Techno-Economic Assessment of Parabolic trough Steam Generation for Hospital

By

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ABSTRACT

Hospitals are one of the most energy consuming centers in which thermal energy is utilized for different medical equipments and others. Sterilizers, laundry and kitchens are the main thermal energy utilizing equipments. In addition, large amount of hot water is utilized mainly for showering and dish washing. The main sources of this thermal energy are fossil fuel for oil fired boilers and solar irradiation for solar thermal steam generation system.

This project aims in analyzing the Technical performance of parabolic trough steam generation and oil fired boiler steam generation system for Black lion general specialized hospital which is located in Addis Ababa and to perform economic assessment on both systems so as to make comparison test.

The result from technical feasibility study shows the parabolic trough can meet the steam demand of the hospital at the required time, more than 8hour per day, as the hospital currently require steam for different activities during the day time for 8hour per day. During cloudy day the conventional back up steam generation system will meet the daily demand for few days of the year. The economic assessment result shows that although the initial investment of concentrated solar steam generation is high as compared to convention steam generation
system, the reverse is observed in operation and maintenance cost, resulting solar thermal steam generation break even (payback) to occur early, after 7 year the system let to operate over the conventional oil fired steam generation. In addition the levelized cost of energy for concentrated solar steam generation is found to be 58% higher than conventional steam generation.

Hence, the result shows that parabolic trough is found to be more economical for steam generation than oil fired boiler. If solar thermal steam generation (parabolic through) is implemented, the fuel consumption and operational cost of the boiler can be reduced appreciably.
ACKNOWLEDGEMENT

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I would like to take this opportunity to sincerely thank all Black lion Hospital technical Staffs for their unlimited kind cooperation, who help me in providing valuable data and suggestions.

Last but not least, I would like to thank my family and friends who were always besides me.
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<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A$</td>
<td>Coefficient</td>
</tr>
<tr>
<td>$A_{\text{eff}}$</td>
<td>Solar field aperture area [m$^2$]</td>
</tr>
<tr>
<td>$B$</td>
<td>Coefficient</td>
</tr>
<tr>
<td>$C$</td>
<td>Coefficient</td>
</tr>
<tr>
<td>$C_{\text{min}}$</td>
<td>The smaller capacitance rate between the steam and the HTF [kW/K]</td>
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<tr>
<td>$C_{\text{max}}$</td>
<td>The bigger capacitance rate between the steam and the HTF [kW/K]</td>
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<td>$C_{p,\text{HTF}}$</td>
<td>Average specific heat of HTF between inlet and outlet [kJ/kg-K]</td>
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<td>$C_{p,\text{steam}}$</td>
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<td>$D$</td>
<td>Coefficient</td>
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<tr>
<td>$D_{HCE}$</td>
<td>Diameter of the steel absorber tube [m]</td>
</tr>
<tr>
<td>$E$</td>
<td>Equation of time E (in minutes)</td>
</tr>
<tr>
<td>$\text{EXP}_{\text{UA}}$</td>
<td>Power law exponent to UA</td>
</tr>
<tr>
<td>$f$</td>
<td>Focal length [m]</td>
</tr>
<tr>
<td>$K$</td>
<td>Incident angle modifier</td>
</tr>
<tr>
<td>$L_{\text{spacing}}$</td>
<td>Distance between the collector rows [m]</td>
</tr>
<tr>
<td>$m_{\text{steam-HTF}}$</td>
<td>Mass flow rate of steam, HTF [kg/s]</td>
</tr>
<tr>
<td>$N_{\text{SCA}}$</td>
<td>Number of SCA loops in the solar field</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{abs}}$</td>
<td>Absorbed energy [W]</td>
</tr>
<tr>
<td>$\dot{Q}_{\text{dot}}$</td>
<td>Transferred power [W]</td>
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<td>$\dot{Q}_{\text{piping}}$</td>
<td>Piping system heat losses [W]</td>
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<td>$\dot{Q}_{\text{net}}$</td>
<td>Net heat transfer between HTF and steam/water [W]</td>
</tr>
<tr>
<td>$T_{\text{amb}}$</td>
<td>Ambient temperature [$^\circ$C]</td>
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<tr>
<td>$T_{\text{steam}}$</td>
<td>Temperature of the steam [$^\circ$C]</td>
</tr>
<tr>
<td>$UA$</td>
<td>Overall heat transfer coefficient [W/K]</td>
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<td>$UA_{\text{REF}}$</td>
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<tr>
<td>$h_{fg}$</td>
<td>Enthalpy of vaporization [KJ/Kg]</td>
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Acronyms:

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<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>CL</td>
<td>Cleanness</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrating solar power</td>
</tr>
<tr>
<td>DNI</td>
<td>Direct normal insolation [W/m(^2)]</td>
</tr>
<tr>
<td>EL</td>
<td>End loss</td>
</tr>
<tr>
<td>HCE</td>
<td>Heat collecting elements</td>
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<tr>
<td>HTF</td>
<td>Heat transfer fluid</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized cost of energy</td>
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Greek Letters:

<table>
<thead>
<tr>
<th>Greek Letter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha)</td>
<td>Solar altitude angle [°]</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>Solar azimuth angle [°]</td>
</tr>
<tr>
<td>(\delta)</td>
<td>Declination angle [°]</td>
</tr>
<tr>
<td>(\Delta T_{\text{in}}, \Delta T_{\text{out}})</td>
<td>Difference between inlet and outlet temperature of the HTF from the solar field and ambient temperature [°C]</td>
</tr>
<tr>
<td>(\varepsilon)</td>
<td>Effectiveness</td>
</tr>
<tr>
<td>(\eta)</td>
<td>Efficiency [%]</td>
</tr>
<tr>
<td>(\eta_{\text{SF}})</td>
<td>Efficiency of the solar field [%]</td>
</tr>
<tr>
<td>(\theta)</td>
<td>Incidence angle [°]</td>
</tr>
<tr>
<td>(\theta_{z})</td>
<td>Solar zenith angle [°]</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density [kg/m(^3)]</td>
</tr>
<tr>
<td>(\phi)</td>
<td>Altitude angle [°]</td>
</tr>
<tr>
<td>(\omega)</td>
<td>The hour angle [°]</td>
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CHAPTER 1

1 INTRODUCTION

Today, the issue of sustainable development is not separately treated with clean energy production and utilization. In this regard renewable energy resources play a great role in shifting towards clean and green energy system. Hospitals are one of the most thermal energy consuming sectors for different medical service equipments such as sterilizers, launders, kitchen and showering. Among this hot water is mainly used for shower, laundry washing and dish washing. The source of the used hot water is from the hot water generator (heat exchanger) where steam from boiler and cold water from city supply exchanges heat. This consumes large amount of fuel in the boiler and hot water generator takes high proportion of the steam generated from the boiler hence the running cost. If the boiler can be substituted with Concentrated Solar Steam generation system (parabolic trough) reduction of fuel cost and CO$_2$ emission from the boiler would be appreciably.

Concentrated Solar Power systems (CSP) employ solar collectors to track the sun and use its energy to produce steam. Parabolic troughs are currently the most common technology today to concentrate the solar thermal energy onto absorbers and the thermal energy transferred to a heat transfer fluid (HTF). These parabolic trough fields replace the boiler part of a conventional Rankine Cycle power plant. The solar field area must however be large enough to satisfy the steam demand. Heat exchangers are used to transfer heat energy from the HTF to steam coming from the feed water heaters.

To date, all commercial (CSP) are hybrid solar/fossil plants. [1] The power plants have a backup fossil-fired capability that can be used to supplement the solar thermal energy output during periods of low solar irradiation. The fossil backup can also be used to produce steam during overcast or nighttime periods. In this project the power cycle (Rankin cycle) will be ignored as only steam generation from solar field is the desire to provide steam for various uses in hospital.
1.1 Background

In the currently ever increasing cost of fossil fuels, renewable energy sources are the primary solution for energy demand of the world. Using renewable energy sources has advantage of no pollution, no greenhouse gas generation and there is no danger on the supply security of the energy resource.

Black lion General specialized hospital is located in Addis Ababa, the capital city of Ethiopia. It has around 800 beds and it gives multi services to the public as it is a governmental hospital. The hospital currently uses diesel boilers for steam generation 365 a year and 9 hours a day, though due to several reasons usually it works for 4 to 5 hours a day. The steam generated will be distributed to sterilizer, hot water generator and laundry drying machine. The total steam consumed in hot water generator reaches two-third of the total steam generated in the boiler and the remaining will be distributed to sterilizer and drying. The hospital uses furnace oil for the generation of the steam, consumes 245 m$^3$ and pays 1,593,087.41 birr (96,550.00 dollar) in the fiscal year, 2008/09 [3]. If concentrated solar steam generation system is implemented, the fuel consumption and operational cost of the boiler can be reduced appreciably.

1.2 Objective of the project

The main objective of the project is to perform technical and economic analysis of CSP parabolic trough steam generation in contrast to fossil fuel (diesel boiler) steam generation system for medium size hospital application in selected site of Ethiopia (case study for black lion hospital).

A major objective is the simulation work, to investigate the performance of CSP parabolic trough in regard to the solar energy absorbed, temperature variation of the circulating water and the instantaneous and total efficiency of the system as a function of time.
The specific objectives of the project are:

1. Modeling of the parabolic trough steam generation system using appropriate modeling software.

2. Simulating the model using the proper simulation software (e.g. TRNSYS) to investigate the performance of parabolic trough steam generation system

3. Making cost and financial analysis of the fossil fuel and CSP steam generating system

4. Discussion of the technical and economical feasibility oil fired boiler and parabolic trough steam generation systems

1.3 Methodology

To achieve the above general and specific objectives the following methodologies are adopted.

1.3.1 Literature review

Review about the potential of renewable energy in Ethiopia, techniques of renewable energy technology (such as solar thermal systems) and review about parabolic trough technology. Hospitals thermal energy demand and supply technical descriptions, benefits and limitations as of today. The literatures available are from electronic media, journals, and books. Secondary data are referred from previous and related research studies, existing statistical data and interviewing hospital personnel’s

1.3.2 Modeling and simulation

After collecting the necessary weather data for the selected site (Addis Ababa), the system is modeled and simulated using TRNSYS software.

1.3.3 Financial and Economic Analysis

Life cycle cost, payback period and LCOE of the two technological systems will be determined and compared with each other. Finally based on the outcome, conclusions and recommendations will be given.
CHAPTER 2

2 LITERATURE REVIEW

2.1 Solar Collectors

Solar thermal energy is often used for heating swimming pools, domestic heating water, and space heating of buildings. Solar space heating systems can be classified as passive or active. In passive solar heating for building heating the air is let to circulate over a solar heated surface inside the building where less dense warm air tends to rise while more dense cooler air moves downward as the heat transfer is due to natural convection. But in active heating system it needs pump and fan for driving the heat transfer fluid and air respectively [1]

The solar collector is main component of solar thermal system. Currently different types of collectors are available commercially based on the construction type.

Solar collectors can be either concentrating or Non-concentrating.

- **Non concentrating collectors** – have a collector area (i.e. the area that intercepts the solar irradiation) that is the same as the absorber area (i.e., the area absorbing the radiation). Flat-plate collectors are the most common and are used when temperatures below about 80°C are sufficient, such as for space heating.

- **Concentrating collectors** – where the area intercepting the solar radiation is greater, sometimes hundreds of times greater, than the absorber area. The concentrator helps to collect large amount of solar incoming radiation within a limited collector area and supplies to the absorber pipe.

Concentrating solar collectors are used for high temperature application. Concentrating collectors reflects the solar radiation falling on the collector the absorber and this enable to collect high amount of solar energy with small absorber area as the convection and radiation losses are minimized, therefore it attains high temperature.

Currently three types of solar concentrators are commercially available, parabolic troughs, parabolic dishes and central receivers. The working concept of the collectors is described in Figure 2.1 schematically.
2.1.1 Concentrating Solar Power

Today international interest on renewable energy systems is getting higher especially in the field of concentrating solar power as the conventional power generation becomes a treat for global warming and environmental pollution. The development of Concentrated Solar Steam generation, troughs, towers, and dishes initiates to harness solar energy for electricity production and other applications with moderate generation efficiency, cost and reliability. Table 2-1 shows commercial applications of CSP with different capacities.

<table>
<thead>
<tr>
<th>System</th>
<th>Peak Efficiency</th>
<th>Annual Efficiency</th>
<th>Annual Capacity Factor</th>
</tr>
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<tbody>
<tr>
<td>Trough</td>
<td>21%</td>
<td>10 to 12%(d)</td>
<td>24%(d)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14 to 18%(p)</td>
<td>25 to 70%(p)</td>
</tr>
<tr>
<td>Power Tower</td>
<td>23%</td>
<td>14 to 19%(p)</td>
<td>25 to 70%(p)</td>
</tr>
<tr>
<td>Dish/Engine</td>
<td>29%</td>
<td>18 to 23%(p)</td>
<td>25%(p)</td>
</tr>
<tr>
<td>(d)=demonstrated</td>
<td>(p)=Projected based on pilot scaling</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Annual capacity factor refers to the fraction of the year the technology can deliver solar energy at rated power.
2.1.2 Parabolic Trough

Parabolic trough collector has a linear parabolic-shaped reflector which tracks and focuses the sun radiation onto a linear receiver where the HTF circulates inside. The tracking axis is east to west to collect the maximum possible throughout the day time as shown in Figure 2-2.

