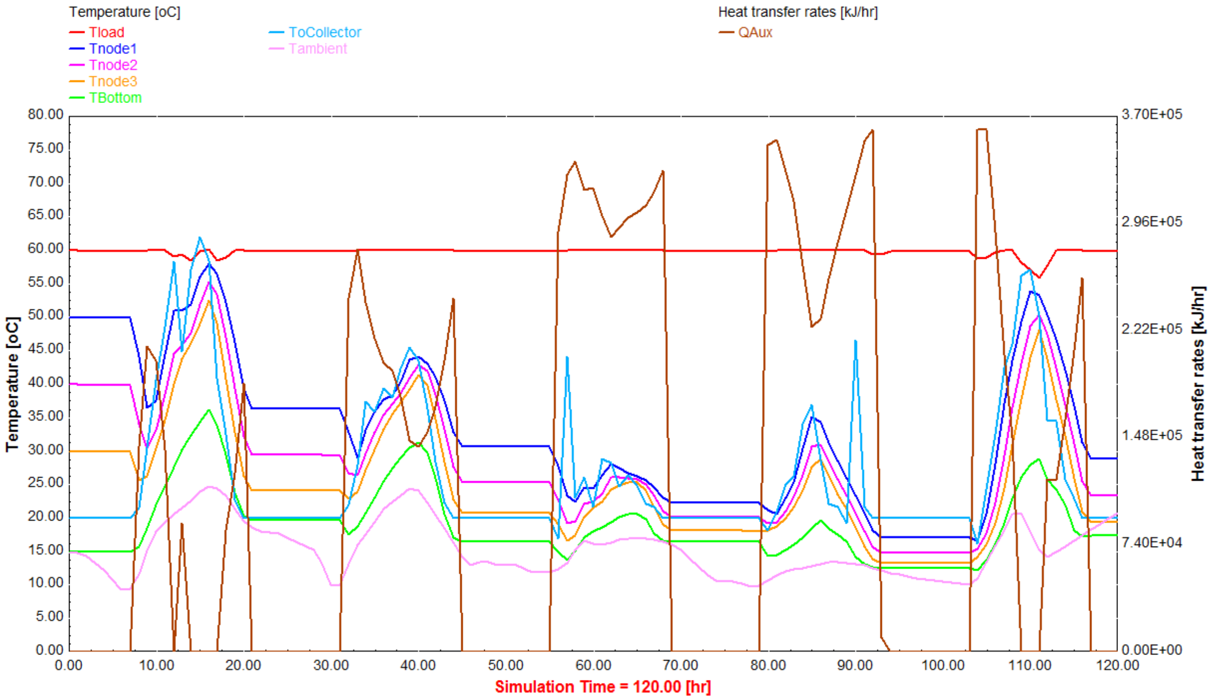


Figure 6-7: Plot of Temperature Distributions in the Storage tank, Load Temperature, Ambient Temperature and Auxiliary Heating Rates on Cloudy Days of the Year Considered

Figure 6.7 shows the output of the program which consists of the variation of water temperature in the stratified storage tank and temperature of the load with respect to the water temperature at the collector outlet, ambient temperature and the heat addition with auxiliary heater for the specified cloudy days of the year considered. As can be seen from the figure the temperature of the nodes of the tank increases from bottom upwards. Most of the daily load is covered by the auxiliary heater and the contribution of solar radiation is very low for these days. For the cloudy day of January 11th the contribution of solar energy to the heating load is only 27.8% and the contribution of Auxiliary heater is 72.2%.

6.3.1.3. Solar Contribution to the Heating Load

The rating factor that is commonly used to assess the performance of a solar water heater is the solar contribution relative to a conventional energy source, Solar Fraction, which is how much the auxiliary energy consumption would be reduced by changing to a solar system. The simulation result of the monthly variation of energy addition to the water heating system by the solar collectors and the auxiliary heaters is shown in Table 6-4.

Table 6-5: Monthly Energy gain Variation Data of the Water Heating System

Month	Total Radiation [MWh]	Collector Energy [MWh]	Auxiliary Energy [MWh]	Energy to Load [MWh]	Solar Fraction	Auxiliary Fraction	Collector Efficiency
January	166.24	57.2	28.2	85.4	0.67	0.33	0.344
February	155.52	53.4	23.4	76.8	0.696	0.304	0.343
March	167.36	56.8	26.4	83.2	0.683	0.317	0.339
April	154.88	51.8	27.4	79.2	0.655	0.345	0.334
May	162.24	54.2	27	81.2	0.669	0.331	0.334
June	143.76	47.6	34.2	81.8	0.583	0.417	0.331
July	122.88	41.2	45.8	87	0.475	0.525	0.335
August	127.12	42.8	44.2	87	0.493	0.507	0.337
September	146	48.6	33.6	82.2	0.592	0.408	0.333
October	174.64	58	26	84	0.692	0.308	0.332
November	178.88	60.2	22.2	82.4	0.73	0.27	0.336
December	171.12	58.4	25.4	83.8	0.697	0.303	0.341
Annual	**1871.12**	**630.2**	**363.8**	**994**	**0.634**	**0.366**	**0.337**

The solar fraction indicates what percentage of the energy required annually for domestic hot water applications are covered by the solar heating system. The plant performance was evaluated in terms of the solar fraction *SF* defined by [24]:

$$\mathrm{SF} = \frac{\mathrm{Q_U}}{\mathrm{Q_L}} = \frac{\mathrm{Q_L} - \mathrm{Q_{Aux}}}{\mathrm{Q_L}} \tag{6.21}$$

Where: SF = Solar fraction

$\mathrm{Q_U}$ = useful solar energy

Q_L = energy delivered to the load

Q_{Aux} = energy supplied by the auxiliary

The monthly (annual variation) summaries of the fraction of solar energy contribution and auxiliary heater contribution to the heating load are shown in Figure 6.8 and Figure 6.9 respectively.

