ASSESSING THE FEASIBILITY OF A SOLAR WATER HEATING SYSTEM BASED ON PERFORMANCE AND ECONOMIC ANALYSIS

By

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DECLARATION

I hereby declare that this submission is my own work towards the Master of Science degree in Mechanical Engineering at the Kwame Nkrumah University of Science and Technology, Kumasi, Ghana under the supervision of the undersigned.

All works consulted have been duly acknowledged in the references.

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ABSTRACT

Solar water heating technology is one of the cost-effective ways of heating water in residential and public buildings such as hospitals and health centres.

This thesis has used the T*SOL® software programme to assess a proposed solar water heating system for the government hospital of the Kwame Nkrumah University of Science and Technology. The assessment is based on thermal performance and economics of two distinct collector configurations; a flat plate and evacuated tube collectors. The thermal performance analyses of the collectors show that the flat plate collector with annual solar contribution of 38, 221 kWh and reduced CO_2 emissions of 25, 456 kg has a better performance over the evacuated tube collector with solar contribution of 37, 946 kWh and reduced CO_2 emissions of 25, 273 kg.

The annual hot water heating load of the hospital is 57 MWh. The technical parameters of the proposed system from T*SOL® gives a total of 13 flat plate collector modules with collector area of 48.05 m^2 and annual collector surface area irradiation of 68.80 MWh. The contribution of the system to the annual heating load is 32.49 MWh with annual solar fraction of 54 percent and collector system efficiency of 47.2 percent. The annual fuel energy savings of the system is 38.2 MWh. The economic analysis of the system from T*SOL provides annual fuel savings of GH¢ 26,640 (US$ 13,320) with annual operating cost of GH¢ 5,400 (US$ 2,700). The total investment of the solar water system is GH¢ 57,658 (US$ 28,829) with a project life span of 20 years and a simple payback period of 6 years. The system gives a positive net present value of GH¢ 63,738 (US$ 31,869). However, an interest rate value of 12 percent or less would yield a payback period of 5 years or less. The thermal performance and economic analysis of the system has therefore shown that it is feasible and worthy of implementation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ASHRAE: American Society of Heating, Refrigeration and Air Conditioning Engineers

SWHs: Solar Water Heater/Heating Systems

RETScreen: Renewable Energy Technology Screen

ETC: Evacuated Tube Collectors

FPC: Flat Plate Collectors

PTC: Parabolic Trough Collectors

ICS: Integral Collector Storage

NREL: National Renewable Energy Laboratory

LCC: Life Cycle Cost

LCS: Life Cycle Savings

NPV: Net Present Value

NPW: Net Present Worth

AES: Alternate Energy Sources

BoG: Bank of Ghana

NOMENCLATURE

			Units
1.	A_c	Collector area	m^2
2.	S	Absorbed incident solar irradiance	W/m^2
3.	Q_u	Useful energy collected	W
4.	T_P	Average absorber plate temperature	°C
5.	T_a	Ambient temperature	°C
6.	T_i	Fluid inlet temperature	°C
7.	T_o	Desired outlet fluid temperature	°C
8.	C_p	Specific heat capacity of fluid	J/kg.°C
9.	U_L	Overall heat loss coefficient	W/m^2.°C
10.	G	Global incident solar radiation	W/m^2
11.	F_R	Collector heat removal factor	dimensionless
12.	τ	Transmittance of the glass cover	dimensionless
13.	α	absorptance of the absorber plate	dimensionless
14.	T_s	Supply (mains) water temperature	°C
15.	T_d	Required hot water temperature	°C
16.	$\dot{m}$	Supply water flow rate	kg/s
17.	L_w	Hot water load	W
18.	t	time of cash flow	year
19.	N	period or life span of system	year
20.	i	Discount rate	year
21.	R_t	Net cash flow	US$
22.	N_p	Payback period	year
23.	C_s	Initial investment for SWH system	US$

24. F	Annual solar fraction	dimensionless
25. L	Annual heating load	W
26. i_F	Auxiliary energy inflation rate	dimensionless
27. C_{F1}	Unit cost of auxiliary energy for first year	US$
28. $\overline{C}_d$	Average hot water consumption	litre/day
29. C_b	Daily hot water consumption	gal/bed
30. n_b	Number of hospital beds	dimensionless

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Finally, my classmates were so supportive, those casual jokes made my work interesting.

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background

Solar water heating is an accepted technology and is increasingly being used as one of the cost-effective means of heating water in residential and public buildings such as hotels, laundries, restaurants, hospitals and health centres [Bennet, 2007].

Harnessing the sun’s radiant energy as a clean and renewable source of energy has proven to be a challenge over the centuries and in modern times has fallen off in favour of other technologies which are easier to commercialise and capitalise on. The last few decades have shown exponential increases in the energy demands and consumption patterns of many countries, which have opted to meet this challenge with more conventional means such as fossil fuels [Bennet, 2007].

Hot water is essential both in industries and homes. It is required for taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Hot water is also required in large quantities in hotels, hospitals, hostels, and industries such as textile, paper, and food processing of dairy and edible oil.

Solar water heating systems can heat water from ambient temperature to temperatures over 90 °C depending on the collector type employed in a given locality. Using solar collector to heat the water can easily attain required temperatures.

1.2 Current Solar Energy Systems

Solar technologies are commonly grouped into three major categories, generally differing in the ways they collect, store and use energy.

Passive solar systems involve direct utilisation of the sun's radiation as light or possibly heat. Examples include energy efficient windows, skylights, greenhouses, and hybrid lighting fixtures, which use fibre optic cable to transmit sunlight into interior rooms. Next are solar thermal, which collect and use the sun's energy as heat. They are different from direct heating in their ability to store thermal energy for later use. Modern applications include domestic and industrial water heating, air and space heating, radiant slab heating, and even the operation of heat pumps and sterling engines [Bennet, 2007].

The energy and the temperature level required to be supplied to carry out everyday tasks will vary. Generally, a domestic hot water supply at temperatures in the range of 50 to 60 degree Celsius is considered to be acceptable [SOPAC, 1999].

1.3 Benefits of solar water heating

The energy saved from using a solar water heating system helps to reduce domestic energy demand from power utilities. A solar water heater is a long-term investment that will save money spent on water heating after the system has paid for itself.

In addition to the reduced electrical energy and cost savings from water heating, there are several other benefits derived from using the sun's energy to heat water. Most solar water heaters come with an additional water tank, which feeds the conventional hot water tank. Users benefit from the larger hot water storage capacity and the reduced likelihood of running out of hot water.

Some solar water heaters do not require electricity to operate. For these systems, hot water supply is secure from power outages, as long as there is sufficient sunlight to operate the system. Solar water heating systems can also be used to directly heat swimming pool water, with the added benefit of extending the swimming season for outdoor pool applications [RET Screen, 2012].

Fossil fuel combustion produces greenhouse gases such as CO, CO_2, NO_x and SO_x. The use of a solar water heating system improves environmental impact and reduces greenhouse gas emissions through reduced use of electricity [Austin, 2003].

1.4 Problem Statement

Currently, most of the commercial and industrial hot water demands in Ghana are met mainly by the use of electric heaters. Unfortunately, the rising energy cost, environmental concerns, and the depleting nature of the current primary energy sources in use have made electric heaters less attractive. This is because the primary energy sources of electric energy utilised are mainly the fossil fuels [Taylor, 2001].

In Ghana, it costs about GH¢ 0.24/kWh (about US$ 0.12/kWh) of electricity consumption in non-residential facilities like hospitals and hotels to heat water [PURC, 2011]. Available electric water heaters on the Ghanaian market can produce about 32 litres of hot water from ambient temperatures of about 24 °C to a desired temperature of 50 °C over a period of one hour. In the case of KNUST Government hospital, with a 100-bed capacity and a 75 percent occupancy rate of patients, it will require about 5621 litres of hot water per day costing about US$ 21 per day for electricity consumed.

In addition, the demand for electricity is growing rapidly; thus within cold weather periods normally mornings and evenings when hot water demand is highest, the electric energy facilities are often overstretched, resulting in some cases to power shedding especially in developing countries like Ghana. These problems can be handled by taking off some of the energy demand for hot water purposes from electricity in locations where the hot water is readily needed such as in hospitals, hotels and schools by using solar water heating systems.

Also, the usage of solar water heating systems in the sub-Saharan Africa is relatively low despite the region being well endowed with solar energy resource.

1.5 Objective

The main objective of this research is to assess the feasibility of a solar water heating system proposed for KNUST Government hospital, Kumasi based on thermal performance and economic analysis.

The specific objectives are;

i. To seek information such as the desired hot water temperature, number of beds in the hospital as well as the occupancy rate of patients in the hospital.
ii. Propose Solar Hot Water systems for the hospital.
iii. Evaluate systems long-term (annual) thermal performance.
iv. Perform the economic analysis of the solar water heating system.

1.6 Methodology

Solar water heating technology would be reviewed. The areas of interest includes the understanding of the various types of solar collectors commonly used, solar hot water sizing and usage habits especially in hospitals, principles of economic evaluation while taking purchase decisions of solar water heaters, calculation of annual energy and cost savings as well as the payback period of solar water heaters.

Mathematical equations for sizing and computing the thermal and economic performance of the solar water heating system would also be generated.

T*SOL® software programme which is a complete simulation programme that allows an analyst to size and simulate solar thermal systems of different categories such as domestic hot water, process heating, air collectors, space-heating, swimming pool, and buffer tank systems would be used to size the proposed solar water heating system for the hospital.

Besides simulating, the thermal and economic analysis and reports would be generated for the proposed solar water heating system using T*SOL®.

1.7 Thesis Organisation

The thesis is organised into five chapters. Chapter 1 introduces the thesis topic. The chapter includes background to the study, benefits of solar water heating systems, current solar energy systems, problem statement, the objectives as well as the methodology of this research work.

Chapter 2 gives the literature review on solar water heating systems. This chapter discusses the commonly used solar collectors in solar water heating system and their technologies including technical description on solar collector components that affects the performance of a system. The principles of economic evaluation such as annual energy and cost savings as well as the payback period of solar water heating systems are also discussed.

Chapter 3 contains information on the methodology the thesis has used in coming up with a solar water heating system using T*SOL® software programme to size and perform the long-term thermal and economic analysis. The chapter includes all the assumptions that have been used in analysing the solar water heating such as solar fraction, hot water storage tanks, estimating hot water load as well as the economic analysis.

Chapter 4 introduces and describes the T*SOL® programme application inputs and outputs that are used in analysing the solar water heating system based on two collector types; one flat plate collector and one evacuated tube collector. The T*SOL® programme results are summarised in terms of collector array performance and thermal performance.

The chapter then discusses the thermal performance of the solar water heating system based on the two collectors to decide which collector gives a better performance in terms of fuel cost (electricity) savings, solar contribution to heating load and CO_2 emissions avoided (CO_2 savings). The economic analysis as well as the annual collector outlet temperature simulation of the system is carried out based on the chosen collector type.

Chapter 5 gives the conclusion and recommendation of the thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Solar heaters, or solar thermal systems, provide environmentally friendly heat for household water heating, space heating, and the heating of swimming pools. Such systems collect the sun's energy to heat a fluid. The fluid then transfers solar heat directly or indirectly to your home, water, or pool.

A schematic diagram of a solar thermal water heating system is shown in Figure 1. In addition to an existing conventional hot water heater, the main components are a solar collector panel and an insulated storage tank and heat exchanger. These are integrated in Figure 1; however, a tank with external heat exchanger could also be used, and such systems are currently on the market. Also shown is a small electric recirculation pump powered by a photovoltaic (PV) panel, the advantage being a system that does not rely on external energy for operation. Strictly speaking, however, the pump can be powered by any means, and often, large scale installations require much larger units than a PV panel can power [Bennet, 2007].

Basic system operation involves the pump circulating a heat transfer fluid, typically water or water/glycol mix, through the solar collector for heating. This hot liquid then passes through a heat exchanger where it warms up cold feed water before being re-circulated back to the roof. The cold feed water remains in this storage tank, constantly being heated while the system is operational, until required. As water is drawn from the existing hot water heater it is replenished with warm water.

In this way the solar thermal system acts as a pre-heater and reduces the heating load on existing conventional hot water heaters but does not replace them. This coupled arrangement saves electric energy and also ensures a constant supply of hot water at the desired temperature [Bennet, 2007].

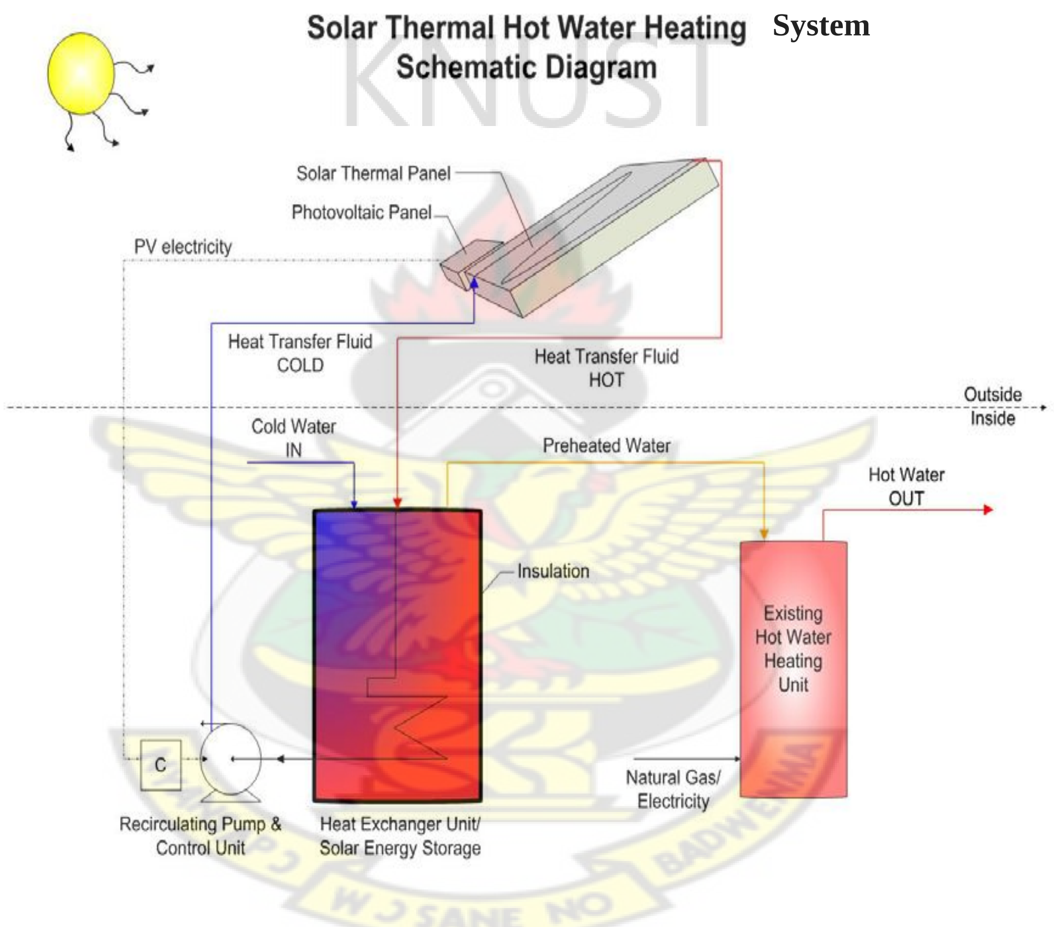

Figure 2.1: Schematic diagram of a solar thermal hot water heating system

Source: solar thermal water heating [Bennet, 2007]

2.2 Solar Collectors

Solar energy collectors are special kind of heat exchangers that transform the sun's radiant energy to internal energy of the transport medium. The major component of any solar system is the solar collector. This is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which can be drawn for use at night and/or cloudy days.

If radiation is converted into electricity directly, the collector is known as a PV collector but since the emphasis is on collectors for solar water heating, the word solar collector is meant to be solar thermal collector.

There are basically two types of solar collectors; non-concentrating or stationary collectors and concentrating collectors. A non-concentrating collector has the same area for intercepting and for absorbing solar radiation, whereas a sun-tracking concentrating solar collector usually has concave reflecting surfaces to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux.

In general, under steady-state conditions, the useful heat delivered by a solar collector is equal to the energy absorbed by the heat transfer fluid minus the direct or indirect heat losses from the surface to the surroundings. The useful energy collected from a collector can be obtained from the following formula:

$$\dot{Q}_u = A_c S - A_c U_L \left(T_p - T_a\right) = \dot{m} C_p \left(T_o - T_i\right) \tag{2.1}$$

Where; $\dot{Q}_u$ is the rate of useful energy collected in W, 'S' is the absorbed incident solar irradiance in W/m^2, 'A_c' is the collector area in m^2, 'T_p' is the average absorber plate temperature in °C, 'T_a' is the ambient temperature in °C, 'U_L' is the Overall heat loss coefficient in W/m^2. °C, 'T_o' is the desired outlet fluid temperature in °C, 'T_i' is the fluid inlet temperature in °C and 'C_p' is the specific heat capacity of the fluid in kJ/ kg. °C.

In the sections following, a review of the various types of collectors currently available will be presented. The review will include flat-plate collectors (FPC), evacuated-tube collectors (ETC), and concentrating collector.

2.2.1 Flat-plate collectors

A typical flat-plate solar collector (FPC) is shown in Figure 2.2. When solar radiation passes through a transparent cover and impinges on the blackened absorber surface of high absorptance, a large portion of this energy is absorbed by the plate and then transferred to the transport medium in the fluid tubes to be carried away for storage or use. The underside of the absorber plate and the side of casing are well insulated to reduce conduction losses. The liquid tubes can be welded to the absorbing plate, or they can be an integral part of the plate. The liquid tubes are connected at both ends by large diameter header tubes.

The transparent cover (glazing) is used to reduce convection losses from the absorber plate through the restraint of the stagnant air layer between the absorber plate and the glass. It also reduces radiation losses from the collector as the glass is transparent to the short wave radiation received by the sun but it is nearly opaque to long-wave thermal radiation emitted by the absorber plate (greenhouse effect). The glazing with low iron content has a relatively high transmittance for solar radiation (approximately 0.85–0.90 at normal incidence) but its transmittance is essentially zero for the long wave thermal radiation (5.0–50 mm) emitted by sun-heated surfaces [Kalogirou, 2003].

FPC is usually permanently fixed in position and requires no tracking of the sun. The collectors should be oriented directly towards the equator, facing south in the northern hemisphere and north in the southern. The optimum tilt angle of the collector is equal to the latitude of the location with angle variations of 10–15 °C more or less depending on the application [Kalogirou, 2003].