![Figure 2-2: Parabolic trough](image)

Due to its parabolic shape parabolic trough has the capacity to focus the sun radiation from the sun 30 to 100 times its normal intensity on a receiver pipe and up to 400°C operating temperature is obtained [1]. Based on the heat demand from the solar field many collectors can be installed in parallel aligned north-south horizontal axis. The plants are designed to operate at full rated power using solar energy alone. But as a backup for the plant during unavailability of solar radiation, conventional plants are also designed to meet the base demand [2]. The Heat Transfer fluid that circulates inside the solar field (primary cycle) is heated and transferred to heat exchanger, including super heaters, evaporators and pre heaters, where steam is generated for the power cycle or other applications such as the case at Black Lion Hospital. The heat transfer fluid (HTF) in the primary cycle returns back to the receiver and gets heated again to complete the cycle. At Black Lion hospital, the steam generated in the secondary cycle could be fed to laundry, dishwasher and sterilizers.
2.2 Limitation of Parabolic trough technology

Despite its many benefits, solar thermal for power generation is still employed on a very limited basis. The technology is still relatively new on the commercial market, and there are disadvantages to solar thermal power generation that have delayed its growth. Primarily, the efficiency of these plants is relatively low compared to that of traditional fossil fuel plants, and their equipment and maintenance costs are higher due to the complexity and vulnerability of the technology.

Many of the problems lie with the receiver tubes, which absorb the intensified solar radiation reflected from the parabolic trough. A typical receiver tube consists of a stainless steel absorber pipe which carries the heat transfer fluid, and a cylindrical glass envelope that is concentric to and surrounds the absorber pipe. The annular space between the two serves as a barrier to convective heat losses, and the absorber pipe is coated with a solar-selective material that maintains a high absorptance while minimizing the emittance of infrared radiation.

After serving for some years hydrogen will permeate through the stainless steel pipe and leaks into the annulus of the receiver tubes. The high conductivity of the hydrogen creates high heat transfer that alters functionality of the receivers and must either be punctured to release the hydrogen or be completely replaced.

Damage to the glass envelopes is likely the most common problem in the field. The glass envelopes are relatively fragile, and can break easily when exposed to severe weather conditions or when pieces of the reflecting mirrors break off and fall onto the receiver tubes.

With a broken envelope, the absorber tube may be fully exposed to the ambient air, greatly increasing thermal losses. The replacement of these highly expensive and easily damaged components upon failure greatly increases the cost of operating and maintaining a CSP solar field. [2]
2.3 Conventional Steam Generation (Boiler)

Conventional steam generation system uses boiler system which consists feed water tank, boiler, end use devices (it may be turbine or other steam driven devices) and condensates pump. The feed water tank supplies treated water for boiler/evaporator and regulated by automatic valves with the steam demand. The steam generated will be distributed via steam pipelines to the point of use. Along the pipeline the steam pressure is regulated as per the demand. The water supplied for the boiler comes from feed water tank where condensate from process and treated make up water are mixed and collected. To improve boiler efficiency, feed water is heated in pre heaters using waste heat in flue gas.

Generally we have two types steam generation system (boiler), fire tube and water tube. Fire tube boilers, feed water is converted into steam in the shell side where as hot flue gas passes through the tubes and this type of boilers are used usually for low steam demand at low pressure. In case of Water tube boilers, flue gases passes over the tube and water is converted to steam inside the tube. (Reverse of Fire Tube system). Black lion hospital uses one three-pass (3p) wet back fire tube boiler, 3000kg/hr steam generation capacity at a pressure of 12bar, with another one standby to satisfy the daily steam demand of different services in the hospital.

2.3.1 Boiler feed water:

The boiler system comprises mainly of a feed water system, fuel system and Steam System. The feed water system provides water to the boiler and regulates it automatically to meet the steam demand. The water supplied to the boiler that is converted into steam is called feed water. The two sources of feed water are:

- Condensate return from the processes and
- Makeup water (treated raw water)
2.3.2 Water treatment:

Proper treatment of makeup and feed water is necessary to prevent scale, other deposits and corrosion in pre-boiler, boiler, steam and condensate systems, and to provide the required steam purity. Absence of adequate treatment can lead to operational upsets or unscheduled outages; it is also ill advised from the point of view of safety, economy, and reliability.

2.3.3 Fuel supply system

The fuel used for boilers is usually light oil or furnace oil, for better combustion usually the fuel is pre-heated to a temperature of $120^0$ C using exhaust gas. Black lion hospital three pass (3P) oil fired boiler is shown partly in Figure 2-3:

![Figure 2-3: Black lion Hospital 3pass Fire Tube boiler picture [3]](image-url)
2.4 Introducing TRANSYS Software

TRNSYS is an acronym for “Transient System Simulation program” which is developed by the University of Wisconsin-Madison since the 1970’s (Klein SA et. al. 1996). TRNSYS is written in ANSII standard Fortran-77 and its component library includes many of the components commonly found in thermal energy systems. This includes a Solar Thermal Electric Component (STEC) library that has been created under the Solar PACES umbrella as well as components that are not ordinary considered part of a system. Such components are utility subroutines that use to handle the weather and insolation data and output simulation results.

TRNSYS relies on a modular structure and system concept, in which a system is defined as a set of components that are interconnected to accomplish the specified task. Each model is the functional relationship between its input and output quantities which are defined using algebraic and first-order differential equations. Thus, system performance simulation can be done by collectively simulating the performance of the interconnected components.

TRNSYS is an absolute and widespread simulation environment for the transient simulation of different solar, HVAC and other conventional fuel power generation. Many researchers use this software for investigation and system analysis to implement new ideas in the field of Alternative Energy Systems. It has a variety of model components in its library including design tools and control units. The DLL-based architecture let users to add custom component models developed using all common programming languages such as (C, C++, PASCAL, FORTRAN and mat lab [4].

Some of TRANSYS software applications areas are:

- Solar thermal and PV systems
- HVAC systems
- Renewable energy systems
- Cogeneration and fuel cells system
When any project is set up in TRNSYS, all model components are connected by links graphically in the simulation studio and the input parameters will be set for each model as shown in Figure 2.4:

![Solar collector TRANSYS 16 simulation model](image)

**Figure 2-4: Solar collector TRANSYS 16 simulation model [Source: TRANSYS examples]**

### 2.4.1 Input parameters for parabolic trough Model

#### 2.4.1.1 Direct Normal Insolation

Extraterrestrial solar radiation follows a direct line from the sun to the Earth. Since the earth’s orbit is slightly elliptical, the intensity of solar radiation received outside the earth’s atmosphere varies as the square of the earth-sun distance and due to this variation Extraterrestrial solar radiation flux varies and it described by the following relation
Upon entering the earth’s atmosphere, some solar radiation is diffused by air, water molecules, and dust within the atmosphere (Duffie and Beckman, 1991). The direct normal insolation represents that portion of solar radiation reaching the surface of the Earth that has not been scattered or absorbed by the atmosphere. The term “normal” refers to the direct radiation as measured on a plane normal to its direction.

\[
I_{\text{ext}} = I_{\text{SC}} \left[ 1.0 + 0.033 \cos \left( \frac{360N}{365} \right) \right] \ (W/m^2) \tag{2.1}
\]

Where: \( I_{\text{SC}} \) is the extraterrestrial solar irradiance constant (1367 W/m²)

N is the day number

2.4.1.2 Solar Time

In solar energy study there is an important distinction between standard time and solar time. Solar time is a time based on the apparent angular motion of the sun across the sky, with solar noon the time with the sun crosses the meridian of the observer. Standard time is described on longitudes and is dependent on the standard meridian for each country. The relation between solar time and standard time in min is given by.

\[
\text{Solar time} = \text{Standard time} + 4(L_{\text{st}} + L_{\text{Loc}}) + E \tag{2.2}
\]

Where: 
- \( L_{\text{st}} \) is the standard meridian for the local time zone
- \( L_{\text{loc}} \) is the longitude of the location in question
- \( E \) is equation of time in minutes, accounts for the small irregularities in day length that occur due to the Earth’s elliptical path around the sun. The equation of time used here, in minutes, comes from Spencer (as cited by Iqbal, 1983):

\[
E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \tag{2.3}
\]

Where: \( B = \left( N - 1 \right) \frac{360}{365} \)
The equation of time as a function of each day of the year is shown in Figure 2-5, minimum and maximum irregularities occurs at February 18 and maximum at June 2 respectively.

\[ \text{Figure 2-5: Equation of time } E \text{ in minutes as a function of Day of the year} \]

2.4.1.3 Hour Angle \((\omega)\)

One of the most important solar angle used to illustrate the earth's revolution with reference to its polar axis is the hour angle \((\omega)\). Hour angle can be described as the angular distance measured between the meridian of the viewer and the meridian whose plane enclose the sun as shown in the figure 2.6. When the sun get to at its highest point in the sky or when it become overhead, the hour angle become is zero at solar noon (12:00). The hour angle increases by 15 degrees every hour.
Hour angle is given by the following equation.

\[ \omega = (ST - 12) \times 15^\circ, \text{ Where ST is solar time} \] (2.4)

2.4.1.4 Declination Angle (\(\delta\))

In the earth’s globe, the plane that comprises the earth’s equator is called the equatorial plane. The declination angle can be known by pinching a line between the center of the earth and the sun. The angle between the pinched line and the earth's equatorial plane is called the declination angle (\(\delta\)) as shown in figure 2-6. The earth’s equatorial plane will inclined 23.45° to a line pinched between the earth and sun, when the earth’s northern part of earth’s revolving axis is liable toward the sun which is around June 21. During this time it is observed that the noontime sun is at its maximum point in the sky and the declination angle (\(\delta\)) attain positive 23.45°. These condition called summer solstice which tells the beginning of summer in the Northern Hemisphere.

Similarly winter solstice occurs around December 22 when the equatorial plane is slanted relative to the earth-sun line in such a way that the northern hemisphere is slanted away from
the sun. During this time the noontime sun reaches at its minimum point in the sky and
declination angle reaches at its maximum negative value -23.45°. General conventions tell,
winter declination angles are negative. Declination (δ) can be found from the equation.

\[
\delta = 23.45 \sin \left( \frac{360 \left( \frac{284 + N}{365} \right)}{365} \right)
\]  \hspace{1cm} (2.5)

Variation of declination with day of the year is shown in Figure 2-7.

![Figure 2-7: Declination angle as a function of day of the year](image)

2.4.1.5 Solar altitude angle (α)
The angle specified between the ray from the sun and a horizontal plane enclose the viewer is
named as solar altitude angle. The equation for the solar altitude angle (α) is given in
Equation (4.10).

\[
\sin \alpha = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi
\]  \hspace{1cm} (2.6)
The sun’s altitude can be illustrated in terms of the solar zenith angle \( \theta_z \), which is basically the complement of the solar altitude angle.

\[
\theta_z = 90^\circ - \alpha \quad \text{(Degrees)}
\]  

(2.7)

This gives the equation for the solar altitude angle to be

\[
\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi
\]  

(2.8)

2.4.1.6 Solar azimuth angle (\( \gamma \))

The additional angle which is most important to describe the position of the sun is the solar azimuth angle. The angle measured in clockwise direction on the horizontal plane between the north-directing coordinate axis and the projection of the sun’s central ray is called solar azimuth angle. As of conventions, displacements east of south are negative and west of south are positive. In figure 2-8, solar altitude, solar azimuth incidence angles are shown clearly with their sign convention.

![Diagram showing solar altitude and azimuth angles](image)

**Figure 2-8: Earth surface coordinate system [4]**

2.4.1.7 Angle of Incidence (\( \theta \))

The angle between the sun’s rays and a vector normal (perpendicular) to the aperture or surface of the collector is the angle of incidence (\( \theta \)). Knowing this angle is of critical importance to the solar designer, since the maximum amount of solar radiation energy that could reach a collector is reduced by the cosine of this angle.
Certain types of concentrating collector such as parabolic trough collectors are designed to operate with tracking rotation about only one axis to minimize the angle of incidence of beam radiation on their surfaces and thus maximize the incident beam radiation. Here a tracking drive system rotates the collector about an axis of rotation until the sun central ray and the aperture normal are coplanar. The angle of incidence (θ) is also shown in Figure 2.8 and 2.9.

For a plane rotated about a horizontal North-South axis with continuous adjustment to minimize the angle of incidence is,

\[ \cos \theta = \left( \cos^2 \theta_z + \cos^2 \delta \sin^2 \omega \right)^{1/2} \tag{2.9} \]

2.4.1.8 Incidence angle Modifier

Measured efficiency of a parabolic trough collector decreases as the solar beam incident angle increases. Collector efficiency is at a maximum only when the incident angle is zero. The decrease in collector efficiency with increasing incident angle is caused by cosine

Figure 2-9: A single-axis tracking aperture where tracking rotation is about the tracking axis [4]

foreshortening of the collector aperture as well as other effects, such as the transmissivity of the glass envelope or the absorption of the selective surface as a function of incidence angle.