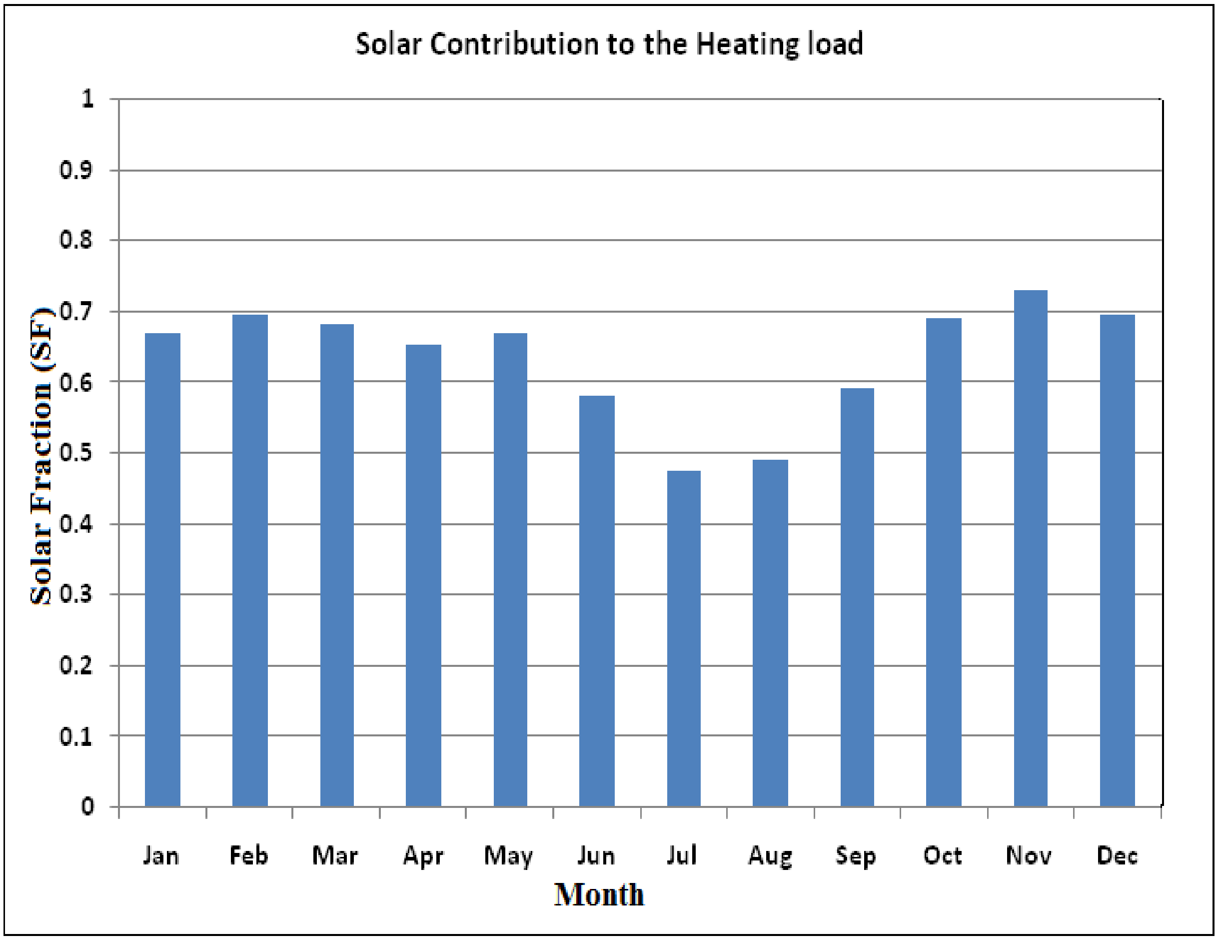


Figure 6-8: Simulated Monthly Fraction of Solar Energy Contribution to the Heating Load

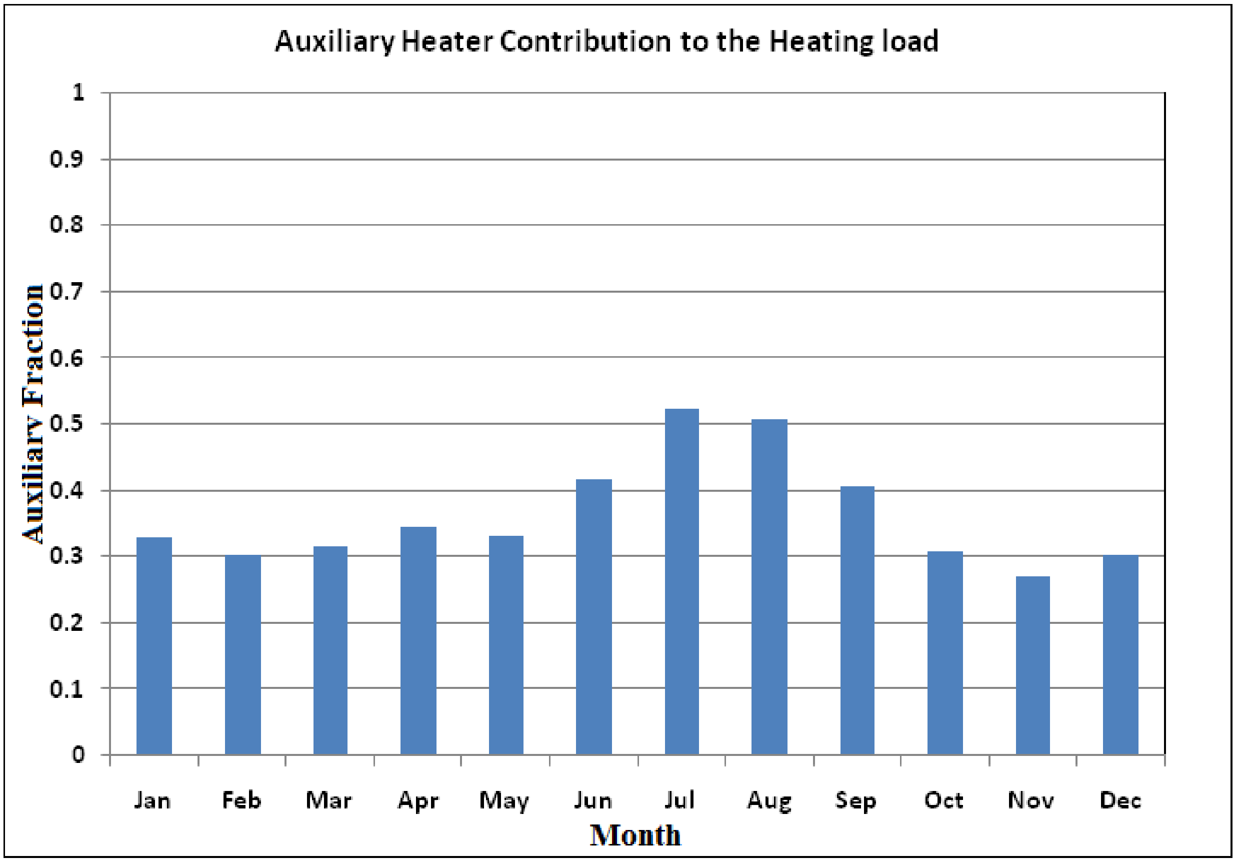


Figure 6-9: Simulated Monthly Fraction of Auxiliary Heater Energy Contribution to the Heating Load

As can be seen from figure 6.8 and Figure 6.9 for the storage tank hot water delivery temperature of 60ºc the maximum solar contribution to the heating load is achieved during the winter season in the month of November and the minimum is achieved during the summer season in the month of July for the year considered.

CHAPTER SEVEN

ECONOMIC ANALYSIS

7.1. Introduction

The economic viability of the solar water heating system is assessed to determine justification of making investment in this field. Economics play a central role in any customer's decision to purchase a SDHW system. The prospective owner of a renewable energy system may have many reasons for the purchase. They may wish to do their part for the environment, or to lead others by example. But one criterion that is likely to be high on the list of most individuals or institutions is the financial benefit of the investment. There seem to be far more publications extolling, and even quantifying the environmental benefits of these systems than the financial benefits. This is likely due in part because the economic analysis is less certain. The annual output of a properly operating SDHW system can be computed with a fair degree of accuracy, though limited by variations in solar Insolation. The financial analysis builds on these uncertainties with the uncertainty of future fuel/electricity prices, and variations in individual's financial situations. But the techniques for actually doing the analysis are well established.

Two systems are used for comparison of cost benefit for the financial analysis and the viability of the investment. These are using the electric power or diesel fuel as a backup system with the solar water heating system.

System simulation was conducted by particular software – **RETScreen Version 4-1**. This software facilitated providing of long-term vision of system operation and economic or environmental effects, based on the local solar irradiation data and specifically selected characteristics of solar hot water systems.

7.2. Overview of RETScreen Program

RETScreen International is a clean energy awareness, decision-support and capacity building tool. The core of the tool consists of standardized and integrated clean energy project analysis software that can be used world-wide to evaluate the energy production, life-cycle costs and greenhouse gas emission reductions for various types of energy efficient and renewable energy technologies (RETs). Each RETScreen energy technology model (e.g. Solar Water Heating Project, etc.) is developed within an individual Microsoft Excel spreadsheet "Workbook" files. The Workbook file is in-turn composed of a series of worksheets. These worksheets have a common look and follow a standard approach for all RETScreen models. In addition to the software, the tool includes: product, weather and cost databases.

RETScreen is a feasibility analysis tool which uses the f-chart design method to predict monthly performance for a solar thermal system. This involves seemingly simple calculations using a few key input parameters and monthly average weather data.

The RETScreen International Solar Water Heating Model can be used world-wide to easily evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for three basic applications: domestic hot water, industrial process heat and swimming pools (indoor and outdoor), ranging in size from small residential systems to large scale commercial, institutional and industrial systems.

The RETScreen worksheets include: Energy Model, Solar Resource and Heating Load Calculation, Cost Analysis, Greenhouse Gas Emission Reduction Analysis (GHG Analysis), Financial Summary and Sensitivity and Risk Analysis (Sensitivity) can be provided in the Solar Water Heating Project Workbook file. The GHG Analysis worksheet is optional analyses. The GHG Analysis worksheet is provided to help the user estimate the greenhouse gas (GHG) mitigation potential of the proposed project. In general, the user works from top-down for each of the worksheets. This process can be repeated several times in order to help optimize the design of the solar water heating project from an energy use and cost standpoint.