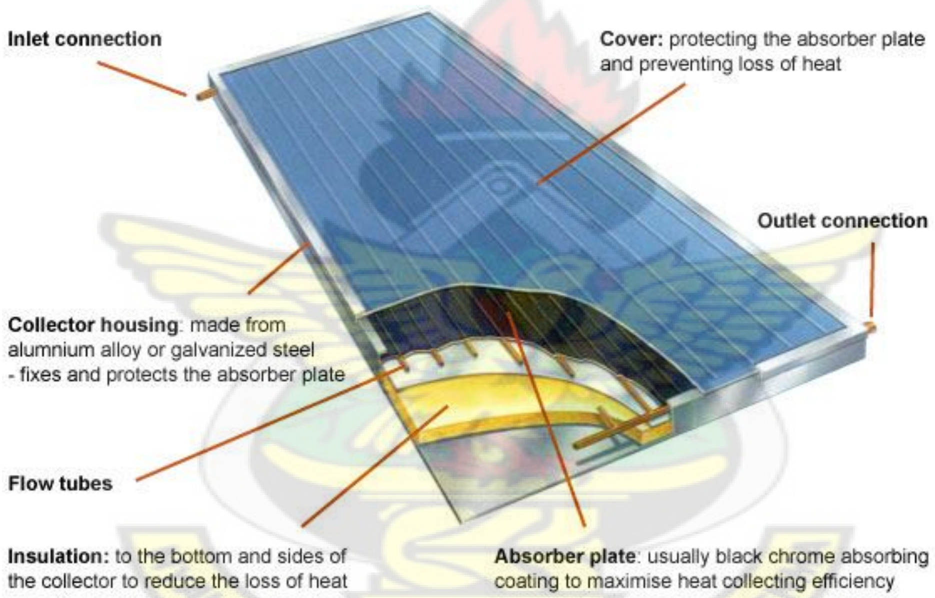

Figure 2.2: Typical Flat-plate solar collector

Source: Alternate Energy Sources, 2008

A properly designed glazed flat-plate collector has a life expectancy of 10 to 25 years or sometimes longer. It is capable of producing temperatures up to 100 °C above the ambient temperature [Duffie and Beckman, 1991]. The design is quite simple, and relatively less expensive. These are the most common types of collectors used in solar water heating (SWH) systems in Africa, supplying hot water in hotels, hospitals, and in wealthier households [Karaekezi and Randa, 1997].

2.2.2 Evacuated-tube collector

Conventional simple flat-plate solar collectors were developed for use in sunny and warm climates. Their benefits however are greatly reduced when conditions become unfavourable during cold, cloudy and windy days.

Furthermore, weathering influences such as condensation and moisture will cause early deterioration of internal materials resulting in reduced performance and system failure. Evacuated heat pipe solar collectors (tubes) operate differently than the other collectors available on the market.

These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Figure 2.3.

In this type of vacuum collector, the absorber strip is located in an evacuated and pressure proof glass tube. The heat transfer fluid flows through the absorber directly in a U-tube or in counter-current in a tube-in-tube system. Several single tubes, serially interconnected, or tubes connected to each other via manifold, make up the solar collector. A heat pipe collector incorporates a special fluid which begins to vaporize even at low temperatures. The steam rises in the individual heat pipes and warms up the carrier fluid in the main pipe by means of a heat exchanger. The condensed liquid then flows back into the base of the heat pipe.

The pipes must be angled at a specific degree above horizontal so that the process of vaporizing and condensing functions. There are two types of collector connection to the solar circulation system. Either the heat exchanger extends directly into the manifold ("wet connection") or it is connected to the manifold by a heat-conducting material ("dry connection"). A "dry connection" allows the exchange of individual tubes without emptying the entire system of its fluid. Evacuated tubes offer the advantage that they work efficiently with high absorber temperatures and with low radiation.

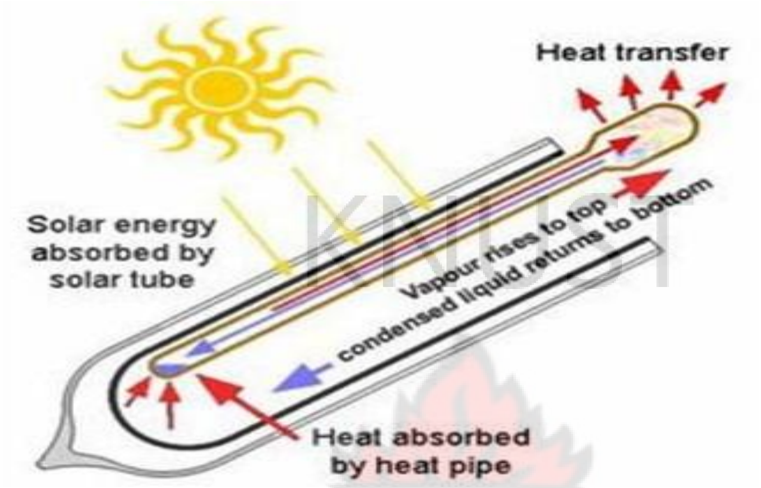

Figure 2.3: Evacuated solar collector tube

Source: Florida solar energy centre

It has been demonstrated through the use of ETC that, the combination of a selective surface and an effective convection suppressor can result in good performance at high temperatures [ASHRAE, 1995]. With the ETC, the vacuum envelope created as an integral part of the collector design reduces convection and conduction losses, resulting in higher operating temperatures than the FPC. Like the FPC, ETCs collect both direct and diffuse radiation. However, their efficiency is higher at low incidence angles. This effect tends to give ETC an advantage over FPC in day-long performance.

ETCs use liquid–vapour phase change materials to transfer heat at high efficiency. These collectors feature a heat pipe (a highly efficient thermal conductor) placed inside a vacuum-sealed tube. The pipe, which is a sealed copper pipe, is then attached to a black copper fin that fills the tube (absorber plate). Protruding from the top of each tube is a metal tip attached to the sealed pipe (condenser).

The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporating-condensing cycle. In this cycle, solar heat evaporates the liquid, and the vapour travels to the heat sink region where it condenses and releases its latent heat. The condensed fluid returns to the solar collector and the process is repeated.

Depending on the insolation level of the locality, temperatures of 80 °C to 200 °C can be achieved [Focus, 2012]. Each evacuated-tube collector consists of a number of parallel tubes arranged in rows.

The thermal performance of both glazed and evacuated collectors are described by the following equation [Duffie and Beckman, 1991]

$$\dot{q} = F_R(\tau\alpha)G - F_R U_L(T_i - T_a) \tag{2.2}$$

Where

$\dot{q}$ is the energy collected per unit collector area per unit time, F_R is the collector's heat removal factor, τ is the transmittance of the cover, α is the short wave absorptance of the absorber, G is the global incident solar radiation on the collector, U_L is the overall heat loss coefficient of the collector, T_i is the fluid inlet temperature and T_a is the ambient temperature. In general, glazed collectors are provided with $F_R(\tau\alpha) = 0.68$ and $F_R U_L = 4.90$ (W/m^2.ºC). These values correspond to test results for thermodynamics collectors [Chandrashekar and Thevenard, 1995]. Generic evacuated collectors are also provided with $F_R(\tau\alpha) = 0.58$ and $F_R U_L = 0.7$ (W/m^2.ºC). These values correspond to a Fournelle evacuated tube collector [Hosatte, 1998].

2.2.3 Concentrating collectors

Concentrating collectors make use of curved reflectors to concentrate sunlight on a receiver. The intensity of sunlight falling on the receiver can be up to 60 times the intensity of normal sunlight.

Figure 2.4 shows the structure of a typical concentrating collector. The parabolic reflector concentrates sunlight on a tube running along the reflector's focal line, thereby heating the water passing through the tube. Usually, the reflector is controlled by a tracking system that keeps the reflector facing direct sunlight throughout the day [AES, 2008].

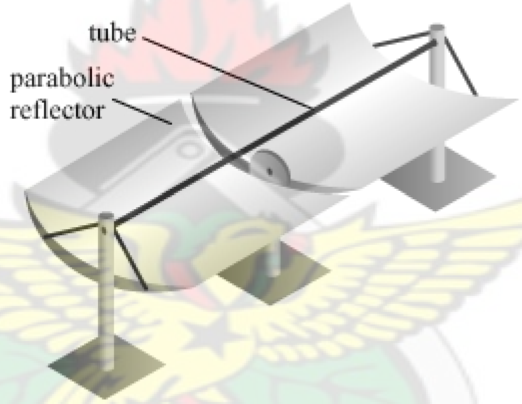

Figure 2.4: Concentrating collector (Parabolic-trough)

Source: Alternate Energy Sources, 2008.

In concentrating collectors, solar energy is optically concentrated before being transferred into heat. Concentration can be obtained by reflection or refraction of solar radiation by the use of mirrors or lens. The reflected or refracted light is concentrated in a focal zone, thus increasing the energy flux in the receiving target. Concentrating collectors can also be classified into non-imaging and imaging depending on whether the image of the sun is focused at the receiver or not.

In order to deliver high temperatures with good efficiency, a high performance solar collector is required. Systems with light structures and low cost technology for process heat applications for hot water temperatures up to 400 °C could be obtained with a type of concentrating collector called parabolic trough collectors (PTCs) [Kalogirou, 2004]. PTCs can effectively produce heat at temperatures between 50 and 400 °C.

PTCs are made by bending a sheet of reflective material into a parabolic shape. A metal black tube, covered with a glass tube to reduce heat losses, is placed along the focal line of the receiver as shown in Figure 2.5 [Kalogirou, 2004].

When the parabola is pointed towards the sun, parallel rays incident on the reflector are reflected onto the receiver tube. The collector can be orientated in an east–west direction, tracking the sun from north to south, or orientated in a north–south direction and tracking the sun from east to west.

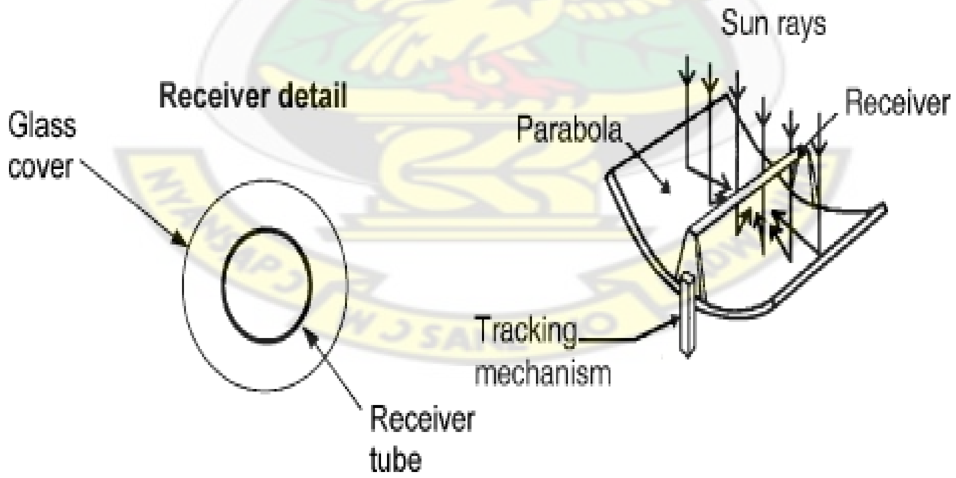

Figure 2.5: Schematic of a parabolic trough collector.

Source: solar thermal application (Kalogirou, 2004)

2.2.4 Components of a solar collector

The components of a solar collector that enhances heat transfer are

- coated flat plate which absorbs solar radiation and transforms it into thermal energy
- A storage tank for the heated water, which is thermally insulated to minimise heat losses. It may be made of glass or plastic material.
- Cover (glass) to reduce upward thermal losses of the collector
- Bottom insulation to reduce downward thermal losses
- Tubes and channels for circulating water to collect thermal energy
- Wooden or metallic frame to house the collector assembly

2.2.4.1 Collector absorber plates

The collector plate absorbs as much of the irradiation as possible through the collector glass cover (glazing), while losing as little heat as possible upward to the atmosphere and downward through the back of the casing.

The collector plates transfer the retained heat to the transport fluid. The absorptance of the collector surface for shortwave solar radiation depends on the nature and colour of the coating and on the incident angle.

The absorber plates can be made of metal, plastic, or rubber compounds. The metals commonly used in order of decreasing thermal conductivity are copper, aluminium, and steel. Plastics (polyolefin) and rubber (ethylene propylene compounds) are relatively inexpensive but due to their low thermal conductivity and their temperature limitations, they are suitable only for low temperature applications, such as heating swimming pool water or for use with water source heat pumps [Basham et al, 2004].

Heat transfer analysis on the absorber plate is carried out by applying the energy balance:

$$E_{in} + E_g - E_{out} = E_{st} + Q_{cond} \qquad (2.3)$$

where

E_{in} is the amount of solar energy entering the absorber plate.

E_g is the amount of energy generated in the absorber.

E_{out} is the amount of energy leaving the absorber, thus the thermal energy losses from the plate.

E_{st} is the amount of energy stored in the absorber plate material.

Q_{cond} is the amount of heat conducted to heat carrier fluid.

Usually, solar thermal heating processes do not involve chemical reactions in the absorber plate material to generate heat and the thermal capacitance for many absorber plates is negligible to account for heat storage. Therefore, as can be deduced from equation (2.3), the heat conducted to the fluid is equal to the absorbed solar radiant energy less energy losses on the absorber. The energy losses from the absorber plate are convection losses, conduction losses and long-wave radiation losses [Kaunda, 2005].

The absorbed irradiation depends on the incident irradiation as well as absorptance (α) and emittance (ε) of the absorber plate. Both α and ε depend on the wavelength (λ) of the incident solar radiation. To ensure that maximum useful energy is collected, the absorber plate should have a value of:

- Absorptance close to unity in the solar radiation region because in solar energy engineering, the wavelengths that are important are in the range of 0.29 μm to 2.5 μm [Duffie and Beckman, 1991].

- Emittance close to unity in the long-wave range of the electromagnetic spectrum, because the absorber plate will emit infrared thermal radiation as a result of the absorbed solar radiation [Duffie and Beckman, 1991].

Normally an absorber plate coating (selective or non-selective) is applied to the surface of the absorber plate to increase absorption and reduce emission from the plate.

The selective coatings have very high absorptance in the solar radiation range and very low emittance in the long-wave range whiles the non-selective coatings have very high absorptance in the solar radiation range and very high emittance in the long-wave range.

Properties of some common absorber coatings are given in Table 2.1 and Table 2.2.

Table 2.1: Properties of non-selective absorber-plate coating

Material	Absorptance (0.29 μm to 2.5 μm)	Emittance (3 μm to 100 μm)
Flat black paint	0.97 – 0.99	0.97 – 0.99
Aluminium paint (bright)	0.3 – 0.5	0.4 – 0.6
Alkyd enamel	0.9	0.9
Black acrylic paint	0.92 – 0.96	0.86 – 0.93
Black inorganic paint	0.89 – 0.97	0.84 – 0.90
Black silicone paint	0.86 – 0.94	0.83 – 0.89
Parson black	0.981	0.98
Ceramic enamel	0.9	0.5

Table 2.2: Properties of selective absorber-plate coating

Material	Absorptance (0.29 μm to 2.5 μm)	Emittance (3 μm to 100 μm)
Copper Oxide over Aluminium	0.93	0.11
Black copper over copper	0.85 – 0.90	0.08 – 0.12
Black chrome over Nickel	0.93	0.06
Crystal clear™	0.94 – 0.96	0.04 – 0.09

2.2.4.2 Glazing Materials

Glass has been widely used to glaze solar collectors because it can transmit as much as 90 percent of the incoming shortwave solar irradiation while transmitting virtually none of the long wave radiation emitted outward by the absorber plate. Glass with low iron content has a relatively high transmittance for solar radiation (approximately 0.85–0.90 at normal incidence), but its transmittance is essentially zero for the long wave thermal radiation (5.0–50 μm) emitted by sun-heated surfaces [Kalogirou, 2004]. Plastic films and sheets also possess high shortwave transmittance, but because most usable varieties also have transmission bands in the middle of the thermal radiation spectrum, they may have long wave transmittances as high as 0.40.

The commercially available grades of window and green-house glass have normal incidence transmittances of about 0.87 and 0.85, respectively. For direct radiation, the transmittance varies considerably with the angle of incidence [ASHRAE, 2005].

The glazing should admit as much solar irradiation as possible and reduce the upward loss of heat as much as possible. Although glass is virtually opaque to the long wave radiation emitted by collector plates, absorption of that radiation causes an increase in the glass temperature and a loss of heat to the surrounding atmosphere by radiation and convection.

2.2.4.3 Collector Insulation

The walls of the collector are insulated to reduce thermal losses by conduction. Insulations should not be flammable, should posses low value of thermal expansion coefficient. The most frequent insulation materials used in solar water heating system are given in Table 2.3 [Soltau, 1992].

Table 2.3: Properties of insulating materials

Material	Thermal conductivity at 25 °C (W/m. °C)	Maximum service temperature in °C
Glass fibre	0.032	343
Polystyrene foam	0.034	74
Polyurethane foam	0.023	104
Isocyanurate foam	0.025	121
Phenolic foam	0.033	135
Cellular plastic	0.40	100
Foamed glass	0.058	900
Mineral fibre	0.0455	843
Perlite	0.048	816
Calcium silicate	0.055	649

2.3 Solar water heating system types

Solar water heating systems are classified depending on how the domestic water is heated or how the heat transfer fluid (water or antifreeze fluid) flows through the collector. Based on this, there are basically two types of solar water heating systems, namely; Direct (open loop) and Indirect (closed loop) water heating systems which can either be passive or active [NREL, 2006].

Direct systems heat up water as it flows directly in the collector whiles indirect systems heat up water through a heat exchanger employed between the collector and the hot water storage tank.

Active systems use electrically driven pumps to circulate water or another heat absorbing fluid, and sometimes use electrically operated valves for freeze protection. Passive systems have no electrical pumps. They rely upon convection to circulate hot water through the collector and storage tank [Duffie and Beckman, 1991].

2.3.1 Passive Systems

In passive systems, hot water is either stored in the collector itself or is transferred to a storage tank located above the collectors by means of a thermosyphon. Passive systems do not employ pumps to circulate water or collector fluid. Two types of passive systems; thermosyphon systems and integral collector storage systems are briefly described below.

2.3.1.1 Thermosyphon systems

A typical thermosyphon system is indicated in Figure 2.6. As the sun shines on the collector, the water inside the collector flow-tubes is heated. As it heats up, this water expands slightly and becomes lighter than the cold water in the solar storage tank mounted above the collector [AES, 2008]. 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.

A thermosyphon 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 [AES, 2008].

This system features a thermally operated valve that protects the collector from freezing. It also includes isolation valves, which allow the solar system to be manually drained in case of freezing conditions, or to be bypassed completely.