The incident angle modifier $K$ is the ratio of collector efficiency at any angle of incidence, to that at normal incidence. It is measured experimentally by varying the angle of incidence under noontime solar irradiance conditions with ambient temperature heat transfer fluid passing through the collector. A regression analysis of the data is used to obtain an equation of the form:

$$K = \cos(\theta) - B(\theta) - C(\theta)^2 \quad (2.10)$$

Where:  
$K = $ Incident angle modifier; value ranges from 0 to 1  
$\theta = $ Solar beam incident angle (0 to 60 degrees)  
$B = $ Coefficient for linear term  
$C = $ Coefficient for nonlinear term

Test results for SEGS LS-2 SCA yield an incident angle modifier expression as given in equation (4.15) [7]. The equation is applied for temperatures between ambient and $400^\circ$C, at any insolation level from 100 to 1100 W/m$^2$, and at any incident angle from 0 to 60 degrees.

$$K = \cos(\theta) - 0.0003512(\theta) - 0.00003137(\theta)^2 \quad (2.11)$$

2.4.1.9 Row Shading

Generally at any solar field the collectors are arranged in parallel rows. The distance between the collector rows is $L_{\text{Spacing}} = 12.5$ m at SEGs VI. Hence, in the morning, at sunrise, when the first sunrays fall on the trough collector field, the first row may be unobstructed, but the following rows are shaded by the first. During the sun’s path in the morning, partial shading of the collectors occurs until a particular zenith angle is reached. The shading reduces the effective width of the collector and thus reduces the effective aperture area of the collector on which the solar beam radiation acts. Consequently, the absorbed solar energy is reduced as well. After a certain zenith angle is reached, there is no mutual shading of the collectors anymore as described very well in figure 2.10. The same phenomenon occurs, of course, in the evening during sunset.
The row shadow factor is the ratio of the effective mirror aperture width to the actual mirror aperture width. This ratio can be derived from the geometry of the solar zenith angle, the incidence angle, and the layout of the collectors in a field [7]:

\[
RS = \frac{L_{Spacing}}{W} \frac{\cos(\theta_Z)}{\cos(\theta)}
\]  

(2.12)

Where: 
- \( RS \) = row Shadow factor
- \( L_{Spacing} \) = length of spacing between troughs
- \( W \) = collector aperture width (5 [m] for LS-2)
- \( \theta_Z \) = Zenith angle
- \( \theta \) = angle of incidence

Where \( RS \in [0; 1] \) A value of 0 for \( RS \) means complete shading whereas a value of 1 for \( RS \) means no shading of the collector.

\[
RS = \min \left[ \max \left( 0.0; \frac{L_{Spacing}}{W} \frac{\cos(\theta_Z)}{\cos(\theta)} \right) ; 1.0 \right]
\]  

(2.13)

The above equation for row shading is plotted and shown in Figure 2.11 for Addis Ababa with latitude 9.02° at summer solstice and the winter solstice.
Figure 2-11: Row shading versus time of day, for June 21 and December 21

2.4.1.10 End losses

End losses occur at the ends of the HCEs, where, for a nonzero incidence angle, some length of the absorber tube is not illuminated by solar radiation reflected from the mirrors. Figure 2-12 depicts the occurrence of end losses for an HCE with a nonzero angle of incidence.
The end losses are a function of the focal length of the collector, the length of the collector, and the incident angle (Lippke, 1995). The relationship between end loss and incident angle is plotted and shown clearly in figure 2.13.

\[ EL = 1 - \frac{f \tan \theta}{L_{SCA}} \]  \hspace{1cm} (2.14)

Where:  
\( f = \) focal length of the collectors (5[m] for LS-2 collectors)  
\( \theta = \) incident angle  
\( L_{SCA} = \) length of a single solar collector assembly (50 [m] for LS-2 Collectors)
2.4.1.11 Piping Heat Loss

In chapter three, the steam distribution line heat loss is estimated to reach the exact demand at the end use devices. Similarly the heat losses in all solar filed (HTF) piping are important factors that have to be included in the model for better design. Usually this loss is approximated as 20W/m² per aperture area [7].

\[ \dot{Q}_{pipe} = 20 \frac{W}{m^2} \]  

(2.15)
2.5 Heat Transfer Fluids (HTF)

The solar field heat transfer fluid (HTF) absorbs heat as it circulates through the heat collection elements in the solar field and transports the heat to the secondary fluid where it is used to run end use devices. Several types of heat transfer fluid are used for trough systems, including hydrocarbon (mineral) s, synthetic s, silicone s and nitrate salts.

Today most CSP plants use Therminol VP-1 HTF. Therminol VP-1 liquid/vapor phase heat transfer fluid is a high temperature medium that delivers process heat at temperatures up to \(400^\circ \text{C}\) with reliability and precise control [10]. For this analysis Therminol HTF is selected for the simulations of Black Lion Hospital, due to better stability in liquid phase at elevated temperature and heat transfer properties. In addition it shows better performance in current CSP plants.

Therminol VP-1 is a mixture of 73.5% diphenyl oxide/26.5% diphenyl, and as such can be used in existing liquid, or vapor phase systems, for top-up or replacement of heat transfer fluids of the same composition. Physical properties of Therminol VP-1 in liquid phase are shown by the following interpolated formulas as a function of temperature (\(^\circ \text{C}\)) [7].

\[
\rho(T) = -0.907977 T + 0.00078116 T^2 - 2.367 \times 10^{-6} T^3 + 1083.25 \text{ \text{[kg/m}^3\text{]}}
\]  

\[ (2.16) \]

\[
h(T) = 0.002414 T + 5.9591 \times 10^{-6} T^2 - 2.9879 \times 10^{-8} T^3
\]
\[ + 4.4172 \times 10^{-11} T^4 + 1498 \text{ \text{[kJ/kg]}} \]

\[ (2.17) \]

\[
k(T) = -8.19477 \times 10^{-5} T - 1.92257 \times 10^{-7} T^2 + 2.5034 \times 10^{-11} T^3
\]
\[ - 7.2974 \times 10^{-15} T^4 + 1.498 \text{ \text{[W/m.k]}} \]

\[ (2.18) \]

\[
T(h) = -1.58 \times 10^{-10} \times h^2 + 0.0006072 \times h + 13.37[^\circ \text{C}] \]

\[ (2.19) \]
2.6 Financial Analysis

2.7 Life Cycle Cost Analysis.

The Life cycle cost (LCC) analysis make up an economics tool to help in making investment decisions mainly by identifying the breakeven point or payback period over the project life time. For renewable energy solutions like solar and wind comparisons with that of conventional energy solutions, the life cycle cost (LCC) approach is very important as most of these renewable energy projects require high initial investment. Mostly renewable energy solutions require high initial investment and low operational cost, whereas conventional energy solutions require low investment cost and high operational cost hence renewable solutions have low payback period over conventional solutions due to costs associated with fossil fuel.

The LCC cost accounts capital cost, operational and maintenance cost throughout the project life time.

\[
\text{LCC} = \text{Capital cost} + \text{Present worth of maintenance, Operating and Replacement cost}
\]

The present worth of money can be described as the equivalent sum of money as of today’s value sometime at a point in the future. Similarly the future worth of money can be described as equivalent sum of money in the future some time at a point for money expend today. The value of money is affected by inflation rate and discount rate over time. Hence the present worth and future worth of money can be estimated by

\[
P_W = \frac{F_W}{(1 + d)^n}
\]

\[
F_W = P_W \times (1 + e)^n
\]

Where:

\( n \) = time period (years)
\( d \) = discount rate (% per annum)
\( e \) = inflation rate (% per annum)
Then, the life cycle cost (LCC) can be obtained by adding up the Present worth (PW) of all capital cost and operational costs.

2.7.1 The Levelized Cost of Energy (LCOE)

The levelized cost of energy is expressed as the present value of all total CAPEX and OPEX of the plant from the day of installation to the project economic life time expressed in birr per total kWh of energy produced over the project life time.

The levelized cost of energy LCOE is estimated using the annual project cost for project financed by be it cash, mortgage or loan.[8]

\[
LCOE = \frac{\sum_{n=0}^{N} C_n (1 + d)^n}{\sum_{n=0}^{N} Q_n (1 + d)^n}
\]

Where: \(C_n\) is the cost in Year \(n\), and \(C_n = 0\) is the cost in year 0, equivalent to the capital cost.

\(Q_n\) is the energy produced by the system in year \(n\).

\(n\) is the project life time

\(d\) is the discount rate,

2.7.1.1 Real and nominal Levelized cost of Energy

For real LCOE, the real discount rate appears in the total energy output term [8]:

\[
real \ LCOE = \frac{\sum_{n=0}^{N} C_n}{\sum_{n=0}^{N} (1 + d)^n} \text{ or } \frac{\sum_{n=0}^{N} R_{\text{required},n}}{\sum_{n=0}^{N} (1 + d)^n}
\]
Similarly, for the nominal LCOE, the nominal discount rate appears in the total energy output term:

\[
\text{nominal LCOE} = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+d)^n} \text{ or } \sum_{n=0}^{N} \frac{R_{\text{Required},n}}{(1+d)^n}}{\sum_{n=0}^{N} \frac{Q_n}{(1+d_{\text{nominal}})^n}}
\]

The real discount rate and nominal discount rate are related by Equation below [8].

\[
d_{\text{nominal}} = (1 + d_{\text{real}})(1 + e) - 1
\]

Where: \(d_{\text{nominal}}\) is the nominal discount rate.

\(d_{\text{real}}\) is the real discount rate.

\(e\) is the inflation rate.
CHAPTER 3

3 GENERAL DESCRIPTION OF BLACK LION HOSPITAL

3.1 Introduction

The current existing Black Lion Specialized hospital has been established for the memorial of prince Mekonnen, Duke of Harar, who is the son of His Imperial Majesty Haile Silassie I; by an organized committee comprised of higher government officials of that period, with the fund contributed by the Ethiopian people, the budget allotted by the government and donation from foreign countries.

The hospital totally holds 123000m² area of land, and its buildings have settled on 45000m² area; there are 1262 various rooms from the basement to the eighth floor. The hospital was attempted to occupy 500 beds, and had modernly planned and accommodated and facilitated without patients department; as well it had seven x-ray, nine surgical and two laboratory diagnostic rooms[13]. Part of the hospital has been shown in figure 3.1.

Figure 3-1: North side view of Black lion Hospital
The hospital was the biggest in Ethiopia during establishment period and was regarded as an exemplary hospital without any other superior one in the continent of Africa. Even at the moment it is renowned and famed as service rendering, training providing and research conducting intuition equipped and facilitated with modern medical equipments and highly skilled medical professionals. In the 1980’s the set up partitions of rooms and the hospital was compelled to accommodate more than 700 patients. As of that period, the hospital was made to carry out duties by accepting unlimited number of patients beyond its capacity, and as a consequence it has 800 beds for adults and pediatric patients to be treated as in patients.

The hospital has provided the appropriate medical services in the internal medicine gynecological and obstetrics, surgical and pediatrics departments from 2001-2005 to 295,642 patients of average who appeared as regular and emergency patients [13]. The number of patients has increased to 363,623 in the year 2006 within the last five years, service provision increased by 23%, of which 47% provided for pediatric patients [13].

In the year 2007 the number of employees is 1234: and among them 444 are medical profession, 97 are contract employees of medical profession and 693 are employees of management. Since the hospital commenced its service there are new buildings constructed on the land under its position like the Ethio-Cuba Friendship Memorial park, Radio Therapy Center, Diabetic center, Children’s Cardiac Center, National Rehabilitation Center and Graduates School Expansion Program Training Center. This data is the same for the year 2008/09. But the exact number of patients during the fiscal year was not known.

3.2 Supplementary Services Held in the Hospital other than Medical Services

3.2.1 Laundry Service

Laundry service is a large energy consuming process, which includes all types of linen for children, Bed linen for patients, Catering linen for patients, Surgery room’s linen, Staff uniforms and others. All the laundry machines are steam heating types. Steam is supplied
directly from the steam headers to with a common line and distributed to the individual machines based on their consumption rate. There are two washing machines with 60kg/hr steam and 120lit/cycle cold water consumption. One cycle takes from 50-60 minutes. Steam is used to heat the cold water to a different temperature ranges based on the hot water temperature demand of the prewash, wash, and rinse steps in each cycle. The condensate and the wastewater from each machine have been discharged to the environment.

The drying process is carried out by drying machine and using wind and solar energy. There is one drying machine in function with 55kg capacity and 90kg/hr steam consumption rate. One cycle takes from 35-40 minutes. The condensate is discharged to the environment.
The series of works carried out in laundry room and the machines are described by pictures in figure 3.2. In addition, there is one drying machine, with a steam consumption rate of 100kg/hr, currently working and one another not operational. When there was rain the drying process for blankets and bed linens were held by wind and ironing machines. Since ironing machines have a tendency to remove water from clothes, they use these machines to dry linens directly from washing machines and clothes which are not dried enough using wind energy. Since no condensate return due to the non functionality of the system, the condensate from the machines is discharged to the environment. The laundry has a constant schedule, operating 9 hours a day and 7 days a week. There are 32 workers in the laundry service.

Minimum energy consumption was happened when drying process has been performed without ironing (washing and then drying by solar energy). Therefore, the energy consumption in the laundering process was the energy consumed by washing process only. Thus the minimum energy consumption referred to one kilogram of dirty linen was 0.62kWh/kg (detail calculation is shown in Appendix F). Maximum energy consumption was happened when drying process has been performed by ironing machines. The energy consumption referred to one kilogram of dirty linen is the sum of energy consumption during washing and ironing processes, which is 1.65 kWh/kg (detail calculation is shown in Appendix F) . Though drying by natural convection using solar and wind requires no thermal energy from the plant, it is time consuming and needs man power as it is done manually to collect from filed. The energy consumption by the laundry process falls out of the range of recommended energy index in medium hospitals hospital which is 2.5 to 4kWh/kg [12].