As part of the RETScreen Clean Energy Project Analysis Software, the Energy Model and Solar Resource and Heating Load Calculation worksheets are used to help the user calculate the annual energy production for a solar water heating system based upon local site conditions and system characteristics.

In addition to the worksheets that are required to run the model, the Introduction worksheet is included in the Solar Water Heating Project Workbook file. The Introduction worksheet provides the user with a quick overview of the model.

RETScreen economic model calculates a project's cash flow over a specified analysis period. The cash flow captures installation and operating costs, taxes, incentives, and the cost of debt.

7.3. Economic Indicators

An economic analysis takes into account a great number of variables that describe the strength of the current market. These variables are combined to form a figure of merit that allows comparison of investment alternatives.

Organizations, whether private, public, or non-profit, are often faced with the opportunity to generate a stream of future benefits (cash payments or avoided costs) by investing a sum of money in the present.

7.3.1. Life Cycle Cost

Life cycle costing or LCC is an important factor for comparing the alternatives and deciding on a particular process for completing a project. The different components taken into account for calculating LCC are:

LCC = Capital + Replacement cost + Maintenance cost + Energy cost –Salvage

Here, Capital is the present worth. Replacement cost that may occur at a later years need to converted to present worth. Maintenance cost is annual maintenance cost and needs to be converted to present worth and so is the energy cost. Salvage is the money that is obtained while disposing the machinery at the end of life cycle period. Even this amount has to be converted to present worth for calculating LCC.

A solar water heater is designed for supplying a specified quantity of hot water per day at a specified temperature. Thus, the annual heating load of water heating becomes:

$$Q_a = 365\rho_w V_w C_w (T_{hot} - T_{cold}) \tag{7.1}$$

Where: ρ_w = Density of water

V_w = Volume of daily hot water consumption

C_w = Specific heat of water heating

T_{hot} = Hot water delivery temperature

T_{cold} = Main water temperature

While a fraction of this heating load is covered by the solar energy, the rest is met by auxiliary energy supply system. Therefore, the annual contribution of solar energy to the heating load becomes [13]:

$$Q_{a,solar} = f_a Q_a \tag{7.2}$$

Where: $Q_{a,solar}$ = Annual contribution of solar energy to the heating load

f_a = Annual fraction of contribution of solar energy to the heating load

In conducting economic analysis of energy conversion systems, life cycle costs and savings are determined. The life cycle costs include investment capital and present worth of operating cost during the useful life of the plant. The operating cost of solar water heating system is mainly the maintenance cost. The life cycle cost of a solar water heating system is determined from the investment cost and the present value of maintenance and pumping costs distributed over the life of the plant [13, 23].

7.4. Financial Summary

Financial Summary worksheet is provided for each project evaluated. This common financial analysis worksheet contains: Annual Energy Balance, Financial Parameters, Project Costs and Savings, Financial Feasibility, Yearly Cash Flows and Cumulative Cash Flows Graph. The Annual Energy Balance and the Project Costs and Savings sections provide a summary of the Energy Model. In addition to this summary information, the Financial Feasibility section provides financial indicators of the project analyzed based on the data entered by the user in the

Financial Parameters section. The Yearly Cash Flows section allows the user to visualize the stream of pretax, after-tax and cumulative cash flows over the project life. The Financial Summary worksheet of each Workbook file has been developed with a common framework so the task of the user in analyzing the viability of different project types is made simpler. This also means the description of each parameter is common for most of the items appearing in the worksheet. One of the primary benefits of using the RETScreen software is that it facilitates the project evaluation process for decision-makers. The Financial Summary worksheet, with its financial parameters input items (e.g. avoided cost of energy, discount rate, debt ratio, etc.), and its calculated financial feasibility output items (e.g. IRR, simple payback, NPV etc.), allows the project decision-maker to consider various financial parameters with relative ease.

7.4.1. Discount rate

The user enters the discount rate (%), which is the rate used to discount future cash flows in order to obtain their present value. The rate generally viewed as being most appropriate is an organization’s weighted average cost of capital. An organization’s cost of capital is not simply the interest rate that it must pay for long-term debt. Rather, cost of capital is a broad concept involving a blending of the costs of all sources of investment funds, both debt and equity. The discount rate used to assess the financial feasibility of a given project is sometimes called the "hurdle rate," the "cut-off rate," or the "required rate of return." The model uses the discount rate to calculate the annual life cycle savings. For example, North American electric utilities currently use discount rates ranging anywhere from 3 to 18% with 6 to 11% being the most common values.

7.4.2. Project life

The user enters the project life (year), which is the duration over which the financial feasibility of the project is evaluated. Depending on circumstances, it can correspond to the life expectancy of the energy equipment, the term of the debt, or the duration of a power/heat purchase or energy service agreement. Although the model can analyze project life's up to 50 years, the project life of a well designed solar water heating system typically falls between 20 and 30 years [25].

7.4.3. Project Costs and Savings

Most of the summary items here are calculated and/or entered in the Cost Analysis worksheet and transferred to the Financial Summary worksheet. Some calculations are made in the Financial Summary worksheet.

7.4.4. Initial Costs

The total initial costs represent the total investment that must be made to bring a project on line, before it begins to generate savings (or income). The total initial costs are the sum of the estimated feasibility study, development, engineering, energy equipment, balance of system and miscellaneous costs and are inputs in the calculation of the simple payback, the net present value and the project equity and debt.

It is important to note that the range of possible costs listed throughout RETScreen do not include sales taxes. In a number of jurisdictions, clean energy project costs are exempt from sales taxes. Users will have to consider these costs for their region when preparing their evaluations. For example, if in a particular region sales tax is applicable to the cost of a solar water heating project then the user must add the amount of sales tax to the cost of the project chosen from the proposed range of values.

7.4.5. Incentives/Grants

The user enters the financial incentive; this is any contribution, grant, subsidy, etc. that is paid for the initial cost (excluding credits) of the project. The incentive is deemed not to be refundable and is treated as income during the development/construction year, year 0, for income tax purposes.

For example, in Canada the Renewable Energy Deployment Initiative (REDI) may provide a 25% contribution for certain renewable energy systems used for heating and cooling applications. The contribution is 40% for systems installed in Canada's remote communities.

7.4.6. Annual Costs and Debt

The total annual costs are calculated by the model and represent the yearly costs incurred to operate, maintain and finance the project. It is the sum of the O&M costs, the fuel/electricity costs and debt payments. Note that the total annual costs include the reimbursement of the "principal" portion of the debt which is not, strictly speaking, a cost but rather an outflow of cash. These costs are described briefly below.

7.4.7. Operation and Maintenance (O&M)

The operation and maintenance (O&M) costs are the sum of the annual costs that must be incurred to operate and maintain the energy system, in excess of the O&M cost required by the base case energy system. The model uses the O&M cost to calculate the total annual costs and the yearly cash flows.

7.4.8. Annual Savings or Income

The total annual savings represent the yearly savings realized due to the implementation of the project. From the perspective of an independent heat/power producer or an energy services company, these "savings" will be viewed as "income." It is directly related to the avoided cost of heating energy derived from implementing the project.

7.4.9. Pre-tax Internal Rate of Return and Return on Investment

The model calculates the pre-tax internal rate of return (%), which represents the true interest yield provided by the project equity over its life before income tax. It is also referred to as the return on investment (equity) (ROI) or the time-adjusted rate of return. It is calculated by finding the discount rate that causes the net present value of the project to be equal to zero. Hence, it is not necessary to establish the discount rate of an organization to use this indicator. An organization interested in a project can compare the internal rate of return of the project to its required rate of return (often, the cost of capital). The IRR is calculated on a nominal basis that is including inflation.

If the internal rate of return of the project is equal to or greater than the required rate of return of the organization, then the project will likely be considered financially acceptable (assuming equal risk). If it is less than the required rate of return, the project is typically rejected. An organization may have multiple required rates of return that will vary according to the perceived risk of the projects. The most obvious advantage of using the internal rate of return indicator to evaluate a project is that the outcome does not depend on a discount rate that is specific to a given organization. Instead, the IRR obtained is specific to the project and applies to all investors in the project. The model uses the pre-tax yearly cash flows and the project life to calculate the internal rate of return.

