National University of Lesotho

Analysis of the Viability of using Solar Thermal Energy for Maluti Mountain Brewery

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Contents

List of Figures

List of Tables

List of Equations

ABSTRACT

It has been established by literature that there is worldly movement towards renewable energy usage because of global warming. Solar energy among many is one form of renewable energy that can be used to reduce conventional energy usage. This study realized an opportunity to reduce the conventional energy (coal) use at Maluti Mountain Brewery (MMB); a brewery in Lesotho by preheating the boiler make up water. The boiler at MMB is serviced by condensate (70°C) and the cold water from the tap. The cold makeup water mixes with the condensate prior to the being carried into the boiler and thus reducing the efficiency of the boiler. This is because the boiler in turn demands a lot of coal to heat up the boiler feed water. A retrofitted solar thermal system into the existing system at MMB was done. This system was aimed at preheating the cold make up water before it mixes with the hot condensate in order to avoid the makeup water from reducing the condensate temperature. An Excel based model was made in order to design a solar thermal system that is cost effective and technically viable. The designed system is an active solar thermal system composed of evacuated tube collector with the EPD of 18 kWh/$), collector area of 80 m^2 which was decided upon by the required maximum storage tank temperature of 100 °C. The storage tank size of the system was found to be 2110 Liters. A tank of such size could not be found on the market; therefore, a 2500 Liters storage tank would be ideal for the purpose. The actual collector area decided upon according to the collector aperture area of 2.998 was found to be 81 m^2. The system was found to be able to preheat 54% of the makeup water (12 % of the boiler feed water is the makeup water). The amount of coal used by MMB would be reduced by 11% and therefore saving the company as the NPVSS is positive, amounting to $25044 for over 20 years.

ACKNOWLEDGEMENTS

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I would like to also appreciate the financial support that was provided to me by SOLTRAIN. It made carrying out this research project easier as I did not have to worry about the finances relating to the project. The articles that they provided me with, came in handy. Maluti Mountain Brewery was also very willing to assist and share information with me. The assistance is very much appreciated.

A very special thanks to my mother and the whole family for their unconditional support in the journey. I would have not done it without them. This is dedicated to Dr. Twala for the greatest role that he played in my academic journey. It is by the grace of God that this research project was carried out.

1 INTRODUCTION

1.1 Background

The world is aimed at moving towards the use of renewable energy because conventional energy forms are depleting day by day and they are the main source of greenhouse gas emissions[1]. Solar energy is one form of renewable energy whose usage is increasing rapidly. The common method to use is solar thermal energy because it is comparatively cheaper[2].

The world is faced with a number of challenges resulting from increasing energy demand, lack of energy security and unsustainability; caused by a great dependence on fossil fuels. Efforts are made to resolve the issues relating to increasing energy cost and security of supply, through implementation of various energy efficiency techniques [3].

Industrial processes are mainly dependent on either electricity or fossil fuels to supply industrial process heat [4]. The use of clean and renewable energy resources is crucial in achieving improved environmental quality, sustainability and a long term solution to global warming [4]. These forms of renewable energy resources are solar energy, bioenergy, hydropower and wind energy [3].

As an abundant source of energy, solar energy technologies have proven potential to substitute conventional energy. Solar heating is a promising method when it comes to reduction of the energy consumption of buildings as it also curbs the rapidly increasing energy crisis as well as global warming [5].

Solar energy has two different forms through which it can be explored, one being solar thermal energy and the other solar photovoltaic (PV) systems [6]. The use of solar energy for industrial processes, especially low- and medium-temperature industrial processes is very feasible due to the natural availability of solar [3]. Solar thermal technology has successfully been explored for domestic purpose applications but not enough exploration has been done for the industrial sector [7]. This sector possesses a significant share of the overall energy demand globally but the percentage varies from country to country [8].

Solar thermal energy is a type of renewable energy produced by conversion of sun rays directly into usable heat through solar thermal collectors [9]. Solar thermal technology and its application is very suited to the industrial and manufacturing sectors [5]. In industries, there are three groups of solar thermal technologies that are useful for process heat namely solar concentrators, solar air collectors and solar water systems [10]. There are conventional solar water systems such as flatplate collectors (FPC) and evacuated tube collectors (ETC) which are commonly used in residential areas, but they can readily be installed on industrial rooftops to service heat demand of up to 125°C [4]. The efficiency of these solar thermal collectors is dependent on their inlet temperature, ambient temperature, irradiance and the efficiency parameters of a certain collector [11].

Breweries are huge consumers of energy within the industrial and manufacturing sector. The heat demand for breweries is largely within relatively low temperature levels but again there is a large potential for heat recovery [12].

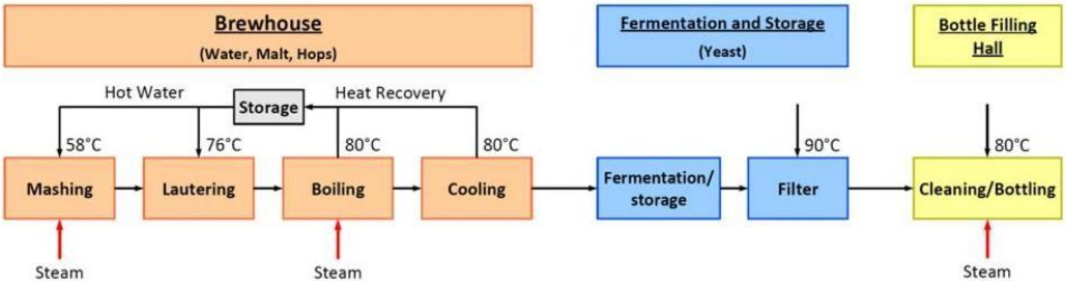


Figure 1: The beer brewing process [13]

Figure 1 shows the beer brewing process as a whole, together with the temperature ranges at which they occur. These are low and medium temperature ranges and can easily be met by common collectors such as FPC and ETC. Conventional flat-plate collectors (FPC) and evacuated tube collectors (ETC) both provide temperature levels up to 120°C [4].

Lesotho has a beer brewing company called Maluti Mountain Brewery(MMB), situated in Maseru. This company uses both electricity and coal to perform the beer brewing processes which costs the company large sums of money. In 2019, MMB produced 440 000 hectoliters of beer from a total of 313063 kWh in electricity and 1777476 kg (coal). Figure 2 shares light on MMB thermal energy usage. The 3 % is electricity produced from coal and exported from South Africa. The company has a goal that by 2025, 100 % of their production heat demand should be serviced by usage of renewables.

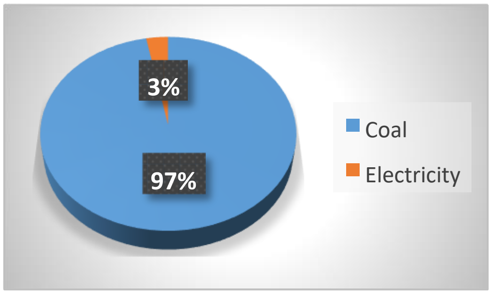


Figure 2: Fuel type servicing the thermal energy demand at MMB

1.2 Knowledge gaps and challenges

Industries such as breweries rely on fossil fuels-for their thermal energy needs; which are not only not environmentally friendly but also expensive [5].

As a contribution to science, this study presents an analysis of how solar thermal energy can cost effectively implemented at breweries using MMB as the case study. This will in turn reduce the electrical load of LEC (which relies on imported electricity from South Africa and Mozambique) [14]. South Africa uses the environmentally unfriendly coal for electricity production. This use of solar thermal energy will reduce the national electricity demand by a certain portion. Moreover, it will reduce the greenhouse gas emissions as coal is used at MMB for production.

Maluti Mountain Brewery uses a lot of electricity and fossil fuels to produce beer of which most of it can potentially be displaced by use of abundant, renewable and environmentally friendly solar thermal energy. Breweries which have integrated solar thermal energy in their production have come out as an interesting solution for CO_2 emissions from breweries. Also there are long term economic benefits of using solar thermal energy even though the initial capital costs are high.

There is no tool that can be used by breweries that is specifically designed to simulate the most economical solar thermal system for breweries. Green Brewery Concept tool was designed to assist breweries by incorporating solar thermal energy in order to reduce greenhouse gas emissions disregarding the most cost effective design[8]. There are different processes in beer brewing and it is not all that can be serviced by solar thermal energy if the aim of the system is to be cost effective so the study will provide brewery industry with a tool that will simulate the most cost effective solar thermal system.

1.3 **Problem Statement**

MMB uses strictly coal for their thermal energy demand which may be expensive and environmentally unfriendly. The thermal energy that is produced by coal can be serviced with solar thermal energy but it is not known which option is economically and technically viable.

The study is aimed at reviewing the opportunities of using solar thermal energy in the beer brewing at MMB and to do a techno-economic design of solar thermal systems at the brewery. Also, this study is to evaluate all the necessary parameters for integration of solar thermal energy in breweries.

The study will evaluate space availability at MMB whereby solar thermal collectors will be placed. The space will likely be the roof tops, taking into consideration any forms of shading, day lengths and the available solar resource for varying seasons in Maseru.

Moreover, this study seeks to determine the thermal energy demand of MMB and the all the processes that go in to brewing so as to know which processes can produce the most economic benefit when serviced with solar thermal energy. Determination of the most cost effective solar thermal system will be simulated by an Excel based model which will determine the most economical solar collector to use at MMB based on the energy per dollar criteria. The model will further establish the economic and environmental benefits of integrating solar thermal energy at MMB by determining the highest Net Present Value of Solar Savings [15].

The largest driver of a collector's cost effectiveness is often the price of alternatives, like coal, oil and natural gas, not the cost of the collector itself hence it is important to build a model that will align the cost effectiveness of solar collectors in comparison with alternatives of energy. It is easier to justify the use of solar thermal energy when fossil fuels become expensive [9]. The most cost effective solar collector field size will be determined in relation to the available solar resource, the cost of solar thermal technology, the price of electricity in Lesotho, price of coal and other economic parameters such as interest rate and collector price on the energy market.

This study seeks to sensitize stakeholders within the beer brewing industry of the importance of switching from conventional energy resources to the use of renewables, specifically solar thermal energy. It is apparent that the use of solar thermal energy in the beer brewing industry will reduce greenhouse gas emissions while providing them with long term economic benefits such as potential new investments from the solar savings.

1.4 Hypothesis and Research Questions

It is hypothesized that solar thermal energy can be used to service the beer brewing energy demand.

The main research questions are as follows: What are the opportunities of using solar thermal energy in the MMB brewing processes? Is it technically and economically viable to use solar thermal energy at MMB?

The questions are addressed by answering the following sub-questions:

a. What is the thermal energy demand of MMB?
b. Which type of solar thermal collector(s) is(are) suitable for the processes at the brewery.
c. Is the use of solar thermal energy economically beneficial to MMB?
d. What size of solar collector field produces maximum benefit to the processes, given the available solar resource, the cost of solar thermal technology, the price of coal and other economic parameters such as discount rates?

1.5 Objectives

The main objective of this study is to determine the technical and economic viability of using solar thermal energy at MMB. This viability will be determined by use of an Excel based model that can carry out thermal and economic analysis of producing thermal energy for MMB.

a. <u>Renewable energy gap at MMB:</u> To reduce the conventional energy content of the thermal energy demand (100% serviced by coal) of MMB production by displacing it with solar thermal energy.
b. <u>Proposed retrofitted solar thermal system design for MMB</u>: To establish a design through which solar thermal energy can be integrated at MMB.
c. <u>Energy demand</u>: To determine the total thermal energy demand of the beer brewing process which will assist in knowing how solar thermal energy can be integrated in the process.
d. <u>Simulation Model:</u> To develop an excel based model that can carry out thermal and economic analysis for breweries using MMB case.

e. <u>Solar radiation data modelling</u>: To determine the usable heat and temperatures of the designed system as well as the sunshine hours at MMB taking into consideration shading which could come from objects such as trees or building.
f. <u>Collector selection</u>: To select the type of solar thermal collector to employ for beer brewing at MMB, based on the energy per dollar criteria as it selects a collector based on the highest energy per dollar and collector area with the highest Net Present Value of Solar Savings which is what this study is mainly focused on.

g. <u>System sizing</u>: To establish the most economical size of solar thermal collector field and its storage size to employ at MMB.

1.6 Justification

The heat requirements of processes in the beer production range between temperatures 25°C105°C [5] which can be achievable by common solar collectors. Solar thermal energy, depending on the system size and solar fraction employed can be more economical than using electricity from the power grid [16]. The use of solar thermal energy in the beer brewing processes can be economical in the long run regardless of the high capital cost compared to the use of electricity and fossil fuels and therefore it would make sense to displace some electricity use by employing solar thermal energy. The use of solar thermal energy will reduce the rate of greenhouse gas emissions from the industry when compared to using fossil fuels.

The Lesotho energy sector is faced with challenges such as low access to modern and clean forms of energy. It relies on imported electricity and fossil fuels and declining forest reserves (which poses an energy security problem) [14].The use of solar energy in large industries such as the beer brewing industry in Lesotho may reduce the country's electricity imports and fossil fuel imports, this means that the costs incurred by the country may be reduced. The use of solar thermal energy will help in reducing the electricity demand and coal demand of MMB, which will be economically beneficial for the company.

1.7 **Dissertation structure outline**

The outline of this dissertation is as follows: introduction in Chapter 1 which discusses all the phenomena around this study, literature review in Chapter 2 to identify the literature gaps and appreciate some of the research made, methodology in Chapter 3 to describe how the study will be carried out, results and discussions in Chapter 4 to elaborate the findings made from the study and lastly the conclusions and recommendations in Chapter 5.

2 LITERATURE REVIEW

2.1 **Energy Situation in Industries**

In industrial production, replacement, and reduction of fossil fuels with renewables are major objectives [17]. It is one of the important elements of increasing the sustainability of energy systems as it reduces carbon dioxide emissions. In civil and industrial sectors, both electricity and process heat can be supplied by the use of Renewable Energy Systems (RES)[18].

In industrial processes, integration of process heat has been a successful in minimizing the amount of energy used. Formal methodologies such as pinch analysis, have been used for quite a number of years, providing useful and proven results. There is need for further development and implementation of technologies such as process heat integration in order to increase energy efficiency and therefore ensuring the profitability of the industrial sector[19].