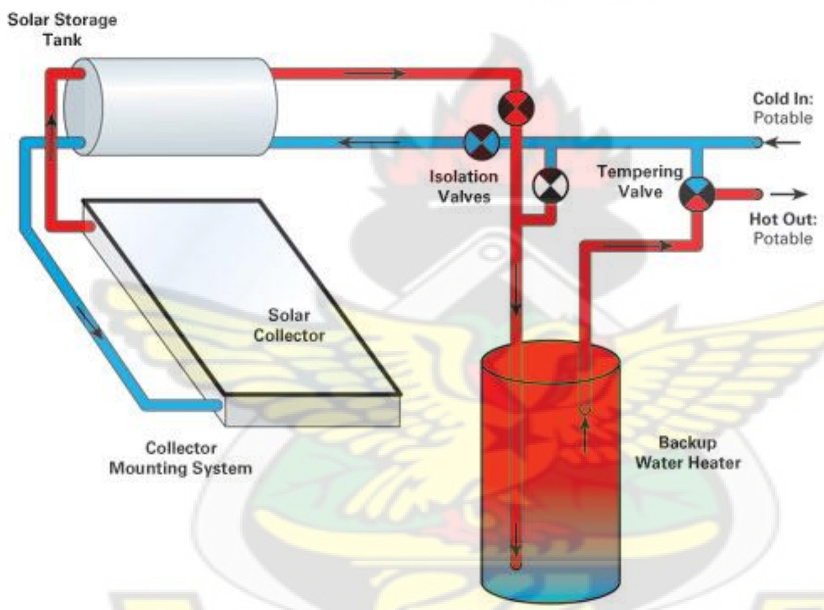

Figure 2.6: Thermosyphon SWH system

Source: Alternate Energy Sources, 2008.

2.3.1.2 Integral Collector Storage (ICS) Systems

In integral collector storage (ICS) or batch systems, water is heated directly by the sun and the storage tank serves as the solar collector. Batch water heaters are almost always passive systems in which hot water is delivered from the solar heated tank to a backup tank or the point of use by the water pressure in the house [Harrison and Tiedeman, 1997].

Most designs use local main water pressure to circulate water in the collector. Water may also flow due to buoyancy forces set up due to differential heating on the collector and valves control the flow direction. These systems are relatively cheaper than thermosyphon systems.

The 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 [Harrison and Tiedeman, 1997].

A freeze protection valve installed in the top plumbing near the collector opens to allow relatively warm water to flow through the collector to prevent freezing.

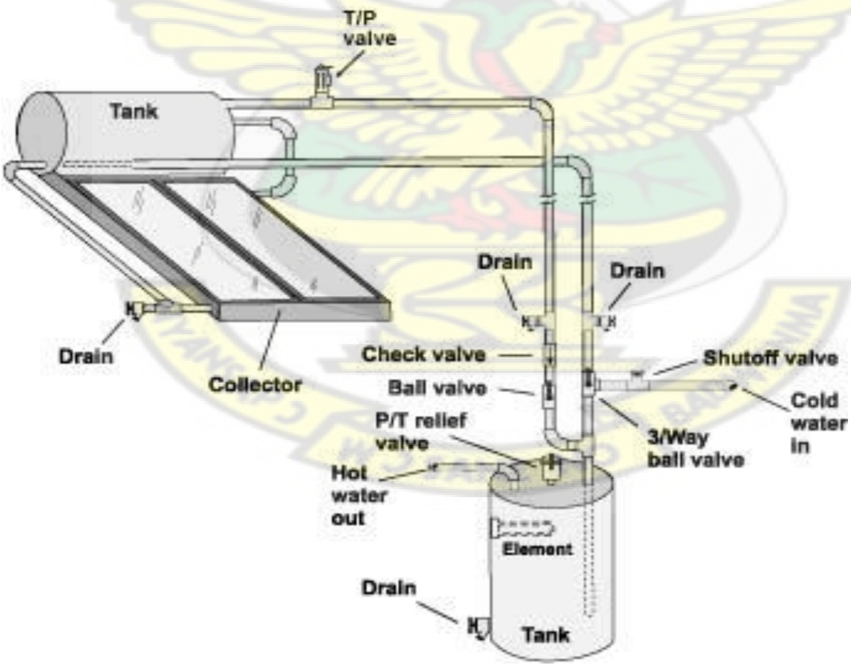

Figure 2.7: Integral collector storage SWH system

Source: Florida solar energy centre

2.3.2 Direct (Open Loop) Active Systems

Direct (Open Loop) Active Systems are similar to thermosyphon systems in that they are direct systems that use a solar collector separate from the storage tank. The difference with direct active systems is that they use an electric pump to circulate water from the storage tank to the collector, and back to the storage tank.

These systems always require a check valve to prevent reverse thermosyphoning at night [Harrison and Tiedeman, 1997]. A typical direct active system is shown in Figure 2.8.

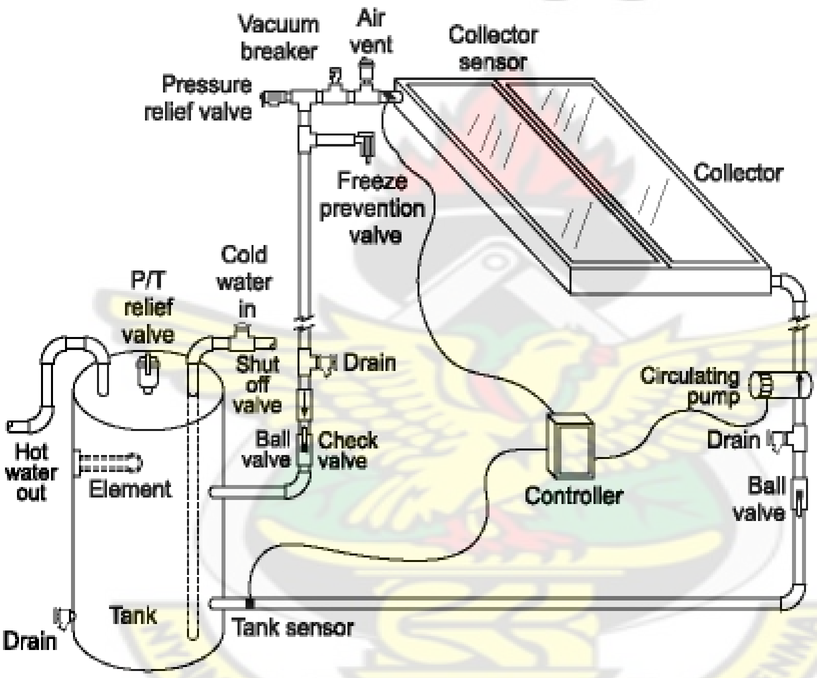

Figure 2.8: Direct Active SWH System

Source: Heliotrope thermal, 2011

2.3.3 Indirect Active Systems (Glycol Antifreeze Systems)

Glycol antifreeze systems are active, indirect systems with a heat exchanger (see Figure 2.9). Freeze resistant propylene glycol is circulated through the solar collector(s) and heat exchanger, while household water is circulated from the storage tank through the heat exchanger [Heliotrope, 2011]. The household water is heated inside the heat exchanger and then stored inside the tank until needed.

The antifreeze and water (if an external heat exchanger is used) are circulated using either AC pumps powered from the utility grid or DC pumps powered by a solar electric PV module.

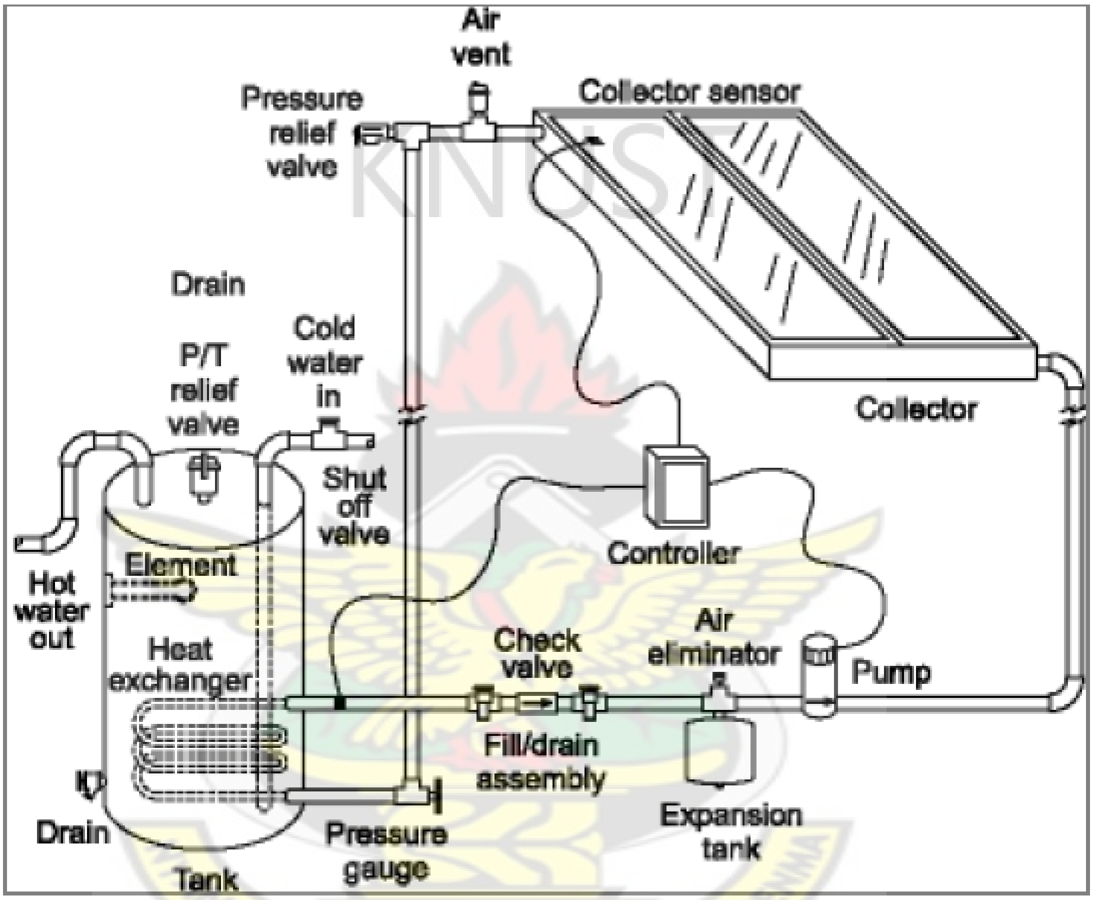

Figure 2.9: Active indirect systems

Source: Heliotrope thermal, 2011

The most common types of solar water heating system in temperature climate regions are indirect active systems mainly to protect the systems against freezing. Direct active systems are used in tropical climates where freezing is not a problem and domestic water is treated, or in cases water is fed directly from water utility supply line (which normally treats domestic water). Active system whether direct or indirect can be easily retrofitted to already existing water heaters because the storage tank can be placed at any place unlike thermosyphon systems which require a storage tank always above the collector.

2.4 Factors Affecting Solar Water Heating (SWH) Performance

The performance of a solar water heating system depends on the following factors

- Ambient conditions
- Collector orientation and tilt
- Collector array arrangement
- Collector and storage tank characteristics
- The transport fluid flow rate

2.4.1 Ambient Conditions

The amount of incident radiation determines the absorbed solar radiation by the collector while the ambient temperature determines the thermal losses from the collector. Cloudy conditions limit the beam insolation levels and thus the radiation absorbed by the collector especially the concentrating collectors [Kaunda, 2005].

2.4.2 Collector Orientation and tilt

Geographic orientation and collector tilt can affect the amount of solar radiation the system receives.

Collector orientation is critical in achieving maximum performance from a solar energy system. In general, the optimum orientation for a solar collector in the northern hemisphere is true south (azimuth of 180°) as illustrated in Figure 2.10.

However, recent studies have shown that, depending on the location and collector tilt, the collector can face up to 90° east or west of true south without significantly decreasing its performance. The Optimum tilt angle for solar collector is an angle equal to the latitude [Duffie and Beckman, 1991].

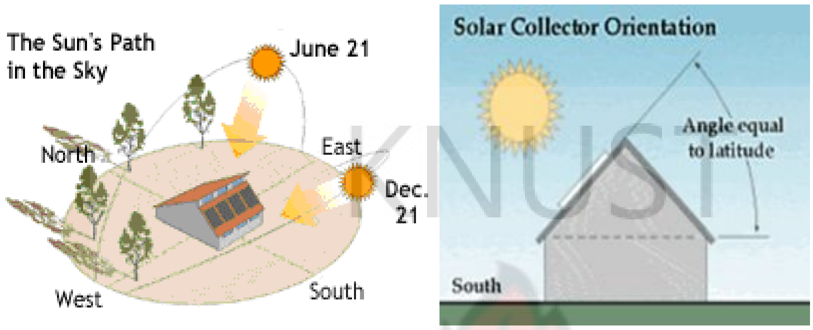

Figure 2.10: Collector orientation in the Northern Hemisphere

2.4.3 Transport fluid Flow Rate

Low collector fluid flow rates of about 1 to 4 gallons per minute increases the thermal performance of the collector by increasing the degree of storage tank thermal stratification. In a stratified tank, the temperature of fluid at the bottom of the storage tank is lower than at the top. Collector inlet temperature is reduced because the collector inlet fluid is fed from the bottom portion of the tank. Lower inlet collector temperature reduces thermal losses. This results in increased useful energy gain.

2.4.4 Collector Array Arrangement

The performance of the collector array depends on how the collector modules are connected. In parallel connection, module inlet and outlet ports are fed to the common respective headers. Assuming identical modules, fluid inlet temperature is the same to all modules in the array.

This is also true to fluid outlet temperature. The performance of the collector array is thus the same as the performance of the individual collector. In series connection, the performance of the second and subsequent modules will not be the same as the first because its inlet temperature is the outlet temperature of the first [Duffie and Beckman, 1991].

2.4.5 Collector Characteristics

Collector area and its glass cover optical properties affect the amount of the incident solar irradiation that can be absorbed while collector insulation thickness and its thermal conductivity affect the overall heat loss coefficient and thus the thermal losses.

2.5 Sizing a Solar Water Heating (SWH) System

Sizing a solar water heating system is by determining the collector area that will meet the heating load, depending upon the insolation level and in some cases, the collector area that will give maximum life cycle solar savings (minimize life cycle cost) of SWH system [Duffie and Beckman, 1991]. It is possible therefore to minimize life-cycle cost by sizing a system that meets 100 percent of the load on the sunniest day of the year.

Such a system will usually produce about 60 percent of the annual load. Other considerations include maintenance, freeze protection, overheating protection, aesthetics of the collector mount, and orientation [Walker, 2010].

SWH system sizing also involves the determination of the required storage tank capacity to provide an energy buffer between periods of low insolation levels such as night and cloudy days, and periods of high insolation levels. Circulating pumps can be selected according to the recommended flow rate of the fluid in the collector as specified by the collector manufacturer [Kaunda, 2005]. Other components such as the sensors and mechanical support structures can be selected as long as they are not out of proportion because they are insensitive to the thermal performance of the SWH system [Duffie and Beckman, 1991].

2.5.1 Required Storage Tank Capacity

The size of the storage tank affects the outer surface area and hence affects the tank's heat loss conductance. The storage tank can be sized according to the total collector area and the daily heating load requirements [Hughes, 2006]. Duffie and Beckman (1991) recommend tank capacities ranging from 50 to 200 litres per square metre of collector for an annual system performance to be insensitive to tank capacity. A standard storage tank capacity of 75 litres per square metre of collector is used in f-chart solar water heating system design procedure [Duffie and Beckman, 1991].

2.5.2 Estimating Total Heating load

The loads to be met by a solar water heating system are generally grouped into two; hot water load and heat losses from tank and piping. The heat losses from the tank and piping are estimated as a fraction of the total hot water load. Fractions ranging from 10 to 25 percent are used [Mclaughlin et al, 1981].

Hot water load, L_w is given by; $L_w = \dot{m}C_p\left(T_d - T_s\right)$ (2.4)

Where; $\dot{m}$ = supply water flow rate, C_p = specific heat capacity of water, T_s = Supply (mains) water temperature, and T_d = required hot water temperature.

2.5.3 Daily Hot Water Consumption

Estimation of hot water consumption is a difficult task in design because the consumption pattern depends on many variable factors difficult to quantify such as living standards, gender and purpose of the building. ASHRAE recommends hot water consumption of 75 litres per day per person. According to the National Energy Renewable Laboratory (NREL) of the US Department of Energy, a workshop on solar thermal technology and applications by Roger Taylor in June 2006 provided the following values for hot water usage in various types of buildings [Taylor, 2006].

Table 2.4: Typical Hot Water Usage in buildings

Type of Building	Consumption per occupant
Dormitory	13 gal per day per person
Motel	15 gal per day per unit
Hospital	18 gal per day per bed
Office	1 gal per day per person
Food Service	2.4 gal per meal
Residence	40 gal per day per person
School	1.8 gal per day per student

Source: NREL consumption data, 2006

Following a research study in South Africa, Austin and Morris (2001), provided a conservative estimate of hot water consumption in high, medium and low income households is given as 90, 60 and 35 litres per person per day, respectively.

2.5.4 Economic evaluation of solar hot water systems

There is a general tendency to look at the initial cost while taking purchase decisions of solar water heaters. Therefore, the concept of life cycle cost evaluation of solar water heater is important for decision making. The initial cost of solar water heater system is recovered through savings of energy bills over a period of time.

Life cycle cost (LCC) is the sum of all the costs associated with an energy delivery system over its lifetime or life span in today's money, and takes into account the time value of money. The life cycle savings (LCS), for a solar plus auxiliary system, is defined as the difference between the LCC of a conventional fuel-only system and the LCC of the solar plus auxiliary system. This is equivalent to the net present value (NPV) of the gains from the solar system compared to the fuel-only system [Kalogirou, 2004].

2.5.4.1 Net Present Value (NPV)

In finance, the net present value (NPV) or net present worth (NPW) of a time series of cash flows for both incoming and outgoing is defined as the sum of the present values (PVs) of the individual cash flows of the same entity. It compares the present value of money today to the present value of money in future, taking inflation and returns into account [Khan, 1993].

The NPV is given by the expression;

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t} \tag{2.5}$$

where 't' is the time of the cash flow, 'i' is the discount rate (thus the rate of return that could be earned on an investment in the financial markets with similar risk; the opportunity cost of capital), 'N' is the total number of periods (life span of the project) and 'R_t' is the net cash flow (the amount of cash, inflow minus outflow) at time t.

2.5.4.2 Payback period

The payback period also known as the amortisation period is defined as the time needed for the fuel cost savings to equal the total initial investment of a project [Duffie and Beckman, 1991]. The payback period of an investment taking into account the time value of money is given by the expression;

$$N_p = \frac{C_s(1 + i_F)}{FLC_{F1}} \tag{2.6}$$

where 'C_s' is the initial investment for solar heating system, 'i_F' is the auxiliary energy inflation rate, 'F' is the annual solar fraction, 'L' is the annual heating load and 'C_{F1}' is the unit cost of auxiliary energy for the first year.

The product of annual solar fraction, annual heating load and the unit cost of auxiliary energy for the first year gives the annual energy savings (also known as annual fuel cost savings) for the first year. In general, in Africa, a solar water heating system with a simple payback period of less than 5 years is considered economically viable [Karaekezi and Randa, 1997].