7.4.10. Simple Payback

The model calculates the simple payback (year), which represents the length of time that it takes for an investment project to recoup its own initial cost, out of the cash receipts it generates. The basic premise of the payback method is that the more quickly the cost of an investment can be recovered, the more desirable is the investment. For example, in the case of the implementation of a solar water heating project, a negative payback period would be an indication that the annual costs incurred are higher than the annual savings generated.

The simple payback method is not a measure of how profitable one project is compared to another. Rather, it is a measure of time in the sense that it indicates how many years are required to recover the investment for one project compared to another. The simple payback should not be used as the primary indicator to evaluate a project. It is useful, however, as a secondary indicator to indicate the level of risk of an investment. A further criticism of the simple payback method is that it does not consider the time value of money, nor the impact of inflation on the costs. On the other hand, the payback period is often of great importance to smaller firms that may be cash poor. When a firm is cash poor, a project with a short payback period, but a low rate of return, might be preferred over another project with a high rate of repayment, but a long payback period. The reason is that the organization may simply need a faster return of its cash investment.

The model uses the total initial costs, the total annual costs (excluding debt payments) and the total annual savings, in order to calculate the simple payback. The calculation is based on pre-tax amounts and includes any initial cost incentives.

7.4.11. Net Present Value - NPV

The model calculates the net present value of the project (NPV), which is the value of all future cash flows, discounted at the discount rate, in today's currency. NPV is thus calculated at a time 0 corresponding to the junction of the end of year 0 and the beginning of year 1. Under the NPV method, the present value of all cash inflows is compared against the present value of all cash outflows associated with an investment project. The difference between the present values of these cash flows, called the NPV, determines whether or not the project is generally a financially acceptable investment. Positive NPV values are an indicator of a potentially feasible project. In using the net present value method, it is necessary to choose a rate for discounting cash flows to present value. As a practical matter, organizations put much time and study into the choice of a discount rate. The model calculates the NPV using the cumulative after-tax cash flows. In cases where the user has selected not to conduct a tax analysis, the NPV calculated will be that of the pre-tax cash flows.

7.4.12. Base Case Heating System (Baseline)

The base case heating system, or baseline system, represents the system to which the solar water heating system is compared. The base case heating system is defined in terms of its fuel types, its emissions of GHG and its conversion efficiencies.

The base case system is normally referred to as the reference or baseline option in standard economic analysis.

7.4.13. Proposed Case Heating System (Solar Water Heating Project)

The proposed case heating system, or mitigation system, is the solar water heating system. It is defined in terms of its fuel types, its emissions of GHG and its conversion efficiencies. Note that in all cases, the pumps, if any, of the solar water heating system are assumed to be electricity driven using the base case electricity system.

The proposed case system is normally referred to as the mitigation option in standard economic analysis.

7.5. Source of RETScreen Program Inputs

The daily hot water use, hot water temperatures required and water supply temperatures are user defined and the inputs are according to the previous analysis. Resource assessment, or the amount of sun available, was taken from the RETScreen climate database. Solar water heater data were obtained from design parameters and manufacturers' catalogue. Other input values were taken from suggested values for the location given in the RETScreen.

The following assumptions are taken during the economic analysis of SWH system:

- Life of the plant = 20 years
- Interest rate = 10.5%
- Discount rate = 5.5%
- Inflation rate = 5%
- Minimum supply water temperature = 3^0C
- Maximum Supply water temperature = 23.5^0C
- Fuel cost = 11.50Birr/L
- Electricity cost = 0.6 Birr/kWh

In this research the total cost break down taken for different components of the solar water heating system from different manufacturers and distributors are summarized in the table below.

Table 7-1: Total Cost Break Down for all systems

Cost Type	Unit cost [Birr/Collector]	Total Cost [Birr]
Solar Collector Cost	5000	2,000,000
Pipes (Material +Insulation) Cost	105	42,000
Auxiliary Heater Cost	300	120,000
Storage Tank Cost	435	174,000
Pump (Electric Drive) Cost	128	51,200
Fittings Cost	16	6400
Labour and Installation cost	500	200,000

taking 10% of collector cost		
5% Contingency	324.2	129,680
Total Initial Investment cost	**6,808.2**	**2,723,280**
Operating Cost (Maintenance & Pumping Cost) Taking 5% of Total Investment cost	3,40.41	136,164

7.6. RETScreen Input Sheets

7.6.1. Introduction Page

The Introduction worksheet provides the user with a quick overview of the model. It is used to input the project name, project location, project type, technology used and so on. Figure 7.1 shows the introduction page with its different inputs.

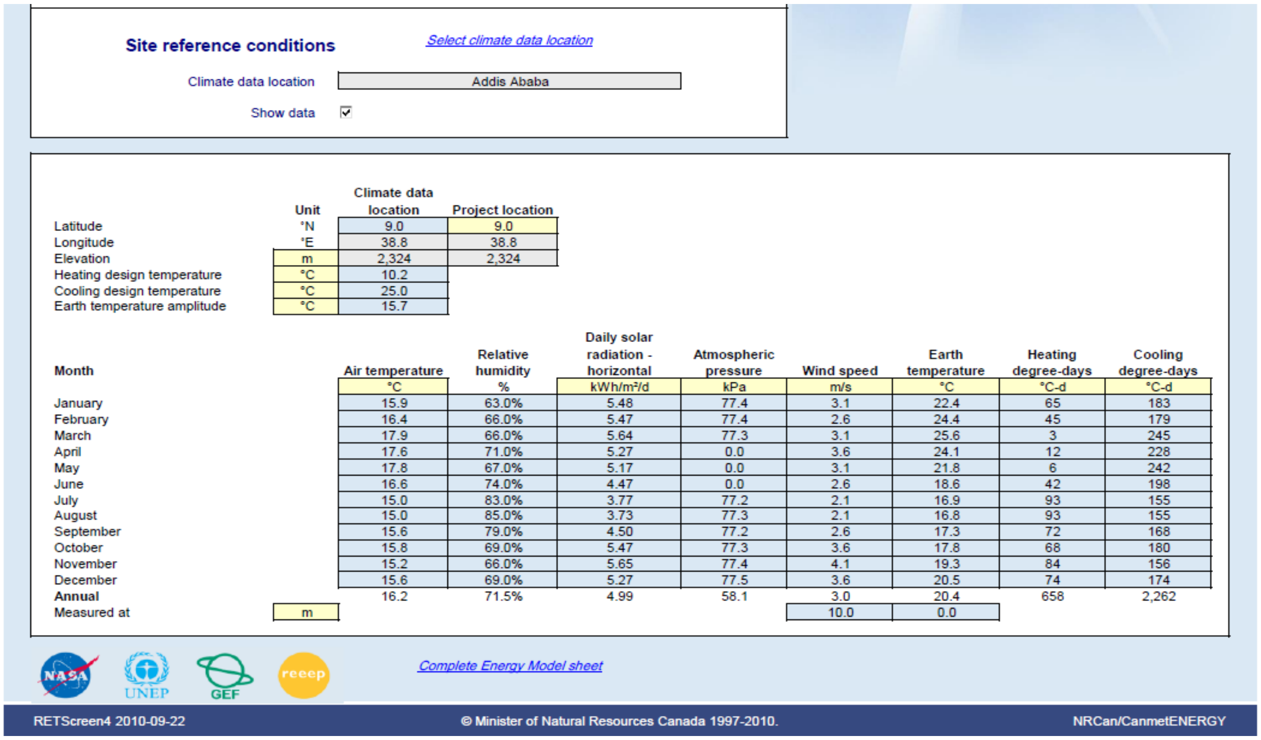
Project information

Project name: Solar DHW for AAIT Students Residence Hall
Project location: Addis Ababa
Prepared for: Masters Research
Prepared by: Tsegaye Seyoum
Project type: Heating
Technology: Solar water heater
Analysis type: Method 1
Heating value reference: Higher heating value (HHV)
Show settings: ☑
Language - Langue: English - Anglais
User manual: English - Anglais
Currency: Ethiopia
Units: Metric units

Figure 7-1: Introduction Page

7.6.2. RETScreen Solar Resource and Weather Data Page

Worldwide Ground-based Meteorological Data has been incorporated directly into the RETScreen Software. The user enters the weather station location in the Solar Resource and weather data worksheet and it is copied automatically to the Energy Model worksheet. The model calculates the total annual solar radiation incident on the solar collector, in MWh/m², from the monthly data in the Solar Resource worksheet. Figure 7.2 shows the solar resource and weather data for Addis Ababa.