This makes the laundry service inefficient as the machines are not working at the desired level due to frequent failure and this may be due to overloading and lack of preventive maintenance. In this regard it is important to resize the laundry machines again so as deliver better service for the patients and staffs.
3.2.2 Kitchen Service

The kitchen provides two properly balanced meals per day for the patients and staffs of the hospitals when on duty excluding office staffs. The kitchen room with its machineries and equipments has been shown in figure 3.3.

Figure 3-3: Black lion Hospital Kitchen room and its accessories
The hospital has a kitchen service for an average of 832 peoples per day. There are six cooking machines three of them are 150lit capacity, two of them are 200lit capacity and the rest with 300lit capacity. There are 74 workers for the kitchen service (37 per shift) and the cooking activity starts at 7:00AM and ends at 4:00PM. There is no dish washing machine rather the dish washing activity is done by manually by taking hot water from the cooking machines.

The cooking kettles are steam types. Steam is supplied to the kettles from the steam header at a pressure of 0.5bar. There are six kettles; three of them are with 27kg/hr steam consumption capacities, two of them are with 36kg/hr steam consumption capacities, and the rest one with a 58kg/hr steam consumption capacity.

The energy intensity of kitchen service can be expressed in kWh per bed per day and it was found in black lion hospital as 1.75kWh/bed/day (detail calculation is shown in Appendix F) which is in the range of the recommended energy intensity for medium size hospitals food preparation kitchen, ranges from 0.6 to 2.0 kWh per bed per day [12].

Though the energy consumption in the kitchen falls near the higher limit of the recommended range, dish washing is done manually in black lion hospital which is time consuming and not safe from quality service point of view. Hence, it is quite important to resize the kitchen kettles and dish washer for the hospital.

### 3.2.3 Sterilization Service

Sterilization is a process capable of rendering microorganisms on contaminated inert bodies permanently inactive without altering the body properties. The strict requirements throughout hospital for absolutely, equipment, instruments and materials, under potentially vast contamination conditions, requires the general availability of sterilizing equipment located in

- Surgery and special departments
- Central sterilization department
- Pharmacy
• Laboratories

Black lion hospital has one central sterilizer. In the sterilization room there are three autoclaves, the one is in function and the rests are out of function. Additionally one non functional sterilizer is located down in ground floor laboratory room. The sterilizer room with its autoclaves and other equipments has been shown in figure 3.4.
The hospital has central sterilizer with only one working autoclave to sterilize instruments, out of 3 large ones that are just sitting next to each other. The steam consumption of the sterilizer unit is 138kg/hr at 5bar.

Based on feed backs from sterilizer operators, there is overload on the sterilizer machine which is an indication of under sizing, of course as it is sensitive equipments its configuration should be N+1 as a back up to assure service delivery. Hence it needs to maintain or replace the existing non functional sterilizers.

3.2.4 Hot Water Service

Even if the hot water system mainly for showering and dish washing is already available but due to lack of maintenance it had been out of service for the past 10 years. As a result the hospital has not had hot water for over 10 years. The hot water generator system for the hospital is shown in figure 3.5.

![Figure 3-5: Storage type hot water generators at black lion hospital](image-url)
The hot water storage capacity is not easy to get as it is old, but it is storage type. As far as the distribution line is installed and the patients must get hot water for shower and dish washing in the kitchen for proper treatment of the patients in the hospital. Hence the amount of hot water and steam demand or hot water generation will be estimated based on the number of patients.

3.3 Utilities

The utilities which the hospital uses are cold water for hand washing and shower for the patients and other hospital utilization, fuel oil for laundry and electric energy for electric appliances.

3.3.1 Cold Water Service

City tape water line is the only source of water for the hospital. The hospital consumes average cold water volume of 18,000m$^3$ per annum for boiler feed-water, shower and drinking for patients, and other services. Out of which about 2555m$^3$ water by volume is consumed by the boiler [3]. The cold water supply pump system is placed in the boiler room as shown in figure 3.6.
3.3.2 Fuel Usage

The energy source of the boiler is furnace oil. Currently the fuel is supplied by Libya Oil Ethiopia Limited (OiLibya). On average 244829 liters of fuel oil was consumed by the boiler annually.

3.3.3 Electric Energy Usage

Electric energy is the source of energy for the hospital to operate electrical appliances including:

• Lighting service
• Computer service
• Motors, belts and drives for end use devices
• Fans and pumps
• Workshop service

The average electric energy consumption of the hospital is about 984,105.7kWh per annum from national grid.
3.4 Assessment of Black lion Boiler

A large fraction of a facility’s total energy usage begins in the boiler plant. The cost of boiler fuel is typically the largest energy cost of a facility. For this reason, a relatively small efficiency improvement in the boiler plant may produce greater overall savings than much larger efficiency improvements in individual end users of energy. Also, most boiler plants offer significant opportunities for improving efficiency. These reasons make the boiler plant a good place to start the search for savings.

Black Lion is the largest hospital in Ethiopia using large amount of thermal energy (steam) for different process purposes and for generating this large amount of energy it uses one three -pass (3p) wet back fire tube boiler with another one standby. In doing so, it is necessary to evaluate the performance of steam generating units (boilers) and to identify different energy conservation opportunities, which can reduce the fuel consumption by increasing the efficiency of the units.

The hospital’s three-pass (3p) wet back fire tube boiler has a 3000kg/hr steam generation capacity at a pressure of 12bar, to satisfy the daily steam demand of different services in the hospital. Boiler plant includes the systems such as: boiler feed water system and the water treatment plant, fuel oil system, and the steam system. Some of the boiler room accessories have been shown in figure 3.6.

The boiler works throughout the year without break (for 365 days). But the daily working hours of the boiler were only four and half hours because the set boiler pressure was in the range of 7.5-8.5bar. The burner was set to start combustion when the steam pressure reaches 7.5bar and stops its combustion process when the boiler pressure reaches 8.5bar. After it reaches the maximum pressure setup then the boiler pressure is reduced back to a pressure of 7.5bar due to steam consumption of the end-use devices. To start and stop the combustion process it takes 57minutes. Therefore, even though, daily working hours of the boiler was 9 hours but, the boiler effective operation hours were only 4.5 hours. On average the boiler deliver 1.5ton steam for all activities which is 50% of its rated capacity [3]. But if the hot
water generator is working the existing boiler may not be enough, and this will be checked in this project work.

Figure 3-7: Components of Black lion hospital oil fired Boiler system

 Boiler feed water: The boiler system comprises mainly of a feed water system, fuel system and Steam System. The feed water system provides water to the boiler and regulates it
automatically to meet the steam demand. The water supplied to the boiler that is converted into steam is called feed water. The two sources of feed water are:

- Condensate return from the processes and
- Makeup water (treated raw water)

But for the case of black lion hospital the only source of feed water for the boiler was makeup water due to the absence of condensate return and the temperature of makeup water (treated raw water) was an ambient temperature 20°C. Since there is no condensate return system for the steam system in the hospital due to system non functionality, make-up water is supplied to the boiler directly after treatment. As a result there was no heat gained for the boiler from feed water.

In black lion hospital though, the condensate return system is actually there but due to incomplete maintenance the system was not functional for over the past 10 years. The condensate from the end-use devices and the steam distribution lines did not recover. Maintaining the system will save 489.983GJ of steam energy per annual. For maintenance estimated cost of 73,161.6birr will be expected to be investing and 185,674.0birr will be saved annually from the condensate recovery. The hospital can obtain a full Return on Investment is 5.5 months from cost savings. [3]

**Water treatment:** Proper treatment of makeup and feed water is necessary to prevent scale, other deposits and corrosion in pre-boiler, boiler, steam and condensate systems, and to provide the required steam purity. Absence of adequate treatment can lead to operational upsets or unscheduled outages; it is also ill advised from the point of view of safety, economy, and reliability. As shown in figure 3.6 above the boiler has a water treatment plant.

**Fuel supply system:** the fuel from the fuel tank is pre-heated to a temperature of 120°C using electric energy before pumped to the burner.
3.4.1 Efficiency of the boiler

From boiler audit work done for black lion hospital [3], the thermal efficiency of the boiler based on indirect method is found to be 78%. Burners of modern boilers can have combustion efficiency of 95 % [13]. From the boiler combustion efficiency analysis conducted combustion efficiency of the burner is about 80% [3]. This implies that the hospital burner wastes about 15% of the energy input compared to the benchmark combustion efficiency. This waste is a sign of concentration to the detail investigation of the causes of combustion efficiency losses and measures must be taken to improve the energy efficiency of the burner to save energy.

The Sankey diagram is very useful tool to represent an entire input and output energy flow in any energy equipment or system such as boiler generation. The sankey diagram for the energy balance of the hospital boiler can be presented as shown in figure 3.8.

![Sankey diagram for the boiler energy balance](image)

**Figure 3-8: Sankey diagram for the boiler energy balance [3]**
3.5 Estimation of Steam and hot water demand of the hospital

Steam and hot water requirement of the hospital in consideration is estimated from existing pipeline layout and demand for a pre-determined number of patients and staffs, the summarized requirements are listed in Table 3.1:

Table 3-1: Steam and hot water requirement summary

<table>
<thead>
<tr>
<th>No.</th>
<th>Equipments</th>
<th>Steam [kg/hr]</th>
<th>Hot water [kg/hr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Laundry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Washing</td>
<td>682</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drying</td>
<td>760</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ironing</td>
<td>540</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>Kitchen</td>
<td>250</td>
<td>389</td>
</tr>
<tr>
<td>3.</td>
<td>Sterilizer</td>
<td>690</td>
<td>-</td>
</tr>
<tr>
<td>4.</td>
<td>Shower</td>
<td>-</td>
<td>22400</td>
</tr>
<tr>
<td></td>
<td><strong>Sub Total</strong></td>
<td><strong>2240</strong></td>
<td><strong>23471</strong></td>
</tr>
<tr>
<td>5.</td>
<td>Hot water Generator</td>
<td>2376</td>
<td>-</td>
</tr>
<tr>
<td>6.</td>
<td>Pipe line heat loss</td>
<td>11.68</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>46286</strong></td>
<td><strong>23471</strong></td>
</tr>
</tbody>
</table>

The existing conventional steam and hot water generation flow cycle along end use devices for the hospital in consideration is shown in Figure 3.1. Steam generated in the boiler partly goes to hot water generator and the rest distributed to sterilizer, laundry and kitchen. Mixing valve adjusts hot water temperature for shower and all condensate from end use devices back to condensate tank, from there pumped to feed water tank by condensate pump.
The feed water demand is met by condensate collected from all end use devices (laundry, kitchen, sterilizer and hot water generator) as of the existing conventional steam generation system. In the existing steam distribution line steam traps are installed to remove condensates and dirt’s from the system which protect foreign materials not to enter in to the boiler.

3.5.1 **Hot water requirement for Shower**

Hot water is used mainly for showering in each bed for the patient using the distribution lines from the hot water generator, based on our country trend the individual consumption is estimated as 40lit/day for each patient, with a recommended hot water temperature for shower in the range of 50 to 60°C. For this project the average 55°C is taken. Assuming, a patient to take shower a maximum of two times a day with a maximum duration 30min for single shower.

Individual consumption=0.04m³/(bed*hr)
Total consumption=800 beds*0.04(bed*hr) =32m³/hr
Assuming a load factor of 0.7 (70% of the patients will take a shower at a time) [9], the design consumption will be 0.7*32=22.4m³/hr
3.5.2 Steam and Hot water requirement for laundry

Beside the medical treatments in hospitals, laundry service for patients and staffs is available in all medium and large size hospitals. The service is sometimes outsourced for small firms. Based on references on energy usage index in hospitals, the daily demand of dry linen is estimated to be 2 to 3 kg/patient for general hospitals. The thermal energy demand per process ranges 2.5 to 4kWh/kg. For this project the average 2.5kg/patient is taken. [6]

The daily need of dry linen (source: Black lion technical staff) in general hospitals includes:

- Beds lines and bathrooms linen (patients)
- Surgery rooms linen
- Staff uniforms

For patients (Bed + bathroom) = 2.5kg/patients
For 4 surgery rooms 25kg each = 100kg
For 200 staff uniform 0.5kg each = 100kg

**Hence total dry linen required = 2.5*800 + 100 + 100 = 2200kg/day**

The complete laundry process may be described by three steps:

a) **Washing**: this is the first step where dirty linen is washed using hot water and it takes about 30% of the total energy involved in the laundry process.

b) **Drying**: this is the second step where the water is removed from the washed linen, about 25% of the total energy demand of the process.

c) **Ironing**: the final step is ironing, where the dried linen are folded using ironing machines using dry steam, about 45% of the total energy demand of the laundry process.

Assuming 8 working hour per day for all laundry equipments:

- **Washer sizing**
Linen process per hour = 2200 kg/day * 7 day / 56 hour = 275kg/hr
Assuming the washer to process 1.3 loads per hour (=1 cycle)
Loading capacity = 275 / 1.3 (kg/hr / loads/hr) = 212kg per cycle

- **Dryer sizing**
Dryer capacity in drying process shall be 1.4 to 1.5 times that of washing capacity due to residual humidity during washing.
Washer capacity=1.45*212kg per cycle=307kg per cycle
Average load per hour for steam heated dryer is 1.3

- **Ironing machine sizing**
Ironing machines are rated based on forwarding speed of the machine, considering the energy index for ironing process it is taken the ironing machine with evaporative capacity 140kg/hr with forwarding speed of 0-15m/min. The technical broacher and specification of all machines is attached under the Appendixes with this report.