In some European countries, it is estimated that more than 25% of the total final energy demand is thermal energy in the form of hot water or steam for industrial processes [1]. An important aspect of such energy demands concerns water at medium to low temperature (between 60 and 100 ◦C). The use concerns various sectors like the food (meat, dairy, beverages, and tinned food), paper, textile, and mechanical (chemical, automotive) industries[10]

In 2016, industries consumed about 37% of the total final energy consumption in the world that was 9.6Gtoe. The current global energy demand is generally supplied by burning of the nonrenewable and unsustainable fossil fuels and most of the greenhouse gas emissions which are a great cause of global warming are due to burning of fossil fuels. In 2016, these emissions were

32.3 Gtoe and 19% of the emissions come from industries [20]. There is need to reduce the emissions from industries.

2.2 Current Solar Thermal Energy Usage in Industries

The most promising technology in the replacement of fossil fuel is solar thermal process heating. This technology can cover low-temperature demand up to 100°C using a very modern and ready market available conventional solar thermal systems[17]. This type of renewable energy can service a substantial amount of heat demand in agricultural food processing and industries in any country regardless of the geographical location[4].

Heating water to low temperatures (below 150 °C) and medium temperatures (between 150°C400°C) using solar thermal energy has gained popularity in the global spectrum because of several favorable characteristics that are possessed. It is used in the residential, industrial, and commercial sectors to displace conventional energy sources in an environmentally and economically sustainable way[15].

The most essential feature in the commercial, industrial, and domestic sector's energy requirements is water heating. The solar water heater has two main elements namely the collector and the water storage tank which serve different purposes; the collector is used for absorbing solar radiation and transferring it to the water while the storage tank stores water for usage [6].

The collectors used for solar water heating can be classified into flat plate and evacuated tube collectors; the former collector has an absorber plate to absorb solar energy and also has a glazing above for reduction of convective heat loss whilst the latter is made up of tubes which have vacuum maintained between the tubes and are glazed for better protection against convective heat losses [12]. One other disadvantage of solar thermal technology is the high upfront costs albeit less recurrent costs.

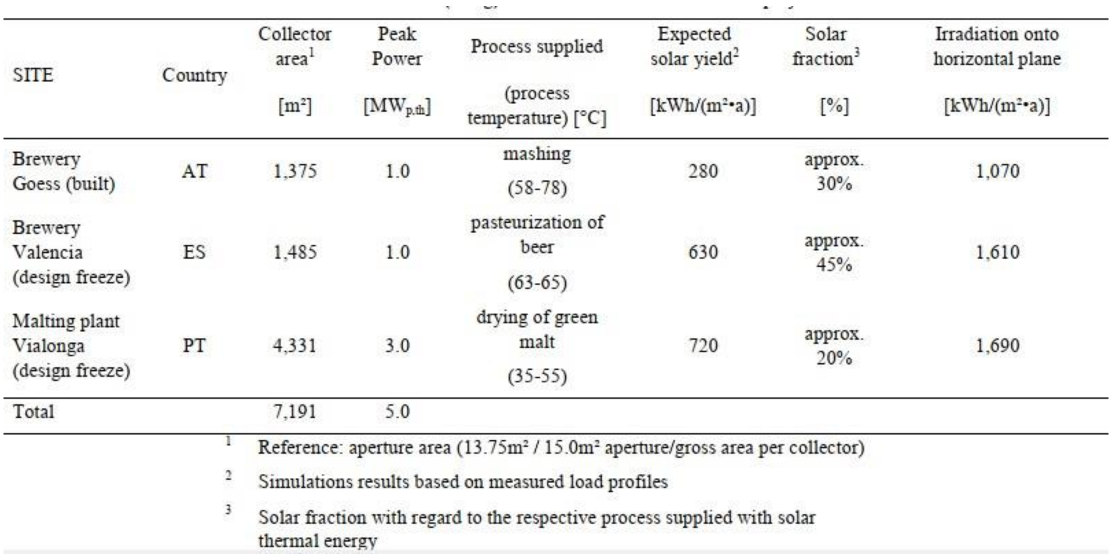
Moreover, the collectors within solar heaters can be classified into two groups called flat plate collectors (FPC) and evacuated tube(ETC) [6]. When designing a solar thermal system, there has to be the selection of a collector to be employed based on different criteria such as the costeffectiveness of using a certain collector and also the performance of the collector in the climatic conditions of the place in question.

The application of solar heat in industries is still very scarce yet they are the largest consumers of energy and great polluters of the environment. A strategic and targeted integration of solar thermal to supply industrial process heat has been proven to be technically feasible and economically viable. Also, it is expected to become one of the main sources of industrial heat in the future[21].

There are many industrial applications of solar thermal energy. It is reported that around 20%, 45%, and 30% of the thermal process energy demand in three European breweries could be fueled by the use of solar thermal systems[21].Table 1 shows these breweries and they have used solar energy for different purposes with different integration levels (solar fraction). It is quite evident the use of solar energy within an industry can be incorporated to do different purposes, with different solar fractions.

The solar fraction varies from place to place depending on the radiation of the place, collector performance, and the costs of using solar thermal energy. Again, it is influenced by the process that it is being used for and the heat requirements. All these breweries use solar thermal energy for different beer brewing purposes[21].

Table 1: Solar thermal incorporation in the European breweries[21]



SITE	Country	Collector area[1] [m²]	Peak Power [$MW_{p,th}$]	Process supplied (process temperature) [°C]	Expected solar yield[2] [kWh/(m²•a)]	Solar fraction[3] [%]	Irradiation onto horizontal plane [kWh/(m²•a)]
Brewery Goess (built)	AT	1,375	1.0	mashing (58-78)	280	approx. 30%	1,070
Brewery Valencia (design freeze)	ES	1,485	1.0	pasteurization of beer (63-65)	630	approx. 45%	1,610
Malting plant Vialonga (design freeze)	PT	4,331	3.0	drying of green malt (35-55)	720	approx. 20%	1,690
Total		7,191	5.0				

[1] Reference: aperture area (13.75m² / 15.0m² aperture/gross area per collector)

[2] Simulations results based on measured load profiles

[3] Solar fraction with regard to the respective process supplied with solar thermal energy

2.3 **Solar Thermal Energy**

Solar thermal technologies use the heat energy from the sun which is harnessed by the use of a solar collector such as an evacuated tube collector or a flat plate collector which use a fluid as at heat exchanger with the storage tank for a variety of purposes. These technologies are very diverse in what they do, they can be used for solar space heating, solar cooking and even solar air conditioning[6].

The most convenient processes of integration of solar thermal energy are those that have lower temperature range and load profile that matches with the available solar resource as much as possible [11]. Amongst a number of processes that require energy in industrial, residential and manufacturing sectors, water heating is the most essential one [6]. It is the key demand of various industrial and domestic heating system [22].

Solar thermal energy systems can potentially provide process heat for industrial processes suited for low pinch temperature such as those in the beverage (such as breweries), food and textile industry [7]. The economic viability of solar thermal energy is greatly dependent on two factors being the initial cost of the installation and the price of alternatives. The high upfront costs may unjustifiably discourage companies from investing in solar thermal technology, despite that their overall lifetime costs would be lower [9].

Solar thermal energy is the best-suited type of solar energy since it converts solar radiation directly into heat at an efficiency of 3-4 times higher than those which are achieved by solar PV. Moreover, the storage technology for solar thermal energy is cheaper than those of solar PV [9]. Solar thermal energy is a type of renewable energy produced by the conversion of sun rays directly into usable heat through solar thermal collectors [23]. Solar thermal technology and its application are very suited to the industrial and manufacturing sectors [5]. On a global scale, there is more demand for heat energy than there is for electricity, implying that it is more effective to substitute fossil fuels by the use of solar thermal energy. Again the storage technology for solar thermal energy are cheaper than those of solar PV [23]. Solar thermal energy is less complex storage than solar PV which uses expensive chemical storage [3].

The challenges faced by use of solar thermal energy is its intermittent and fluctuating nature. The available solar radiation varies by hour and day and is dependent on the clearness of the sky. Again the solar collectors experience some thermal losses which are dependent on the ambient temperature and causes some sort of uncertainty in predicting the available energy from the sun. These challenges can be solved by use of solar thermal energy storage or use of hybrid systems [11].

Studies have clearly indicated that there are challenges faced by implementation of solar thermal energy in industries such as breweries. There needs to be proper sensitization on the benefits of switching to solar energy from conventional energy, such reduction of CO_2 emissions, opportunity of getting carbon credits and subsidies like the ones provided by SOLTRAIN when companies switch to solar thermal energy and opportunities of new investments from savings made from switching to solar energy[9].

2.4 **Industrial Application of Solar Thermal Energy**

The techno-economic studies in the available literature have clearly shown that the use of solar energy for process heating is very possible but limited by the economic viability of such systems [8]. Even though this is the case, whatever amount incorporated; the use of solar energy in industries makes a huge difference in the reducing the long run cost of production and the reduction of the greenhouse gas emissions.

The economic viability of solar thermal energy is greatly dependent on two factors; the initial cost of the installation and the price of alternatives. The high upfront costs discourage companies from investing in new technology, like solar thermal, even if the overall lifetime cost would be lower [9]. There needs to be proper sensitization on the benefits of switching to solar energy from conventional energy, such as reduction of CO_2 emissions, an opportunity of getting carbon credits and subsidies like the ones provided by SOLTRAIN when companies switch to solar thermal energy, and opportunities for new investments from savings made from switching to solar energy[9].

There are three main temperature ranges of industrial heating needs: low, medium, and hightemperature ranges. All of these ranges can be achieved with solar energy. The low-temperature range consists of everything below 80°C which can be met by solar collectors which are commercially available today. The medium temperature ranges between 80°C and 250°C. Solar collectors that can meet this level of heat demand are relatively limited, they are on the verge of emerging into competitive commercial production. Above 250°C are high-temperature ranges[9]. The low and medium temperature ranges can be serviced by collectors such as the ETC and the FPC which are common in the solar energy field.

The most common application of solar thermal energy is solar water heating. A solar water heater is made up of two major elements being, the collector and the storage tank. These elements have their respective functions; collector absorbs solar radiation and transfers it to the water and the storage tank serves the purpose of storing the water for usage[12]. In designing of a solar thermal system, these elements have to be correctly sized for the load that they will serve with regards to the temperature requirements.

The thermal performance and efficiency of a solar network depend greatly on the constantly changing ambient conditions. It is important to ensure that before implementing the solar thermal energy strategies within the framework of industrial solar thermal design, analysis of the dynamic behavior and time-variant disposition of meteorological parameters is done[9]. This will help in proper sizing of the system, taking into consideration all the factors affecting system performance. For instance, knowledge of the radiation of the place informs decision making of where solar panels are to be placed, sunshine hours, and shading. These factors affect the performance of solar thermal collectors.

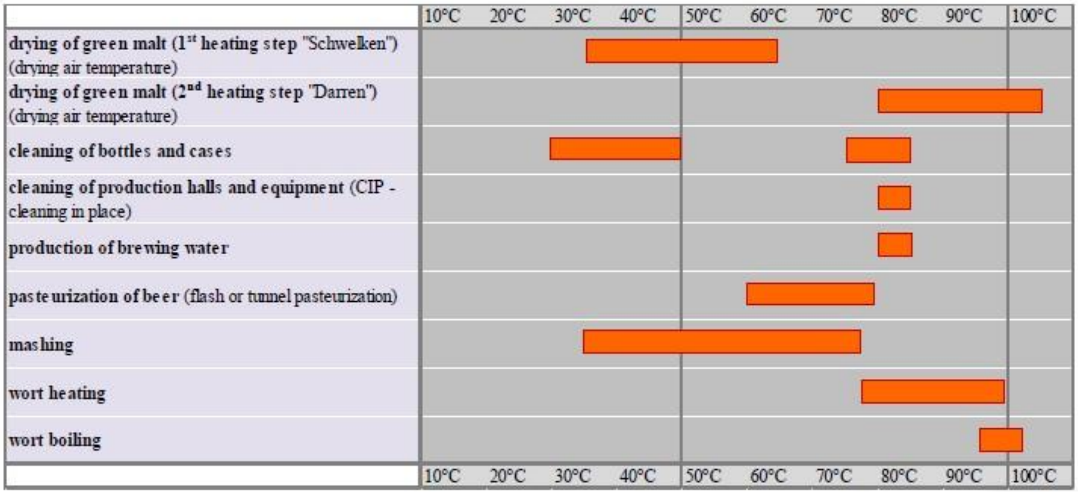
Solar thermal energy applications are prudent in countries where the daily average solar irradiation is higher than 4.5 kWh/m^2 This is the common case in most Southern African countries[17]. It is of great importance that solar energy which is quite abundant in Lesotho and environmentally friendly be used to uplift the socio-economic situation in the country [24]. Lesotho's daily sunshine hours range between 10.2 and 13.8 hours while the daily solar radiation in Lesotho ranges between 5 kWh/m^2 and 7 kWh/m^2 [24]. This solar radiation can be harnessed and used as solar thermal energy in different industries in Lesotho such as breweries

2.5 **Solar Thermal Energy for Breweries**

Breweries are huge consumers of energy within the industrial and manufacturing sectors. The heat demand for breweries is largely within relatively low-temperature levels but again there is a large potential for heat recovery[25]. The energy consumed in the production of beer is equal to 3 – 8% of the production costs of beer. Therefore, improvements on energy efficiency is the most important way of reducing costs, especially when the prices are highly volatile[26]. These show a great need and potential for integration of solar thermal energy in breweries.

The integration of a solar heating plant can only be achieved via a thorough study of the production process, its heat supply, and modification of the existing heat recovery or heat supply system [17]. Therefore, when integrating solar thermal energy in breweries, there needs to be a thorough analysis that will ensure that everything about thermal energy needs and supply is addressed. The processes within breweries and malting plants can be met by temperatures ranging between 25 and 105 °C as indicated in Table 2 [21].

Table 2: Temperature range requirements for all the processes within breweries[21].



The temperatures are low and can easily be attained by the use of common solar collectors such as the evacuated tube collectors (ETC) and flat plate collectors (FPC) which are mostly used for residential applications of solar thermal energy.

Due to the temperatures that are used within the beer brewing and malting being able to be serviced by solar thermal energy, it was deemed important to gain a real scale experience of such. This was done so as to be able to transfer the knowledge to other beer brewing and malting plants[21].

The utilization of renewable energy resources in breweries has been studied through what is called “Green Brewery Concept tool”. This was developed based on three case studies. It is an Excel based tool that provides breweries with guidance towards a GHG emission free production whereby renewables cover the thermal energy demand. It is important to develop a tool instead of a basic guideline because of the small technological differences of brewing and packaging capacity which influence the energy management of breweries to a very large extent [7]. Integration of solar thermal energy in breweries can be done through water preheating to increase the boiler efficiency.

The Green Brewery Concept is aimed at demonstrating the potential for reducing thermal energy consumption in breweries to substantially lower fossil CO2 emissions. Furthermore, it aimed at developing an expert tool that will share light on a strategic approach to reach this reduction. One of the studied breweries with optimized heat recovery could potentially supply its thermal energy demand over its resources excluding space heating. This method focuses on incorporating both bioenergy and solar energy in the production of beer. The bioenergy is generated from the organic wastes from the breweries such as spent grains. The biological processes that occur in breweries are very delicate when it comes to temperature and therefore integration of storage tanks into hot water management is a very crucial matter [8].It is possible to substitute a certain amount of the energy demand with renewable energy while the rest is serviced by fossil fuels. This will reduce the greenhouse gas emissions while also economically benefiting the industry.