Site reference conditions

Climate data location: Addis Ababa

Show data ☑

	Unit	Climate data location	Project location
Latitude	°N	9.0	9.0
Longitude	°E	38.8	38.8
Elevation	m	2,324	2,324
Heating design temperature	°C	10.2	
Cooling design temperature	°C	25.0	
Earth temperature amplitude	°C	15.7	

Month		Air temperature	Relative humidity	Daily solar radiation - horizontal	Atmospheric pressure	Wind speed	Earth temperature	Heating degree-days	Cooling degree-days
		°C	%	kWh/m²/d	kPa	m/s	°C	°C-d	°C-d
January		15.9	63.0%	5.48	77.4	3.1	22.4	65	183
February		16.4	66.0%	5.47	77.4	2.6	24.4	45	179
March		17.9	66.0%	5.64	77.3	3.1	25.6	3	245
April		17.6	71.0%	5.27	0.0	3.6	24.1	12	228
May		17.8	67.0%	5.17	0.0	3.1	21.8	6	242
June		16.6	74.0%	4.47	0.0	2.6	18.6	42	198
July		15.0	83.0%	3.77	77.2	2.1	16.9	93	155
August		15.0	85.0%	3.73	77.3	2.1	16.8	93	155
September		15.6	79.0%	4.50	77.2	2.6	17.3	72	168
October		15.8	69.0%	5.47	77.3	3.6	17.8	68	180
November		15.2	66.0%	5.65	77.4	4.1	19.3	84	156
December		15.6	69.0%	5.27	77.5	3.6	20.5	74	174
Annual		16.2	71.5%	4.99	58.1	3.0	20.4	658	2,262
Measured at	m					10.0	0.0		

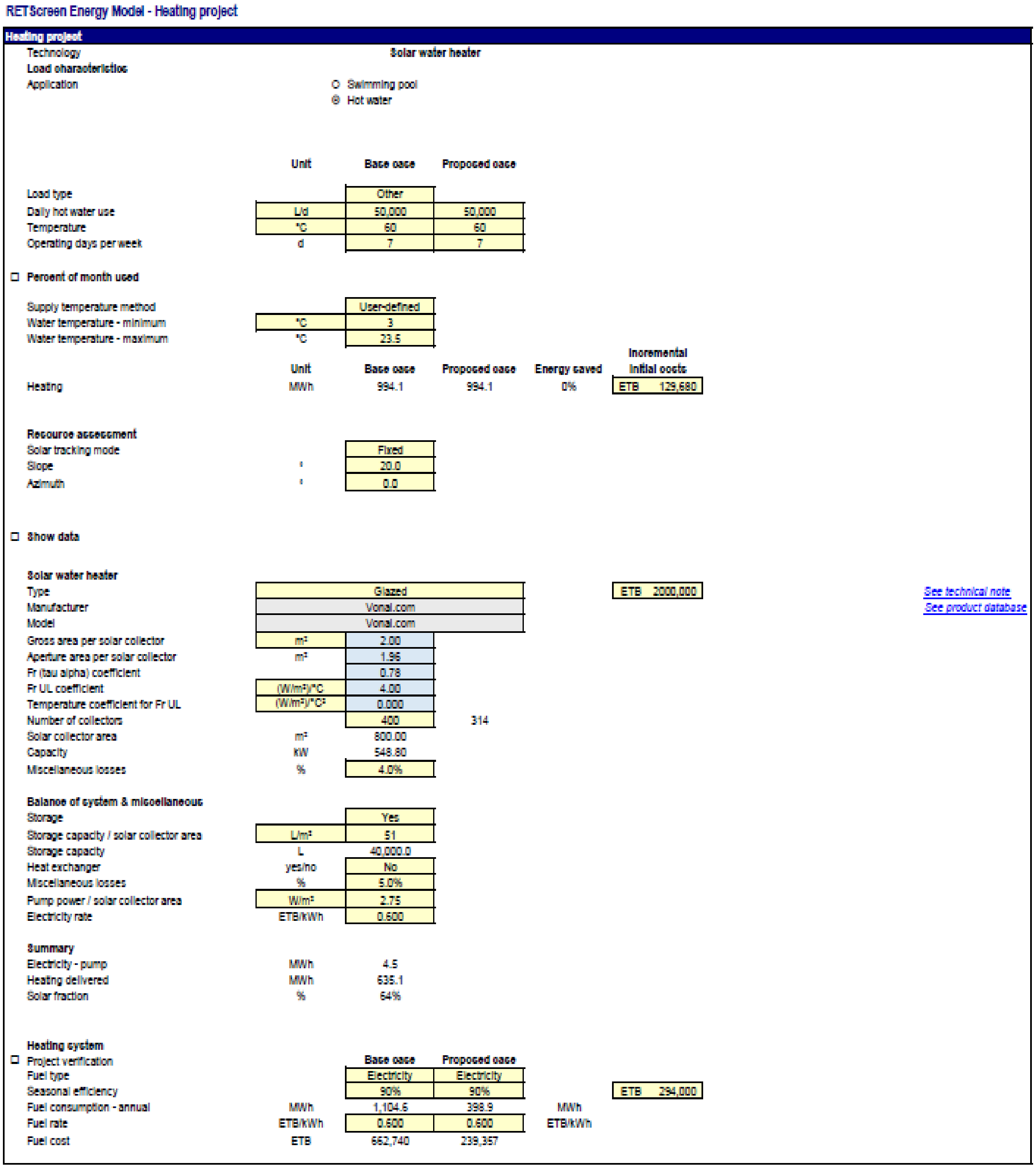
RETScreen4 2010-09-22 © Minister of Natural Resources Canada 1997-2010. NRCan/CanmetENERGY

Figure 7-2: Solar Resource and Weather Data page

7.6.3. Energy Model Page

As part of the RETScreen Clean Energy Project Analysis Software, the Energy Model worksheets are used to help the user calculate the annual energy production for a solar water heating system based upon local site conditions and system characteristics. Results are calculated in common megawatt-hour (MWh) units for easy comparison of different technologies. Figure 7.3 shows the Energy model page of the solar water heater with its different inputs.

The energy model is done for solar water heating system with electricity and furnace Oil respectively as a backup auxiliary heating system for comparison of which system have more financial benefit.