### 3.5.3 Hot water for launder washing

Usually washing process is accomplished in modern equipment at temperature not higher than 60°C, whereas in old machines the temperature is in the range of 70-80°C. For this analysis modern machine is taken with supply temperature of 60°C. From the washing machine (4 in number) specification total hot water consumption=4*140=560lit/cycle. The daily cycles are 10 per day, hence Total consumption=0.7m³/hr. In this project, laundry machines scheduled to work 8 hour a day and four washing machines, four drying machines and three ironing machines are assigned to carry out the task.

### 3.5.4 Steam and Hot water requirement for Kitchen

Energy usage Index for food preparation in kitchen shows that the average demand ranges from 0.6 to 2.0 kWh/(bed*day)[6]. For this project average value 1.3kWh/bed is used. 
Total amount thermal energy required=1.3 kWh/(bed*day)*800 beds =1040kWh/day
For 6 hour daily working schedule thermal energy demand is =174kW
Steam is supplied at 0.5bar for all models of kitchen equipments hence we can determine the steam flow rate at this pressure.

Mass of steam=174/hₐっております@0.5bar=174/2500kJ/kg=0.0952kg/s=250kg/hr

In this regard we recommend four steam kettle equipments of capacity 300litre, with steam flow rate of 70kg/hr and brand Firex model PF300A to meet the requirement. The hot water consumption for dish washing is 3liter/day/person. Total hot water demand for 6hour daily schedule and 800 beds will be 800*3=2400lit/day.
The recommended hot water temperature for dish washing is between 60° to 90°. Based on the requirement from suitable manufacturer a dish washing machine is selected having the
3000 dish/hour capacity and hot water consumption 400 litre/hour. At an average supply temperature of 80°C density (ρ) = 974 kg/m³, hence hot water consumption = 974 * 0.4 = 389 kg/hr

3.5.5 Steam requirement for Central sterilization
Sterilizers are one of very important tools in hospital for protection of medical equipments, instruments and materials from contamination. To accomplish this task usually a central sterilization system is available in medium and large hospitals.

The capacity of sterilization in a give hospital depends on, the activities, number of beds and number of departments. Considering Black lion activities and departments, and assuming that the installed five sterilizers having 18 cu-ft (595 litre) capacity each are sufficient for the current 800 bed in Black lion hospital.

From manufacturer catalogue the nearest standard 18cu-ft sterilizer of Brand tuttnauer model H69 (see Appendices A) with steam supply pressure of 5 bar and steam supply of 138 kg/hr is selected.

3.5.6 Steam requirement for hot water generation

Hot water is generated using steam from the boiler as a heating fluid, to know the total steam demand, it needs to calculate the amount of steam that need to be supplied the hot water generator using heat balance in the hot water generator.

From Heat balance \[ m_s \times h_{fg} = m_w \times c_p \times \Delta T \]  

Total hot water demand = 23471 kg/hr

Inlet temperature of cold water to the generator is 20°C.

Outlet temperature from the generator is 80°C.

The cold water properties (specific heat) can be evaluated at the mean temperature T = 50°C.

\( C_p @ 50°C = 4.181 \text{kJ/kg.K} \)

The heat of evaporation of steam \( (h_{fg}) \) at 7 bar = 2065.3 kJ/kg
Total amount of steam required in the heat exchanger for hot water generation is estimated to be 2375.3 kg/hr.

### 3.5.7 Steam line losses

In order to assure the delivery of the exact amount of steam required at end use device, steam loss needs to be considered along the distribution line. Considering the existing installed steam distribution line of the hospital, recommended insulation thickness for each pipe line size is used to estimate line heat losses.

#### 3.5.7.1 Pipeline Insulation

To avoid heat loss and reduced efficiency pipe work in heating systems should always be insulated. Very hot systems, like hot water and steam systems should also be insulated to avoid potential personal injuries.
### Table 3-2: Recommended insulation thickness. [6]

<table>
<thead>
<tr>
<th>Nominal Pipe Size NPS (inches)</th>
<th>Temperature Range (°C)</th>
<th>Temperature Range (°C)</th>
<th>Temperature Range (°C)</th>
<th>Temperature Range (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50 - 90</td>
<td>90 – 120</td>
<td>120 - 150</td>
<td>150 - 230</td>
</tr>
<tr>
<td>Hot Water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Pressure Steam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium Pressure Steam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Pressure Steam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 1&quot;</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
<tr>
<td>1 1/4&quot; - 2&quot;</td>
<td>1.0</td>
<td>1.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>2 1/2&quot; - 4&quot;</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>5&quot; - 6&quot;</td>
<td>1.5</td>
<td>2.0</td>
<td>3.0</td>
<td>3.5</td>
</tr>
<tr>
<td>&gt; 8&quot;</td>
<td>1.5</td>
<td>2.0</td>
<td>3.0</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Based on the temperature range pressure class the insulation thickness for the existing pipeline is taken as follows in Table 3.3.
### Table 3-3: Insulation thickness for existing pipeline [6]

<table>
<thead>
<tr>
<th>No</th>
<th>Pipeline</th>
<th>Pipe Diameter (mm)</th>
<th>Insulation Thickness (mm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>To laundry</td>
<td>65</td>
<td>63.5</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>63.5</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td>2.</td>
<td>To sterilizer</td>
<td>40</td>
<td>63.5</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td>3.</td>
<td>To kitchen</td>
<td>80</td>
<td>63.5</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>63.5</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32</td>
<td>50.8</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td>4.</td>
<td>Steam main</td>
<td>125</td>
<td>76.2</td>
<td>Fiber Glass</td>
</tr>
<tr>
<td>5.</td>
<td>From Boiler</td>
<td>125</td>
<td>76.2</td>
<td>Fiber Glass</td>
</tr>
</tbody>
</table>

#### 3.5.7.2 Pipeline Heat loss

Pipeline heat loss is calculated based on recommendations from well known manufacturer and installer SpiraxSarco [6]. Length of pipe line for each end use device, pipe diameter and insulation thickness is used to estimate heat loss from each pipe line. The steam distribution lines for all units are shown under Appendix B of this report.
Table 3-4: Pipeline heat loss summary [6]

<table>
<thead>
<tr>
<th>No.</th>
<th>Pipeline</th>
<th>Heat loss(w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>To laundry</td>
<td>16853</td>
</tr>
<tr>
<td>2.</td>
<td>To sterilizer</td>
<td>9688</td>
</tr>
<tr>
<td>3.</td>
<td>To kitchen</td>
<td>24309</td>
</tr>
<tr>
<td>4.</td>
<td>Steam main</td>
<td>3440.5</td>
</tr>
<tr>
<td>5.</td>
<td>From Boiler</td>
<td>12779</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>67069.5</strong></td>
</tr>
</tbody>
</table>

The total estimated heat loss from the pipe line is for bare pipe (without insulation), to estimate heat loss after insulation, it is practical to assume 90% insulation efficiency, Total heat loss=0.1*67069.5=6.7kw/hfg@7bar (2065.2)=11.68kg/hr  
Total steam flow required=4616+11.68=4628kg/hr  
Working pressure required=8bar considering 10% allowance

Here we have determined the pressure and steam required from the trough to end use devices and hot water generator.
CHAPTER 4

4 TRANSYS MODELING OF PARABOLIC TROUGH STEAM GENERATION

4.1 Solar Thermal Electric Components (STEC) Model for a Parabolic Trough Collector

The STEC model for parabolic trough collector uses Lippke model [4]. The model uses an integrated efficiency equation as described below in equation 4.4 to account for HTF temperature difference at collector inlet and outlet. Using equation 4.1, the required mass flow rate of HTF to exist in the system so as to deliver the required net heat transfer to the steam will be determined:

\[
\dot{M} = \frac{\dot{Q}_{\text{net}}}{C_p (T_{\text{out}} - T_{\text{in}})}
\]  

(4.1)

The net heat collected by the collector is described by using equation 4.2

\[
\dot{Q}_{\text{net}} = \dot{Q}_{\text{abs}} - \dot{Q}_{\text{pipe}}
\]  

(4.2)

The total absorbed heat by the collector is estimated by using equation 4.3.

\[
\dot{Q}_{\text{abs}} = A_{\text{eff}} \cdot DNI \cdot \eta
\]  

(4.3)

\[
\eta = K \cdot E \cdot R \cdot S \left[ A + B \frac{\Delta T_{\text{out}} + \Delta T_{\text{in}}}{2 \cdot DNI} \right] + (C + C_w \cdot W \cdot S) \frac{\Delta T_{\text{out}} + \Delta T_{\text{in}}}{2 \cdot DNI}
\]  

\[
+ D . \frac{\Delta T_{\text{out}} \cdot \Delta T_{\text{in}} + \frac{1}{3} (\Delta T_{\text{out}} + \Delta T_{\text{in}})^2}{DNI}
\]  

(4.4)

Equation 4.4 represents the heat absorber efficiency based on Lippke model [4], the input variables in the equation can be described as follows;
• The empirical factors A, B, C, C_w and D are describes the performance of the collector. In this paper SEGS LS-2 collector is used for the analysis [4].

• K is the incident angle modifier

• EL and RS are end loss and shading factor respectively

• ΔT_in and ΔT_out are the temperature difference between collector inlet and collector outlet temperature with that of ambient temperature, respectively

• DNI is the direct normal irradiation.

• $\dot{Q}_{piping}$ is heat losses in the solar field piping.

4.2 Pre heater Model

The pre heater model used here is a zero capacitance sensible heat exchanger model in counter flow heat exchange system. Water is assumed to be the cold side input having quality of zero. The property of the water is taken from property data at the respective temperature and pressure. The overall heat transfer coefficient is used to find effectiveness $\eta_{ECON}$. This component works based on equations commonly used to describe the behavior of counter flow heat exchangers. First, the derived effectiveness, $\eta_{ECON}$, relationship is shown (Schwarzbözl, 2006)[4].

\[
\eta_{ECON} = \frac{1 - \exp\left(-\frac{UA}{C_{min}} \left(1 - \frac{C_{min}}{C_{max}}\right)\right)}{1 - \frac{C_{min}}{C_{max}} \exp\left(-\frac{UA}{C_{min}} \left(1 - \frac{C_{min}}{C_{max}}\right)\right)}
\]  

Where: $C_{min}$ and $C_{max}$ represent the minimum and maximum thermal capacitance rates of the two fluids passing through the heat exchanger respectively. The relationship for UA depends on the ratio of the cold-side fluid mass flow rate to its reference mass flow rate, scaled by an exponent. This exponent was set as 0.8 in this paper.
\[
\frac{UA}{UA_{REF}} = \left( \frac{\dot{m}_{\text{feedwater}}}{\dot{m}_{\text{feedwater,REF}}} \right)^{0.8}
\]  \hspace{1cm} (4.6)

Here, UA is allowed to be in the range \(0.1*UA_{REF}\) to \(2*UA_{REF}\). User can specify \(A_{REF}, m_{\text{feedwater,REF}}\) and \(UA_{\text{exp}}\) based on the requirement steam output and HTF temperature at receiver inlet for specified heat exchanger conductance and hence pressure loss is scaled in a similar way where the user has the freedom to specify a satisfactory exponent [4]. \(UA_{REF}\) and \(P_{REF}\) are design values of the heat exchangers.

\[
\frac{\Delta P}{\Delta P_{REF}} = \left( \frac{\dot{m}_{\text{feedwater}}}{\dot{m}_{\text{feedwater,REF}}} \right)^{\Delta P_{\text{exp}}}
\]  \hspace{1cm} (4.7)

Here \(\Delta P\) is allowed to be in the range of \(0.1*\Delta P_{REF}\) to \(2*\Delta P_{REF}\). User can specify \(m_{\text{feedwater,REF}}\) and \(\Delta P_{\text{exp}}\) based on the requirement, hence pressure loss is scaled in a similar way where the user has the freedom to specify a satisfactory exponent.

### 4.3 Evaporator Model

The TRANSYS Type 316 evaporator model is used to simulate water. The input variables are, outlet temperatures demand and flow rate of both cold and hot side fluids. In addition to this, a certain amount of modulated inlet water for complete evaporation (to have unity steam quality). This model approached analytically and uses the fluid conductance to determine the effectiveness. Water is set to be the cold side fluid, and is determined by its temperature, quality and pressure. The method used here to describe heat transfer between the two streams in the evaporator is effectiveness method using UA (Overall heat transfer Coefficient). Overall heat transfer coefficient (UA) and Pressure loss are evaluated using Equ 4.6 and 4.7 [4].

\[
\eta_{\text{evaporator}} = 1 - \exp \left( -\frac{UA}{\dot{m}_{\text{hot}} \cdot C_{p_{\text{hot}}}} \right)
\]  \hspace{1cm} (4.8)

\[
Q_{\text{trans}} = \eta_{\text{Evaporator}} \cdot C_{p_{\text{hot}}} \cdot \dot{m}_{\text{hot}} \cdot (T_{\text{hot,in}} - T_{\text{saturated}})
\]  \hspace{1cm} (4.9)
4.4 Storage Tank

The solar field model does not include thermal capacitance effects; consequently, a storage tank has been implemented into the TRNSYS model (Type 4a) to account for the thermal capacitance of the heat transfer fluid in the solar field and the expansion vessel as the specific volume of the HTF is dependent on temperature. The storage tank is located between the solar field and the evaporator (boiler) in this paper as described in the schematic diagram in figure 4.1.