2.6 **Case Studies of Solar Thermal Energy Application in Breweries**

2.6.1 Brewery Goess

Brewery Goess in Austria has a solar thermal system which was commissioned in June 2013. It has two steam supplied vessels (mash tuns) which are retrofitted by a specially designed internal plate heat exchanger templates that allow a hot water-based supply system instead of steam. The hot water came from waste heat from a nearby biomass combined heat and power plant together with a large scale ground-mounted solar thermal system. The solar thermal system was made up of 100 collectors that make up a total of 1,500 m² gross collector area which is hydraulically connected to a 200 m³ pressurized solar energy storage tank [21].Figure 3 shows a schematic diagram of this system..

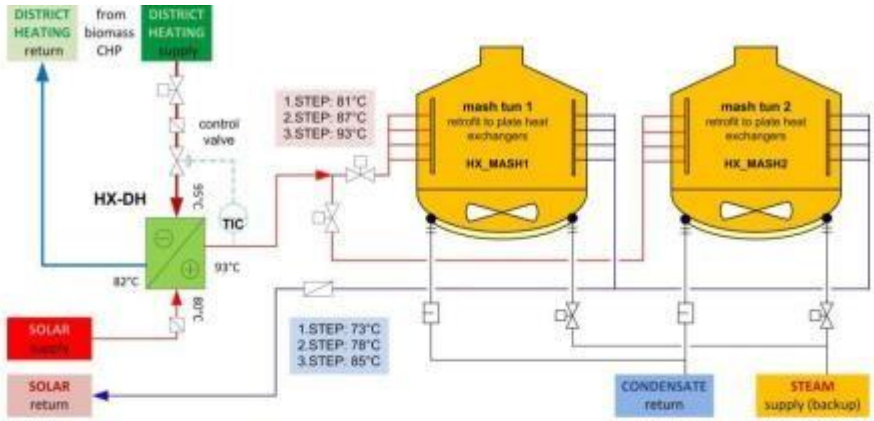


Figure 3: Schematic diagram of Brewery Goess mashing plant [21]

In Brewery Goess, a solar thermal system is used for one beer brewing process called mashing; a process whereby soluble substances are dissolved directly into water and then undergo enzymatic hydrolysis which is followed by separation of the dissolved substances[27].

The temperature of the mash is increased continuously from the starting temperature of approximately 58°C to a final temperature of about 78°. The system works by taking out the solar thermal energy from the solar energy storage tank if the right temperature is reached and then pumped into the retrofitted plate heat exchangers. This means that if the system cannot provide the required temperature, it is left to idle, which shows some inefficiency [21].

2.6.2 Brewery Valencia

In 2014, a solar thermal system that supplies heat to a tunnel pasteurizer was put into operation in Valencia (Spain) which is used for pasteurizing canned beer. The system is made up of 108 m^2 large-area flat plate collectors making up a gross collector area of 1,620 m² which are mounted on the ground and hydraulically connected to an atmospheric solar energy storage tank with a water volume of 350 m³. The system uses the energy from the sun to supply the tunnel pasteurizer to pasteurize canned beer with hot water at a temperature of 85°C. The process initially used a steam-based supply system which was altered by the solar thermal system. Figure 4 shows the modification of the steam-based system. Figure 4 (left) shows a schematic diagram of the steam heated sprayer loop in the existing can tunnel pasteurizer in the brewery Valencia and Figure 4 (right) shows a schematic diagram of hydraulically integrated solar hot water with a serially connected plate heat exchanger[21].

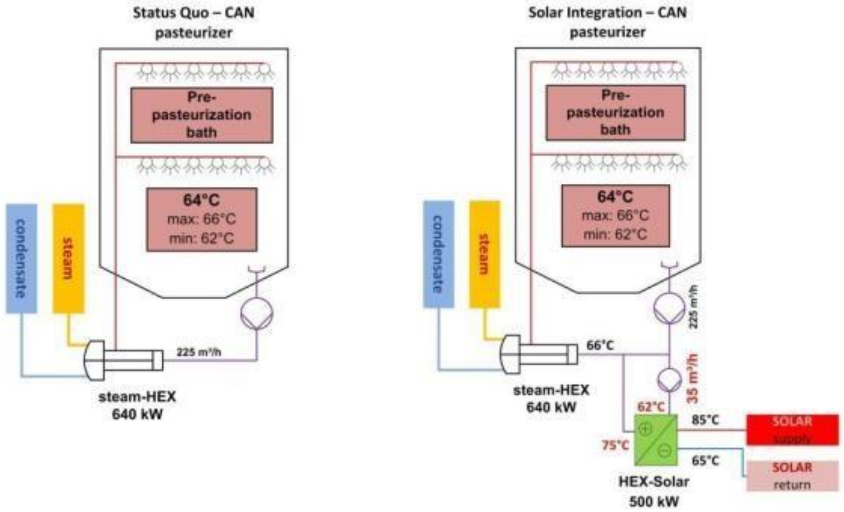


Figure 4: Schematic diagram of a pasteurizing plant at Brewery Valencia[21]

2.6.3 South-Eastern Scotland Brewery

In a study conducted in Scotland which focused on the energy optimization of a medium-sized brewery, it was found that reduction of the hot utility demand due to heat recovery measures and insulation improvements was 1030 MWh/a while using solar heat integration. The fossil fuel demand could be further reduced by 206 MWh/a. In the analysis between two solar collectors within the study, ETC to be preferred over FPC due to their higher yearly solar heat output, lower annual total cost and resulting in lower CO2 emissions. Payback periods of 6.4–6.8 years depending on the used collector type were identified in conjunction with a CO_2 saving potential of up to roughly 38 tons per year [10]. The fact that ETC was preferred over FPC does not impose that this is an option that cuts across all the other solar thermal breweries, FPC can be preferred over ETC depending on the situation at hand.

2.6.1 Cape Brewing Company

Cape Brewing Company (South Africa) installed a solar thermal system in its plant in 2015. The solar fraction is 29.6% of total paraffin demand with an annual saving of 19 386 liters of paraffin. The gross collector area is 120 m^2 and R 1.4 million was invested into this system including installation. The heating of process water is between 70°C and 90 °C. SOLTRAIN provided a subsidy of 30 000 Euro to this company. This subsidy should be a form of encouragement to other brewing companies to use solar thermal energy in their processes. The chief executive officer of this company declared that the solar system was integrated within a day and that they have maintained a minimum interruption of their day-to-day operations[12]. The use of solar thermal energy in breweries is thereof declared reliable.

2.6.2 Hütt brewery

The integration of solar thermal energy at the Hütt brewery in Germany has shared light on the barriers to such systems. There needs a lot of procedural knowledge is required to plan a solar process heat plant which may be difficult to keep the planning time economical. Often the company staff cannot supply the desired data. Convincing the staff and management of companies presents another major problem for the implementation of solar thermal energy systems due to lack of understanding. Rebuilding effort for the integration of the solar plant into the overall system may be difficult. Lastly, there is a quick and safe possibility to create files for simulation of industrial loads for standard planning of solar plants for industry [13]. Hence the importance of this study for a brewery company in Lesotho, Maluti Mountain Brewery. The study will tackle such barriers.

2.6.3 Maluti Mountain Brewery

The processes that go into beer brewing at MMB are namely malt loading which is followed by malt transfer, malt milling, mashing, lautering, boiling, wort cooling, fermentation, maturation, filtering, washing of kegs and halls, filling, packaging, pasteurization, labelling and lastly packing into crates. Figure 1 and Table 2 show the temperatures at which this processes take place.

Maluti Mountain Brewery uses thermal energy in their boiler house and the brew house in which the boiler house heats up water up to 70°C, the water at ambient temperature is mixed with the condensate from the brew house and then returned to the brew house to be heated up more. The processes that occur in the brew house require hot water and steam.

The first process that requires thermal energy is mashing which occurs after loading of the ingredients into the mash tun. The mash is heated up to 63 °C, then the temperature is increased to 68°C,72°C up to the last temperature being 76°C by using steam fueled by coal. The mashing water is heated up to the 85°C and then transferred into the mash tun. The temperature is dropped from 85°C to 63°C so as to begin the mashing process. Figure 5 shows the mash tun at MMB.

Figure 5: Mash tun at MMB

Following the process of mashing, is separation of the wort with the spent grains and then the wort is transferred into the wort kettle. In this kettle the wort is heated up to 95°C using the steam volume of 185 hectoliters for an hour. The wort is passed into another vessel whereby the residues are separated from the wort. The hot wort is cooled using a heat exchanger with the cold water from the chiller, the hot water coming out of the heat exchanger at 70° C is transferred back into the hot water tank and heated up to 85°C. These temperatures are carefully regulated. The wort is allowed to cool so as to allow fermentation to occur at lower temperatures such as 30°C. Figure 6 shows the wort kettle at MMB.

Figure 6: Wort kettle at MMB

The beer brewing process is done around the clock (24 hours) with one cycle being completed within 8 hours, depending on the beer being brewed.

The boiler house is the central hot water boiling system for the makeup water (at T_{mains} temperature /cold water temperature) mixed with the condensate from the collecting tank which is called boiler feed water. The temperature of the boiler feed water is at around 70°C which is then heated up to 161.92°C in the boiler. The boiler feed water is made up of the makeup water and the condensate. The makeup water at temperature T_{mains} lowers the condensate temperature from 80 °C to 70 °C which makes heating of the boiler feed water more energy intensive and less efficient. A lot of coal in the boiler is required for this purpose.

The boiler is used for heating water to be used in other processes within the beer brewing. It is the main source of thermal energy to the brew house and the packaging house so there is a real need to increase the efficiency of the boiler in order to reduce the amount of heat and coal required in the boiler house. The efficiency of the boiler can be increased by preheating the makeup water or the boiler feed water using solar thermal energy[28]. One study has shown that the efficiency of a boiler can be improved by preheating the boiler contents using air preheater which uses flue gas[29].

Table 3: 2019 MMB Energy usage together with beer production

Production Volume of beer	HL(hectoliters)	440 285.40
Electricity supplied-Main Boiler House	kwh	313 063.0
Coal Supplied-Boiler 1	kg	916 568.0
Boiler 2	kg	860 908.0
Total coal	kg	1777 476.0

Table 3 shows the production details of MMB for 2019. The rate at which MMB purchased electricity from LEC for this year was at an industrial tariff while coal the price of buying coal at the year was R950/ ton ($65.50/ton) of coal. About $200418 is spent on coal for thermal demand. The operations of this company are expensive and environmentally unfriendly. This place receives solar radiation which can be used to displace a certain portion of electricity and coal.

2.7 The procedural designing of a solar thermal system and equations

The system needs to be properly sized to adequately serve its load. The initial step is the determination of the heat demand. It can be determined from the company record of their thermal demand or studying the company's processes to determine the load. The determination of solar resources of the site of interest is also another important step.

Maseru solar resource

It is important to know the meteorological data of the place in question to size and determine every aspect properly. The daily solar radiation in ranges between 5 kWh/m^2 and 7 kWh/m^2 [24], this numbers portray the availability of solar radiation in Lesotho which can be harnessed by solar collectors and used for different purposes. Table 4 shows the monthly solar radiation of Maseru [22].

In Zimbabwe, isolated solar PV home systems were designed and it is from this study that it was determined that the average solar irradiation of Zimbabwe is 5.7 Kwh/m^2/day. The radiation was suitable for harnessing and producing solar PV[30]. A lot of solar thermal energy can be harnessed from such irradiance.

Table 4: Monthly mean horizontal ground-derived solar radiation [kWh/m^2][31]

Lat	Lon	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sept	Oct	Nov	Dec
-29.45	27.58	7.2	6.8	5.8	4.7	3.91	3.42	3.4	4.6	5.89	6.3	7.0	7.6

The reason for the collection of the solar radiation data is to determine the amount of solar radiation that can be usable to the solar thermal collector. The most important figure is average daily global irradiance on a horizontal surface[24]. The collected solar radiation data is used to calculate or find all the parameters that are needed to obtain radiation on a tilted surface (Gt), Equation 1 [32] is used to calculate radiation on a tilted place which is dependent on Equation 2, Equation 3, Equation 4,Equation 5 [32], Equation 6, Equation 7, Equation 8 and Equation 9 [33].

$$G_T = G_{Bt} + G_{Dt} + G_{Gt} \qquad \text{Equation 1}$$

Beam radiation- (G$_{Bt}$

Diffuse radiation - G$_{Dt}$

Ground-reflected solar radiation - (G$_{Gt}$)

$$G_{Bt} = G_{Bn} Cos\theta \qquad \text{Equation 2}$$

$$G_B = G_{Bn} Cos\theta_z$$ Equation 3

$$R_B = \frac{Cos\theta}{Cos\theta_z}$$ Equation 4

R_B – beam radiation tilt factor

$$G_{Bt} = G_B R_B$$ Equation 5

ϕ-Latitude, the angular location north or south of the equator, north positive; $-90^\circ \leq \varphi \leq 90^\circ$.

δ- Declination, the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive; $-23.45^\circ \leq \delta \leq 23.45^\circ$.

$$\delta = 23.45 sin(360 \frac{284 + n}{365})$$ Equation 6

n-day number

β - Slope, the angle between the plane of the surface in question and the horizontal; $0^\circ \leq \beta \leq 180^\circ$. ($\beta > 90^\circ$, means that the surface has a downward-facing component.) **γ**- Surface azimuth angle, the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive; $-180^\circ \leq \gamma \leq 180^\circ$. **ω** -Hour angle, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour; morning negative, afternoon positive.

$$\omega = 15(t - 12)$$ Equation 7

t= hour number, whether it is hour 1 or hour 2

Θ- Angle of incidence, the angle between the beam radiation on a surface and the normal to that surface.

$$\cos\theta = \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega \qquad \text{Equation 8}$$

Θz- Zenith angle, the angle between the vertical and the line to the sun, that is, the angle of incidence of beam radiation on a horizontal surface.

$$\cos\theta z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \qquad \text{Equation 9}$$

One other step that should be taken before implementing a solar thermal system is studying the site for space availability for the mounting of the collector array.

Water heating plays the central part in the thermal energy systems, it can be integrated in any solar thermal systems to serve different purposes such as preheating or delivering the exact amount of thermal energy needed Figure 7 shows a schematic diagram of a solar water heating system whereby a smaller storage tank receives heated water by the solar loop which is then passed on to the load. If need be, there is boosting of the water temperature to the required load temperature, T_{load}. An assumption of a well-mixed storage tank of mass (M) and fluid specific heat capacity (Cp) is made and simple energy balance can be expressed in Equation 10[15].