RETScreen Energy Model - Heating project

Heating project

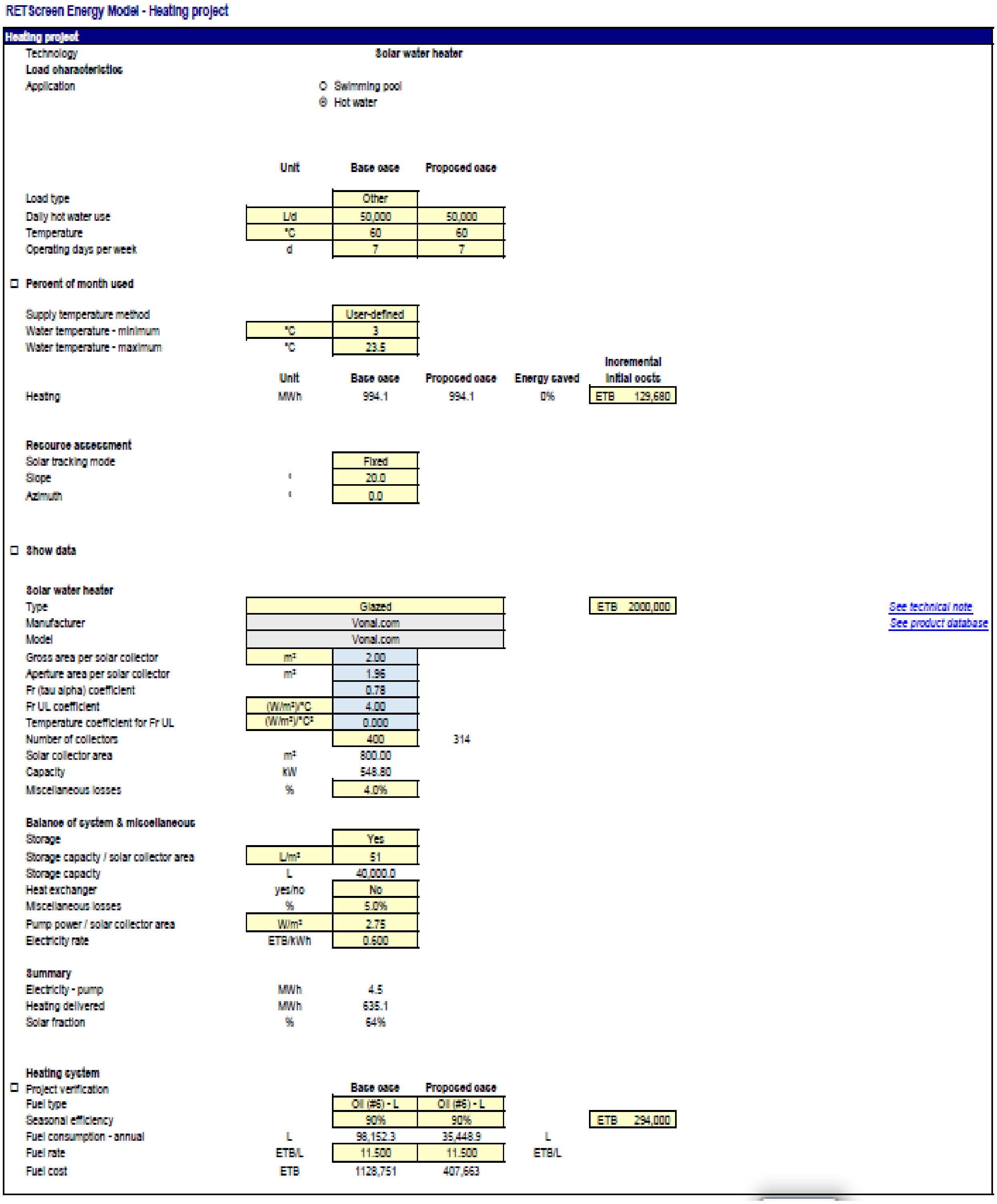
Technology: **Solar water heater**

Load characteristics

Application: ○ Swimming pool ● Hot water

	Unit	Base case	Proposed case	Energy saved	Incremental initial costs	
Load type		Other				
Daily hot water use	L/d	50,000	50,000			
Temperature	°C	60	60			
Operating days per week	d	7	7			
☐ **Percent of month used**						
Supply temperature method		User-defined				
Water temperature - minimum	°C	3				
Water temperature - maximum	°C	23.5				
Heating	MWh	994.1	994.1	0%	ETB 129,680	
Resource assessment						
Solar tracking mode		Fixed				
Slope	°	20.0				
Azimuth	°	0.0				
☐ **Show data**						
Solar water heater						
Type		Glazed			ETB 2000,000	See technical note
Manufacturer		Vonal.com				See product database
Model		Vonal.com				
Gross area per solar collector	m²	2.00				
Aperture area per solar collector	m²	1.96				
Fr (tau alpha) coefficient		0.78				
Fr UL coefficient	(W/m²)/°C	4.00				
Temperature coefficient for Fr UL	(W/m²)/°C²	0.000				
Number of collectors		400	314			
Solar collector area	m²	800.00				
Capacity	kW	548.80				
Miscellaneous losses	%	4.0%				
Balance of system & miscellaneous						
Storage		Yes				
Storage capacity / solar collector area	L/m²	51				
Storage capacity	L	40,000.0				
Heat exchanger	yes/no	No				
Miscellaneous losses	%	5.0%				
Pump power / solar collector area	W/m²	2.75				
Electricity rate	ETB/kWh	0.600				
Summary						
Electricity - pump	MWh	4.5				
Heating delivered	MWh	635.1				
Solar fraction	%	64%				
Heating system						
☐ Project verification		Base case	Proposed case			
Fuel type		Electricity	Electricity			
Seasonal efficiency		90%	90%		ETB 294,000	
Fuel consumption - annual	MWh	1,104.6	398.9	MWh		
Fuel rate	ETB/kWh	0.600	0.600	ETB/kWh		
Fuel cost	ETB	662,740	239,357			

Figure 7-3: Energy Model Page for Solar Water Heater with Electricity as Backup System



RETScreen Energy Model - Heating project

Heating project

Technology		Solar water heater	
Load characteristics			
Application		○ Swimming pool ● Hot water	

	Unit	Base case	Proposed case
Load type		Other	
Daily hot water use	L/d	50,000	50,000
Temperature	°C	60	60
Operating days per week	d	7	7

☐ **Percent of month used**

Supply temperature method		User-defined
Water temperature - minimum	°C	3
Water temperature - maximum	°C	23.5

	Unit	Base case	Proposed case	Energy saved	Incremental initial costs
Heating	MWh	994.1	994.1	0%	ETB 129,680

Resource assessment

Solar tracking mode		Fixed
Slope	°	20.0
Azimuth	°	0.0

☐ **Show data**

Solar water heater

Type	Glazed			ETB 2000,000	See technical note
Manufacturer	Vonal.com				See product database
Model	Vonal.com				
Gross area per solar collector	m²	2.00			
Aperture area per solar collector	m²	1.96			
Fr (tau alpha) coefficient		0.78			
Fr UL coefficient	(W/m²)/°C	4.00			
Temperature coefficient for Fr UL	(W/m²)/°C²	0.000			
Number of collectors		400	314		
Solar collector area	m²	800.00			
Capacity	kW	548.80			
Miscellaneous losses	%	4.0%			

Balance of system & miscellaneous

Storage		Yes
Storage capacity / solar collector area	L/m²	51
Storage capacity	L	40,000.0
Heat exchanger	yes/no	No
Miscellaneous losses	%	5.0%
Pump power / solar collector area	W/m²	2.75
Electricity rate	ETB/kWh	0.600