![Figure 4-1: Solar field and steam line connection](image)

4.4.1 Sizing of the Tank

The storage tank is modeled using TRNSYS component Type 4a (TRNSYS 16). The HTF circulating through a solar field has considerable thermal capacitance. During normal operation throughout the day, the field runs at a quasi-steady condition and the thermal capacitance effects of the solar field heat transfer fluid become less important. During nighttime the HTF circulating pump continue to operate at a reduced flow to avoid thermal shocking; hence stress the collectors during the following day start-up.

When the storage tank is sized, the governing equation behind the storage tank from an energy balance over the tank is given by [7].

\[
M_{tank} \cdot C_{tank} \frac{dT}{dt} = \dot{m}_{HTF} \cdot c_{HTF} (T_{in} - T_{out}) + U A_{loss} (T_{env} - T_{in})
\]  

(4.10)
Where:

\( c_{\text{HTF}} \) = Specific heat of HTF [kJ/kg-K]

\( T_{in} \) = diameter of the steel absorber tube = 70 [mm]

\( T_{out} \) = HTF temperature outlet to the tank [°C]

\( UA_{\text{loss}} \) = heat loss coefficient from the tank [kW/K]

\( M_{\text{tan}} \) = Mass of HTF in the tank [kg]

\( C_{\text{tan}} \) = heat capacity of HTF in the tank [kJ/kg-K]

\( \dot{m}_{\text{HTF}} \) = mass flow rate of HTF [kg/hr]

\( \frac{dT}{dt} \) = change in average temperature of the storage tank with time [°C/hr]

\( T_{\text{env}} \) = temperature of ambient air surrounding the tank [°C]

The mass of HTF in the tank is assumed to be constant and the tank is sized to provide an equivalent mass as the HTF exists in the solar field and expansion vessel. These can be evaluated by using receiver tubes (LS-2 collector) and expansion vessel volumes multiplied by the density of HTF at solar field outlet temperature.

\[
M_{\text{tan}} = \frac{\pi (D_{\text{HCE}})^2}{4} \cdot L_{SCA} \cdot \rho_{\text{SCA}} \cdot \rho(T_{\text{outlet}}) + V_{\text{tan}} \cdot \rho(T_{\text{outlet}}) \]  

(4.11)

Where:

\( M_{\text{SF}} \) = the mass of the HTF in the solar field [kg]

\( D_{\text{HCE}} \) = diameter of the steel absorber tube = 70 [mm]

\( L_{SCA} \) = length of one solar collector assembly (SCA) loop = 47 [m]
$N_{SCA} = \text{number of SCA loops in the solar field} = 47$

$V_{tank} = \text{volume of expansion vessel} = 0.35 \text{[m}^3\text{]}$

$\rho = \text{density of heat transfer fluid (Therminol VP-1), from equation (4.20)} = 751 \text{[kg/m}^3\text{]}$

This gives the total mass of the HTF in the tank to be equal to 6,789.00kg.

### 4.5 TRANSYS model connectivity

The desired TRANSYS model for steam generation for this paper includes parabolic trough, weather data processor and storage tank in the solar field model. The steam generation side includes pre-heater, evaporator and feed pump as shown in Figure 4.2. In this model the hot water generator is common for both existing fossil fuel steam generation system and proposed Solar steam generation system, hence it is not useful to include here in the simulation as the main target is to rate this two technologies. The steam generated from the evaporator will be sent to hot water generator and end use devices in both cases.

![Figure 4-2: TRANSYS model component connectivity](image)

55
For this solar field model Type 9a is used to read the weather data. Type 16 g, a solar radiation processor with total horizontal and normal beam radiation known, is used to find the azimuth and zenith angles which are the inputs to the parabolic trough model.

The expansion vessel is modeled by storage tank component, part of the standard TRNSYS library, which serves to compensate for variation in the volume of the heat transfer fluid throughout the day, since the specific volume of the HTF is dependent on temperature.

The pre-heater Type 315 uses to raise the condensate temperature to evaporator saturated temperature at 8bar using counter flow heat exchanger analysis. Similarly Evaporator model Type 316 uses to convert saturated water to saturated steam which is the main objective of this work.

4.6 Solar Steam Generation model Result

Based on STEC components in put parameters requirement for the simulation collector area, HTF mass flow rate and overall heat transfer coefficients of the heat exchangers (counter flow) are determined considering different assumptions.

As described in the objective, the main target of solar collector model is to generate 5000kg/hr saturated steam at 8bar. Condensate collected from end use devices (sterilizer, kitchen, hot water generator and laundry) in the vented condensate tank will pumped to pre-heater. Since the condensate collector tank is vented to atmosphere, the temperature of in the tank considering line loss reaches 80° and 1bar.

Recommended pinch point temperature difference ranges 10-15° C which is important parameter to set the inlet and out let HTF temperature. The outlet temperature of the HTF from the pre-heater affects the solar field area, the boiler pressure of the steam, and the thermal efficiency. With the increase of this temperature, the solar field area decreases while the boiler pressure and the thermal efficiency increase.

For different temperature difference between inlet and outlet of the trough collector area and thermal efficiency is checked using mat lab (Appendix E), optimal thermal efficiency of 62.76% and collector area 11000m² is found for 300° C at outlet and 150° C at inlet to the
trough for HTF Maximum temperature after the trough for the selected HTF can reach 400\(^{0}\)C in liquid state, hence for this work 300\(^{0}\)C is set for HTF outlet from the collector, and also considering thermal efficiency and pinch point, 150\(^{0}\)C is set at the inlet of the collector. In addition to these, for this paper type of collectors chosen is LS-2. These collectors are chosen because a lot of research has been done on this collectors and enough information is found with respect to others.

- **Collector Area**

The required steam temperature, pressure and flow rate at the evaporator and pre heater are known at inlet and outlet. Hence the total energy needed by to raise temperature from pre-heater inlet to evaporator outlet at the given pressure can be determined. Using equation (4.1 to 4.4), the collector area \((A_{\text{eff}})\) is found to be 11000m\(^2\). Single SCA of LS-2 is 235 m\(^2\). This gives the total number of SCA needed for the solar field to be 47.

- **Overall Heat transfer coefficient**

Since all temperatures and required energy from the evaporator and pre-heater is known, using logmean temperature difference for counter flow the overall heat transfer coefficient \((U_{A_{\text{REF}}} \frac{\text{kW}}{\text{K}})\) for evaporator and pre-heater is found to be 60.36kW/K and 10.10kW/K respectively.

### 4.7 Direct Normal Irradiation (DNI) for Addis Ababa

The most important input for the simulation model is the direct normal irradiation at Addis Ababa. The data is taken from SWERA weather data [9]. The maximum daily average occurs on February 2 and minimum daily average on January 11, Figure 4.3. These days are, therefore, used as clear and cloudy day representatives respectively for system simulation.

Clear day in this context is a representative day for occurrence of relatively higher daily average DNI from the days of the year considered.
Figure 4-3: SAM Output of Daily average DNI for Addis Ababa
CHAPTER 5

5 SIMULATION RESULT

The TRNSYS program is used in order to simulate the solar steam generation model as described in chapter four. The behavior of the parabolic trough depends on the site meteorological conditions such as solar radiation and wind speed. These data are provided to the TRNSYS component (Type 9a) by the meteorological data file and the component is connected to the solar radiation processor (Type16g) that interpolates the solar radiation data at time steps of one hour and at any incident angle. The meteorological site selected for this analysis was Addis Ababa, Ethiopia, as the hospital is located at the capital city. The trough gets DNI data from the data reader and the solar azimuth and solar zenith angles from radiation data processor.

The hot HTF from the central receiver is continuously charged to hot thermal storage tank from which a controlled amount of HTF is sent to the steam generator (Evaporator) where saturated steam is required for hot water generator and hospital equipments through the existing steam distribution line. Type 65a online system plotter is used for plotting of simulation results that are used for result analysis. The simulation is done for clear day, cloudy day, monthly and annual. The monthly and annual results are shown in Appendix G of this paper.
5.1 Simulation result for Clear Day

Figure 5-1: Heat transfer fluid Temperature [°C] and DNI [W/m²] for clear day of February 2.
For the clear day simulation the available DNI ranges from 0 to 3800W/m². During the periods 11:00AM to 19:00AM the available DNI is somewhat tends to be constant within a small range. The HTF outlet temperature from parabolic trough shows similar temperature profile within the same period of time, this shows that the simulation result seems practical and enough to generate saturated steam at 8bar and 170°C constantly which meet the required steam flow rate for daily activity of the hospital.
Figure 5-2: Heat transfer fluid and Steam output Temperature [°C] for clear day of February.
From the clear day simulation result it is observed that the plant works for more than 9 hours (from 10:00AM to 19:00AM) saturated steam at 8bar and 170\(^{0}\)C constantly (the flat part of the red curve) which meet the required steam flow rate for daily activity of the hospital as clearly shown in figure 5.2. During four hours periods from 9:00AM to 10:00AM and 19:00AM to 20:00AM the plant output is not constant as the available DNI for this range of time is not sufficient to heat up the HTF enough to generate steam at the required temperature. The Heat transfer fluid temperature from the trough for the clear day simulations varies in the range of 80\(^{0}\)C to 300\(^{0}\)C (blue curve) where the highest occurs at start up of the system(300\(^{0}\)C).The peak HTF temperature occurs at 15:00 as expected, which align with the peak DNI time.
Figure 5-3: Heat transfer fluid and Steam output Temperature ($^\circ$C) for the month of February
From the monthly simulation result shown in figure 5.3, for which the clear day occurs it is observed that the plant works for the whole days of the month for more than 9 hours (from 10:00AM to 19:00AM) saturated steam at 8bar and 170°C constantly which meet the required steam flow rate for daily activity of the hospital in the entire days of the month.
5.2 Simulation result for Cloudy Day

Figure 5-4: Heat transfer fluid Temperature [°C] and DNI [W/m²] for cloudy day of January 11.
As shown in Figure 5.4 for the cloudy day simulation, the maximum available DNI is not sufficient to heat up the heat transfer fluid enough to generate saturated steam at 8bar and 170°C to meet the required steam flow rate for daily activity of the hospital, rather the heat transfer fluid temperature is shown to be below the feed water temperature. As this days are very few, conventional steam generation systems (oil fired boiler) is used as backup, like the existing system in the hospital should be installed to meet the daily steam flow demand.
Figure 5-5: Heat transfer fluid outlet Temperature and Steam Temperature for cloudy day of January 11
From the cloudy day simulation result it is observed that the plant has not the capability to generate saturated steam at 8bar and 170°C to meet the required steam flow rate for daily activity of the hospital. As shown in Figure 5.4, the HTF outlet temperature from the trough is below the feed water which is practically impossible to generate steam. Hence for such days therefore oil fired boilers steam generation systems should be installed as backup to achieve the required daily steam flow.
Figure 5-6: Heat transfer fluid and Steam output Temperature [°C] for the month of January
From the monthly simulation result shown in figure 5.6, for which the cloudy day occurs it is observed that the plant works for the whole days of the month except January 11 and to some extent January 12, for more than 9 hours (from 10:00AM to 19:00AM) saturated steam at 8bar and 170°C constantly which meet the required steam flow rate for daily activity of the hospital in the remaining 28 days of the month. Hence the oil fired back up boiler will fill this gap for 2 days in which the available DNI is not sufficient to heat up the heat transfer fluid enough to generate saturated steam at 8bar and 170°C.
CHAPTER 6

6 COST AND FINANCIAL ANALYSIS OF PARABOLIC TROUGH AND FOSSIL FUEL STEAM GENERATION SYSTEMS

In this chapter economics of parabolic through steam generation system and conventional steam generation system (fossil fuel boiler) will be analyzed and comparative analysis of the two systems will be done. Economic analysis plays a vital role in the decision of using these systems after the technical feasibility is identified.

6.1 Costs associated with Parabolic Trough Solar Steam Generation

The costs associated with parabolic trough solar steam generation system can be divided mainly in two categories:

- Capital costs: include equipment purchases cost and installation work of the system.
- Operation and maintenance (OM) costs: include equipment, labor and other miscellaneous expenditures during the life time of the project after the system is installed and let to operate.

6.1.1 Capital Costs

The capital costs represent all expenditures associated with the purchase of equipment and installation works of the project. These costs are classified as direct and indirect costs.