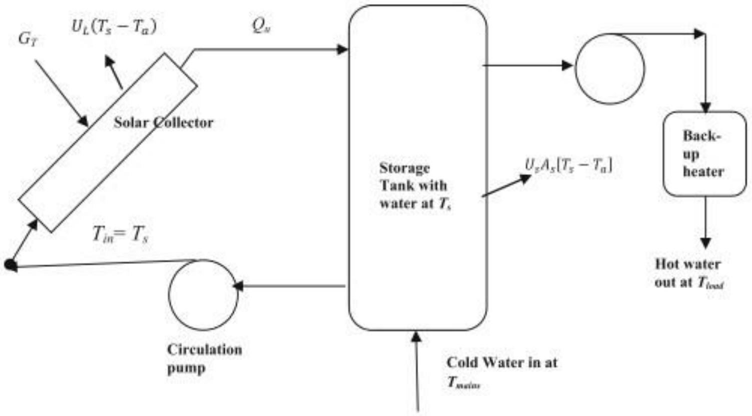


Figure 7: Schematic diagram of a solar water heating system[15]

Ts-storage tank temperature, Ta-ambient temperature.

$$MCp = \frac{dT_s}{dt} = Q_u - L_s - U_s A_s [T_s - T_{\mathrm{a}}]$$ Equation 10

The rate of change in the internal energy of the storage tank is equal to the energy interactions which occur over a time step Equation 11[15] shows how this is calculated. In the presence of a heat exchanger with the solar thermal system Equation 12 is used to calculate the rate of change in the internal energy of the storage tank.

$$T_s^+ = T_s + \frac{\Delta t}{(MCp)_s}(Q_u - L_s - U_s A_s (T_s - T_a)$$ Equation 11

$$T_s^+ = T_s + \frac{\Delta t}{(MCp)_s}(Q_u - L_s - \mathrm{U_s A_s (T_s - T_a)} \times \mathrm{He}$$ Equation 12

The energy interactions are solar-collector-generated heat input (Qu), the rate of heat removal (Ls), He is the heat exchanger coefficient and the storage tank heat losses UsAs. A time step $\Delta \mathrm{t} = 1\mathrm{h}$. Qu is calculated using Equation 15, Ls is calculated using Equation 16 and the storage tank area (A_s) is given by Equation 13 (assuming that the ratio of the storage tank length to diameter is 1:2) [15].

as

– 2

Equation 13

$A_s = (5.81 \times V)3$

The temperature of the cold water to be heated has to be determined. Cold water temperature (T_{mains}), was calculated as it varies with the ambient temperature. The cold water temperature was assumed to be equal to the soil temperature as the pipes are embedded a few meters in the soil. The relationship between the ambient temperature and soil temperature gives of the cold water temperature. Equation 14 shows this relationship. The standard error for this equation is 4.15°, [34].

$$y = 4.648 + 0.986x \qquad \text{Equation 14}$$

y- cold water temperature x-ambient

temperature

The rate of useful thermal energy gained for a collector of area (Ac) with solar irradiance ($G_{T)}$ incident on its plane, is given by the Hottel-Whillier-Bliss equation, Equation 15 [15].

Equation 15

$$Q_u = A\{G_T K_{\alpha\tau} F_R(\alpha\tau)_n - F_R U_L(T_s - T_a)\}$$

Solar collector characteristics data $F_R\alpha\tau$ (the y-intercept of the collector efficiency curve); F_R U_L (the negative of the slope of the efficiency curve) and the incident-angle-modifier $K\alpha\tau$ are used for the prediction of collector energy performance under specific operating-temperature and climatic conditions. The data is provided by manufacturers' product data sheets[15].

$$L_s = m_s c_p(T_s - T_{mains}) \qquad \text{Equation 16}$$

m_s (kg/s)- the mass rate of water withdrawal, C_p-the specific heat capacity of water; T_s- temperature of water in the storage tank and T_{mains}-temperature of the cold water from the mains supply. Discount rate (d) is calculated using Equation 17, whereby i-interest rate per annum and j- inflation rate per annum[15].

$$d = \frac{1 + i}{1 + j} - 1 \qquad \text{Equation 17}$$

Annualized cost of a solar collector is determined using Equation 18, whereby Ac (m^2)- array area, Cc- cost per unit area ($/m2) with annual operation and maintenance cost OM over years of warranty [15].

$$C_{annual} = A_c C_c \frac{d}{1 - (1 + d)} - OM \qquad \text{Equation 18}$$

The hourly conventional energy displaced by solar energy each hour is 3600 x SF x m_{load} $(T_{load}$ $+T_{mains})$. The solar fraction is the ratio of the amount of input heat energy that is supplied by solar energy into the total input energy that is required for the water heating application for a certain period, Equation 19 and Equation 20 (mass flow rate) have to be determined before finding the solar fraction (percentage of the energy demand serviced by solar energy)[15].

$$\mathrm{SF} = \frac{m_s(T_s - T_{mains})}{m_{load}(T_{load} - T_{mains})}$$ Equation 19

m_{load}-amount of water heated per hour.

$$m_s = \mathrm{MIN}\left(\frac{T_{load} - T_{mains}}{T_s - T_{mains}}\right) m_{load}$$ Equation 20

The selection of a collector is central in the designing of a solar thermal system. There are different methods of solar collector appraisal, one is energy per dollar criteria which is based on the cost-effectiveness of using a solar collector. The energy-per-dollar (EPD) comparison metric (Equation 21), calculated as the annual heat energy output of the collector in an average year, at the so-called “sweet-spot” size of the collector array, divided by the annualized life-cycle cost, based on warranty life and collector initial cost, was recommended as instructive for comparing the cost-effectiveness of different solar collectors[15].Figure 8 shows the relation of the EPD with the collector specific yield and the solar fraction.

Equation 21 $$\mathrm{epd} = \frac{\quad}{C_{annual}}$$ Q_{annual}

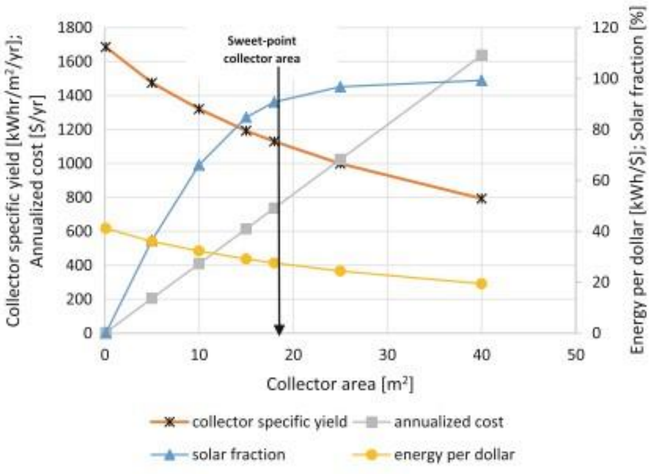


Figure 8: Variation of solar fraction concerning collector specific yield, annualized cost, and energy per dollar with collector area deployed in a solar water heating system[15].

Selection of a collector is central in the designing of a solar thermal system. There are different methods of solar collector appraisal, one is energy per dollar (EPD) criteria which is based on cost effectiveness of using a certain solar collector at the climatic conditions in question as rated by Solar Ratings & Certification Corporation (SRCC) [15]. Collectors are ranked with respect to their EPD at the highest Net Present Value of Solar Savings and then the collector with the highest EPD is employed. According to the energy-per-dollar comparison metric the most cost effective collector area is at the knee of the solar fraction curve [15]. After selecting the most cost effective solar collector, the most cost effective collector area determined. The value to be maximized when designing the most cost effective solar collector area is the NPVSS which varies with the marginal specific yield, NPVSS is calculated using Equation 22 [15].

$(L_{annual} \times P_E)(\ 1 - [1 + d]^n$ Equation 22 NPVSS $=$ ______________ _____________

$\eta_E\ d - (A_c C_c + V_s C_s + C_{BOS})$

PE -the price of electricity [$/kWh], η_E- the electric-to-heat efficiency, Vs the hot water tank storage volume, Cs- the cost of the storage tank per unit volume. C_{BOS}-cost of balance-of-system components (inclusive of installation labor costs) Annualized cost of a solar collector array of the area- Ac (m^2) and Cc- cost per unit area ($/$m^2$), C_S –the cost of the storage tank. The annual solar energy contributed -L_{annual} (kWh) [15]. All the equations that are mentioned, have to go into developing a solar thermal system while ensuring that the system is also cost effective.

2.8 Economics related to solar thermal energy

There are a number of ways through which project appraisal can made, namely net present value (NPV), payback period, internal rate of return and profitability index[35].These are the methods of determining the economic viability of a project. The best method to use in determination of the economic viability of a project is net present value (NPV), this is because it determines the present value cash flows formulated on the opportunity cost of capital while establishing the value added by the project to the investors [35].

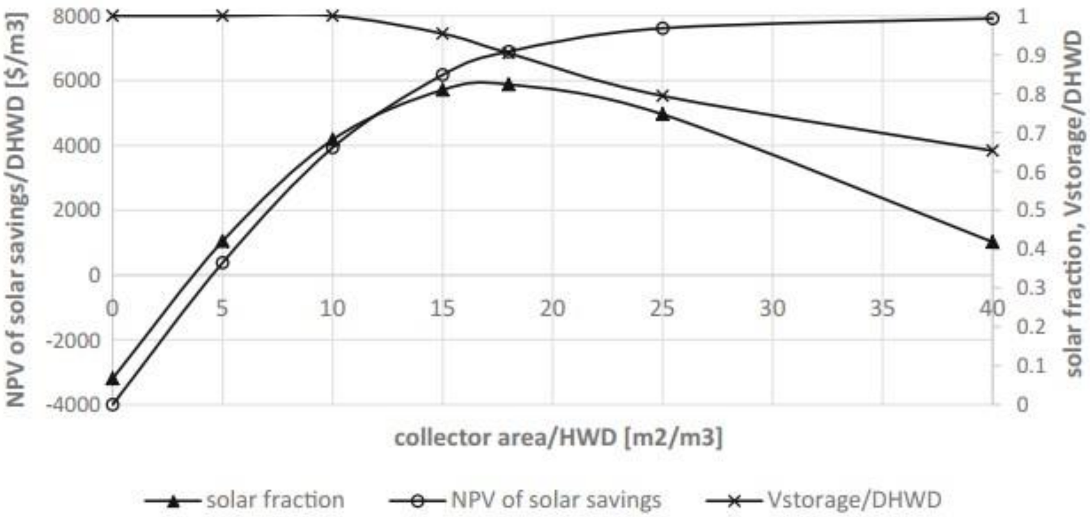


Figure 9: optimal collector area and the solar fraction to be employed for a certain solar thermal system in relation to the Net Present Value of Solar Savings (NPVSS).

Figure 9 shows the optimal collector area and the solar fraction to be employed for a certain solar thermal system in relation to the Net Present Value of Solar Savings (NPVSS). When the number of collectors is increased, the NPVSS also increases but there is a point where the NPVSS starts to decrease, it is at this point that the collector area stops being economical. The marginal specific yield of collectors decreases with increasing the collector area, this results in the solar fraction rapidly increasing and then flattening as the collector area increases Figure 9. The optimal collector area is found at the region of the graph where the NPVSS starts to decrease with increase in the collector area which in turn decides on the solar fraction and the storage tank ratio to be employed. A certain increase in the number solar collectors, increases the temperature within the collector array which therefore increases the thermal losses which therefore makes increase in the collector area less economical [19].

The solar fraction may not be 100% with regards to the economics, increasing the number of collectors may be less economical than supplementing a certain solar faction with conventional energy resources. It is therefore important to take into account the economics of using other conventional energy resources in the heating systems in order to make an informed decision when designing the most cost effective solar thermal system.

It is expected that brewery companies will perpetuate spending capital on effective energy conservation measures which will still meet its taste, drinkability and quality requirements. Therefore, for individual plants there is a gap for further research on the economics of those measures together with their applicability in different beer brewing companies in order to analyze the implementation of the selected technologies[26].This study will pursue this mission of the solar thermal technology.

The cost of solar technologies is decreasing but the financial investment in solar remains more stable than many of the markets for fossil fuels. Thus, the largest driver of a collector’s costeffectiveness is often the price of alternatives, like coal, oil, and natural gas, not the cost of the collector itself. Hence it is important to build a model that will align the cost-effectiveness of solar collectors in comparison with alternatives of energy. It is easier to justify the use of solar thermal energy when fossil fuels become expensive[9].

Another method of project appraisal is the payback period. This is the calculated period through which the initial investment into the project will be recovered [35]. This is criterion of rejecting the project of accepting the project.

One other method used to determine the profitability of a project is by the use of internal rate of return. This was done by variation of the discount rate with the net present value. The point whereby the NPV is zero that is where the IRR of the system is found, the rate of return on initial investment [36]. The IRR does not take economies of scale and dollar value of the project into consideration. It is not able to differentiate between projects with the same IRR and different dollar returns [35].

Lastly, profitability index is used for the same purpose. The ratio between the discounted cash flow and the initial cash outflow indicates the value of the times that the investment is returned in the form of discounted cash flows [35].

A study conducted in Europe for the meat industry indicated that the use of evacuated tube collectors can be profitable in a large number of locations. The type of energy supply in the industry and the difference in energy price sources in each country affect the size of solar systems and the reduction in annual energy consumption and the savings generated[22].

2.9 **Sizing of the storage**

There size of the storage tank for solar water heating system has to be determined when designing such a system. One method is the one that is commonly used for domestic solar water heating system whereby the size of the storage tank is determined by the daily hot water demand [37]. Sizing a system this way may bring about the issue of oversizing or under sizing of storage tank. This is because during the sunshine hours, water is heated more than during the morning and the evening hours (where there is less radiation) which in turn need to be mixed with cold water. Therefore, the amount of hot drawn during the sunshine hours is lower than the water drawn in the absence of the sun. The domestic water heating system storage size also has to be designed in such a way that the fact that water usage varies throughout the day is taken into consideration. It is import to ensure when sizing the storage tank, it does not exceed its critical threshold which is the boiling point of water on all weather conditions [15].

For instance, the solar water heating system in Zimbabwe had maximum hot water withdrawal at 7 and 8 am. It then rises from 9 am to 2 pm due to powerful solar radiation, irrespective of some substantial hot water withdrawal[15]. The rate at which temperature rises, slows down (between 2 pm and 5 pm) because of tapering down of the solar radiation and little withdrawal of hot water during this period. After 5 pm, there is no radiation but there is a substantial withdrawal of water. There are also storage tank heat losses which influence the lowering of the tank temperature. This is typical behavior all year round.