Summary

Electricity - pump	MWh	4.5
Heating delivered	MWh	635.1
Solar fraction	%	64%

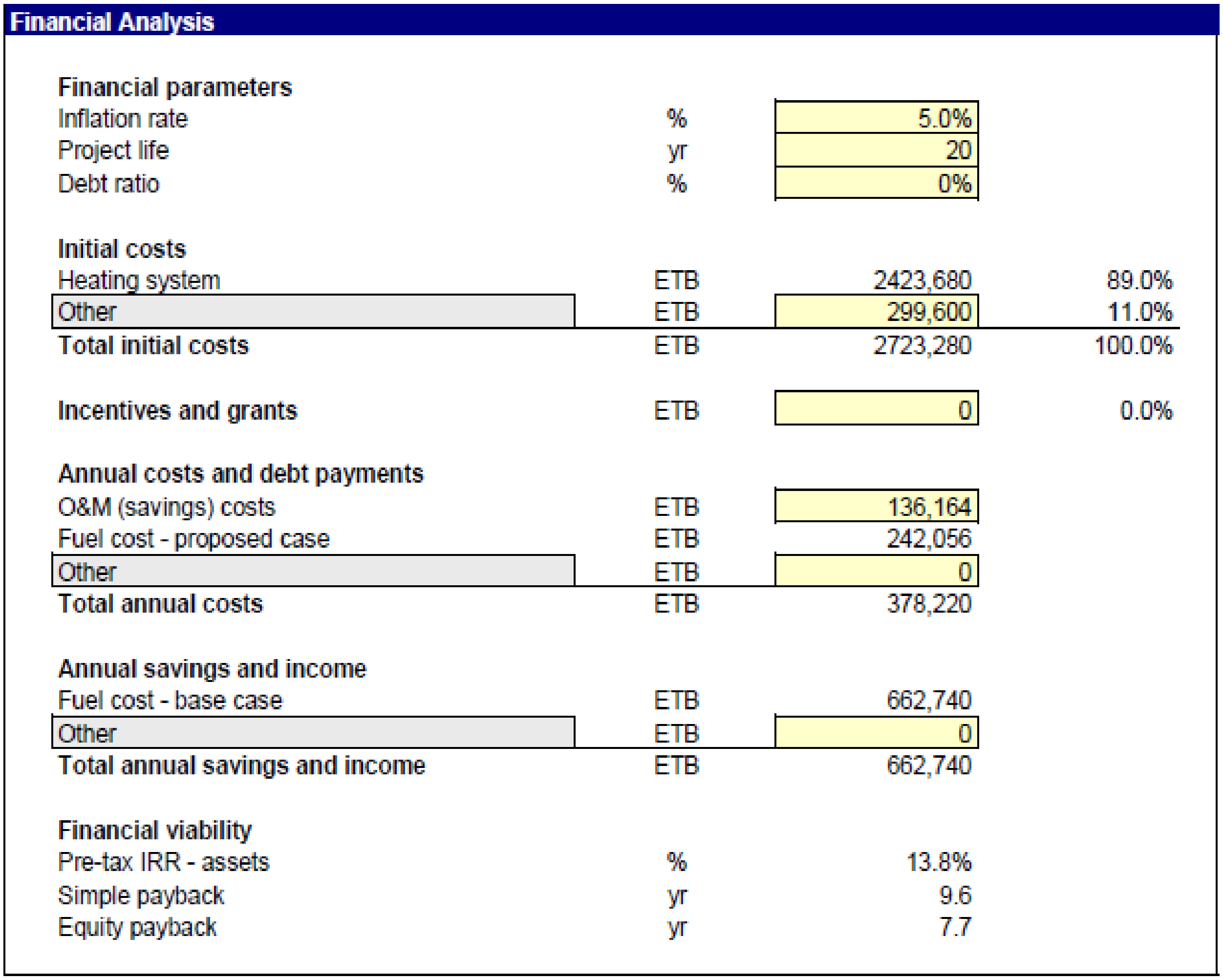
Heating system

		Base case	Proposed case		
☐ Project verification					
Fuel type		Oil (#6) - L	Oil (#6) - L		
Seasonal efficiency		90%	90%		ETB 294,000
Fuel consumption - annual	L	98,152.3	35,448.9	L	
Fuel rate	ETB/L	11.500	11.500	ETB/L	
Fuel cost	ETB	1128,751	407,663		

Figure 7-4: Energy Model Page for Solar Water Heater with Furnace Oil as Backup System

6.6.4. Financial Analysis Page

The Financing page displays the variables that RETScreen uses to calculate the project cash flow and other related financial metrics. The Financial Feasibility section provides financial indicators of the project analyzed based on the data entered by the user in the Financial Parameters section. The variables that appear on the Financing page depend on the financing option specified. Figure 7.5 to 7.8 shows the financial page and cumulative cash flows of the solar water heating system with electricity and furnace oil respectively as a backup system with its different inputs.



Financial Analysis

Financial parameters			
Inflation rate	%	5.0%	
Project life	yr	20	
Debt ratio	%	0%	
Initial costs			
Heating system	ETB	2423,680	89.0%
Other	ETB	299,600	11.0%
Total initial costs	ETB	2723,280	100.0%
Incentives and grants	ETB	0	0.0%
Annual costs and debt payments			
O&M (savings) costs	ETB	136,164	
Fuel cost - proposed case	ETB	242,056	
Other	ETB	0	
Total annual costs	ETB	378,220	
Annual savings and income			
Fuel cost - base case	ETB	662,740	
Other	ETB	0	
Total annual savings and income	ETB	662,740	
Financial viability			
Pre-tax IRR - assets	%	13.8%	
Simple payback	yr	9.6	
Equity payback	yr	7.7	

Figure 7-5: Financial Analysis Page for Electricity Backup System

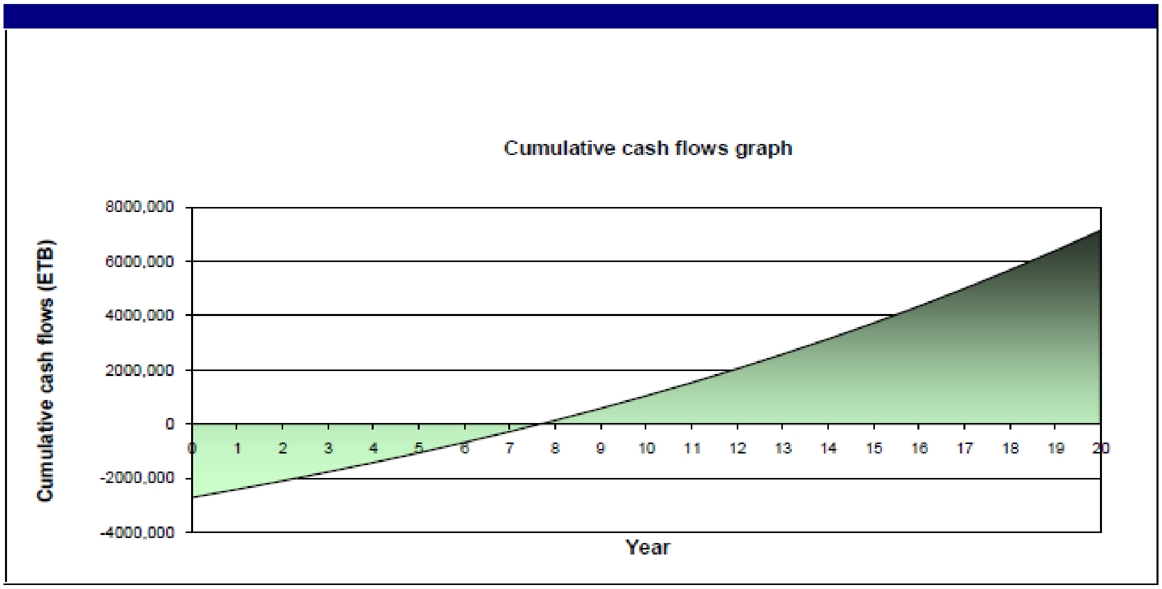
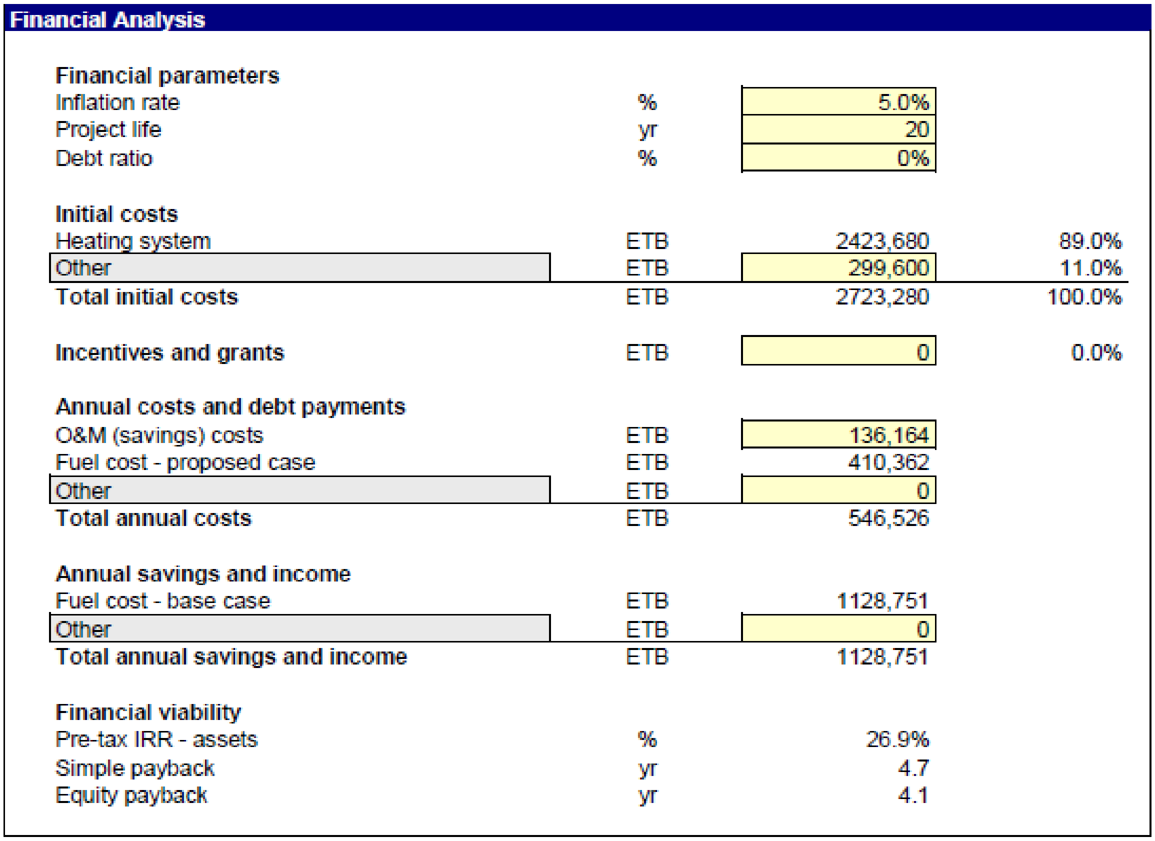