6.1.1.1 Direct Capital Cost

The direct capital cost represents expenditure for specific equipment or installation service. The direct costs for CSP system are solar field, storage, HTF and steam generating units. Site pre parathon for installation and labor costs are also direct costs. All costs referred in this paper are in birr (Ethiopian currency). The direct capital costs associated with solar thermal systems are listed in Table 6.1:
Table 6-1: Direct Costs for Concentrated Solar Steam Generation system [8]

<table>
<thead>
<tr>
<th>No.</th>
<th>Item description</th>
<th>Unit Cost</th>
<th>Total(birr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Site preparation for 11000m²</td>
<td>51birr/m²</td>
<td>561,000.00</td>
</tr>
<tr>
<td>2</td>
<td>Solar Field for 11000m²</td>
<td>5100birr/m²</td>
<td>56,100,000</td>
</tr>
<tr>
<td>3</td>
<td>HTF System for 3525kW</td>
<td>2550birr/kW</td>
<td>8,988,750.00</td>
</tr>
<tr>
<td>4</td>
<td>Storage for 3525kW</td>
<td>680birr/kW</td>
<td>2,397,000.00</td>
</tr>
<tr>
<td></td>
<td><strong>Sub Total</strong></td>
<td></td>
<td><strong>68,046,750.00</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Contingency10%</strong></td>
<td></td>
<td><strong>6804675</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total Direct Cost</strong></td>
<td></td>
<td><strong>74,851,425.00</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total Direct Cost($USD)</strong></td>
<td></td>
<td><strong>4403025.00</strong></td>
</tr>
</tbody>
</table>

6.1.1.2 Indirect Capital Cost

Indirect cost is normally not identified in a specific term like the direct cost of equipment and installation services; rather it includes all other costs that can be included throughout the installation period or after plant start up. Concentrated solar steam generation system indirect capital costs includes; Engineer, Procure, Project, Land, Miscellaneous and Sales taxes. The Indirect capital costs associated with solar thermal systems are listed in Table 6.2:

Table 6-2: Indirect capital costs of Concentrated Solar steam generation system [8]

<table>
<thead>
<tr>
<th>No.</th>
<th>Item description</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineer, Procure and construction -16% of direct cost</td>
<td>11,976,228.00</td>
</tr>
<tr>
<td>2</td>
<td>Project, land and miscellaneous-3.5% of direct cost</td>
<td>2,619,800.00</td>
</tr>
<tr>
<td></td>
<td><strong>Total Indirect capital Cost</strong></td>
<td><strong>14,596,028.00</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total Indirect capital Cost($USD)</strong></td>
<td><strong>858589.88</strong></td>
</tr>
</tbody>
</table>

The Total capital cost of the system will be the sum of direct and indirect capital costs found as 89,447,452.88birr or 5261614.8$USD. This cost is used to calculate the levelized energy cost and other key financial indexes.
6.1.2 Operation and Maintenance Costs

The cost associated with Concentrated Solar steam generation system after installation plant start up is Operation and Maintenance (OM) costs. These represent all expenditures on equipment and services throughout the project life.

- OM Fixed cost per year: Annual fixed first year cost typically include all recurring costs except for water-related costs.

Variable OM cost: For parabolic trough steam generation system, variable OM costs include cost of chemicals for water treatment and water purchases, and usually proportional to annual energy production of the plant.

The operational and maintenance costs associated with solar thermal systems are listed in Table 6.3:

<table>
<thead>
<tr>
<th>No.</th>
<th>Item description</th>
<th>Unit Cost</th>
<th>Total(birr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual fixed operation &amp; maintenance cost</td>
<td>850birr/kW</td>
<td>2,996,250.00</td>
</tr>
<tr>
<td>2</td>
<td>Annual variable operation &amp; maintenance cost</td>
<td>119birr/MWh</td>
<td>1,216,180.00</td>
</tr>
<tr>
<td></td>
<td><strong>Total operation &amp; maintenance cost</strong></td>
<td></td>
<td><strong>4,212,430.00</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Total operation &amp; maintenance cost($USD)</strong></td>
<td></td>
<td><strong>247790.00</strong></td>
</tr>
</tbody>
</table>

The source of all capital costs related to concentrated solar steam generations is SAM 2009 cost database.
6.2 Costs associated with conventional (boiler) steam generation system

The costs associated with conventional steam generation system can be divided mainly in two categories:

- Capital costs: include equipment purchases cost and installation work of the system.
- Operation and maintenance (OM) costs: include spare parts, fuel, labor and other miscellaneous expenditures during the life time of the project after the system is installed and let to operate.

6.2.1 Capital Costs

The capital costs represent all expenditures associated with the purchase of equipment and installation works of the project. These costs are classified as direct and indirect costs.

6.2.1.1 Direct Capital Cost

The direct capital cost represents expenditure for specific equipment or installation service. The direct cost for conventional steam generation system includes fire tube boiler, feed tank, and condensate pump and pre heater. All costs referred in this paper are in birr (Ethiopian currency). The direct capital costs associated with conventional (oil fired boiler) steam generation systems are listed in Table 6.4:
Table 6-4: Direct Costs for Conventional steam generation system (source: Henan Sitong Boiler Co.Ltd.)

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Equipment Name</th>
<th>Unit</th>
<th>Specification</th>
<th>Qty</th>
<th>Price (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mainframe set</td>
<td>set</td>
<td>WNS5-1.25-Q</td>
<td>1</td>
<td>46224.96</td>
</tr>
<tr>
<td>2</td>
<td>Steam Header set</td>
<td>set</td>
<td>SCI-273-1.25</td>
<td>1</td>
<td>462.25</td>
</tr>
<tr>
<td>3</td>
<td>Burner set</td>
<td>set</td>
<td>BGN350P</td>
<td>1</td>
<td>6163.33</td>
</tr>
<tr>
<td>4</td>
<td>BFW Pump set</td>
<td>set</td>
<td></td>
<td>1</td>
<td>616.33</td>
</tr>
<tr>
<td>5</td>
<td>Water Treatment set</td>
<td>set</td>
<td>FLECKφ400</td>
<td>1</td>
<td>847.46</td>
</tr>
<tr>
<td>6</td>
<td>Pressure Gauge block</td>
<td>block</td>
<td>0–2.5MPa. class 2.5</td>
<td>2</td>
<td>770.42</td>
</tr>
<tr>
<td>7</td>
<td>BEnt Pipe of Pressure Gauge</td>
<td>piece</td>
<td>Factory Standard</td>
<td>1</td>
<td>24.65</td>
</tr>
<tr>
<td>8</td>
<td>Three-way Cock of Pressure Gauge</td>
<td>piece</td>
<td>PN1.6</td>
<td>2</td>
<td>27.73</td>
</tr>
<tr>
<td>9</td>
<td>Spring Type Safety Valve piece</td>
<td>piece</td>
<td>PN1.6.DN50</td>
<td>2</td>
<td>7.70</td>
</tr>
<tr>
<td>10</td>
<td>Main Steam Valve piece</td>
<td>piece</td>
<td>PN1.6.DN80</td>
<td>1</td>
<td>123.27</td>
</tr>
<tr>
<td>11</td>
<td>Drain Valve piece</td>
<td>piece</td>
<td>PN1.6.DN50</td>
<td>2</td>
<td>46.22</td>
</tr>
<tr>
<td>12</td>
<td>Pressure Controller set</td>
<td>set</td>
<td></td>
<td>3</td>
<td>89.37</td>
</tr>
<tr>
<td>13</td>
<td>Feed Water Valve piece</td>
<td>piece</td>
<td>PN1.6.DN40</td>
<td>1</td>
<td>77.04</td>
</tr>
<tr>
<td>14</td>
<td>Check Valve piece</td>
<td>piece</td>
<td>PN1.6.DN40</td>
<td>1</td>
<td>35.44</td>
</tr>
<tr>
<td>15</td>
<td>Pressure Controller Seat piece</td>
<td>piece</td>
<td></td>
<td>1</td>
<td>40.06</td>
</tr>
<tr>
<td>16</td>
<td>Water Level Sensor set</td>
<td>set</td>
<td></td>
<td>2</td>
<td>30.82</td>
</tr>
<tr>
<td>17</td>
<td>Water Level Gauge set</td>
<td>set</td>
<td></td>
<td>2</td>
<td>184.90</td>
</tr>
<tr>
<td>18</td>
<td>Auxiliary Steam Valve piece</td>
<td>piece</td>
<td>PN1.6.DN40</td>
<td>1</td>
<td>123.27</td>
</tr>
</tbody>
</table>

Sub Total: 55895.22

Contingency (10%): 5589.50

Total in $USD: 61484.74

Total in Eth.Birr: 1,045,240.6

6.2.1.2 Indirect Capital Cost

Indirect cost is normally not identified in a specific term like the direct cost of equipment and installation services; rather it includes all other costs that can be included throughout the installation period or after plant start up. Conventional steam generation system indirect capital costs includes; Engineer, Procure, Project, Land, Miscellaneous and Sales taxes. The Indirect capital costs associated with conventional (oil fired boiler) steam generation systems are listed in Table 6.5:
Table 6-5: Indirect capital costs of Conventional steam generation system [8]

<table>
<thead>
<tr>
<th>No.</th>
<th>Item description</th>
<th>Total(birr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineer, Procure and construction -16% of direct cost</td>
<td>167238.9</td>
</tr>
<tr>
<td>2</td>
<td>Project, land and miscellaneous-3.5% of direct cost</td>
<td>36583.40</td>
</tr>
<tr>
<td></td>
<td><strong>Total Indirect capital Cost</strong></td>
<td>203822.30</td>
</tr>
<tr>
<td></td>
<td><strong>Total Indirect capital cost in $USD</strong></td>
<td>11989.547</td>
</tr>
</tbody>
</table>

The Total capital cost of the system will be the sum of direct and indirect capital costs found as 1,249,062.90 birr or 73474.30 $USD. This cost is used to calculate the levelized energy cost and other key financial indexes.

### 6.2.2 Operation and Maintenance Costs

The cost associated with Conventional steam generation system after plant start up is Operation and Maintenance (OM) costs. These represent all expenditures on equipment and services throughout the project life.

- OM Fixed cost per year: Annual fixed first year cost typically include all recurring costs except for fuel cost.
- Variable OM cost: For convention steam generation system, variable OM costs include cost of fuel.

**Boiler Fuel Specification**

- Furnace Oil of ASTM Grade 6
- HHV of the oil is 42.39MJ/kg
- Density of oil 0.9g/cc

The lower heating value of furnace oil is most important to rate efficiency of steam boilers. Hence the LHV can be estimated using the following equation

\[
LHV = HHV - 2.44 \times (8.94 \times h_2 + F)\ [MJ / kg]
\]

Where: \( h_2 \) is the mass fraction of hydrogen in the fuel (12%)
- \( F \) is Humidity of the fuel (50%)
2.44 is a mean value for heat of vaporization in [MJ/kg H2O] at 25°C

The efficiency of boiler can be estimated using the direct method by equation:

$$\eta = \frac{m_{\text{steam}} (h_g - h_{\text{feed}})}{m_{\text{fuel}} \times LHV}$$

$$m_{\text{fuel}} = \frac{m_{\text{steam}} (h - h_{\text{feed}})}{\eta \times LHV}$$

The efficiency of oil fired boiler is around 92%. The enthalpy at feed water inlet and saturated steam from boiler outlet at 8bar is taken from saturated steam table as 84.72kJ/kg and 2768.0kJ/kg respectively. Hence mass of fuel can be found as:

$$m_{\text{fuel}} = \frac{5000(2768 - 84.72)}{0.92 \times 39930} = 360\text{kg} / h$$

The plant works 8hour per day and 2920hour per annual and the total amount of fuel used per year is estimated to be 1051200kg or 1168m³. Currently light furnace oil price in Addis Ababa is 14.17 birr/liter (source: Oilbya limited Ethiopia branch) and escalation rate is 5%. Annual fuel cost become 17,169,600.00birr. The operational and maintenance costs associated with conventional (oil fired boiler) steam generation systems are listed in Table 6.6:

<table>
<thead>
<tr>
<th>No.</th>
<th>Item description</th>
<th>Unit Cost</th>
<th>Total(birr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual fixed operation &amp; maintenance cost</td>
<td>5birr/kW</td>
<td>20,000.00</td>
</tr>
<tr>
<td>2</td>
<td>Annual variable operation &amp; maintenance cost</td>
<td>-</td>
<td>17,169,600.00</td>
</tr>
<tr>
<td></td>
<td>Total operation &amp; maintenance cost</td>
<td></td>
<td>17,189,600.00</td>
</tr>
</tbody>
</table>

The source (reference) of all costs except direct cost (package boiler with accessories) to conventional steam generations is SAM cost database. The source of packaged boiler cost is Henan Siltang Boiler Co.Ltd.
6.3 Results of Economic analysis

6.3.1 Life Cycle Cost

The life cycle cost of concentrated solar steam generation and conventional steam generation as shown in Figure 6-1, shows the true cost incurred over the project lifetime for the same service provide. The financial parameters used for this project work is found from National Bank of Ethiopia (NBE). As per the bank, inflation rate and nominal discount rate is 5% and 12% respectively. Similarly furnace oil (light oil) fuel escalation rate is 5% as of Oilbiya Ethiopia limited branch head office. Regarding the project life time analysis period is set to be 30 year as most industrial oil fired boilers and Concentrated solar troughs life time is in the range of 30 to 40 Years.

![Figure 6-1: Life cycle cost analysis for parabolic trough and oil fired boiler](image)

The preference between concentrated solar steam generation and that of Conventional steam generation system should be made based on comparative life cycle costing where the solution with a lower cost over the project life is selected. An indicator of attractiveness is the years to breakeven, which is when the cumulative LCC of Concentrated solar steam generation becomes lower than the cumulative LCC of Conventional steam generation. The shorter the years to breakeven, the more attractive the concentrated steam generation solution becomes and the higher the cost savings over the project life. As seen in Figure 6-1 above, breakeven
occurs early 7 year after letting the system in to operation. This makes concentrated solar steam generation system very attractive over conventional steam generation system.

![Figure 6-2: Capital and operating cost analysis for parabolic trough and oil fired boiler](image)

The reason behind break even to occur early stage of the project life time is better explained in Figure 6-2, where the operating cost for oil fired boiler is very high as compared to parabolic trough steam generation. Although the initial investment of parabolic trough steam generation is very high, the operating cost of oil fired steam generation offsets the high initial cost of concentrated solar steam generation system.
6.3.2 Levelized Cost of Energy (LCOE)

The real levelized cost of energy (LCOE) estimated using equation 6.2 and found to be 1.30birr/kWh and 3.10birr/kWh for concentrated solar steam generation (Parabolic trough) and convention steam generation (oil fired boiler) systems respectively as shown in Figure 6.3.