2.6 Conclusion

In light of the extensive literature, for tropical climates like Ghana where freezing is not a problem, the proposed solar water heating system would be of the direct active system type where both flat plate and evacuated tube collectors thermal performance would be analysed because they are the mostly used collectors in Africa. The solar collector modules would be better if identical and parallel connected so as to have the same fluid inlet and outlet temperatures in all the modules in the array. Low inlet collector temperature would be preferred so as to reduce thermal losses and increase useful energy gain and thermal performance.

CHAPTER THREE

METHODOLOGY OF THE PROPOSED SWH SYSTEM

3.1 Introduction

The analysis of a solar water heating system includes system sizing, system optimisation and integration with existing heating system. The proper sizing of the components of a solar system is a complex problem which includes both predictable (collector and other components performance characteristics) and unpredictable (weather data) components.

3.2 Software programs

Different computer analysis tools have been developed for analysing solar water heating systems, ranging from simulation techniques to system optimisation such as F-chart, RET Screen, T*SOL and TRYNSYS. These analysis tools help to eliminate the expense of building prototypes, optimise the system components, estimate the amount of energy delivery from the system, provide temperature variations of the system and estimate the variable changes on system performance by using the same weather conditions [Kalogirou, 2004]. In this research, the T*SOL® analysis tool is used for analysing the solar water heating system.

The T*SOL® is a dynamic software programme used to simulate and optimise solar thermal systems such as hot water systems and space heating applications. This is preferred to other analysis tools because it has an integrated MeteoSyn tool which allows users to create climate data for locations outside of the included data base. It also requires a few input parameters such as project climate data location, system consumption, collector type selection and system configuration selection to automatically size the collector and storage tank. It provides project report, economic efficiency calculation and annual simulation of the system as output [Valentin, 2005].

In this thesis, the T*SOL® method of simulating and analysing the performance of the solar water heating is based on two distinct collectors; one with a flat plate collector and the other with an evacuated tube collector.

3.3 Methodology

The steps used to assess the feasibility of the solar water heating system based on the thermal and economic performance in this thesis are;

i. Determining the incident solar irradiation level on the plane of the collector
ii. Estimating the daily hot water heating requirement of the hospital
iii. Sizing the solar water heating (SWH) system
iv. Analysing the system's thermal performance through annual simulation using the T*SOL® simulation programme for solar thermal heating systems.
v. Evaluating the economic analysis of the system using economic indicators integrated into the T*SOL® programme.

3.3.1 Incident solar irradiation

Solar irradiation is the total solar radiation reaching the plane of the collector. It can come from beam, diffuse and ground reflected radiation. The first step in the design of any solar thermal system is the determination of the solar resource available in the location where the system will be installed. The monthly daily average values of the incident solar irradiation in the plane of the collector can be determined by using the Liu and Jordan isotropic sky model approach [Duffie and Beckman, 1991].

However, the source of climate data for Kumasi is already available in RETScreen which was the measured data obtained from KNUST and it provides results for monthly average daily solar irradiation levels throughout the year as given in Table 3.1 [RETScreen, 2012].

Table 3.1: Monthly average daily global solar irradiation data for Kumasi

Month	**Daily solar radiation - horizontal**	**Earth temperature**
	kWh/m²/day	°C
January	4.18	26.7
February	4.68	26.9
March	5.04	27.0
April	5.09	26.9
May	4.97	26.5
June	4.38	25.4
July	3.67	24.4
August	3.35	24.4
September	3.80	24.8
October	4.44	25.3
November	4.66	25.7
December	3.87	25.9
Annual	4.34	25.8

Source: RETScreen International climate data for Kumasi, 2012.

The absorbed solar irradiation on the tilted collector is a function of the incident solar irradiation and the collector optical characteristics, $(\tau\alpha)$, known as the absorptance-transmittance product. The monthly average daily absorbed irradiation by the tilted collector is given by:

$$S = \overline{H}_T(\tau\alpha) \tag{3.1}$$

Where S is the monthly average daily absorbed solar irradiation on the tilted collector and $\overline{H}_T$ is the mean monthly daily incident solar irradiation in the plane of the collector.

3.3.2 Estimating hot water load

Determining the hot water load is to estimate the daily energy required to heat water. It is calculated from the average gallons of hot water required per month, and the rise in temperature from the cold water mains to the output temperature of the system. The number of gallons per day can be arrived at using NREL hot water consumption data for various types of facilities provided in Table 2.4 (Taylor, 2006). For hot water consumption in hospitals, the table assumes an average hot water requirement per bed per day to be 18 gallons. The hot water load is the amount of energy required to heat water from the mains temperature (averaged to be 24 °C) to the recommended desired hot water temperature of 50 °C for the hospital. The hospital beds are not fully occupied with patients and hence an average occupancy level of 75 percent has been chosen for the design (from an interview conducted with a staff Nurse). The system will eventually lose heat to the ambient because heat will naturally flow whenever there is a temperature gradient to a body with a lower temperature. However, this heat loss can be minimised by inducing resistance to heat transfer through insulating hot water storage tank and hot water piping. This thesis accounts for losses in tanks and piping systems by increasing the daily hot water load by 10 percent. The average daily hot water consumption is given as

$$\overline{C}_d = 3.785 \times 0.825 \times C_b \times n_b \qquad (3.2)$$

Where; $\overline{C}_d$ is the average hot water consumption in litres per day, C_b is the daily hot water consumption in gallons per bed, n_b is the number of hospital beds available, the 0.825 takes account of the 10 percent losses in tanks and piping system as well as the 75 percent occupancy level of patients whiles the 3.785 is a conversion factor from gallons to litres.

Hence, for a 100 -bed capacity and a hot water requirement of 18 gallons per bed per day, the average daily hot water requirement of the hospital is 5,621 litres. This is an input data to the T*SOL® software programme to analyse the system.

3.3.3 Solar collector characteristics

The most important consideration of any solar thermal system is to find out the available solar collectors. This solar water heating system considers flat plate and evacuated tube collectors to determine the type of collector that will give better thermal as well as economic performance when installed on the roof of the hospital. The life span of the vacuum of evacuated tube varies from collector to collector, anywhere from 5 years to 15 years whiles flat plate collectors have up to 25 years of service life [Marken, 2009]. This research assumes a life span of 15 years for evacuated tube collectors and 20 years for flat plate collectors.

The flat plate collector (type AE-40) is supplied by Alternate Energy Technologies and the evacuated tube collector (type AS-CPC-18) is supplied by Andy Schroder Solar Technology. The collector performance parameters and their technical specifications are given in the Table 3.2 below.

Table 3.2: Collector performance parameters and technical specifications

Performance parameters	Type of collector	
	Flat plate collector (AE-40)	Evacuated tube collector (AS-CPC-18)
Gross Area (A_g)	3.70 m^2	3.41 m^2
Aperture (active) Area (A_p)	3.48 m^2	2.99 m^2
Conversion factor (η_o)	69.1 %	64.2 %
Linear heat loss coefficient (a_1)	3.40 W/ (m^2. K)	0.885 W/ (m^2. K^2)
Quadratic heat loss coefficient (a_2)	0.002 W/ (m^2. K)	0.001 W/ (m^2. K^2)
Collector fluid	water	water
Specific heat capacity (C_p)	4200 J/kg-°C	4200 J/kg-°C
Nominal flow rate per collector	0.0391 kg/s	0.05 kg/s

Source: T*SOL® software programme catalogue data

These two collectors can be specified from the catalogue data in the T*SOL® programme when analysing a solar water heating system.

3.3.4 Solar fraction

The solar fraction is defined as the percentage of the overall heating load that is supplied by the system over a specific period of time being it daily, monthly or annually. For service hot water applications, the proportion of the annual energy needs covered by a SWH system are typically between 10 to 70 percent of the annual water heating load, depending on climate, system size and load. The optimal size in terms of system cost effectiveness is generally obtained for solar fractions between 30 to 60 percent, on a year-long operation basis [Gravely, 2012].

A solar fraction of 50 to 55 percent would then make the proposed solar water heating system to be cost effective.

3.3.5 Hot water storage tanks

Hotels, apartment buildings, hospitals and other facilities that need constant supplies of hot water usually have a storage tank that has been sized to meet peak demands, even though the usage at these times exceeds the output of the heater. This is achieved by selecting a tank of sufficient size, with adequate insulation, and designed to prevent incoming cold water from mixing with the hot water supply [Gravely, 2012]. Stratification improves the thermal performance of a solar water heating system because a stratified tank provides lower inlet temperatures than a fully mixed tank. In this research, the solar water heating system would be designed with a stratified solar preheating tank and auxiliary tank (conventional water heater with storage capacity of its own) to supply hot water to the hospital. This method has the advantage of using the maximum possible solar energy from the tank without driving up the collector temperature [Duffie and Beckman, 1991].

3.3.6 Economic analysis

The economic analysis of solar energy systems is carried out in order to determine the least cost of meeting the energy needs, considering both solar and non-solar alternatives. The method employed for the economic analysis in this research is the life cycle savings analysis. This method takes into account the time value of money and allows detailed consideration of the complete range of costs. Solar processes are generally characterized by high initial cost and low operating costs.

Thus, the basic economic problem is of comparing an initial known investment with estimated future operating costs.

Software programmes such as T*SOL® described in previous section have routines for the economic analysis of solar water heating systems. It accepts the following parameters as inputs; life span of the system, interest on capital, price increase rate of energy and running cost, investment, running cost, loan capital, repayment free initial period and the term of loan. Once these input parameters are given, the economic efficiency calculation in the T*SOL® programme provides figures for the following; cash value of savings (life cycle savings), cost of solar energy per kWh, net present value (total present worth), annual installment and payback (amortisation) period of solar plus auxiliary system.

The lifespan is the period given by the manufacturer as being the estimated operating life of a system. For the majority of solar systems this is between 10 to 25 years.

The interest on capital is the interest rate at which the capital for the investment is borrowed from a bank, or the interest that might be charged on the capital used. The current Bank of Ghana interest rate is 15 percent [BoG, 2012]; however, a long-term average interest rate value of 16.7 percent quoted for Ghana [BoG, 2012] is used as the interest on capital in this analysis.

The loan capital is the amount of credit that is taken out. This is taken to be equal to or less than the investment required starting the project.

The term of loan is the amount of years in which the loan has to be repaid. It is assumed in this thesis to be 5 years.

The annual installment is the fixed annual amount with which the loan and interest are repaid over the agreed term. This is calculated by the programme.

The loan interest rate is the percentage of interest that has to be paid on the loan. If the loan interest rate if less than the capital interest rate, the loan takes on the function of a subsidy; if it is more, the total costs increase. With identical interest rates they remain the same. The analysis is therefore carried out with the loan interest rate equal to the capital interest rate, thus a value of 16.7 percent is used.

The price increase rate on energy and running cost is the percentage at which an annual change in the price levels of the goods are expected to occur. It is also known as the escalation rate. The price increase rate has been taken to be 4 percent for running cost and 8 percent for energy. The running cost is the amount of money required to operate and maintain the proposed system. It is assumed to be 5 percent of the total initial investment per year.

3.4 Conclusion

The chapter has looked at the methodology that will be used in the T*SOL® software programme to access the thermal and economic performance of the solar water heating system for the KNUST hospital. The analysis of the solar water heating system will be presented in the next chapter.

CHAPTER FOUR

THE SWH SYSTEM PERFORMANCE ANALYSIS AND DISCUSSION

4.1 Introduction

The thermal performance and economic analysis of the solar water heating system proposed for KNUST hospital is carried out in this research using the T*SOL® programming software. The programme uses the methodology employed in chapter 3 to compute total global annual irradiation for the climate location, fraction of diffuse component of total global annual irradiation, mean outside temperature, the collector surface area irradiation, required size of collector area, thermal performance of the system in terms of the energy produced by the collectors and collector loop, installed collector power, CO_2 emissions avoided, solar fraction, electricity savings and system efficiency. The programme then performs the economic analysis of the system in terms of life cycle savings, total running cost, net present value, payback period and the cost of solar energy.

4.2 T*SOL® programme inputs and outputs

The T*SOL® software programme accepts the following parameters as inputs; weather data, average daily hot water consumption, desired hot water temperature, type of collector, tank capacity, slope of collector, collector azimuth angle, cold water temperature, life span of system, interest on capital, operating cost, installed cost of the system, loan interest rate, terms of loan, price escalation rate of energy and operating cost.

The programme outputs the following;

1. Total annual global solar irradiation in the plane of the collector and fraction of diffuse component of solar irradiation.
2. System components in terms of required number of collectors, total gross collector area, total collector aperture (active) area, collector surface area irradiation, annual circulation losses, volumetric flow rate per m^2 of collector area and collector manufacturer.
3. Thermal performance in terms of the resulting annual energy requirement, annual circulation losses, energy produced by collector and collector loop, contribution of solar to annual energy requirement, energy from auxiliary heating, CO_2 emissions avoided, fractional energy savings, energy savings from electricity, solar fraction and system efficiency.
4. Economic performance in terms of net present value of solar savings, cash value of operating cost, cash value of savings (life cycle savings), annual loan installment (annual loan payment), cost of solar energy and payback period (amortisation period).
5. Summary of the proposed SWH system in terms of required collector area, number of modules required, annual life cycle savings, annual life cycle cost and annual simulation in terms of daily maximum collector temperature.

4.3 Proposed SWH system for the hospital

The solar water heating system for the KNUST hospital has been analysed using T*SOL® software programme by providing technical and economic input parameters described in chapter 3. The detail procedure for the analysis is provided in appendix A.

The Table 4.1 below shows the summaries of the annual performance of the solar water heating system based on the two proposed solar collectors from the T*SOL® software programme in terms of the collector array and thermal performance.

Table 4.1: Summary of the SWH System Annual Performance

Description	Flat plate collector (AE-40)	Evacuated tube collector (AS-CPC-18)
COLLECTOR ARRAY PERFORMANCE		
1. Required number of collector modules	13	13
2. Required optimum size (total gross collector area) of the solar collector in m^2	48.05	44.33
3. Required volumetric flow rate per m^2 of collector area in litres per hour	34.11	43.41
4. Collector surface area irradiation in MWh	68.80	59.29
5. Installed collector power in kW	33.63	31.03
THERMAL PERFORMANCE		
6. Hot Water Heating Energy Supply in MWh	57.65	57.77
7. System efficiency in percent	47.2	54.4
8. Energy produced by collectors in MWh	34.82	34.78
9. Energy produced by collector loop in MWh	33.72	33.57
10. Solar contribution to annual required heating load in MWh	32.49	32.25
11. Energy from auxiliary heating in MWh	28.12	28.48
12. Annual fuel savings in MWh	38.2	37.9
13. Annual solar fraction in percent	53.6	53.1
14. Fractional energy savings in percent	53.9	53.3
15. CO_2 emissions avoided in kg	25,455.28	25,272.73

Therefore, from the summaries of the results in Table 4.1 above, any of the two collectors can be used to provide hot water for the hospital since the solar contribution to the required annual heating load given by both collectors is almost the same although the collector array performance of the flat plate collector is higher than that of the evacuated tube collector in terms of the energy produced by the collector and collector loop, collector power and collector surface area irradiation. However, from table 4.1, it can be inferred that the flow rate through the collector loop in the evacuated tube collector is about 15 percent higher than the flat plate collector.

The schematic arrangement of the proposed solar water heating system is show in Figure 4.1 below.

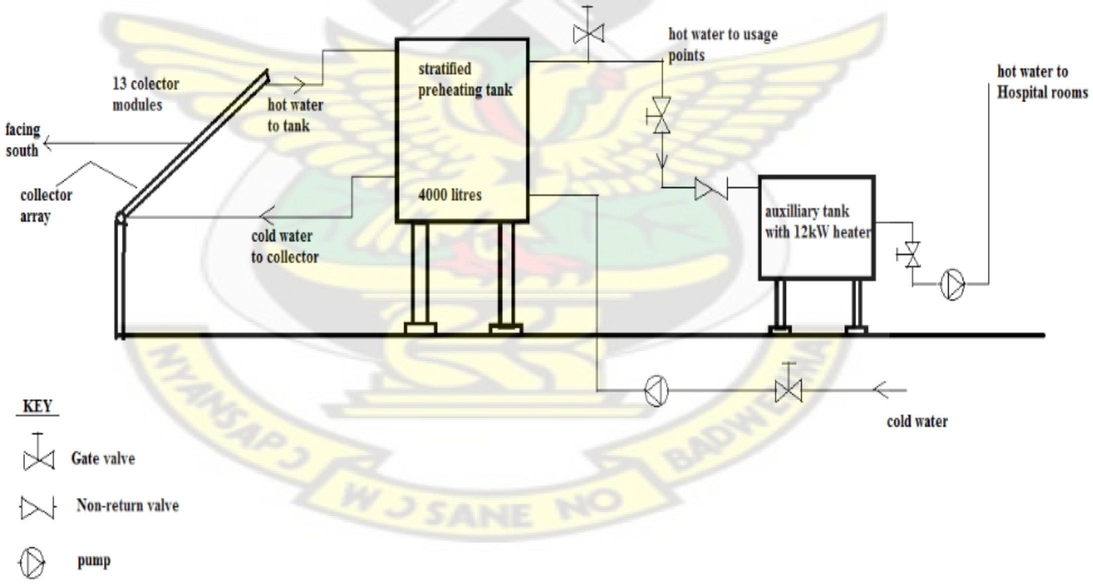

Figure 4.1: Schematic arrangement of the proposed SWH system for the Hospital

4.3.1 Thermal Performance Analysis of the System

The thermal performance of the SWH system based on the two collector types is given in terms of the fuel savings, solar fraction, solar contribution to domestic hot water heating load (E- Solar-DHW), energy required for auxiliary heating (E- Aux) and CO_2 emissions avoided and system efficiency as shown in Table 4.2 below.

Table 4.2: Thermal Performance Analysis

MONTHLY AVERAGE THERMAL PERFORMANCE COLLECTOR ANALYSIS										
	Fuel Savings (kWh)		Solar Fraction (%)		E- Solar-DHW (kWh)		E- Aux Heating (kWh)		CO_2 Emissions (kg)	
MONTH	FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC
Jan	3,477	3,393	57.1	55.7	2,955	2,884	2,222	2,297	2,316	2,260
Feb	3,471	3,361	62.4	60.3	2,950	2,857	1,775	1,881	2,311	2,238
Mar	4,025	3,900	64.8	62.8	3,422	3,315	1,856	1,966	2,681	2,598
Apr	3,390	3,380	57.8	57.6	2,882	2,873	2,105	2,114	2,258	2,251
May	2,979	3,083	57.0	59.0	2,532	2,620	1,911	1,819	1,984	2,053
Jun	2,318	2,451	42.1	44.3	1,970	2,084	2,708	2,615	1,544	1,633
Jul	2,208	2,339	38.9	41.1	1,877	1,988	2,946	2,854	1,471	1,558
Aug	2,250	2,329	38.7	39.9	1,912	1,980	3,026	2,983	1,498	1,551
Sep	2,765	2,773	45.0	44.9	2,350	2,357	2,868	2,891	1,841	1,847
Oct	3,456	3,333	55.4	53.4	2,938	2,833	2,361	2,477	2,302	2,220
Nov	4,247	4,090	66.9	64.4	3,610	3,477	1,786	1,924	2,829	2,724
Dec	3,635	3,514	54.8	52.9	3,090	2,987	2,551	2,663	2,421	2,340
	38,221	**37,946**	**53.4**	**53.0**	**32,488**	**32,255**	**28,115**	**28,484**	**25,456**	**25,273**

In terms of the annual collector performance analysis, the FPC increases its value in terms of fuel cost savings (saving electricity), solar fraction, solar contribution to annual heating load and the amount of CO_2 emissions avoided more than that of the ETC as shown in Figures 4.2 and 4.3 respectively. The ETC system efficiency is higher than that of the FPC; however, it requires more energy for auxiliary heating to meet the same annual heating load as that of the FPC resulting in a reduced fuel cost savings.