One other method which is used by hydrologists in determining the size of the storage capacity of water by the use of Rippl mass curve method [38]. This method uses the most critical period of recorded flow in order to dete0rmine the storage capacity. This is the period whereby the water in the full reservoir is exhausted, passing through a number of stages and then completely empties without any spillage. In this method, “a sequence of stream flows containing a critical period is routed through an initially full reservoir in presence of specified demands” [38]. The storage (reservoir) capacity is the determined by establishing the maximum difference between the cumulative demand curves and cumulative inflows[38].

2.10 **Heat Exchangers**

In a solar water heating system, there has to be transfer of heat between the solar loop and the water being heated. In some solar thermal systems, there are heat exchangers while there are no heat exchangers. The way to pass heat from one medium to another is through a heat exchanger. A heat exchanger has a “wall” which is a membrane separating the two fluids passing through it. Some heat exchangers are double walled while others are single walled. The modern models are single walled because there are comparatively more efficient. The fact that the heat passes through less material that is made of either stainless steel or copper makes the heat exchanger more efficient [39].

In the installation of solar systems, it was ruled that the heat exchangers used should be the double walled ones. This was because of the infancy stage at which solar thermal technologies was at then. Those systems used infancy and toxic liquids were used as the solar fluids hence the need for double walled exchangers. These exchangers are still available but unnecessary in systems where the solar fluid is non-toxic (modern systems) [39].

The doubled walled heat exchangers have an advantage which is given by the issue that there is usually a gap between the two layers, for "positive leak detection" so if it so happens that either side gets damaged, the fluid that is leaking will be quickly discerned and then the heat exchanger can be repaired or replaced [39].

The transfer of heat in the heat exchangers is done through the use of pipes or plates. The two liquid fluid are then manipulated through plumbing so as to allow antagonistic fluid movement. This counter-flow arrangement is done in order to make sure that as much heat as possible is transferred between the fluids because the temperatures of the two fluids are kept at maximum all the way through the heat exchanger. The more efficient heat exchanger is the one that uses plates because the two liquids pass through a stacked block of alternating rectangular plates with fluids always moving in opposite direction [39].

2.11 **Emissions**

The benefit of using solar thermal systems is the reduced reliance on fossil fuels which leads to reduced greenhouse gas emissions (Equation 23). The emissions are not easy to quantify and they are external to the system users[40]. It is important to quantify these great outcomes of using solar thermal systems in order to know the impact one is doing to the environment and how much they are saving. There is a need for a model that will simulate the greenhouse gas emissions averted (which in some countries are rewarded in monetary terms) with ease together with the savings made from substituting fossil fuels with renewable energy forms. This study will provide one such model which will focus on solar thermal systems.

$$\begin{aligned}\text{greenhouse}\ gas\ emissions\ averted &= CO2\ emission\ factor \times fossil\ fraction \\ &\times annual\ energy\ produce\ by\ so\text{lar}\ \text{energy}\end{aligned} \qquad \text{Equation 23}$$

2.12 **Simulation Models**

Solar thermal system designs are done through various simulation models. "To achieve sustainable and green design, performance simulations are often used to verify these criteria and modify the design. The conventional approach of manual trial-and-error is too time-consuming to be practical" [41]. There are different programs that can be used for this purpose. These are CARNOT, which uses the commercial software called MATLAB Simulink, TRNSYS, and
Transol

TRNSYS is a widely used simulation program[42]. This is complete but extensible simulation program[33]. Most engineers and researchers use this program to validate new energy concepts, from the designing of simple domestic hot water systems to the designing of buildings and their equipment. This program uses the common programming languages such as PASCAL, FORTRAN and C++ [33]. TRNSYS is an open source software but the fact that it uses programming languages which may not be familiar to all users poses a problem.

There is another model called Transol, it is used for designing, making calculations and optimizing the solar thermal systems. It is based on TRNSYS models but does not have a single configuration as it includes about 40 system configurations. This model provides the collector area to install for a solar thermal system but it is unable to determine the energy savings associated with the installation [43]. If the solar savings cannot be evaluated by the program being used by the designer, it is difficult to determine the cost effectiveness of that system which plays an important role in the system design [44].

CARNOT (Conventional and Renewable Energy Optimization Toolbox) is a tool for simulation of thermal systems with conventional and renewable components using the commercially available MATLAB-Simulink as an environment [45]. This simulation model was developed and used in the food industry (diaries and breweries) case studies and it still needs further investigation to verify the application of this methodology[46]. Even though this is the case, the methodology is not ideal because of the programming software that it uses (which is not open source and not everyone is familiar with the programming languages that it uses). There is need for a much easier and user friendly model.

Selection of the most cost-effective solar thermal plant using an FPC was studied, the methodology used cost equations for flat plate collectors with a model that linked MatLab and General Algebraic Modeling System (GAMS) platform[47]. Even though this model provides the designer with all the necessary information for decision making, it has its shortcomings. It focuses only on flat plate collectors and excludes other types of collectors. It is important to note that the designs built with this model are carried out for the conditions that guarantee operation throughout the year while showing a solar saving of up to 50% and less than six years of payback time [17]. Simulation models such as Matlab are not open source and this poses an economical problem.

In the designing of a solar thermal system for breweries there is a need to develop a model customized for this purpose only, so that it does not offer limited detail considering issues of solar thermal beer brewing. The simulation model needs to be open source and uses the commonly known Excel based mathematical equations. This study is aimed at developing such a model which will be used in the designing of a solar water heating system at Maluti Mountain Brewery which will be used for preheating boiler water. The model will simulate the right collector to use for a certain case, cost effectiveness of using such a collector and the cost effectiveness of the entire system while encompassing all the beer brewing processes. Simulation of solar thermal systems has been done in a study conducted in Zimbabwe for solar water heating system using an Excel based model[15], which in turn gave out reliable results. This shows the feasibility of using MS Excel to do simulations of solar thermal systems designs

3 METHODOLOGY

3.1 Background

The research methodology is divided into 6 parts: the production cycle of MMB was studied on site and then the processes that use thermal energy from coal were established. The aim is to just reduce the conventional energy content of MMB so preheating of the boiler make up water was decided upon as a way to reduce the amount of coal used at MMB. This was followed by designing of a proposed retrofitted solar thermal design for the case of Maluti Mountain Brewery (MMB) to improve the efficiency of the boiler, determination of the solar thermal energy demand for MMB, modelling of the solar radiation data and temperature data of MMB location using MS Excel tool, solar thermal system sizing using economic data (collector costs, storage costs, inflation, interest rates) in MS Excel tool and lastly, designing of the most technically and economically viable solar thermal system for MMB.

The MS Excel model was built using the solar water heating system equations and solar radiation equations. The system inputs are solar radiation data, economic data and solar collector parameters which will be used to perform calculations using the input equations. The Excel tool is designed in such a way that the sheets are linked and changing the variables (inputs) to these equations, influences the outputs of those equations. These are the Equation 1 up to Equation 22 [32],[33].

The last three parts of the methodology are based on the procedure that was followed in designing a solar water heating system for a hotel in Zimbabwe [15]. The difference is that it did not follow the Collares-Pereira and Rabl model which uses the monthly-average values[15], as it was done for the system in Zimbabwe. The meteorological data (daily data for years 2005-2016) for the location in question was collected.

The approach can be used in designing solar water heating system for industrial purposes. In this case a MS Excel model designed for the brewery was used to simulate and optimize results for MMB solar water heating system. An Excel model was developed it which was specifically made for the thermal energy demand of breweries. It was designed in such a way that the preheated water temperature does not exceed 100°C.

There are different ways through which solar radiation reaches the surface of the Earth and this is evaluated using a set of angles and equations. There is need to study the solar resource of a place when designing a solar thermal system so as to know the amount of energy from such that can be harnessed. The solar radiation angles were calculated using Equation 6 to Equation 9 [33].

Energy demand can be determined through energy intensity or specific energy consumption, as it indicates the amount of energy that is needed per unit of output [26]. An alternative done specifically in domestic hot water systems is through the estimation of the average daily hot water consumed for different entities such as sport facilities, accommodation and residential buildings [37]. In determination of energy demand for the operation of a steam boiler, the hourly water demand for a typical week was determined for this purpose [48]. This method possesses a comparatively higher degree of accuracy as the demand is done on an hourly time step and then average over time. This is the method that was used in the energy demand determination for MMB in order to design a solar thermal energy water heating system. The average hot water demand was established for over a year and the system was designed for that. Designing the system for the peak demand would then lead to system oversizing because that certain amount of hot water demand may be for just a few days as it differs with what is being brewed.

The system did calculations for over a typical year. The ambient temperature for each day was taken into account and used to determine the cold water temperature for each day, collector losses, collector efficiency and storage tank temperature for every day. This was done carefully ensuring that the water in the storage tank does not reach boiling point which 94°C in Maseru (after a series of experiments of determining the boiling point in Maseru). The amount of makeup water that needs preheating to 94° C was determined MMB heats different amounts of water in the boiler, depending on what beer is being brewed. The information was obtained from MMB yearly records. The amount of makeup water was determined (which is the water aimed at heating with solar thermal energy). Figure 10 shows the existing system at MMB whereby water is heated. Table 5 shows the average daily hot water demand for MMB.

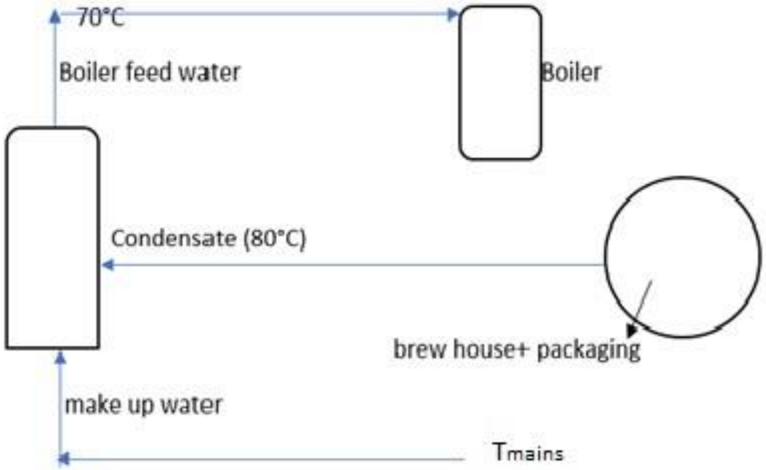


Figure 10: The existing system at MMB which use thermal energy

Table 5: Average amounts of daily hot water demand and flow rates for MMB

Average amount of makeup water	7.42 m^3
Average amount of boiler feed water	51 m^3

Average amount of condensate	44 m^3
Percentage of makeup water/total boiler feed water	12%
Condensate flow rate	0.51 m^3/s
Boiler feed water flow rate	0.59 m^3/s

3.1.1 Solar thermal system design

The main source of hot water and steam in the MMB processes in the boiler which is fueled by coal. The water from the boiler goes to the brew house and packaging house to be used, the unused water (still possessing heat) is returned to the boiler house and mixed with the cold makeup water (replacing the used water) which lowers the condensate temperature from approximately 80°C to 70°C. The condensate and makeup water mixture is carried into the boiler to be heated and carried to the brew house and packaging house all over again, Figure 10 describes this process. This is a continuous process for 24 hours and 365 days. The amount of water heated only differs slightly due to the brand of beer being brewed on a particular day but can be averaged.

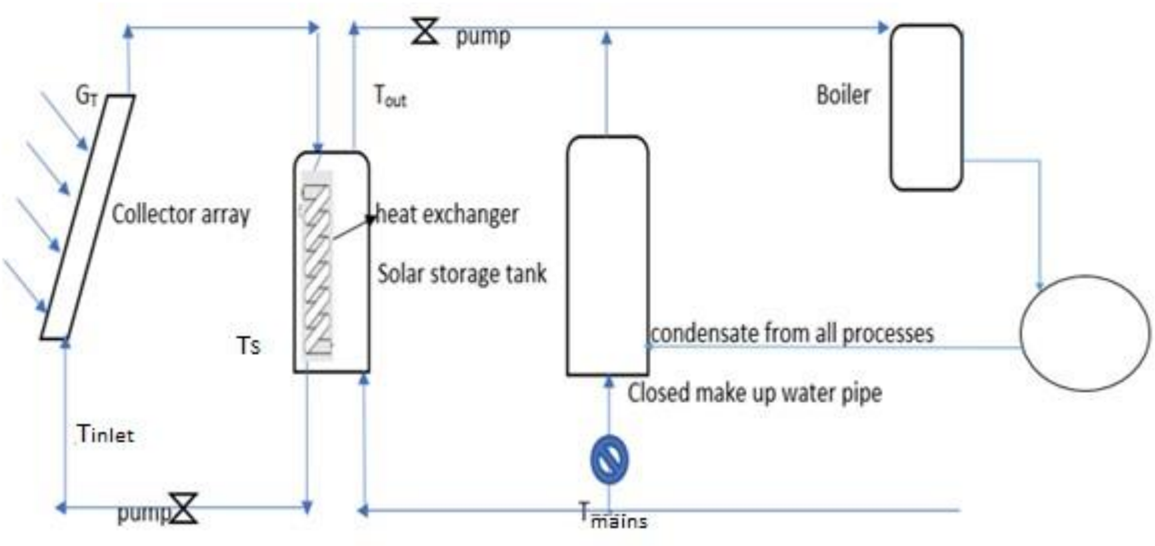


Figure 11: Retrofitted solar thermal system design at MMB

Figure 11 shows the proposed retrofitted solar water heating system for MMB. The existing system Figure 10 is supplemented by a solar water heating system which possess a collector array to harness the solar radiation, pipes to carry water between the storage tank and the collector array, a heat exchanger within the storage tank to warm the cold water through transfer of heat between the glycol water (from the collector side) and the cold makeup water from the water source. Glycol water is used because it has a high boiling point comparative to water so even if the collector temperature increases it will not boil as easily as when it was water which would therefore lead to destruction on the pipe works[49]. Also, glycol has a low freezing point such that in the freezing weather conditions of Lesotho is will remain a fluid.

There is a pump to carry water up to the collector array after heat exchange between water and glycol water. The heated water is the carried out at outlet temperature (T_S). The solar heated water will be pumped to a mass flow rate equaling to the condensate flow rate subtracted from the boiler feed water flow rate. The sum of the makeup water flow rate(solar heated),Table 6 and the condensate mass flow rate has to be equal to the flow rate of the boiler feed water. Table 6: Flow rate of the solar heated make up water

Solar heated make up water flow rate	0.09 m^3/s

This is to ensure that the mass flow rate of the condensate and the boiler feed water is maintained even with the new additions to the system to avoid many changes being done to the system; also to avoid backflow of water into the condensate tank[25]. The condensate (approximately 80°C) mixes with the solar heated makeup water (approximately 95°C) in the pipes and then goes into the boiler. The makeup water is heated to a maximum of approximately 95°C so as to make sure that it does not lower the condensate temperature when mixing while making sure that it does not boil from solar water heating. The boiler feed water is then carried into the boiler and then heated. To get a maximum of 95°C from solar water heating, the system has to be properly designed according to the available resources.