![Figure 6-3: Levelized cost of energy (LCOE) for oil fired boiler and parabolic trough](image)

Figure 6-3: Levelized cost of energy (LCOE) for oil fired boiler and parabolic trough

The LCOE give an indication of the actual cost of steam generation using either of the concentrated steam generation or conventional steam generation systems and it is also an indication of how the two systems rate each other. The higher LCOE for conventional steam generation is due to high operational costs incurred throughout the 30years project life time.
CHAPTER 7

7 CONCLUSION

Technical and economic assessment of parabolic trough steam generation and conventional steam generation system has been done for Hospital application in consideration of Black lion General and specialized hospital located in Addis Ababa.

The hospital uses furnace oil for the generation of the steam, consumes 245 m$^3$ and pays 1,593,087.41 birr (96,550.00 dollar) in the fiscal year, 2008/09. As described in chapter 3, currently the hot water generator is not functional, if the hot water generator let to operational the steam demand also increases hence, the fuel consumption will become twice as that of the existing consumption. In addition to this the steam demand can’t be met by the currently installed 3ton/hr boiler hence it should be either substituted by parabolic trough or needs to be upgrade.

The result from technical feasibility study shows the parabolic trough can meet the steam demand of the hospital at the required time, more than 8hour per day, as the hospital currently require steam for different activities during the day time for 8hour per day. During cloudy day the conventional back up steam generation system will meet the daily demand for few days of the year. Similarly the economic analysis shows that although the initial investment of concentrated solar steam generation is high as compared to convention steam generation system, the reverse is observed in operation and maintenance cost, resulting concentrated solar steam generation break even (payback) to occur early, after 7 year the system let to operate over the conventional steam generation. One of the key economic parameters in rating two or more technologies, levelized cost of energy for concentrated solar steam generation is found to be 58% higher than conventional steam generation. Hence, the result shows that parabolic trough is found to be more economical for steam generation than oil fired boilers if enough DNI is available in the site.
CHAPTER 8

8 RECOMMENDATION

In the technical and economic assessment result, it is found that if concentrated solar steam generation (parabolic through) is implemented, the fuel consumption and operational cost of the boiler can be reduced appreciably. It is thus recommended that the government and hospital management to consider this outcome for its implementation so as to overcome the high operational cost of the existing boiler by using the parabolic trough steam generation system.

Though enough space is available within the hospital compound, in this work detail site preparation for installation is not done as this needs the management decision to prepare suitable space for parabolic trough installation such as dismantling small buildings, like stores and others. In addition to this even if the hospital has condensate recovery system; currently it is not functional due to lack of proper maintenance. Hence it needs condensate return pipes repair and maintenance, Pump replacement, Condensate return control systems maintenance and Steam traps assembly units replacement for each equipment to recover the condensate, so that large amount of heat can be recovered.

Though this work is done for hospital located in Addis Ababa, there are also other places like Afar and Somali regions in Ethiopia where high solar radiation (DNI) is available for long period over the year. These places are the best locations for concentrated solar steam generation as this place has more clear days than Addis Ababa. Hence solar thermal systems can be used for hospitals and universities in these regions as this institutions require steam for different activities.
9 REFERENCES


[8] Sam User Guide, SAM Software, Available at:


## A. Laundry and Kitchen Equipments Technical Specification

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Brand</th>
<th>Model</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Washing machine</strong></td>
<td>Grandimpanti</td>
<td>WFM55</td>
<td>Capacity 51.8kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hot water consumption 140lit/cycle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of units 4</td>
</tr>
<tr>
<td><strong>Drying machine</strong></td>
<td>Grandimpanti</td>
<td>EM75</td>
<td>Loading capacity 75kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Working Pressure 6bar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steam flow 190kg/hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of units 4</td>
</tr>
<tr>
<td><strong>Ironing machine</strong></td>
<td>BMM Weston</td>
<td>BMM Weston 850 Steam heating</td>
<td>Working Pressure 6bar</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steam flow 180kg/hr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of units 3</td>
</tr>
<tr>
<td><strong>Dish Washing Machine</strong></td>
<td>LN70COLGED</td>
<td></td>
<td>Capacity 3000dish/hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hot water consumption 400lit/hour</td>
</tr>
</tbody>
</table>
B. Steam distribution layout of the Hospital

Figure: Pipeline layout from steam Main to Sterilizer Units

Figure: Pipeline layout from steam Main to Laundry Units
Figure: Pipeline layout from steam main to Kitchen Units

Figure: Pipeline layout from steam header to hot water generator
## C. Heat Transfer Fluid Properties

### Table: Heat Transfer Fluids

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Min HTF Temp [°C]</th>
<th>Max Operating Temp [°C]</th>
<th>Freeze Point</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Salt</td>
<td>Salt</td>
<td>260</td>
<td>600</td>
<td>220</td>
<td></td>
</tr>
<tr>
<td>Caloria</td>
<td>Mineral Hydrocarbon</td>
<td>-20</td>
<td>300</td>
<td>-40</td>
<td>Used in first Luz trough plant, SEGS I</td>
</tr>
<tr>
<td>Hitec XL</td>
<td>Nitrate salt</td>
<td>150</td>
<td>500</td>
<td>120</td>
<td>New generation</td>
</tr>
<tr>
<td>Therminol VP-1</td>
<td>Mixture of Biphenyl and Diphenyl Oxide</td>
<td>50</td>
<td>400</td>
<td>12</td>
<td>Standard for current generation HTF systems</td>
</tr>
<tr>
<td>Hitec Nitrate Salt</td>
<td>Nitrate Salt</td>
<td>175</td>
<td>500</td>
<td>140</td>
<td>For high-temperature systems</td>
</tr>
<tr>
<td>Dowtherm Q</td>
<td>Synthetic</td>
<td>-30</td>
<td>330</td>
<td>-50</td>
<td>New generation</td>
</tr>
<tr>
<td>Dowtherm RP</td>
<td>Synthetic</td>
<td>-20</td>
<td>350</td>
<td>-40</td>
<td>New generation</td>
</tr>
</tbody>
</table>
## D. STEC Evaporator and Pre heater Input, Output parameters

### Table: STEC Pre heater (Type 315) configuration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>MODE</td>
<td>only mode 2 for counter flow is available</td>
<td>THI inlet temperature hot side</td>
</tr>
<tr>
<td>UAREF reference overall heat transfer coefficient</td>
<td>FLWH mass flow hot side</td>
<td>FLWH hot side mass flow rate</td>
</tr>
<tr>
<td>DPREF reference pressure loss</td>
<td>TCI inlet temperature cold side</td>
<td>TCO Cold side outlet temperature</td>
</tr>
<tr>
<td>FLWCREF cold side reference mass flow</td>
<td>FLWC cold side mass flow</td>
<td>FLWC cold side mass flow</td>
</tr>
<tr>
<td>EXP_UA power law exponent</td>
<td>XCI cold side quality</td>
<td>QT heat transfer rate</td>
</tr>
<tr>
<td>EXP_DP power law exponent</td>
<td>PCO cold side outlet pressure</td>
<td>EFF Exchanger effectiveness</td>
</tr>
<tr>
<td></td>
<td>CPH specific heat for hot side</td>
<td>XCO Outlet quality for cold side</td>
</tr>
<tr>
<td></td>
<td>PCI Pressure for cold side inlet</td>
<td></td>
</tr>
</tbody>
</table>

### Table: STEC Evaporator (Type 316) configuration

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAREF reference overall heat transfer coefficient</td>
<td>THI inlet temperature hot side</td>
<td>THO outlet temperature hot side</td>
</tr>
<tr>
<td>BD blow down fraction</td>
<td>FLHI mass flow hot side</td>
<td>FLHO mass flow hot side</td>
</tr>
<tr>
<td>DPREF reference pressure loss</td>
<td>TCI inlet temperature cold side</td>
<td>TCO cold side outlet temperature</td>
</tr>
<tr>
<td>FLWCREF reference mass flow cold side</td>
<td>PCO cold side outlet pressure</td>
<td>PCI cold side inlet pressure</td>
</tr>
<tr>
<td>EXP_UA power law exponent</td>
<td>XCI cold side quality</td>
<td>XCO cold side outlet quality</td>
</tr>
<tr>
<td>EXP_DP power law exponent</td>
<td>CPH hot side specific heat</td>
<td>FLCDM cold side mass flow demand</td>
</tr>
<tr>
<td></td>
<td>FLCO cold side mass flow</td>
<td>Qdot Transferd power</td>
</tr>
<tr>
<td></td>
<td>EFF Exchanger Effectiveness</td>
<td></td>
</tr>
</tbody>
</table>
E. Mat lab Code for collector Area

Aref= 73.6; % Thermal Efficiency of a LS-2 SCA
CR =0.94; % Clean Reflectivity
Cl =0.94; % Cleanliness Solar Field
A = Aref*(CR/0.94)*Cl*(1+Cl)/2;
B=-0.004206;
C = 7.44;
Cw = 0;
D = -0.0958;
f = 1.8; % [m] Focal Length of the SCA
Lsca = 47; % [m^2] Length of one SCA
theta = 0;

% Shading of Parallel Rows % This factor can be taken to be equal to 1 because at solar noon, no SCA shades other SCA.
sh = min (max(0,(12.5/5)*cos(zenith(h))/cos(teta(h))),1.0); sh =1; %
Ws = 3; % [m/s] Wind Speed
T_amb = 16.5; % [oC] Ambient Temperature
T_in=150;
T_out=300
DNI = 0.806; % [W/m^2] Direct normal Insolation
A_sca = 235; % [W/m^2] Aperture area of one SCA

K= cos(theta) - 0.0003512*theta -0.00003137*(theta)^2;

% End Losses
M = 1 - (f*tan(theta)/Lsca);

DeltaT_in = T_in -T_amb; % [oC] Diff. between collector inlet temp. and ambient temp.
DeltaT_out = T_out-T_amb; % [oC] Diff. between collector outlet temp. and ambient temp.

%Efficiency
eta_SF = K*M*sh*(A + B*((DeltaT_in+DeltaT_out)/2)) + (C+ Cw*Ws)* ... (((DeltaT_in+DeltaT_out)/(2000*DNI)))+D*(DeltaT_in*DeltaT_out + ... ((DeltaT_out-DeltaT_in)^2)/3)/(1000*DNI);

Qnet =3254;
%Average Temperature of the Solar Field Inlet and Outlet Temperatures
Tavg_sf = (T_out + T_in)/2;
xx=(0.02*Tavg_sf/225);
yy = (2.57*10^3)*Tavg_sf/275;
zz=DNI*eta_SF/100;

% Effective Area of the Solar Field
Aeff= (Qnet +yy)/(zz-xx);
% Piping Heat Loss
Qpipe = (xx * Aeff + yy);

% Total Number of Collector in the Solar Field
TN_coll = Aeff / A_sca;

% Absorbed Energy
Qabs = Aeff * zz;

% Specific Heat of HTF at Average Temperature
Cp_HTF = (0.0007755 * Tavg_sf^2 + 2.484 * Tavg_sf + 1511) / 1000;

% Reference Maximum Flow Rate of the HTF to Achieve Tout
mHTF_T = (Qnet / (Cp_HTF * (T_out - T_in))) ;
F. Laundry and kitchen Energy Consumptions

Laundry energy Consumption

1. Washing the Dirty Linen

\[
Averag\ energy\ consumption\ for\ washing = \frac{Energy\ consumption\ per\ cycle}{Linene\ loading\ per\ cycle}
\]

\[
= \frac{60kg\ of\ steam/ h \ast 2048kJ/ kg}{55kg}
\]

\[
= 0.62kWh/ kg
\]

2. Drying the Dirty Linen

\[
Averag\ energy\ consumption\ for\ drying = \frac{Energy\ consumption\ per\ cycle}{Linene\ loading\ per\ cycle}
\]

\[
= \frac{90kg\ of\ steam/ h \ast 2048kJ/ kg}{55kg}
\]

\[
= 0.93kWh/ kg
\]

3. Ironing the Dirty Linen

\[
Averag\ energy\ consumption\ for\ ironing = \frac{Energy\ consumption\ per\ cycle}{Linene\ loading\ per\ cycle}
\]

\[
= \frac{100kg\ of\ steam/ h \ast 2048kJ/ kg}{55kg}
\]

\[
= 1.03kWh/ kg
\]
The Average Energy Intensity of Kitchen Service

Average number of peoples having meal=832
Daily Energy consumption of kitchen service=1455.3kWh

\[
\text{Daily Average energy intensity} = \frac{\text{daily energy consumption of kitchen service}}{\text{average number of peoples having meal service}}
\]

\[
= \frac{1455.3\text{kWh}}{832}
\]

\[
= 1.75\text{kWh/ bed – day}
\]
G. Monthly and Annual simulations

March

[Graph showing HTF Temperature and Steam Temperature over simulation time]
April
June

Graph showing HTF Temperature and Steam Temperature over Simulation Time = 720.00 [hr].
July
August
September

![Graph showing HTF and Steam Temperature data for September.]

- HTF Temperature
- Steam Temperature

Simulation Time = 720.00 hours
October
November
Annual