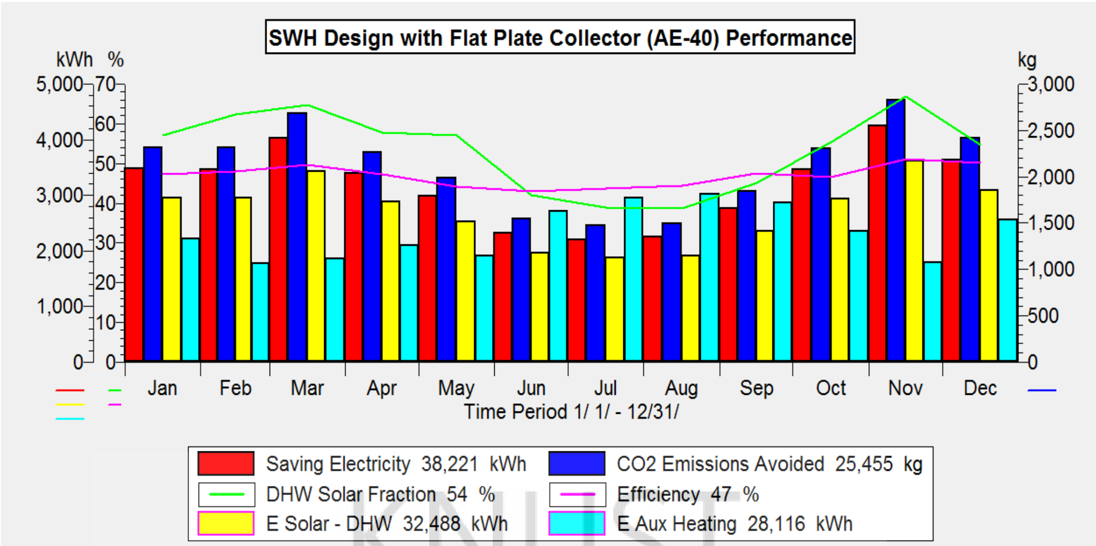

Figure 4.2: Flat Plate Collector Performance

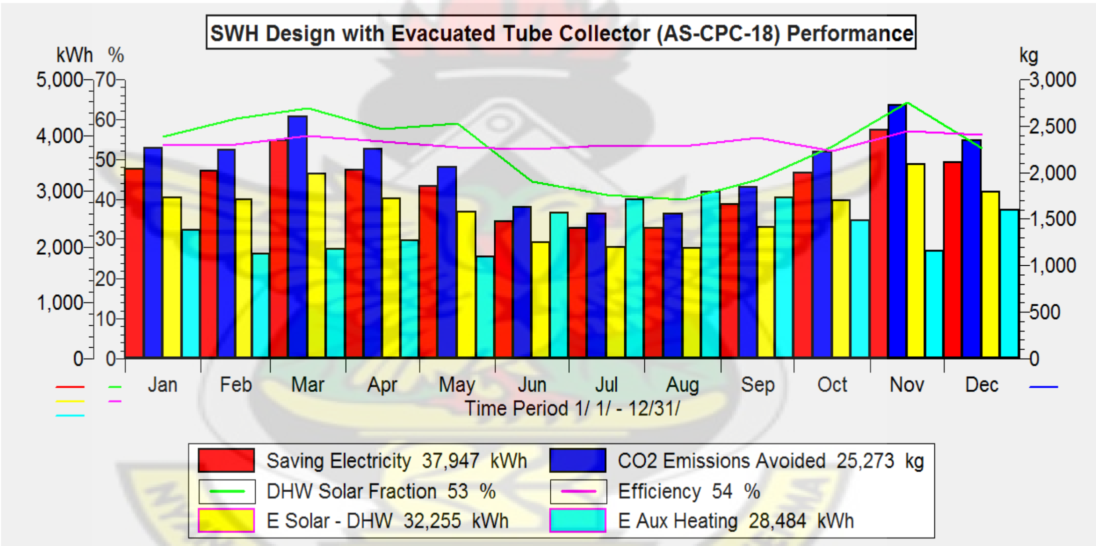

Figure 4.3: Evacuated Tube Collector Performance

In terms of the monthly average collector performance analysis, both collectors give about the same performance in April and September with their maximum collector performance values occurring in November as shown in table 4.2 as well as Figures 4.2 and 4.3.

In periods where the sunshine hours in the location increases (thus from January to May and October to December), the FPC Performs better (about 3 percent more) than the ETC in contributing to the monthly heating load and fuel cost savings with a reduced amount of energy required for auxiliary heating (about 3 percent lower than ETC) as seen in Table 4.2 and Figure 4.4. However, the ETC, from May to August (periods of low sunshine hours or cloudy conditions) gives a better performance than the FPC.

The performance analysis of the two collectors therefore explains that the flat plate collector is more efficient than the evacuated tube collector in full sunshine conditions but the energy output of the flat plate collector is reduced slightly more than the evacuated tube collector in cloudy or extremely cold conditions.

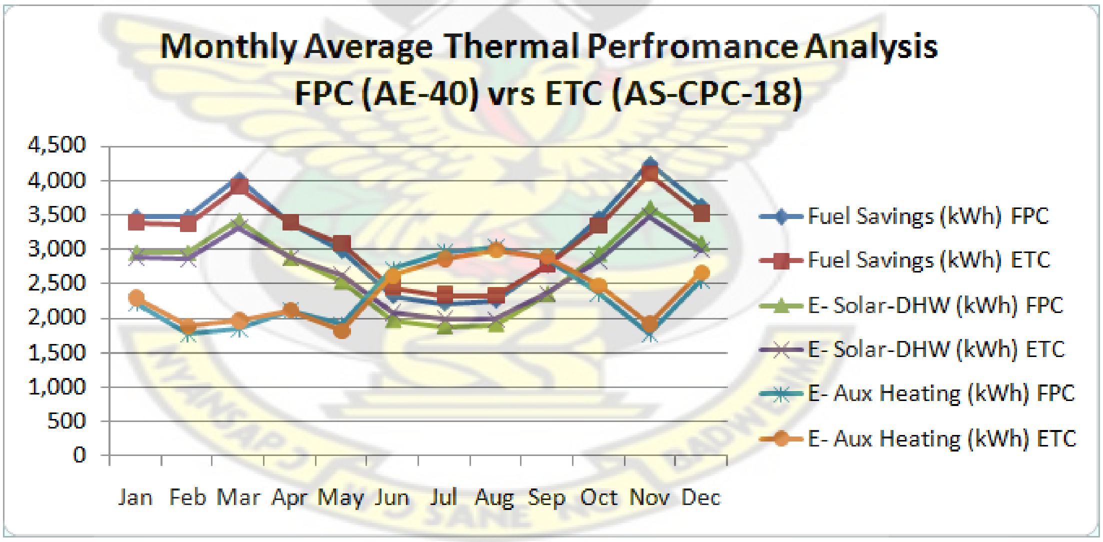

Figure 4.4: Monthly Average Performance Graph (FPC vs. ETC)

However, the amount of solar contribution to the required monthly and annual heating load of the FPC is more than the ETC leading to a higher fuel cost savings (thus, high electricity savings) and a lower energy for auxiliary heating.

Also, since flat plate collectors have longer life span periods than evacuated tube collectors, the collector choice best suited for the proposed solar water heating system is the flat plate collector. The economic analysis of the system as well as annual simulation using the flat plate collector is therefore carried out in the next section.

4.3.2 Economic Analysis of the System

The economic performance of the system is carried out annually using the economic efficiency calculation entry parameters dialog box in the T*SOL® software programme with its interface shown in appendix B. The total initial investment (equipment cost plus installation) of the solar water heating system is US$ 28,829 from RET Screen product database [RETScreen, 2012] as shown in Figure 4.5 with a five year term payment loan of US$ 20,000 borrowed from government institutions like the Central Bank with a long-term average interest rate of 16.7 percent and a repayment free initial period of two (2) years as pointed out in section 3.3.6.

Show data

Solar water heater			
Type	Glazed		$ 28,829
Manufacturer	Alternate Energy Technologies		
Model	Alternate Energy AE-40		
Gross area per solar collector	m²	3.70	
Aperture area per solar collector	m²	3.48	
Fr (tau alpha) coefficient		0.71	
Fr UL coefficient	(W/m²)/°C	4.91	
Temperature coefficient for Fr UL	(W/m²)/°C²	0.008	
Number of collectors		13	
Solar collector area	m²	48.05	
Capacity	kW	31.68	
Miscellaneous losses	%	4.0%	

Figure 4.5: Cost of the proposed solar water heating system

The analysis is done with no consideration to any subsidy or discount rate. The solar water heating system yielded an annual load of 32.49 MWh with annual electricity consumption for pumps to be 3,676.29 kWh and fuel cost savings of 38.221 MWh. With the input parameters and assumptions pointed out in section 3.3.6 where the life span of the project is taken to be 20 years, interest on capital of 16.7 percent, price increase rate of running cost and energy to be 4 percent and 8 percent respectively with 5 percent of initial investment as fixed running cost (US$ 1,441) and annual pump running cost of US$ 736. The output from the programme gives an annual fuel cost savings of US$ 13,320 and annual operating cost of US$ 2,700. The cash value of savings (life cycle savings), running cost (life cycle cost), payback period (amortization period) and the net present value of the solar plus auxiliary system is presented in Table 4.3 below.

Table 4.3: Economic calculation output from T*SOL® Programme

Economic Efficiency Parameters	
Life Span:	20 Years
Interest on Capital:	16.7 %
Price Increase Rate - Energy Use:	8.0 %
Price Increase Rate - Running Costs:	4.0 %
Loan	
Loan Ref:	
Loan Capital:	20,000 $
Period/Loan Interest:	5 Years/ 16.7 %
Annual Instalment:	9,008 $
Payment Free Initial Years:	2 Years
Costs (Cash Value)	
Investments:	-28,829 $
Subsidy:	0 $
Saving:	76,127 $
Running Costs:	-15,428 $
Subsidy above :	0 $
Net Present Value:	**31,869 $**
Amortization Period:	**6 Years**
Cost of Solar Energy:	**0.24$/kWh**

The table 4.3 shows an annual loan instalment of US$ 9,008 payable to the financial institution that granted the loan for a period of 5 years. The life cycle cost of the system (comprising an initial investment and total operating cost) amounts to US$ 44,257 with a life cycle savings of US$ 76,127 given a positive net present value of US$ 31,869 indicating the economic viability of the solar water heating system as proposed for the hospital. The proposed system, also from the economic analysis, has a payback period of 6 years.

4.3.4 Results of Annual Collector Performance Simulation

This is carried out by the T*SOL® simulation programme for solar thermal heating systems. The results are determined by a mathematical model calculation with variable time steps of up to 6 minutes. Actual yields can deviate from these values due to fluctuations in the weather, consumption and other factors. As can be seen from the graph in Figure 4.6, the collector outlet temperature is not constant because of the daily variation of irradiation and the presence of a controller, which shuts off the pump when there is little or no useful solar energy gain.

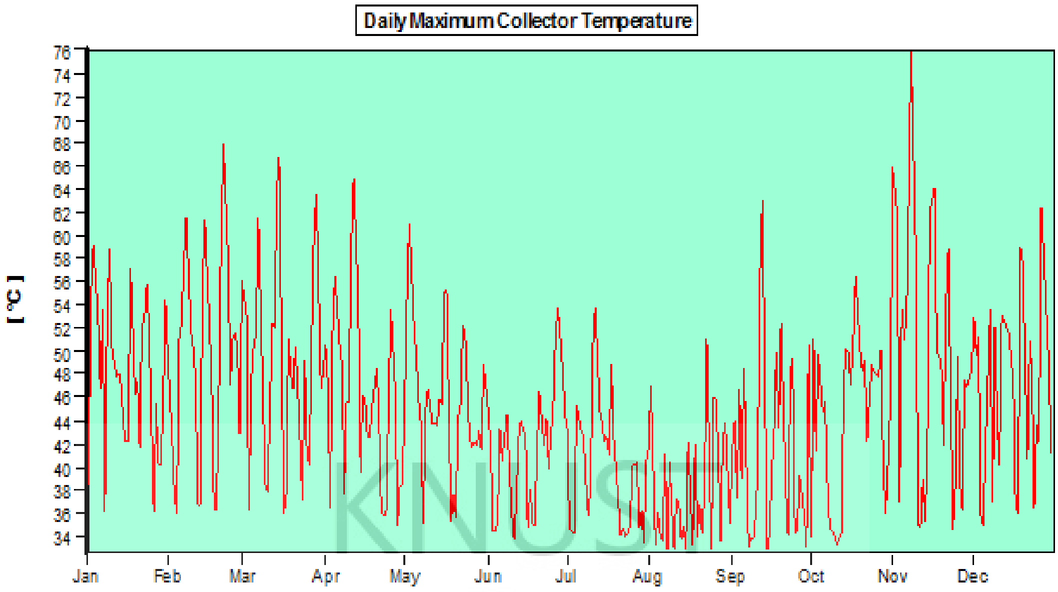

Figure 4.6: Annual collector outlet daily temperature simulation

The details of the proposed solar water heating system specifications based on the T*SOL® software programme is given in Table 4.4 below.

Table 4.4: Proposed SWH system Specification

PROPOSED SOLAR WATER HEATING SYSTEM SPECIFICATIONS			
System Type: Direct Active Solar Water Heating System			
	COLLECTOR SPECIFICATION		
Manufacturer:	Alternate Energy Technologies		
Type:	AE-40		
Reference:	Flat-Plate Collector		
Number of collectors:	13		
Gross Surface Area:	48.048 m^2		
Active Surface Area:	45.253 m^2		
Azimuth Angle:	0° (South Facing)		
Inclination(Tilt) Angle:	30°		
	COLLECTOR LOOP CONNECTION		
Volumetric Flow Rate:	34.11 l/h per m^2 of collector surface area		
Medium:	Water		
Specific Heat Capacity:	4180 J/ kg. K		
Flow temperature:	8K above tank reference temperature		
Collector Loop Pump:	Speed Controlled		
		Piping System	
Length			
Inside piping Length:		12 m	
Outside piping Length		2 m	
Distance between collectors		200 mm	
Thermal Conductivity Coefficient for Insulation:		0.045 W/(m.K)	
Nominal Width			
Mains:	35 mm	Between collectors:	22 mm
Thickness of Insulation			
Inside piping:	40 mm	Outside piping:	40 mm
Between collectors:	30 mm		
	HOT WATER HEATING LOAD		
Parameters			
Average Daily Consumption:	5,621 litres		
Desired Temperature of Hot water:	50 °C		
Circulation			
Temperature Range- Flow/Return:	5 K		
Specific losses:	0.3 W/(m.K)		
Annual circulation losses:	1011.78 kWh		
	PREHEATING STORAGE TANK		
Capacity:	88 litres per m^2 of collector Surface Area		
Dimension:	Height = 1.6 x Diameter		
Thickness of Insulation:	100 mm		
Effective Thermal Conductance:	0.065 W/ (m.K)		

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this thesis is to assess the feasibility of a solar water heating system based on its long- term thermal performance, based on two collector types; flat plate collector (AE-40) and evacuated tube collector (AS-CPC-18). This has been done using T*SOL® simulation programme for solar thermal heating systems. The programme has been used to propose a SWH system for the Government Hospital of the Kwame Nkrumah University of Science and Technology.

The outputs from the programme suggest a SWH system with a better long-term thermal performance when using the flat plate collector than the evacuated tube collector and as such the proposed SWH system was based on the flat plate collector (AE-40).

The proposed solar hot water heating system has the following annual thermal performance parameters;

- Required number of collector modules is 13
- Required size of collector area is 48.05 m^2
- Annual solar contribution to hot water load is 32.49 MWh
- Energy from auxiliary heating is 28.12 MWh
- Fuel (Electricity) savings of 38.2 MWh
- Amount CO_2 emissions avoided is 25,455.28 kg
- Annual solar fraction is 54 percent
- System efficiency is 47.2 percent

The economic analysis of the system was done with an initial total investment of US$ 28,829 and a life cycle savings of US$ 76,127. The economic performance of the system has proved that the proposed solar water heating system is feasible because it gives a positive net present value of US$ 31,869 with a payback period of 6 years. However, bank negotiations to reduce the interest rate to 12 percent or less would ensure a payback period of 5 years or less.

The analysis of the SWH system with regards to the estimation of the daily heating load for the hospital was based on the occupants only with no regards to other usage of hot water in the hospital such as laundries etc.

Since the prices of solar water heating system components are dynamic, using the cost of the system from RETScreen product database and making assumptions with regard to increase in energy and running cost might deviate from the real economic scenarios of the analysis that has been carried out in this thesis.

5.2 Recommendations

The proposed SWH system has to be implemented by solar water heating companies like DENG and Dizengoff Ghana limited who have made installations of solar hot water systems in various places in Ghana such as Anita hotel in Ejisu and Africa regent hotel in Accra.

The information with regards to the architectural plan of the hospital building was not provided and as such a detailed design of the proposed solar water heating system to include piping arrangements, valve positions, storage tank layouts, available floor space and roof dimensions that will allow for easy installation was not specified. It is recommended therefore that further studies should focus on the installation design.