3.2 Solar radiation data modelling

In the thermal and economic analysis of the solar preheating of steam boiler feed water ,TMY (typical meteorological year) hourly weather data from Rio de Janeiro was used in solar radiation modelling[48] and also in the designing of a solar water heating system in Zimbabwe[15]. This the commonly used method of solar radiation data collection even though less accurate comparative to ground data.

The meteorological data of MMB (latitude -29.297^{o} and longitude 27.483^{o}) for 2005 to 2016 was used to calculate the TMY data [50]. The ambient temperature, global horizontal radiation, diffuse radiation and beam radiation were obtained. The data was collected from satellite records because the ground data, which is more precise, is not available with a continuous temporal resolution [31].

These equations were input into the MS Excel tool in order to perform the calculation of radiation on a tilted plane for everyday of every year (2005- 2016). Radiation on a tilted plane was calculated using (ratio of beam radiation on a tilted surface to the horizontal surface) is an input in the model. The solar radiation data was used to determine the solar radiation angles namely: the angle of incidence (zenith angle), declination angle and the hour angle Equation 6, Equation 7, Equation 9 respectively which are mentioned 2.7.

Temperature calculations

The temperature of the makeup water, change in temperature and storage tank temperature have to be determined from the results of the modelled solar radiation data. In the determination of the cold water temperature. Equation 14 was used [15]. In another case the cold water temperature was assumed to be equal to the average annual air temperature[37], this lacks accuracy because often times the cold water pipes are embedded in the soil.

Condensate temperature is 80°C coming from the brewing processes but it is then reduced to 70°C when mixed with the makeup water, leaving the boiler feed water at temperatures around 70°C. To avoid lowering the condensate temperature while improving the boiler efficiency, the solar water heating system was introduced.

The maximum temperature at which the makeup water is heated(T_{load}) is 100°C, this is the set temperature in order to make sure that the condensate temperature does not drop from 80°C but rather increase and also does not reach the boiling point of water.

The temperature of the hot water in the storage tank (T_s) was calculated using Equation 12 [15]. The equation has another input as heat exchanger effectiveness as it affects the storage tank temperature. He- Heat exchanger effectiveness which was collected from the market.

The solar fraction(SF) was calculated Equation 19 using in order to know the amount of heat input supplied by solar thermal energy into the total energy that is required by the entire system. The equations and values were also input into the MS Excel tool to perform calculations for each hour for years 2005-2016.

The heat exchanger is used in the solar water heating system so as to avoid calcification that can be caused by hard water. Also, the heat exchanger is used to allow the use of antifreeze in the collector loop, it is placed between the storage and the collector. It is crucial that heat exchanger performance is as high as possible with a very low pressure drop[37].

3.3 **Collector Selection**

A solar collector to employ in a solar thermal system has to be chosen. It can be chosen according to different selection criteria being its efficiency and operating temperature amongst others.

The collector selection for a cost effective solar thermal design in Zimbabwe was done through the energy per dollar criteria[15]. Because the solar thermal system design for MMB is aimed at being cost effective, the energy per dollar criteria was used.

Different collector information was collected as rated by SRCC [51] which was used in determining the useful energy gained (Qu) using uses the optical efficiency of collector (yintercept) and heat loss coefficient of a collector (slope). The energy per dollar is calculated at optimum solar collector and then compared from collector to collector.

3.3.1 Energy per dollar criteria

The collector area was varied until the sweet spot (highest net present value of solar savings) and the corresponding energy per dollar calculated for each collector. Different collectors have different parameter as rated by SRCC and they were used for calculating the energy per dollar for each collector using the MS Excel tool. These parameters are heat loss coefficient, optical efficiency obtained from the collector product sheets, the collector cost was also used in the calculation of the EPD. EPD was calculated using Equation 21 for each collector. Selection of the optimal collector was done by ranking the collectors using the energy per dollar criteria, selecting the collector with the highest EPD to be the optimal one.

3.3.1 Selection of a heat exchanger

There are coil and plate heat exchangers of different sizes. Solar thermal systems with solar collector areas of 15 m^2 and more require the use of plate heat exchangers [37].When selecting a heat exchanger for a system, it needs to be sized accordingly; the size of an internal heat exchanger has to be 1 square feet/ 14 square feet of collector area. When sizing a smooth tube heat exchanger, approximately 0.2 m^2 of heat exchanger surface is needed per collector area m^2. When sizing the corded tubes heat exchangers, there needs approximately 0.3 – 0.4 m² of heat exchanger surface per m² collector area[37].

3.4 Optimal System sizing

A solar hot water system can be sized according to the thermal energy demand, to meet the hot water demand [37]. This may not be ideal because it is expensive to implement such because the system efficiency lowers with increase in the collector area, also the system costs increase. Multiple smaller collectors may be less efficient than one large system of the same area due to losses in the collector connections. The small multiple collectors are expensive to use and because the system is aimed at being cost effective, they will not be ideal. When the collector area increases, the thermal losses within the collector array increase so optimal system design is need to curb this problem[15]. A method used for designing the most cost effective solar hot water system is optimization of the net present value of solar savings. The collector area with the highest net present value of solar savings is the most cost effective system design[15]. This is the method that was adopted for designing the solar hot water system because it is economically beneficial. The possible limitation for this method is that the most cost effective collector area may be not give the maximum heat output but the energy per dollar criteria which was used in collector selection takes into consideration the technical and the economic parameters being collector characteristics, collector warranty and costs. The NPVSS of the collector with the highest EPD was then determined.

The economic data relating to the system namely interest rates and inflation rates were collected from statistics reports of Lesotho, coal price/kWh was obtained from the 2019 reports, collector cost, storage cost and heat exchanger cost were collected from the market. The energy per dollar collector appraisal method was used in this case to select the optimal collector as it was deemed best. The other parameters costs estimation of the operations and maintenance percentage to the capital costs, estimation of the percentage installation, inflation rates and interest rate in order to calculate the price escalation and discount rates. Discount rate was calculated using Equation 17 and the annualized cost was calculated using Equation 18

After the determination of the optimal solar collector, the most cost effective collector area is then designed, using NPVSS as the objective function (the collector area with the highest NPVSS was deemed best. The collector area was varied, taking a very close look at what happened to the NPVSS. It increased with the increase in the collector area up to a point where the NPVSS started to decrease with the increase in collector area. It is at this collector area that the it was deemed cost effective Equation 22 was used to calculate NPVSS.

3.4.1 Storage Sizing

The storage tank size was determined using the mass balance curve and is introduced in order to ensure that the system still get solar heated water even in the absence of the radiation (at night). The effective collector heat output for a certain day together with the amount of heat needed by the load were determined and the area under the different curves equalized by varying the collector area. The collector area was varied up to a point where the sum of the effective collector heat output equals to the sum of the actual heat going to the load. This was done to ensure that the heat demand is fully serviced by the heat from the collector after removing the thermal losses. The curves of the cumulative heat going to the load and the cumulative effective collector heat output were drawn against each other and the difference between then were calculated. The maximum deficit and the maximum surplus between the two were determined and then summed up together to give the actual storage size.

3.4.2 Emissions

It is important to determine the amount of greenhouse gas emission averted by replacing conventional energy forms with renewable energy forms. These are the environmental benefits of using solar thermal energy at MMB. The CO2 gas emission factors were determined [52] together with the fossil fraction at MMB. These values were used in determining how much of the of the emissions have been curbed by introducing solar thermal energy into the system which used coal. Equation 23 shows the determination of greenhouse gas emissions averted. In the design of a solar hot water system in Zimbabwe [15], the same equation was used when determining the amount of greenhouse gas emissions averted.

3.4.3 Simulations

When designing solar thermal system, various software such as Matlab and TRYNSYS are used but the downside is that is that they are not open source. Moreover, not every individual understands the programming languages of these software. There is a simpler method of designing solar thermal systems namely MS Excel. In the designing of a solar hot water system for a hotel in Zimbabwe; MS excel tool was used to perform all the needed simulations and system optimization[15].

A computer spreadsheet program was designed to handle the thermal and economic calculations necessary for appraisal of solar collectors and optimal sizing of the most cost effective solar water heating system for MMB.

4 RESULTS AND DISCUSSIONS

4.1 **System Energy demand inputs**

The daily hot water demand for MMB is varies due to the type of beer being brewed but the average daily hot water demand was determined. The boiler makeup water varies from 30 hectoliters to 100 hectoliters, the average boiler makeup water is 74 hectoliters (7.42 m^3), this is the amount of water needed to be preheated with solar thermal energy. This is the amount of water that was used to design the system.

The mass flow rates of the system were established. This was done because when the mass flow rate is constant, the only parameter that affects the collector efficiency is the global irradiance.

But change in the mass flow rate affects the collector efficiency. The higher flow rates generate more turbulent flow which in turn cause a higher rate of interaction with the pipe walls, allowing the heat transfer rate within the fluid to increase and therefore increasing the efficiency [53].

The mass flow rates of the makeup water, boiler feed water and the condensate have to be maintained to constant values because the mass flow rate determines the amount of the transfer fluid in the collector that can be heated.

The mass flow rate values were averaged; the mass flow rate of the makeup water was found to be 0.09 m^3/s while the boiler feed water mass flow rate average was 0.59 m^3/s and the condensate flow rate being 0.51 m^3/s. The flow rate of makeup water from the solar storage tank was found from subtracting the condensate mass flow rate from the boiler feed water flow rate. The plant operates for 24 hours.

4.2 Solar radiation data modelling and temperature results

Solar radiation data was modelled in order to determine the amount of heat that can be usable to solar collectors. The ambient temperature was used to determined collector usable heat output (Q) while the horizontal radiation and diffuse radiation were used in the determination of solar radiation on a tilted plane, which is the radiation usable to the solar collector. Table 7 shows the ambient temperature, horizontal radiation, beam radiation and diffuse radiation for a typical day for years 2005 to 2016. The ambient temperature ranges between 16°C and 30°C.

Table 7: Hourly Ambient Temperature, Horizontal irradiation, diffuse radiation (Gd) and beam radiation (Gb) at MMB for a typical day in June for years 2005-2016 from satellite records [kWh/m^2]of Maseru [27]

Time and day	Ambient temperature (°C)	Horizontal irradiation G(h)	Gb(n)	Gd(h)
0:00	21.58	0	0	0
1:00	21.71	0	0	0
2:00	21.84	0	0	0
3:00	21.97	0	0	0
4:00	22.1	0	0	0
5:00	22.23	0	0	0
6:00	22.36	11	0	11
7:00	22.49	343	692.05	92
8:00	28.17	576	827.06	113
9:00	28.85	734	710.55	214
10:00	29.54	923	843.14	192
11:00	30.22	1078	1009.29	113
12:00	28.59	1076	874.02	208
13:00	26.97	838	376.23	471
14:00	25.34	868	580.51	343
15:00	22.96	746	582.39	289
16:00	20.58	100	0	100
17:00	18.21	92	0	92
18:00	17.8	21	0	21
19:00	17.4	0	0	0
20:00	16.99	0	0	0
21:00	16.88	0	0	0
22:00	16.76	0	0	0
23:00	16.65	0	0	0

The horizontal radiation and the diffuse radiation were used to calculate the radiation on a tilted plane(Gt) which is one used by the collector was used to perform this calculation. The other parameters used in calculating radiation on a tilted plane were determined ,Table 8 shows this parameters. The ambient temperature was used to calculate the temperature of the makeup water using. The temperature of the makeup water was then increased by solar thermal energy.

Table 8 shows the calculated solar radiation parameters for every hour of the day (in June) starting at midnight, which are used for designing the solar water heating system . The radiation on a tilted plane, change in storage tank temperature and the storage tank temperature for every hour of the day were calculated. The solar fraction for each hour was also calculated. Temperature of the makeup water (T_{mains}) was also calculated. It was found to range between 16 °C and 24 °C meaning that a lot of solar radiation will be needed to increase the temperature to around 100°C. Radiation on a tilted plane differs according to the time of day; for the selected day, there is no radiation on a tilted plane in the morning hours (1 am -7 am) and in the evening hours (7 pm- 12 am). It was found that it ranged between 300 W/m^2 and 924 W/m^2. The solar radiation maximizes at 12 noon.

The collector efficiency was also determined. Collector efficiency can either be positive or negative. Also when it gets cloudy or when it is raining and there is blockage of the global irradiance which results in the decrease of the heating capacity of the collector. The absorber temperature decrease induces a decrease in the efficiency but sometimes when the absorber plate temperature increases, the efficiency decreases [53]. This could be due to the fact that when the absorber plate gets hotter than the ambient air temperature, the collector emits heat to the surrounding instead of absorbing it. The efficiency is therefore decreased. The collector was found to have the highest efficiency at 10 am (approximately 50%), more solar thermal energy was harnessed by the collector at this hour.