Figure 7-6: Cumulative Cash Flows Graph for Electricity Backup System



Financial Analysis

Financial parameters			
Inflation rate	%	5.0%	
Project life	yr	20	
Debt ratio	%	0%	
Initial costs			
Heating system	ETB	2423,680	89.0%
Other	ETB	299,600	11.0%
Total initial costs	ETB	2723,280	100.0%
Incentives and grants	ETB	0	0.0%
Annual costs and debt payments			
O&M (savings) costs	ETB	136,164	
Fuel cost - proposed case	ETB	410,362	
Other	ETB	0	
Total annual costs	ETB	546,526	
Annual savings and income			
Fuel cost - base case	ETB	1128,751	
Other	ETB	0	
Total annual savings and income	ETB	1128,751	
Financial viability			
Pre-tax IRR - assets	%	26.9%	
Simple payback	yr	4.7	
Equity payback	yr	4.1	

Figure 7-7: Financial Analysis Page for Furnace Oil Backup System

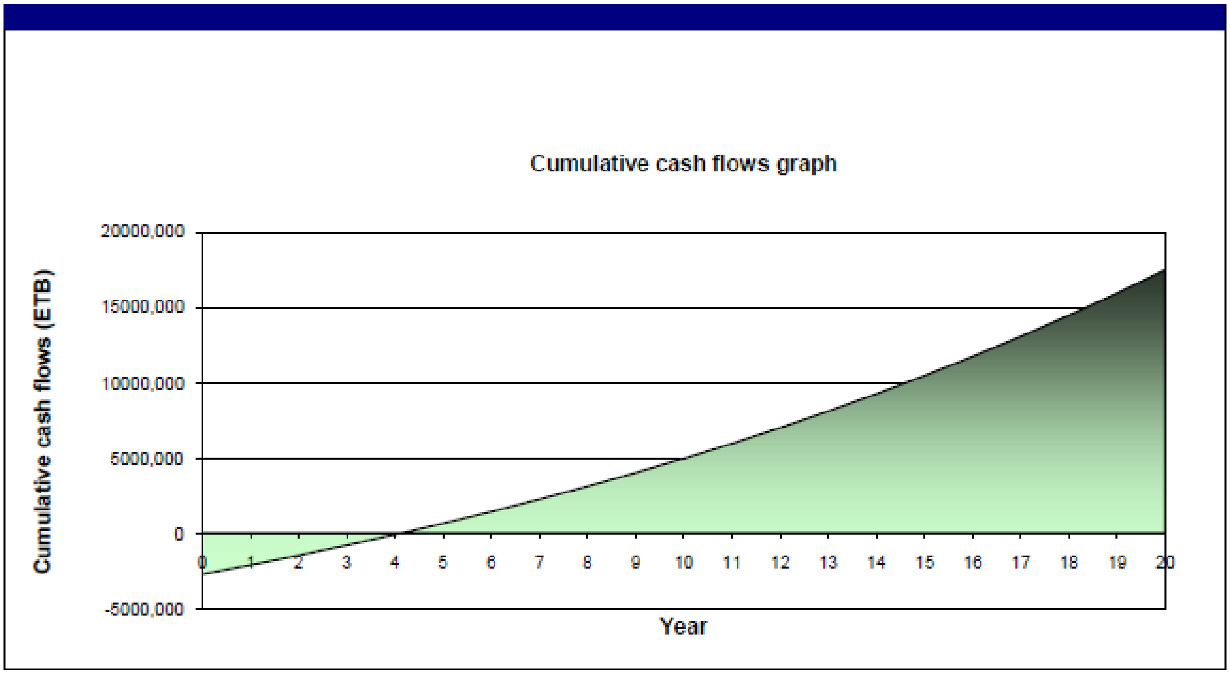


Figure 7-8: Cumulative Cash Flows Graph for Furnace Oil Backup System

The RETScreen analysis of electricity backup auxiliary heating system shows that the simple payback period is 9.6years with Pre tax - IRR of 13.8% and the total annual costs of 378,220Birr with annual savings of 662,740Birr. And the RETScreen analysis of furnace oil auxiliary heating backup system shows that the simple payback period is 4.7years with Pre tax - IRR of 26.9% and the total annual costs of 546,526Birr with annual savings of 1,128,751Birr.

The analysis also shows that the solar fraction has been determined to be 64% and the Renewable energy delivered annually is 635.1MWh or 2286.4GJ and the auxiliary energy delivery is 359MWh or 1292.4GJ for the total load energy of 994.1MWh or 3578.76GJ.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

8.1. Conclusions

The solar water heater was modeled and simulated using existing TRNSYS 16.0 components simulation studio and the financial analysis is done using RETScreen 4.1 software.

It was found that for the solar water heater plant analyzed in this paper the total daily hot water consumption is 50 m^3 and storage capacity of 40 m^3 was used at 60^0C and a total of 400 collectors with four storage tanks of each capacity 10 m^3 are needed with initial capital cost of **6,808.2** Birr per collector.

The plant model was simulated to predict the performance for representative clear and cloudy days at Addis Ababa weather condition. Simulation results have shown that the contribution of solar energy to the heating load on clear day of the year considered is 87.4% and it is only 27.8% on cloudy day of the year considered. Hence, only 12.6% of the heating load is covered by the auxiliary heater on the clear day and about 72.2% energy of the heating load is covered by the auxiliary heater on cloudy day considered. Also, temperature of the solar water heater in the storage tank increases from bottom up which shows the fully thermal stratification of the storage tank.

The RETScreen analysis was done for two cases of auxiliary heating systems for comparison. These are electricity heating system and furnace oil heating system. The RETScreen analysis of electricity backup auxiliary heating system shows that the simple payback period is 9.6years with Pre tax - IRR of 13.8% and the total annual costs of 378,220Birr with annual savings of 662,740Birr. And the RETScreen analysis of furnace oil auxiliary heating backup system shows that the simple payback period is 4.7years with Pre tax - IRR of 26.9% and the total annual costs of 546,526Birr with annual savings of 1,128,751Birr.

The RETScreen analysis also shows that the solar fraction has been determined to be 64% and the Renewable energy delivered annually is 635.1MWh or 2286.4GJ and the auxiliary energy delivery is 359MWh or 1292.4GJ for the total load energy of 994.1MWh or 3578.76GJ which is similar to the simulation result of TRNSYS.

Therefore, it is better to use furnace oil as a backup auxiliary heating system than electricity for the investment of the solar water heating system of this research.

8.2. Recommendations for Future Work

To keep the confidence of people in the investment on solar water heating, the manufacturing systems must be reliable and operate according to specifications. Good quality components must be used with good quality installation. That will help to decrease maintenance cost and extend the system’s life.

- The maintenance and replacement cost can increase the overall cost of a solar water heating system to high standards. Hence, the installers should give longer-term warranties as this seem one of the major factors for people consider about.
- For the specified hot water demand at a specified temperature, the collector area and the storage tank volume parametric optimization must be done as the optimal design of solar water heating has the task of minimizing costs of hot water generation.
- After two years of functioning, it is recommended that a program of annual service is begun.
- If there is a breakage of collector’s glass, it must be replaced immediately so that the absorber will not be damaged.
- If there is a lot of dust in the area, then the glass of the collectors will have to be washed at least twice a year with water, except if it often rains.
- After the installation is complete, the installer will have to inform the client about the functioning of the system.
- There should no shading of the collectors by any obstacles

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