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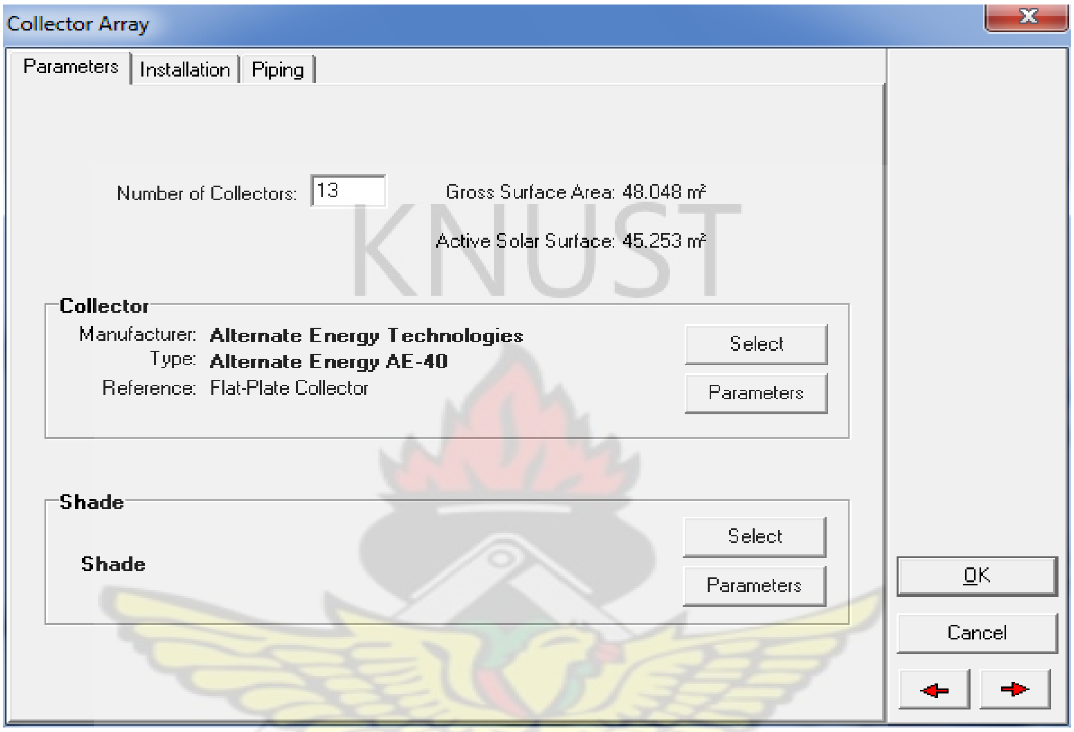
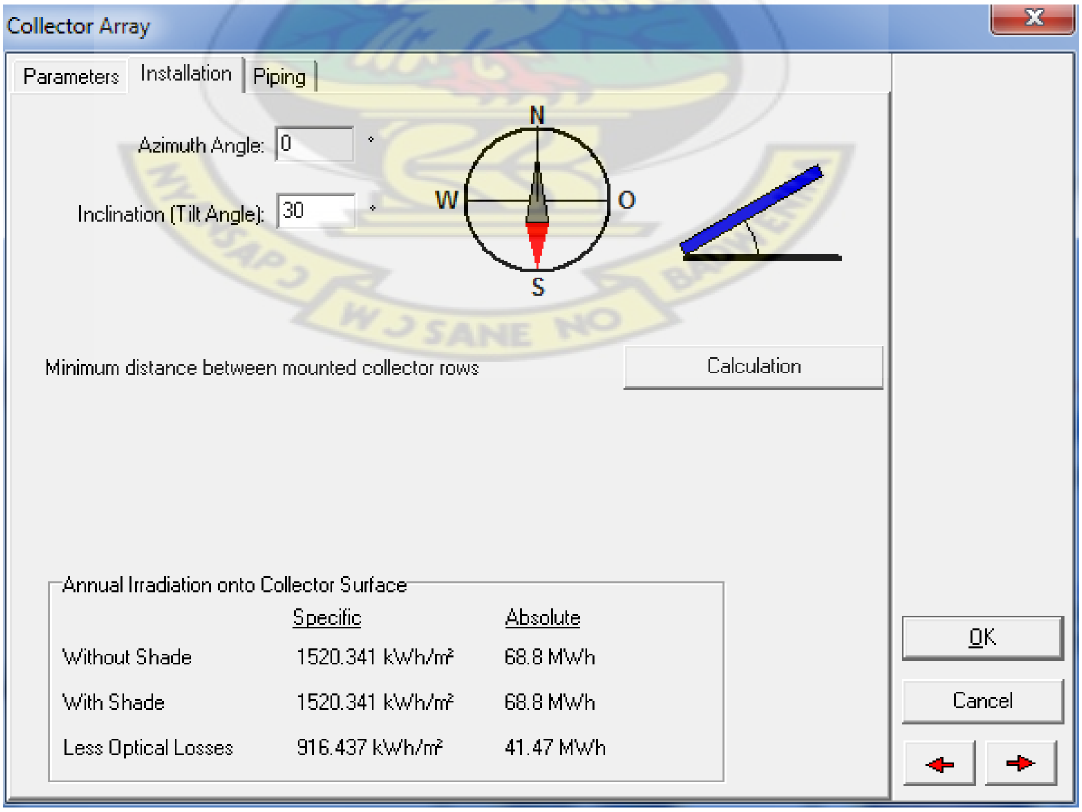
LIST OF APPENDICES

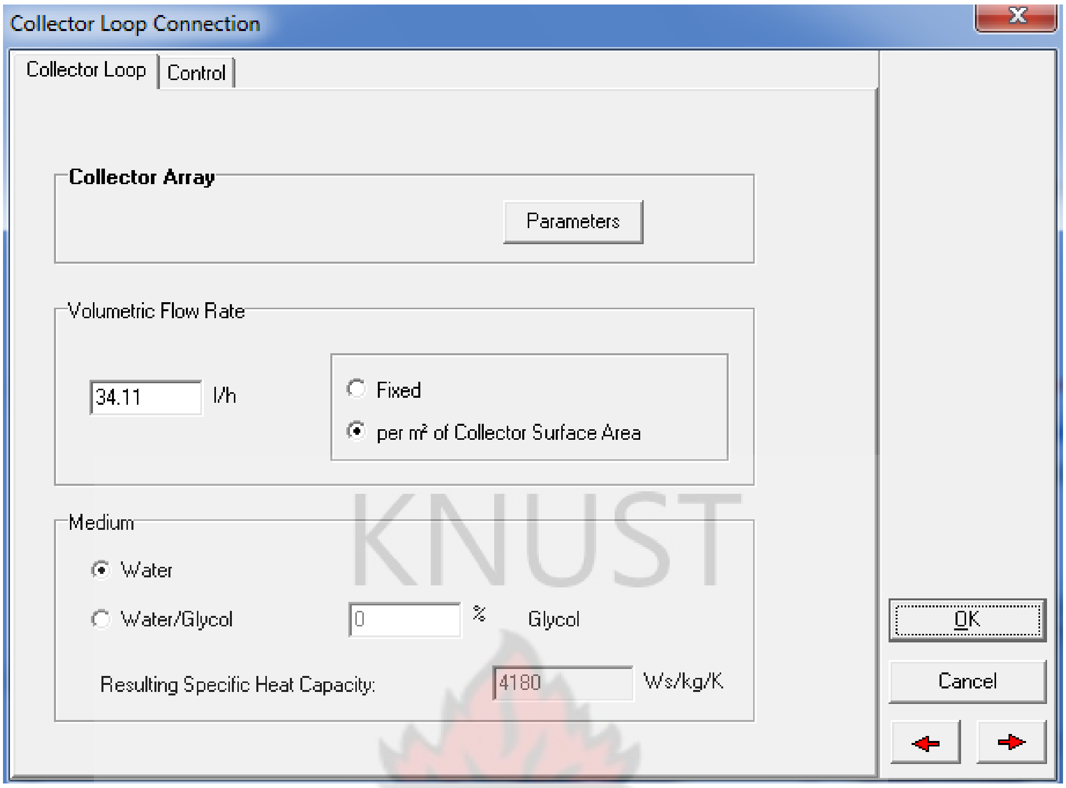
APPENDIX A

T*SOL Pro 4. 4 Solar Thermal System Software Programme

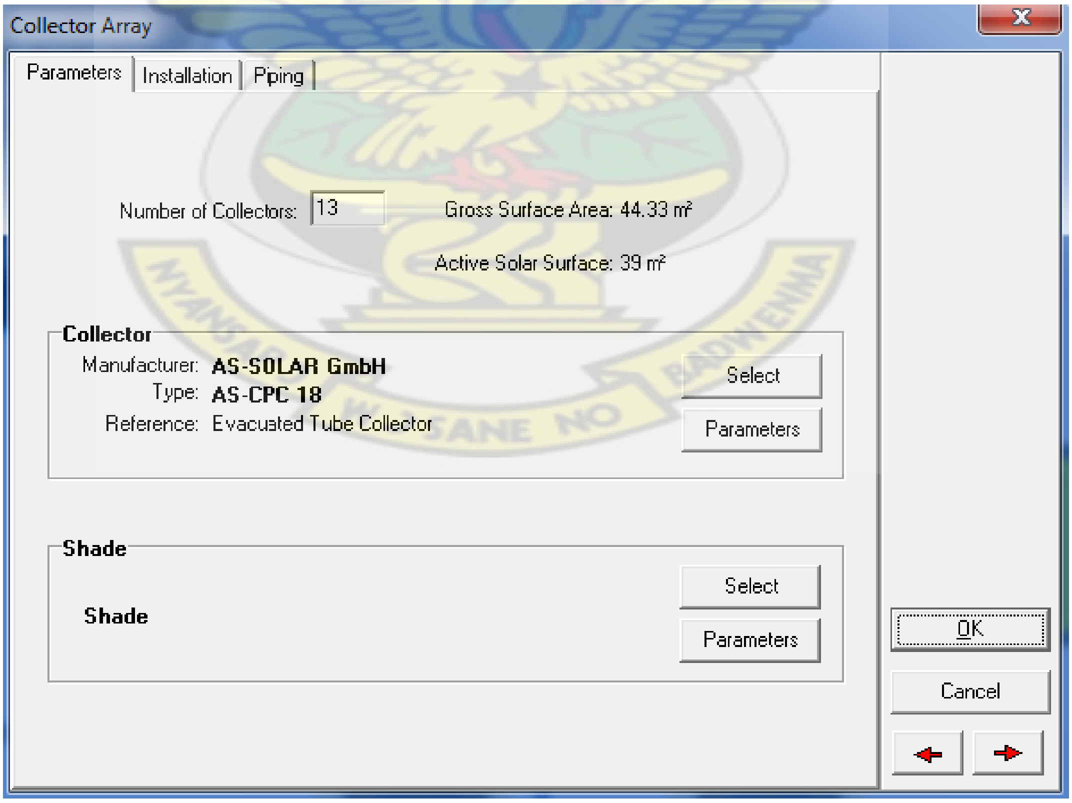
Flat plate collector specifications

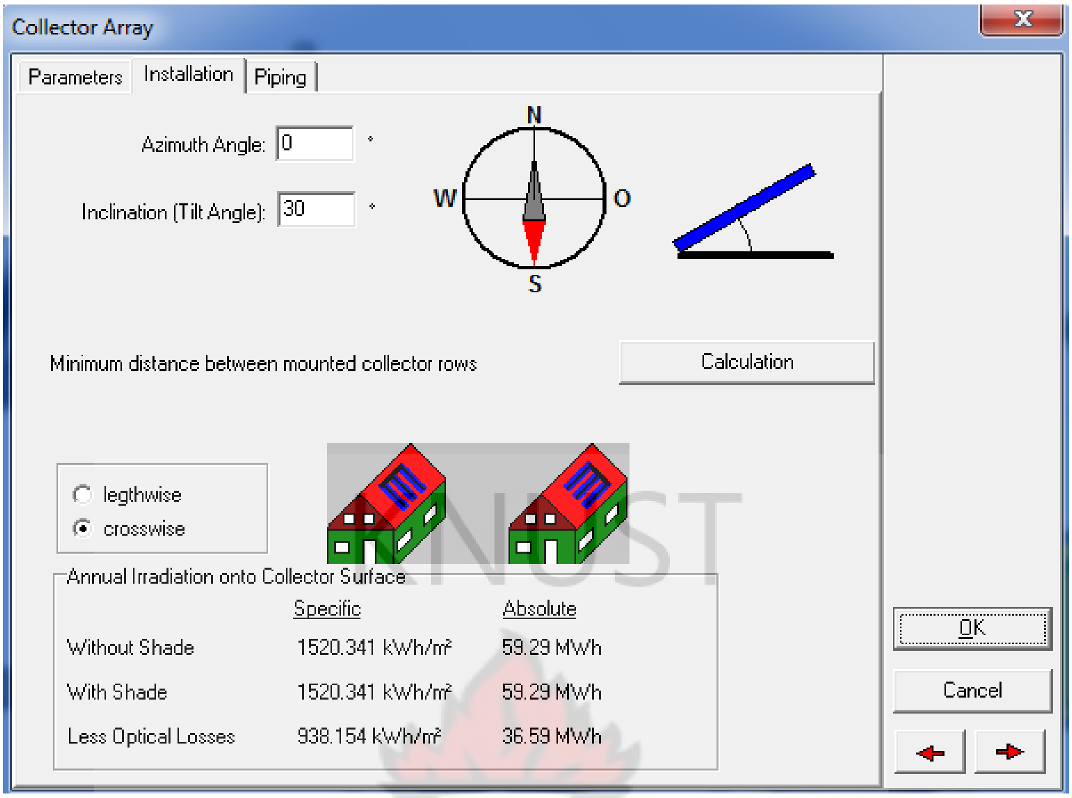


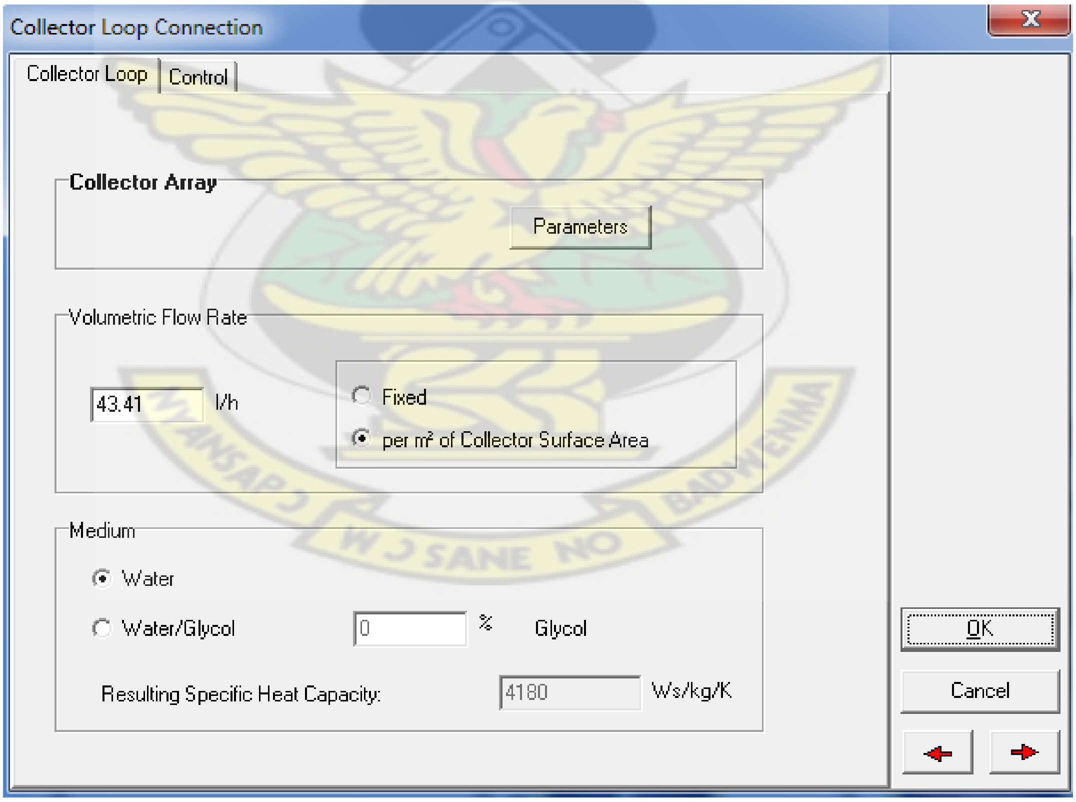




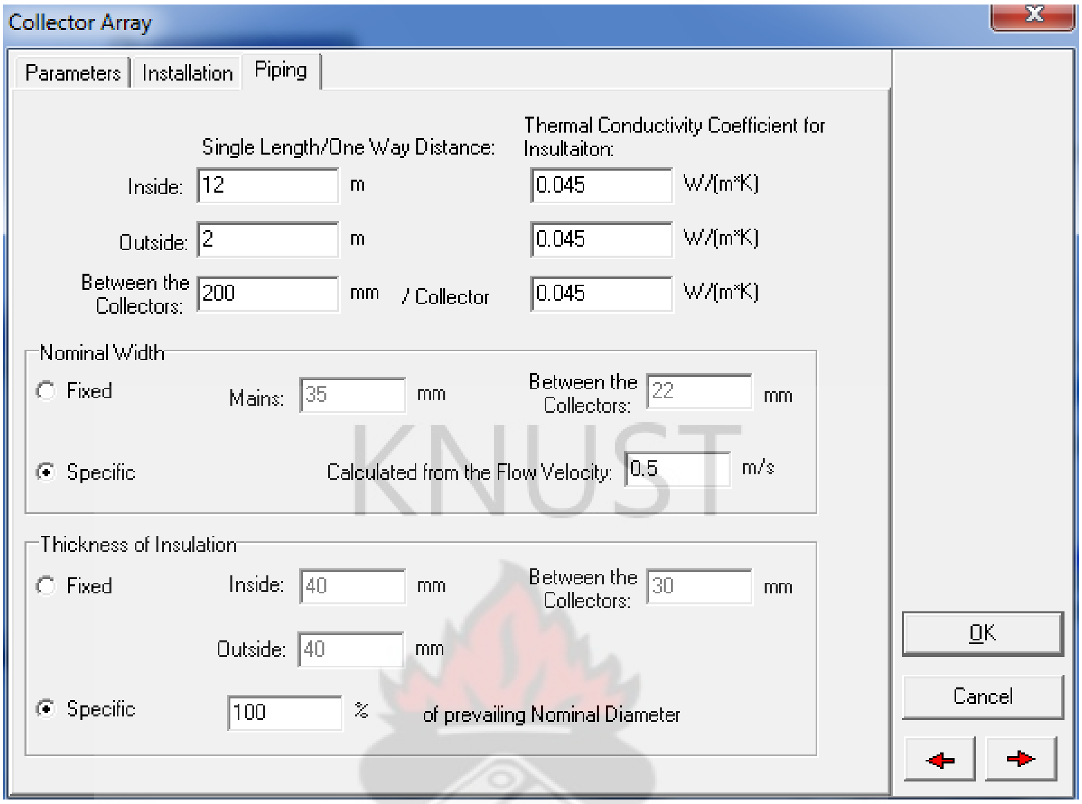
<u>Evacuated tube collector specification</u>