The actual energy demand (L_O) and the effective energy from the solar side of the system (L_s) were determined and compared in order to know the solar fraction at each hour. The collector losses and the pipe losses were determined and compared with the collector heat output (Qcoll) in order to determine the actual amount of heat used by the system. The storage tank temperature (Ts+) was calculated for each hour of the day and it was found that it ranged between

Table 8: Modelled solar radiation data for solar water heating performance determination

Time(hour)	1	2	3	4	5	6	7	8	9
Ambient Temperature (°C)	-5	-5.37	-4.71	-4.06	-3.4	1.71	6.82	11.93	13.32
Gd(h) (Wh)	0	0	0	0	0	0	0	44	70
G(h)(Wh)	0	0	0	0	0	0	0	155	338
(Omega)ωs	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608
Rb	0	0	0	0	0	0	19.33667	2.312762	1.79263
COS Θ	-0.86711	-0.77549	-0.62976	-0.43983	-0.21866	0.018694	0.256044	0.477219	0.667147
sinΘz	0.253465	0.461078	0.64978	0.804241	0.915989	0.981005	0.999912	0.97848	0.928168
CosΘz	-0.96734	-0.88736	-0.76012	-0.5943	-0.4012	-0.19398	0.013241	0.206342	0.372161
γs	-6.75779	-3.81242	-2.81515	-2.39044	-2.21856	-2.19403	-2.27687	-2.45085	-2.70272
Declination angle(δ)	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609
omega, ω	-2.87979	-2.61799	-2.35619	-2.0944	-1.8326	-1.5708	-1.309	-1.0472	-0.7854
Gt(Wh)	0	0	0	0	0	0	0	300.7165	550.4247
Tmains(°C)	3.95	3.7391	4.1153	4.4858	4.862	7.7747	10.6874	13.6001	14.3924
Collector efficiency	0	0	0	0	0	0	0	0.194241	0.459411
Collector heat output$_{(Qcol)}$	0	0	0	0	0	0	0	7009.383	30344.52
UAs(Ts-Ta)	1089.707	1047.657	992.9601	940.8829	891.014	779.5505	672.1649	568.6599	558.9756
Pipe losses	163.456	157.1485	148.944	141.1324	133.6521	116.9326	100.8247	85.29899	83.84633
ΔTs	-2.25616	-2.1583	-2.03381	-1.91565	-1.80289	-1.56008	-1.32901	1.300195	4.260464
Ts+(°C)	49.3554	47.09924	44.94094	42.90712	40.99148	39.18859	37.62851	36.29949	37.59969
ms	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421
Ls	6873.382	6556.408	6194.437	5850.755	5523.302	4951.716	4409.287	3894.605	3886.668
m	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421
Lo	9851.795	9873.427	9834.84	9796.838	9758.252	9459.498	9160.744	8861.99	8780.724
SF(Solar fraction)	0.697678	0.664046	0.629846	0.597208	0.566014	0.523465	0.481324	0.439473	0.442636

10	11	12	13	14	15	16	17	18	19	20
14.72	16.11	14.44	12.76	11.08	10.23	9.38	8.53	6.66	4.79	2.92
77	89	92	90	85	74	56	0	0	0	0
492	591	632	607	521	381	200	0	0	0	0
1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608	1.32608
1.627725	1.561137	1.542441	1.561137	1.627725	1.79263	2.312762	19.33667	0	0	0
0.812883	0.904496	0.935744	0.904496	0.812883	0.667147	0.477219	0.256044	0.018694	-0.21866	-0.43983
0.866373	0.815055	0.794958	0.815055	0.866373	0.928168	0.97848	0.999912	0.981005	0.915989	0.804241
0.499398	0.579383	0.606664	0.579383	0.499398	0.372161	0.206342	0.013241	-0.19398	-0.4012	-0.5943
-2.99953	-3.26174	0	3.261739	2.999531	2.70272	2.450853	2.276872	2.194027	2.218557	2.390442
0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609	0.407609
-0.5236	-0.2618	0	0.261799	0.523599	0.785398	1.047198	1.308997	1.570796	1.832596	2.094395
752.5057	872.6909	924.9183	897.1080	794.6879	624.3373	389.0376	0	0	0	0
15.1904	15.9827	15.0308	14.0732	13.1156	12.6311	12.1466	11.6621	10.5962	9.5303	8.4644
0.496662	0.470352	0.408222	0.326505	0.214038	0.038766	0	0	0	0	0
44848.91	49256.62	45308.62	35149.2	20411.25	2904.379	0	0	0	0	0
671.6463	854.7232	1095.602	1304.697	1450.825	1501.114	1457.369	1400.726	1361.673	1324.99	1290.562
100.7469	128.2085	164.3403	195.7045	217.6238	225.1671	218.6054	210.1089	204.251	198.7485	193.5843
6.364814	7.287284	7.069286	5.919126	3.99267	1.510147	-1.50672	-2.96346	-2.87707	-2.79485	-2.71662
41.86015	48.22497	55.51225	62.58154	68.50066	72.49333	74.00348	72.49676	69.5333	66.65623	63.86138
0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421
4754.008	6124.31	7772.934	9193.858	10164.58	10486.65	10136.39	9693.903	9332.201	8987.441	8658.804
0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421	0.024421
8698.874	8617.608	8715.244	8813.464	8911.685	8961.38	9011.074	9060.769	9170.098	9279.427	9388.756
0.546508	0.710674	0.891878	1	1	1	1	1	1	0.968534	0.922253

21	22	23	24
1.31	-0.3	-1.9	-2.41
0	0	0	0
0	0	0	0
1.32608	1.32608	1.32608	1.32608
0	0	0	0
-0.62976	-0.77549	-0.86711	-0.89836
0.64978	0.461078	0.253465	0.103534
-0.76012	-0.88736	-0.96734	-0.99463
2.815147	3.812416	6.757793	16.39562
0.407609	0.407609	0.407609	0.407609
2.356194	2.617994	2.879793	3.141593
0	0	0	0
7.5467	6.629	5.717	5.4263
0	0	0	0
0	0	0	0
1254.55	1220.693	1188.745	1143.116
188.1825	183.104	178.3117	171.4674
-2.63424	-2.55586	-2.48096	-2.37649
61.14476	58.51052	55.95466	53.4737
0.024421	0.024421	0.024421	0.024421
8330.309	8017.227	7718.228	7369.491
0.024421	0.024421	0.024421	0.024421
9482.884	9577.012	9670.555	9700.372
0.878457	0.837132	0.798116	0.759712

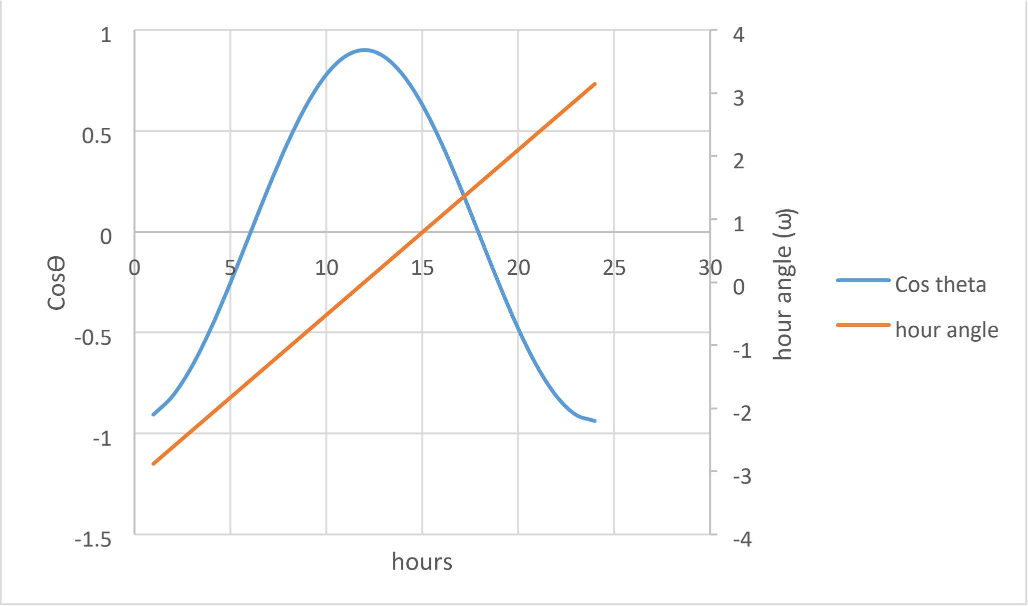


Figure 12 : Variation of the angle of incidence between the beam radiation on surface and normal to the surface and hour angle throughout the 24 hours

The radiation collected increases when the collector is North facing in the Southern Hemisphere and vice versa. It should always be facing the sun[54]. This could be solved by installation of a sun tracking device which may be expensive. Moreover, optimal tilt angle can be determined to solve this problem, the angle through which radiation will come in at a right angle to the surface[54]. The optimal tilt angle was found to be 32 °(Table 9). When the angle of incidence (Ɵ) is little, its cosine will be greater, ensuring that the cos Ɵ is maximized; maximizing the solar radiation reaching the surface. The optimum tilt angle is obtained when the cos Ɵ is maximized[54]. The hour angle behaves in such a way that it is zero at midday, negative in the morning while positive in the afternoon; Figure 12 shows this behavior.

Figure 12 shows how the angle of incidence varies throughout the 24 hours. It increases with the increase in radiation and vice versa. The cos ϴ is highest at 12 noon and lowest in the early morning hours and late evening hours. This indicates the solar radiation reaching the collector [54]throughout the day.

The MS Excel program was designed in such a way that all the sheets are linked and they have influence on each other. There are inputs into the system and there outputs which were calculated using to Equation 23 [40]. Table 9 shows the system inputs which were used in the designing of the system. The meteorological data inputs, collector type input, system inputs, economic inputs and the greenhouse gas emission inputs.

Table 9: System inputs from the MS Excel model

METEOROLOGICAL INPUTS	**INPUTS**
Latitude (ϕ)	-29.297
longitude	27.483
azimuth(γ)	180
Tilt (β)	32
Design month	June
SYSTEM	
Cp	4200
Tload(°C)	95
Heat exchanger effectiveness	0.9
Average daily hot water demand(Liters)	7421.92
Average daily hot water demand(m^3)	7.421917808
COLLECTOR TYPE	
optical efficiency (FRτα)	0.409
heat loss coefficient(FRUL)	1.676
Collector Area	155
P $_{losses}$	0.15
As (Surface area) (m^2)	22.13
UAs	24.34
ECONOMICS	

Collector Warranty (years)	5
C/a($/m2)	$175.00
Cs/m3($/m3)	$1500.00
Installation (%) total	40.00%
Inflation (%)	4.90%
Interest rate (%)	8.56%
O&M cost (%)	2%
Electricity Price ($/kWh)	0.004933333
coal price ($/kWh)	0.068
GHG EMISSION FACTORS	
CO2 emission factor (%)	0.94
Fossil fraction (energy produced directly from coal)	0.97

4.3 Collector Selection

The system is aimed at being cost effective so the first stage is finding the most cost effective collector to employ. Table 10 shows ranking of collectors according to their energy per dollar for the case of MMB. They are ranked in descending order. The collector at rank 1, has the highest energy per dollar of 18 kWh/$/m^2 hence it was selected to be the optimal collector. The collector that was selected is an evacuated tube collector(ETC). The names of the collectors are not mentioned.

Table 10: Collector ranking in descending order according to the energy per dollar

Rank	Type	Area(m2)	Cost /m2	Interce-pt	Slope	Warranty (years)	Annual Energy/m2	Annualized Cost/m2	Energy kWh/$	SF	Price Source
1	ETC	2.998	175	0.409	1.676	5	61791	7445	18	0.81	http://vacano-gmbh.de/HCA-30-HeatpipeVakuumroehrenkollektor
2	ETC	1.89	157	0.383	2.037	5	51575	5949	16	0.68	www.alibaba.com
3	ETC	2.486	114	0.406	1.753	15	70547	5249	15	0.93	www.alibaba.com
4	FPC	1.853	100	0.679	4.653	15	62436	5398	14	0.82	www.alibaba.com
5	FPC	2.68	140	0.679	4.653	10	56115	5645	12	0.74	Dimas-solar.gr.com
6	FPC	2.024	183	0.728	4.158	10	63642	5855	11	0.84	www.siliconsolar.com

7	ETC	2.792	200	0.458	1.579	15	70598	3537	8	0.9	www.focussilar.en.made-inchina.com
8	FPC	3.64	300	0.767	4.345	10	54048	3388	5	0.71	www.bcfocus.com
9	ETC	2.983	270	0.406	1.753	10	43802	1804	4	0.58	www.ressuppl y.com
10	FPC	2.024	390	0.661	6.579	10	27218	1323	2	0.36	www.made-in-china.com

The finding from this research was that, for the case of MMB, ETC performed better compared to the FPC. The reasons for this behavior could be that the data that was used when selecting the optimal collector is that of the month of June (coldest month is Lesotho) and ETC perform better in the cold compared to the FPC. The ETC has a vacuum which reduces the collector heat losses [55]. June was selected as the design month because it has the least global radiation and therefore all other months would perform better than June. The design was done for the worst case scenario.

4.3.1 Selection and sizing of heat exchanger for the system

Heat exchangers are used for transferring the absorbed energy by the heat transfer fluid between the collector and the heat exchanger to the storage tank contents[56].

The coil heat exchanger was selected to be the one used for the system. This is because of the advantages of coil heat exchangers compared plate heat exchangers are high efficiency, low pressure drop, flexibility, light weight and they require little maintenance. The plate heat exchangers have a lower efficiency, high pressure drop and expensive due to the need for gaskets to hold the plate together. Coil heat exchangers were used and their size was determined by the collector area.

The size of the heat exchanger was established in relation to the collector area. The corded heat exchanger needs to be sized such that there is approximately 0.3 – 0.4 m² of heat exchanger surface per m² collector area [37]. The size of the heat exchanger was found to be 62 m^2.

4.4 Parameters of the optimal system

4.4.1 Thermal results of the system

The collector area of the ETC that was found to have the highest EPD (rank 1) was deemed to be the actual collector area to use for the system as it occurred at the highest NPVSS. The collector area was found to be 155 m^2. The thermal outputs of this collector area were determined in order to establish the thermal viability of the system.

The system is aimed at ensuring that the storage tank temperature does not exceed 100°C which is the standard boiling point of water but may be lower in Maseru due to altitude and pressure. Even though this is the case the study assumed the boiling point to be 100°C. The collector area 155 m² has the storage tank temperature above 100°C. Figure 13 shows that as the collector area increases, the storage tank temperature increases too, even above hundred. To address this problem, the MS Excel function called "Goal Seek" was used to determine the collector area that will give the maximum storage tank temperature of 100°C out of the whole year. 79.54 m^2 was found to be the collector area needed to be used for the designed system.

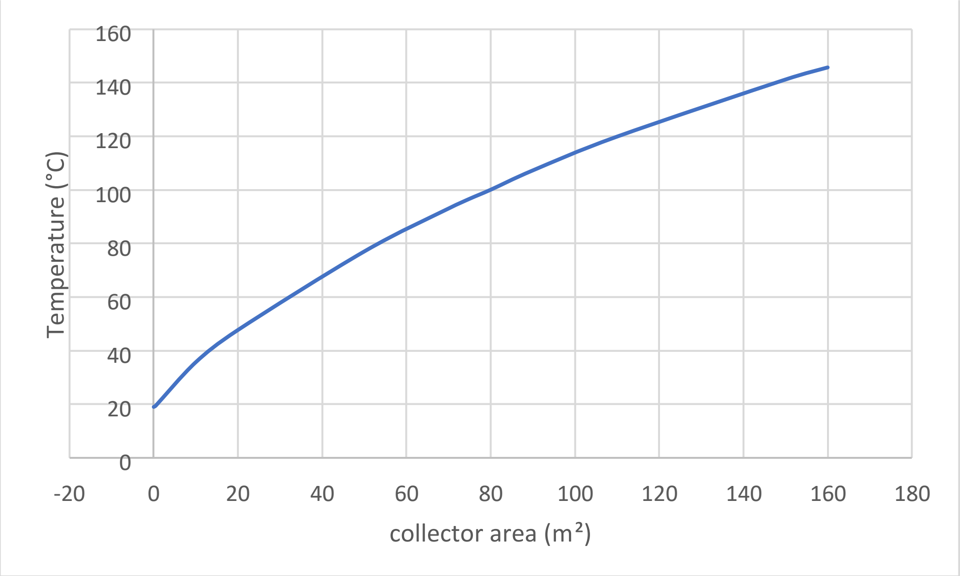


Figure 13: Variation of storage tank temperature in relation to the collector area.