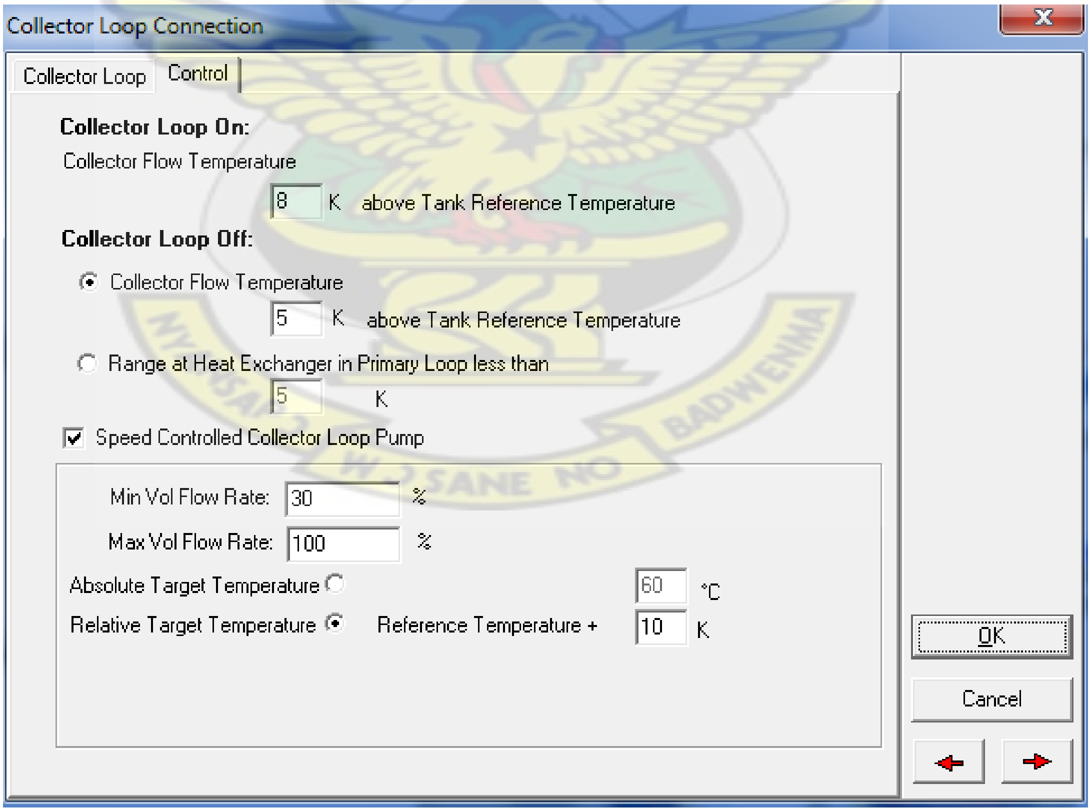



Collector Array
Parameters
Installation
Piping
Azimuth Angle: 0 °
Inclination (Tilt Angle): 30 °
N
W
O
S
Minimum distance between mounted collector rows
Calculation
legthwise
crosswise
Annual Irradiation onto Collector Surface
Specific
Absolute
Without Shade 1520.341 kWh/m² 59.29 MWh
With Shade 1520.341 kWh/m² 59.29 MWh
Less Optical Losses 938.154 kWh/m² 36.59 MWh
OK
Cancel

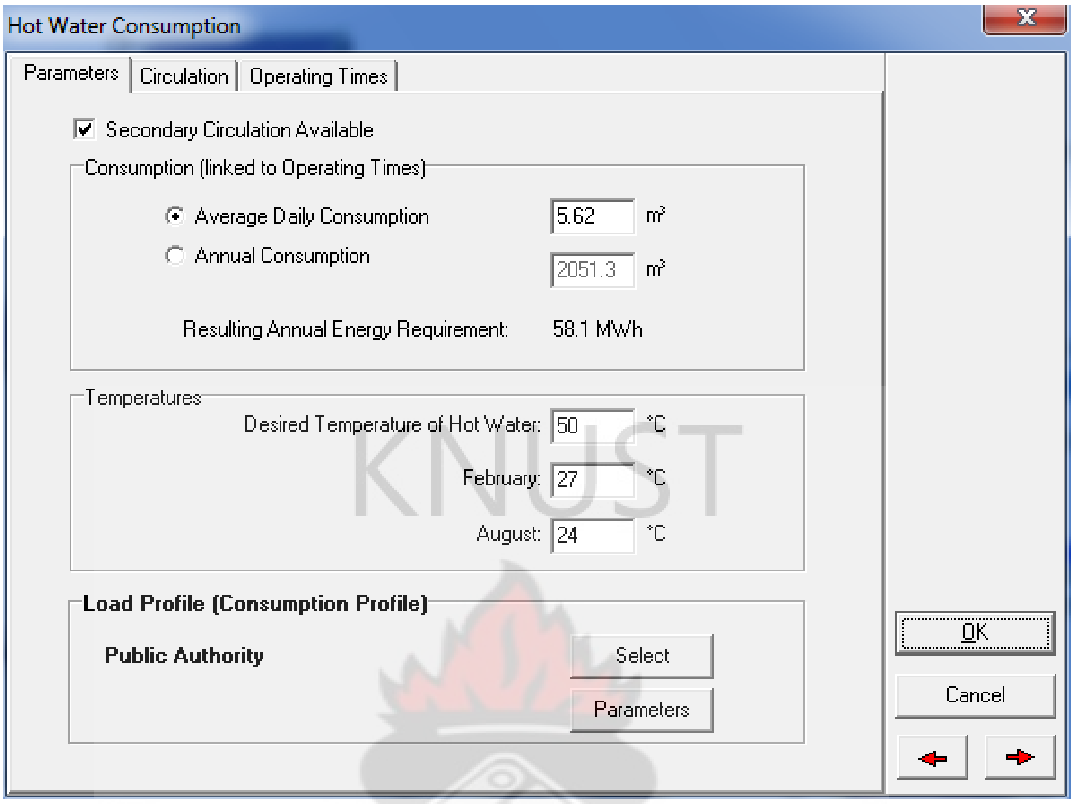

Collector Loop Connection
Collector Loop
Control
Collector Array
Parameters
Volumetric Flow Rate
43.41 l/h
Fixed
per m² of Collector Surface Area
Medium
Water
Water/Glycol 0 % Glycol
Resulting Specific Heat Capacity: 4180 Ws/kg/K
OK
Cancel

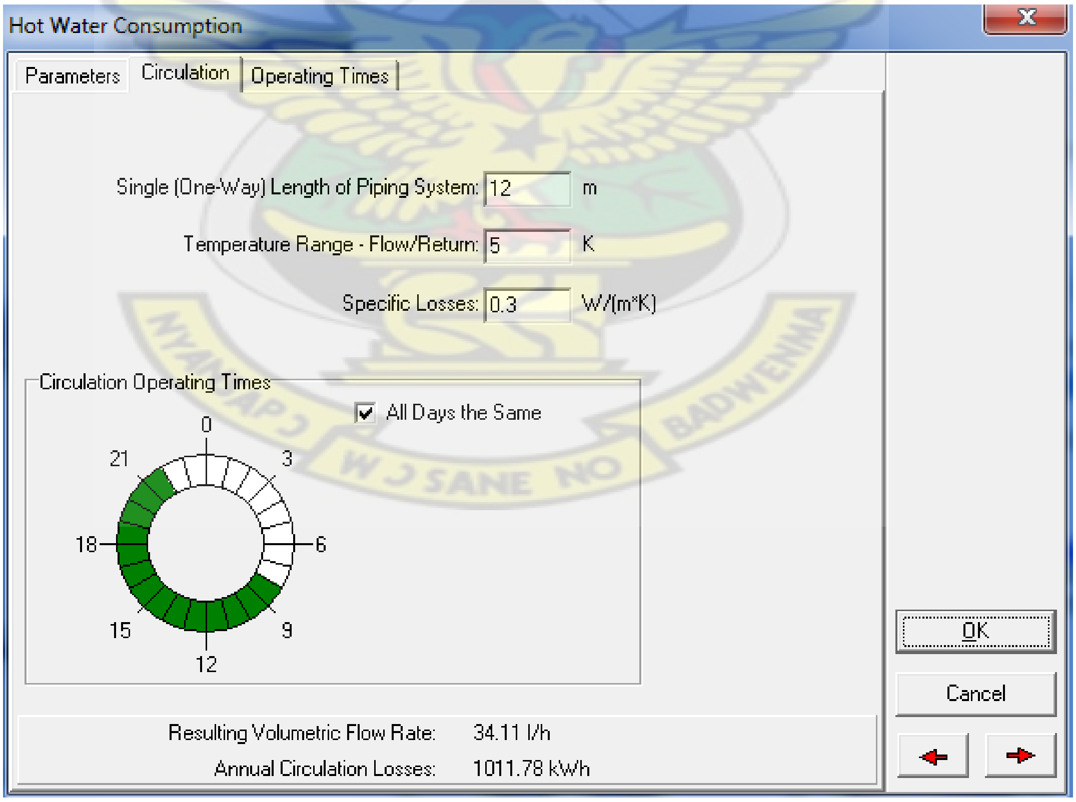
Collector array piping and installation specification

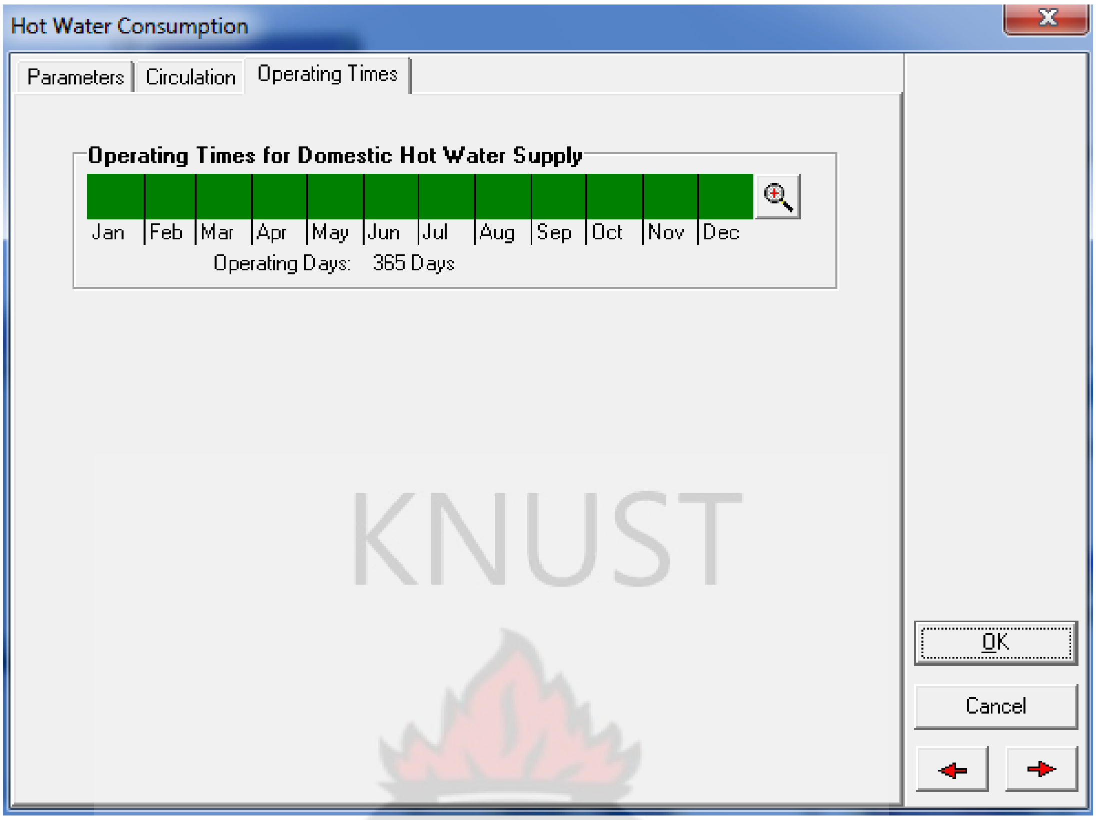




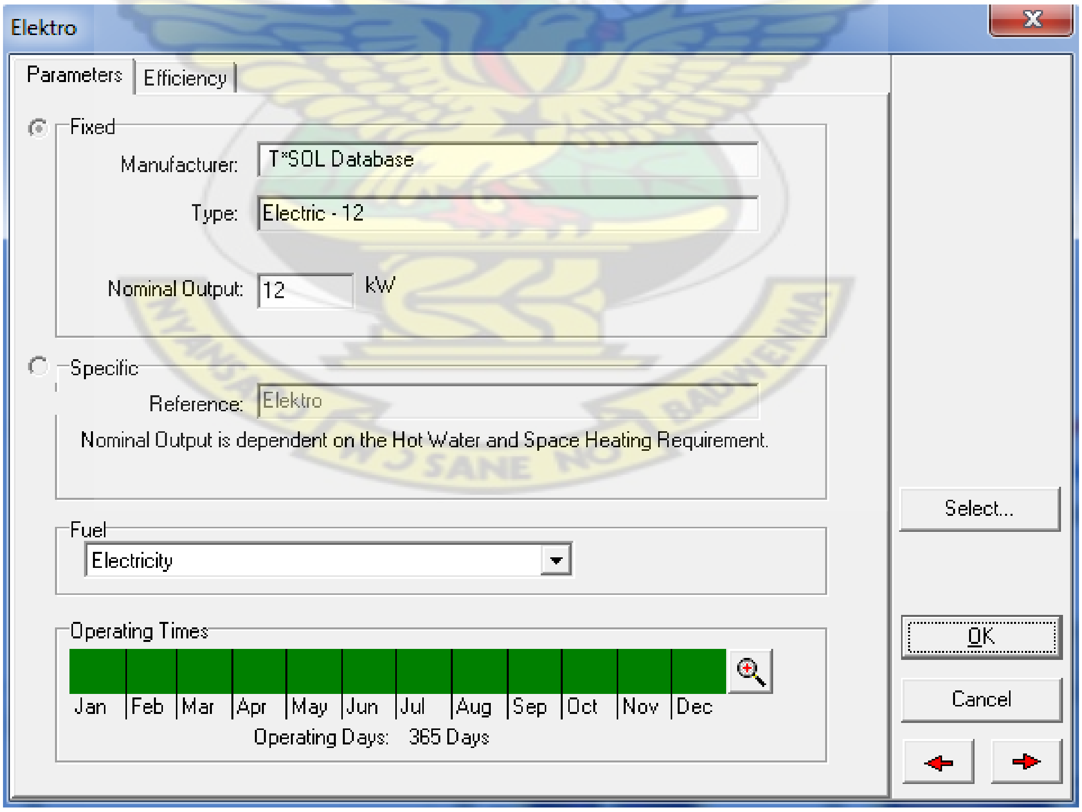
Hot water heating load calculation

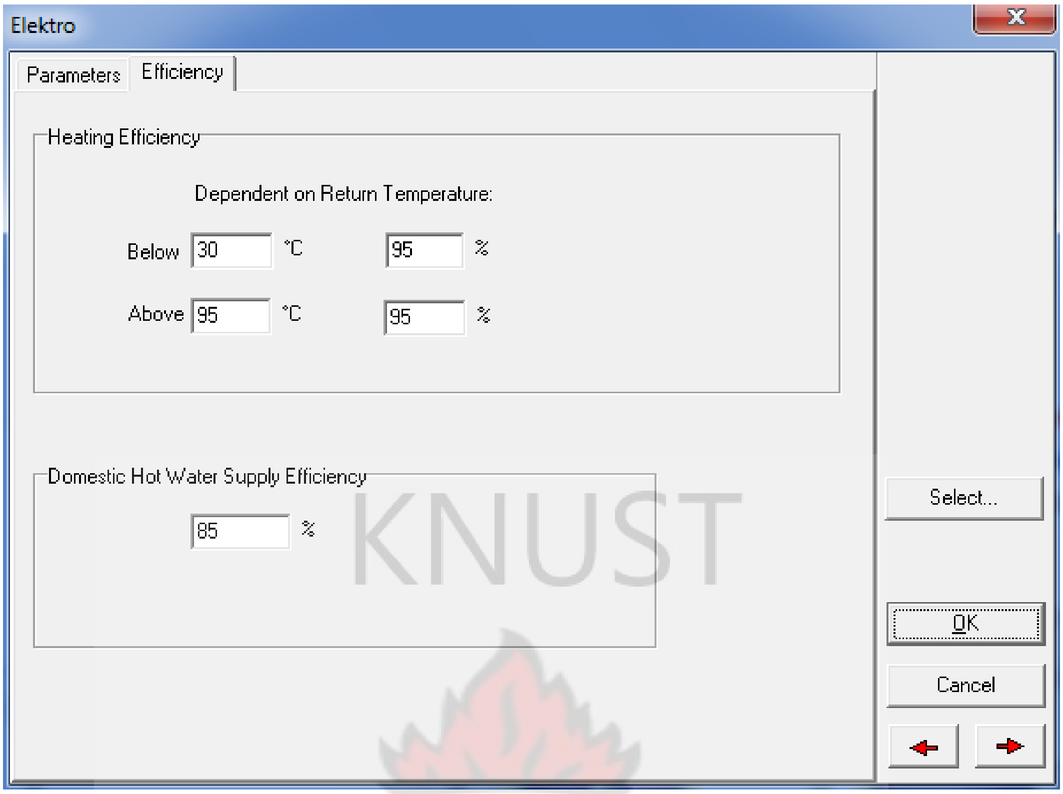




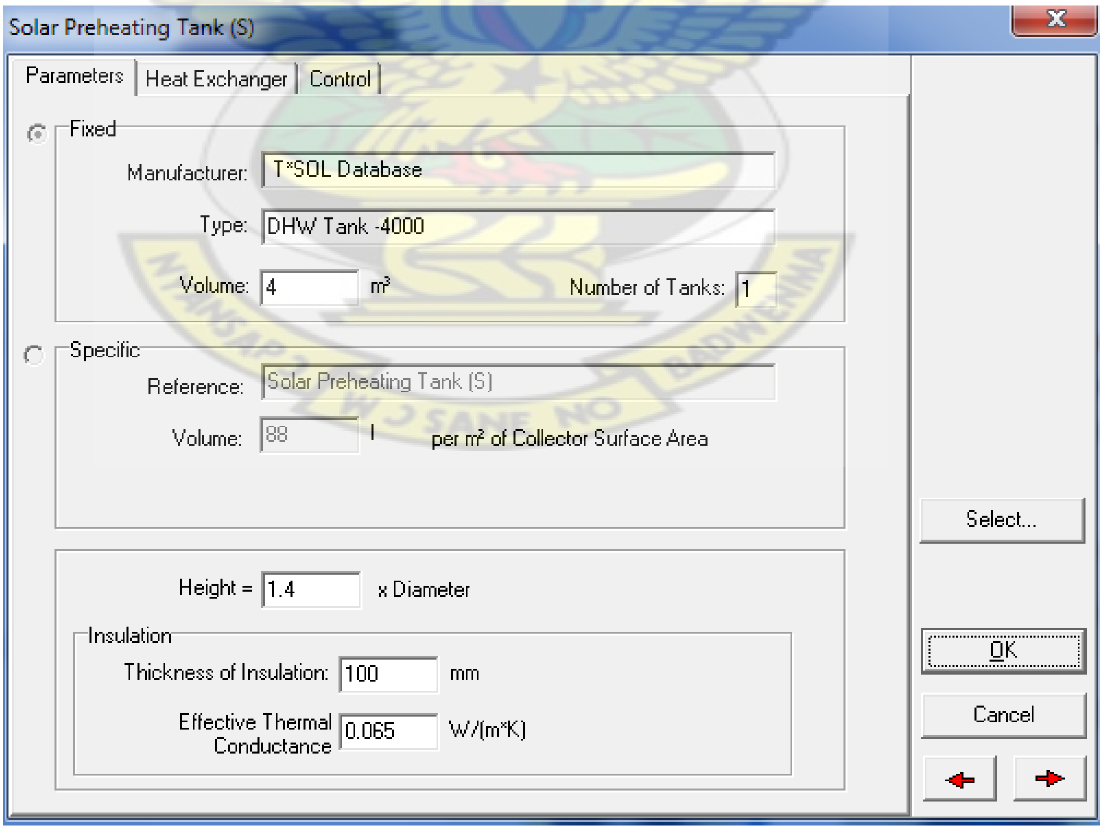


Auxiliary heating system characteristics

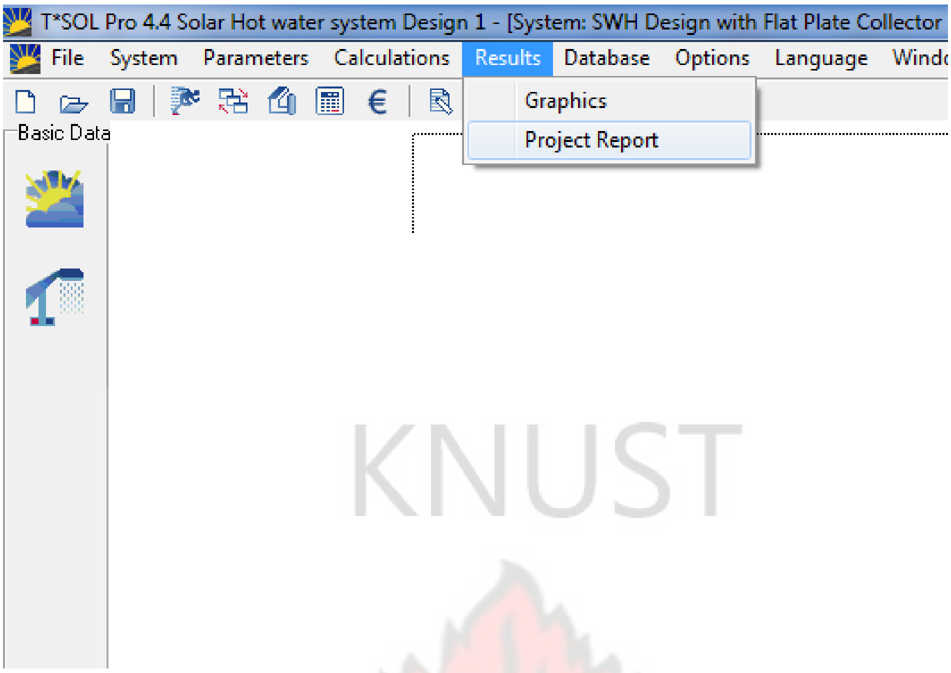




Solar Preheating storage tank parameters

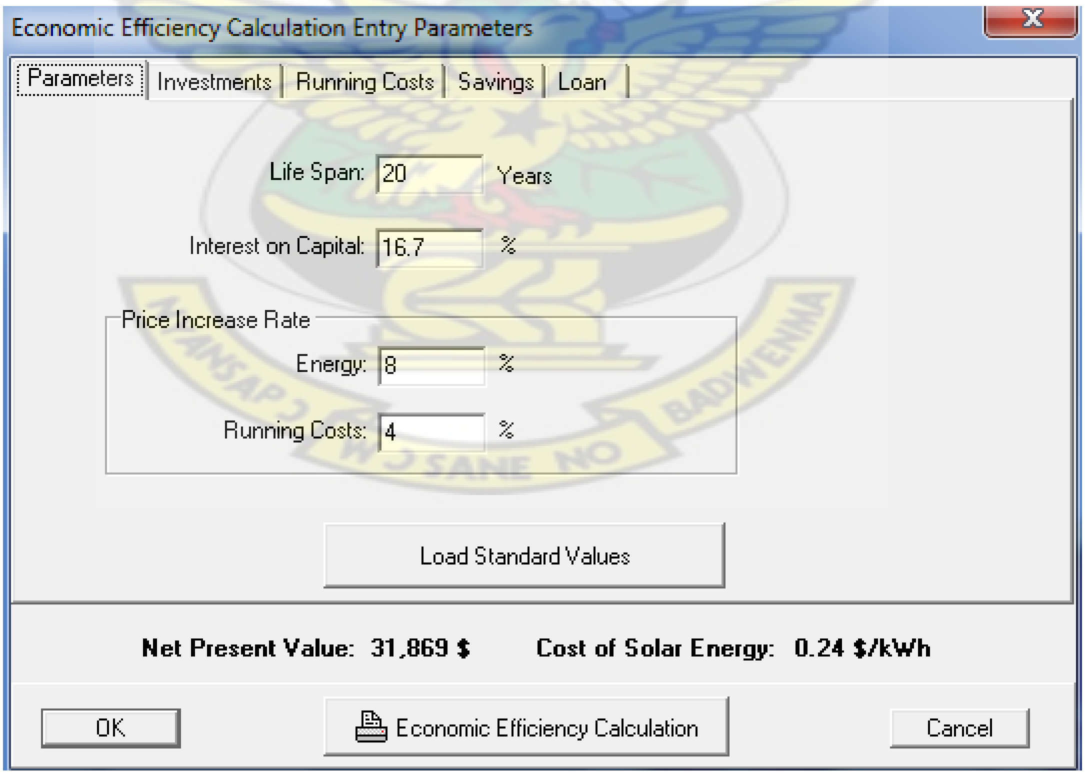


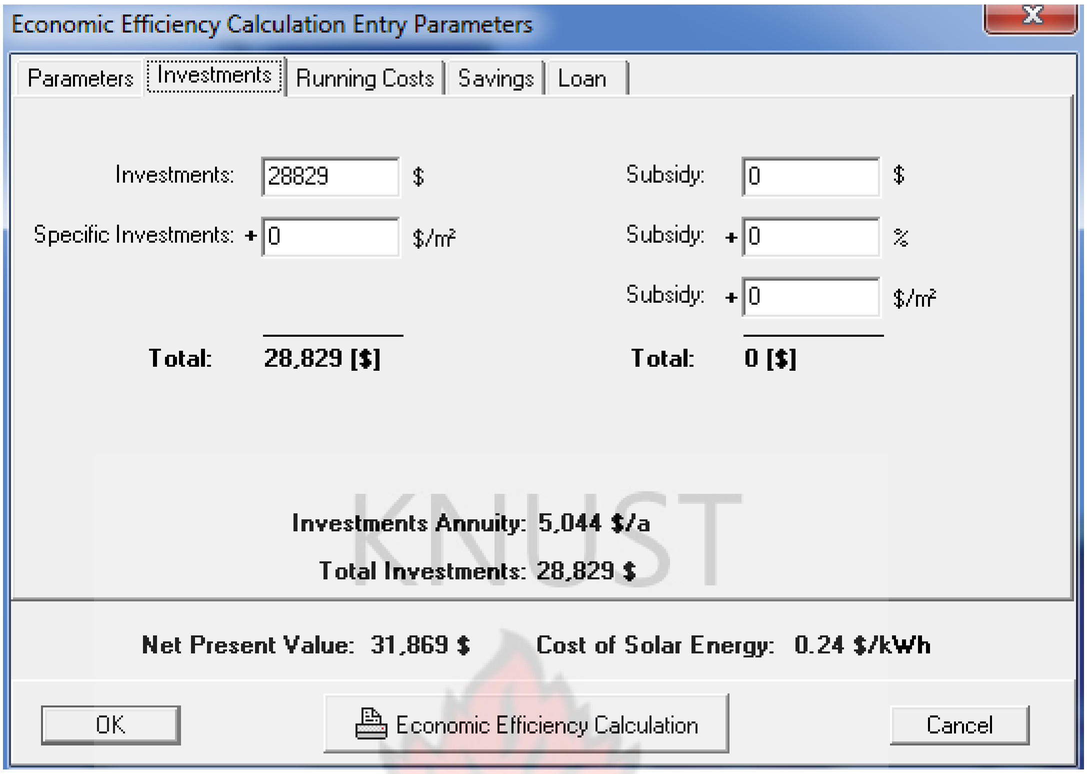
The results tool bar gives the summary of the SWH system (project report)



APPENDIX B

Economic efficiency calculation parameters

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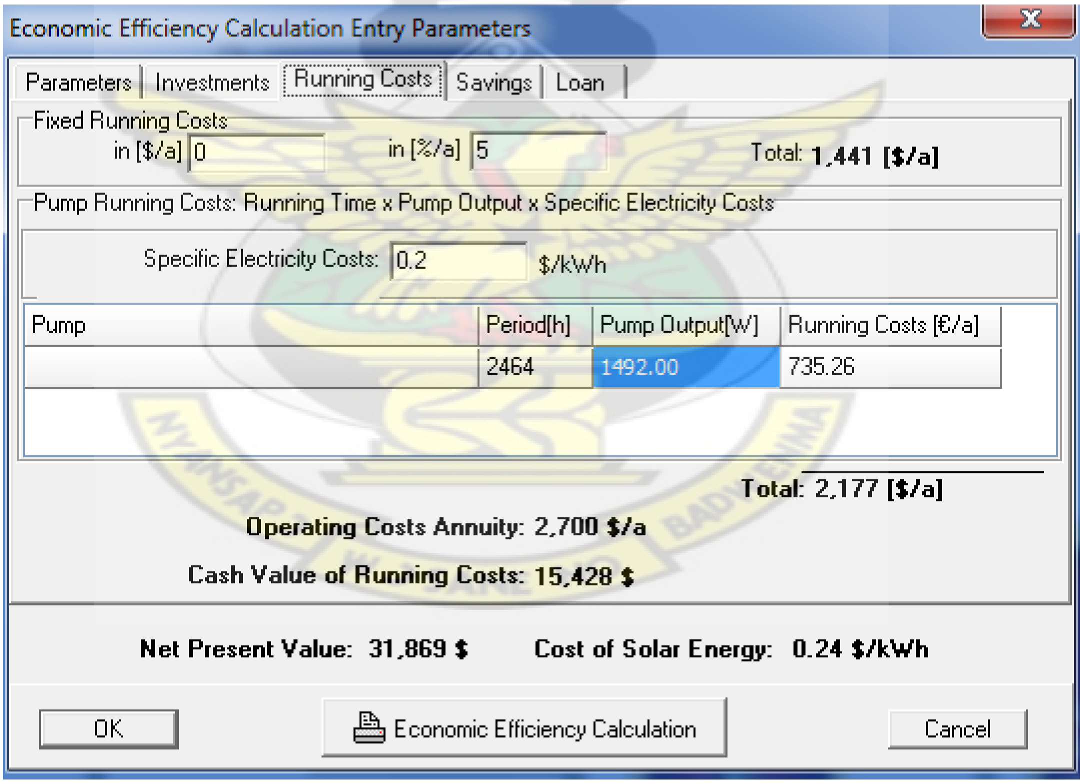
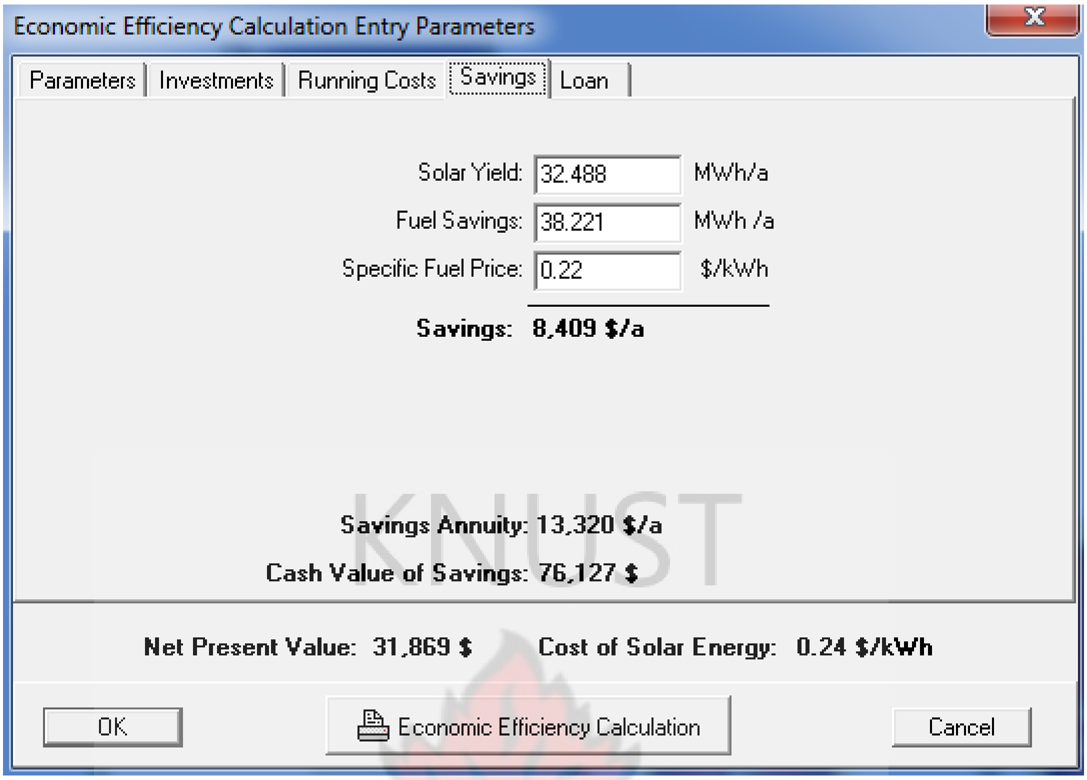
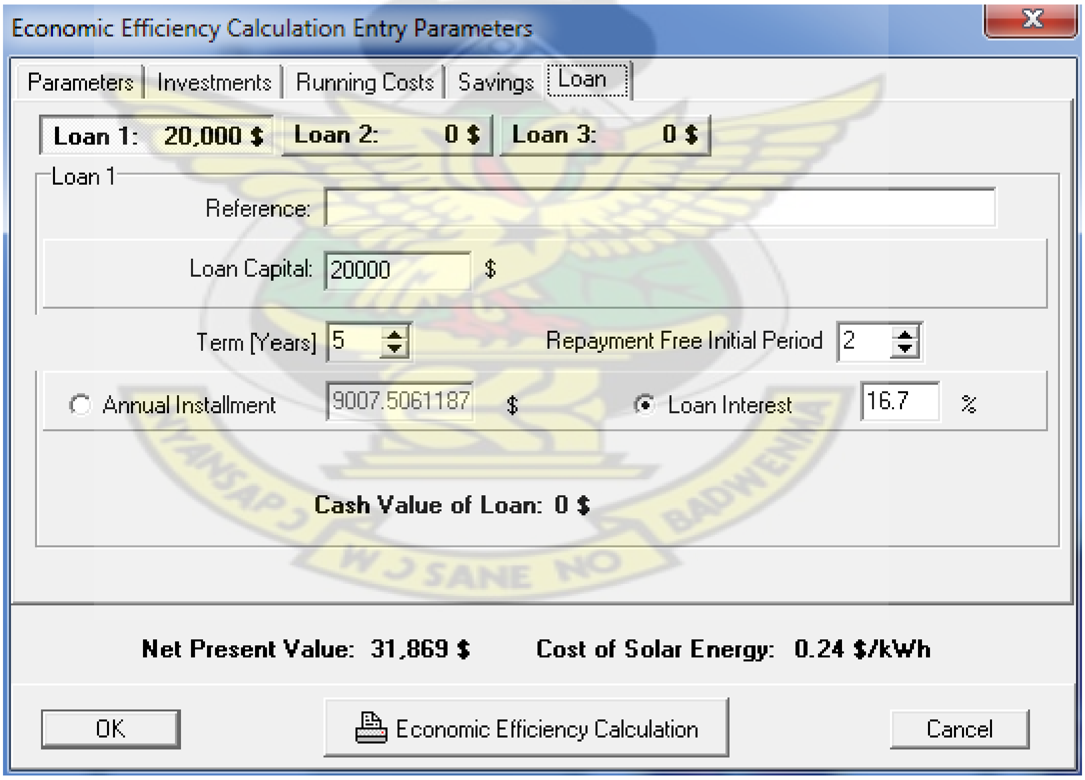
Parameters
Investments
Running Costs
Savings
Loan
Investments: 28829 $
Specific Investments: + 0 $/m²
Total: 28,829 [$]
Subsidy: 0 $
Subsidy: + 0 %
Subsidy: + 0 $/m²
Total: 0 [$]
Investments Annuity: 5,044 $/a
Total Investments: 28,829 $
Net Present Value: 31,869 $
Cost of Solar Energy: 0.24 $/kWh
OK
Economic Efficiency Calculation
Cancel


Economic Efficiency Calculation Entry Parameters
Parameters
Investments
Running Costs
Savings
Loan
Fixed Running Costs
in [$/a] 0
in [%/a] 5
Total: 1,441 [$/a]
Pump Running Costs: Running Time x Pump Output x Specific Electricity Costs
Specific Electricity Costs: 0.2 $/kWh
Pump
Period[h]
Pump Output[W]
Running Costs [€/a]
2464
1492.00
735.26
Total: 2,177 [$/a]
Operating Costs Annuity: 2,700 $/a
Cash Value of Running Costs: 15,428 $
Net Present Value: 31,869 $
Cost of Solar Energy: 0.24 $/kWh
OK
Economic Efficiency Calculation
Cancel


Economic Efficiency Calculation Entry Parameters
Parameters
Investments
Running Costs
Savings
Loan
Solar Yield: 32.488 MWh/a
Fuel Savings: 38.221 MWh /a
Specific Fuel Price: 0.22 $/kWh
Savings: 8,409 $/a
Savings Annuity: 13,320 $/a
Cash Value of Savings: 76,127 $
Net Present Value: 31,869 $
Cost of Solar Energy: 0.24 $/kWh
OK
Economic Efficiency Calculation
Cancel


Economic Efficiency Calculation Entry Parameters
Parameters
Investments
Running Costs
Savings
Loan
Loan 1: 20,000 $
Loan 2: 0 $
Loan 3: 0 $
Loan 1
Reference:
Loan Capital: 20000 $
Term [Years] 5
Repayment Free Initial Period 2
Annual Installment 9007.5061187 $
Loan Interest 16.7 %
Cash Value of Loan: 0 $
Net Present Value: 31,869 $
Cost of Solar Energy: 0.24 $/kWh
OK
Economic Efficiency Calculation
Cancel