The thermal outputs of the solar thermal system with collector area of 79.54 m^2 were determined, as it is the design collector area. Table 11 shows the thermal outputs of the system. There is enough radiation to be harnessed and the collector energy output is high regardless of losses incurred. The annual average incident irradiance was found to be 6.26 kWh/day/m^2.This amount of radiation is good for harnessing and usage [24]. This shows that the use of solar thermal energy at MMB is feasible or viable in terms of energy production. The solar fraction was found to be 54%, meaning that 54% of the energy demand in the solar side of the system is serviced by solar thermal energy. The rest is heated by coal in the boiler. The required storage to keep the heated water for when there is no radiation was found to be 2110 Liters.

Table 11: System thermal outputs

PARAMETER	VALUE	UNITS
Annual average Incident Irradiation/m2	6.259272687	kWh/day/m2
Annual average specific Collector Output	1.825421278	kWh/day/m2
Collector Output Energy/m2	0.0229469	Wh/day/m2
Daily Collector Efficiency	29%	
Storage Losses as fraction of collector output	10.86%	
Other Losses as fraction of collector output	2%	
Daily Energy Demand	75904.13252	kWh/day

Energy Met By Solar	40964.58096	kWh/day
Percentage of makeup water that is preheated	54%	
Storage Size	2,110.00	Liters

4.4.2 Storage volume determination

The size of the storage volume for a solar thermal system has to be thoroughly determined. This is because the storage tank size influences how the system performs. Some designers can just design large storage tanks due to lack of some physical accuracy and basic rules. The larger storage tanks than what is needed lowers the efficiency of the system, maybe costly and consume excessive space[2]. The efficiency of the collector is easily influenced by the collector size; it decreases with the increase of the storage size. Therefore the temperature of water in the storage tank is lowered when the volume of the tank is increased[2]. It is crucial to properly size the storage tank in order to avoid this from occurring.

Figure 14 shows the heat variation between the heat that is actually going to the load and the effective collector heat output. These differences were actually used in designing the storage tank size for the solar thermal system because there is need for storage for when there is no radiation. The heat needed by the load is constant throughout the 24 hours while the effective collector heat output is variant with hours of the day, it maximizes at 12 noon. The mass balance curve was used in the sizing of the storage of the system. Figure 15 shows that the cumulative heat demand increases uniformly throughout the day while the cumulative effective collector heat output is low in the morning hours but increases during the hours where there is radiation and the decreases in the evening hours due to the absence of radiation. The maximum deficit between the cumulative heat needed by the load and cumulative effective collector output was found to be 55313kWh and the maximum surplus between the cumulative heat needed by the load and the cumulative effective collector output was found to be 78166 kWh. These values were summed together giving 133479kWh (heat to be stored). The heat to be stored was then divided by the specific heat capacity and the minimum temperature in order to convert it into mass. The storage tank volume was found to be 2110 Kg (2110 Liters). There is no storage tank of this size on the market so the closest storage tank size found was that of 2500 Liters for the system.

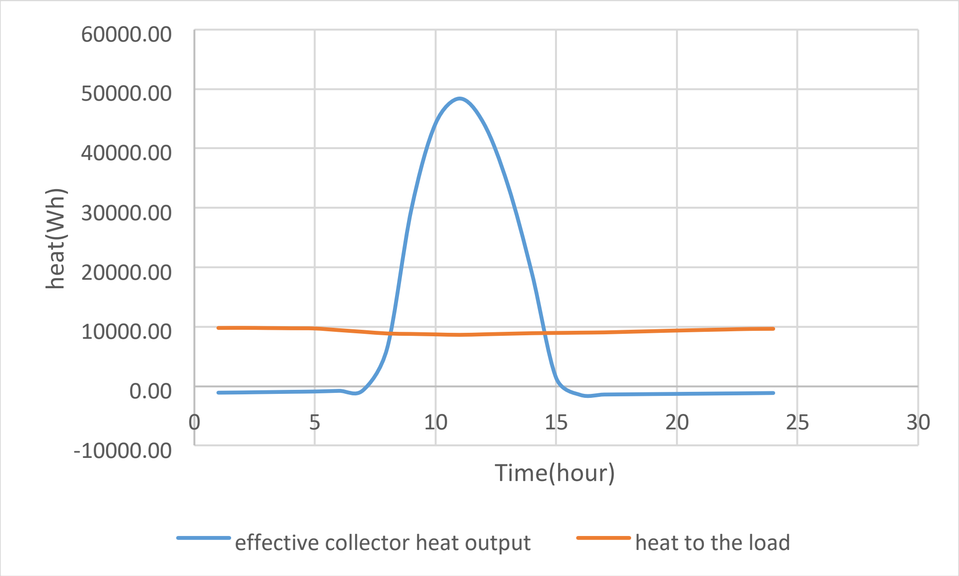


Figure 14 : Heat variation between the heat needed by the load and the effective collector heat output

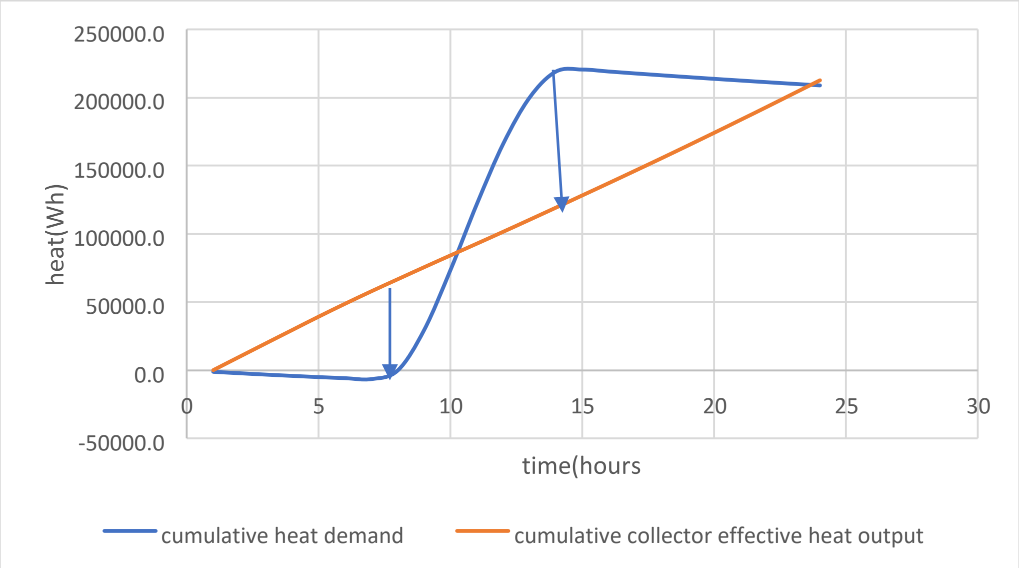


Figure 15: Mass balance curve for storage size determination

Figure 16 indicates that both the makeup water temperature and the storage tank temperature vary with the change in solar irradiance. When the irradiance increases, ambient temperature increases and vice versa. The storage tank temperature increases as the solar irradiance increases but remains at high temperature even when the solar irradiance decreases because the tank is heavily insulated and does not loose heat easily. This makes it easy to transfer hot water from the storage tank to the boiler without temperature being lowered by low irradiance.

The storage tank temperature for this selected day starts at a temperature approximately 70°C higher than that of the cold water because the water in the storage tank (heavily insulated) has retained/stored heat and therefore making sure that in the absence of radiation the makeup water is still heated. The storage tank temperature is lowered down due to heat extraction from the storage tank and the thermal losses when the tank contents mix with the cold water. The temperature then starts to increase with the increase in radiation and the heat gain surpasses the thermal losses hence the continuous storage tank temperature increase. When the radiation decreases, there is a decrease in the storage tank temperature but it does not decline very much due to the insulation and heat retention by the storage tank. The temperature decreases because of cold water introduction into the tank and the thermal losses.

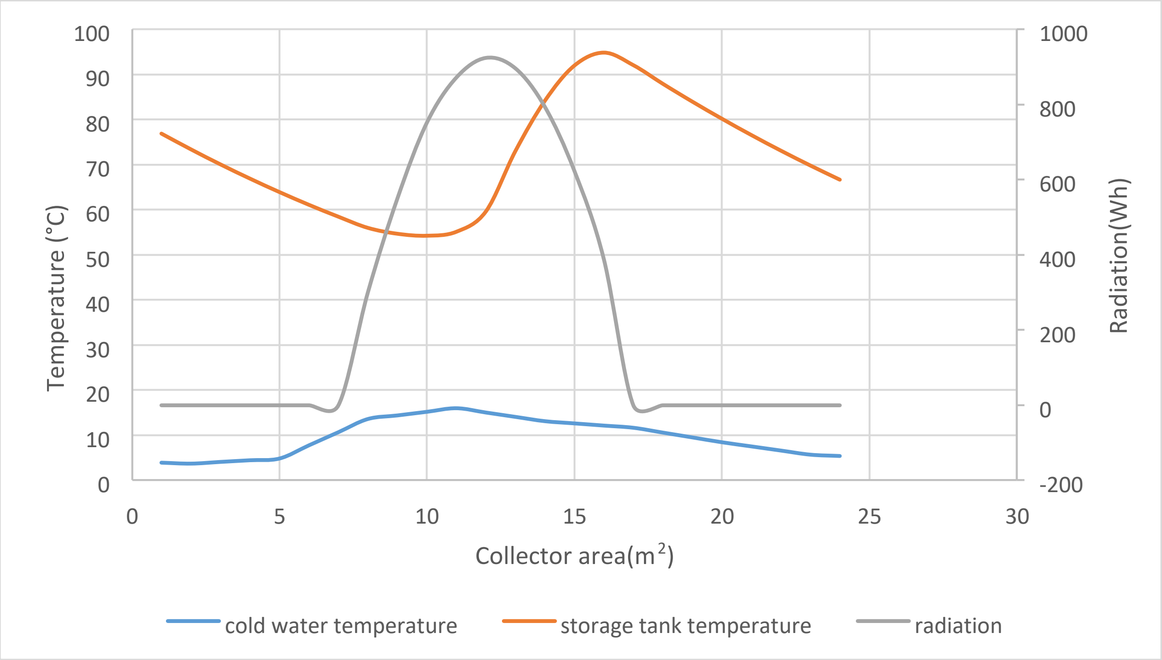


Figure 16: Hourly variation of the system temperatures (°C) in relation to solar irradiance(Wh/m^2)

4.4.3 Economic and Environmental outputs of the system

Table 12 show the economic inputs of the system. The cost of coal is the one that was used to determine whether it is economically feasible to use solar thermal heating or the system should continue using coal. The cost of producing energy from coal in 2019 was found to be 0.068$/kWh [57].

Table 12 shows the economic and environmental parameters of the solar thermal system. The capital cost of the collector array was found to be $ 13921, the capital cost of storage and the heat exchanger were found to be $3165 and the installation cost of $6834 which make the total capital cost of $23921. The specific investment (money invested per m^2) was found to be 301 $/m^2. The profitability index of the system was found to be 90%. Which is quite good for the investors and therefore making the project acceptable [35].

Table 12 : Economic and Environmental outputs

PARAMETER	VALUE
Collector Capital Cost	\$13921.21457
Storage and heat exchanger capital Cost	\$3165
Installation cost	\$6834
Total Capital Cost	\$23921
Specific Investment	301 \$/m^2 of collector
Annual Maintenance Cost	\$478
Net Present Value of Solar Savings	\$25044
Profitability index	96%
Specific Net Present Value	315 \$/m^2 of collector
Annual Energy by Solar	40965 kWh/year
Greenhouse gas averted	37 tons of carbon dioxide/annum
Assumed heat to electricity efficiency	30%
Amount of coal reduced	11%

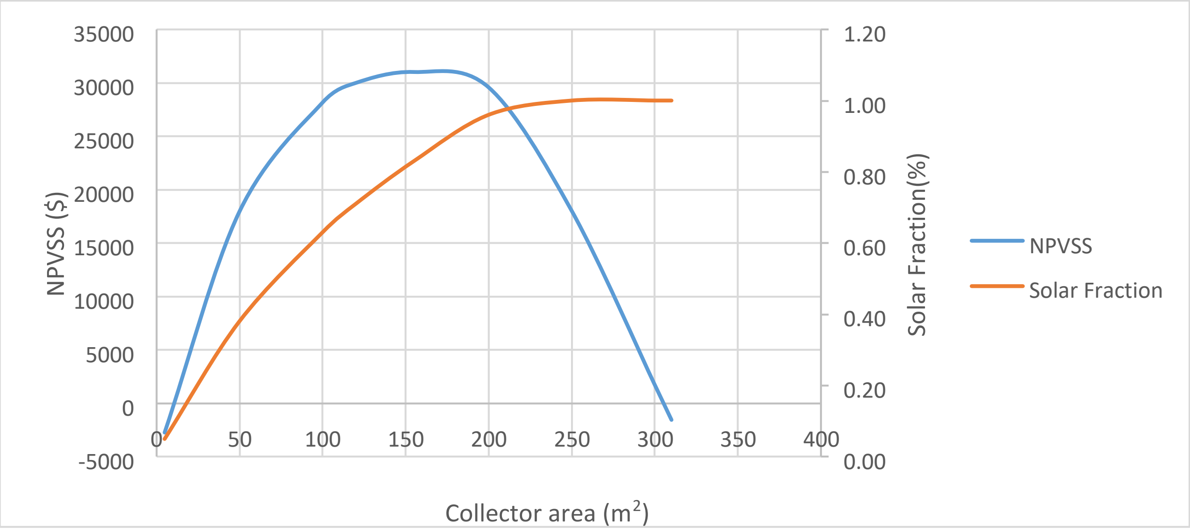


Figure 17: Variation of NPVSS, Solar fraction against collector area

Figure 17 shows the relationship between solar fraction, collector area and NPVSS. The elbow of the NPVSS is the most cost effective collector area. It is at 155m^2, solar fraction of 83% and NPVSS of $31007.The optimal collector area is at the knee of the NPVSS curve and solar fraction and this is called the "sweet spot"[15]. The most cost effective collector gives the storage tank temperature above 100°C so the optimal collector area being 79.54 has the NPVSS of $25044 with the solar fraction of 54%. The NPVSS and the solar fraction increase with the increase in collector area up to around 190 m^2 and solar fraction around 90%. The NPVSS then starts decreasing and the solar fraction remains constant at 100%. Increasing the collector area beyond this point will be costlier with minimum benefit but can still be done. The collector area beyond 300 m^2 will give a negative NPV making the investment not worthwhile[58]. The NPVSS of the designed system is still positive even if it is not giving the maximum benefit. The system projections were done over twenty years

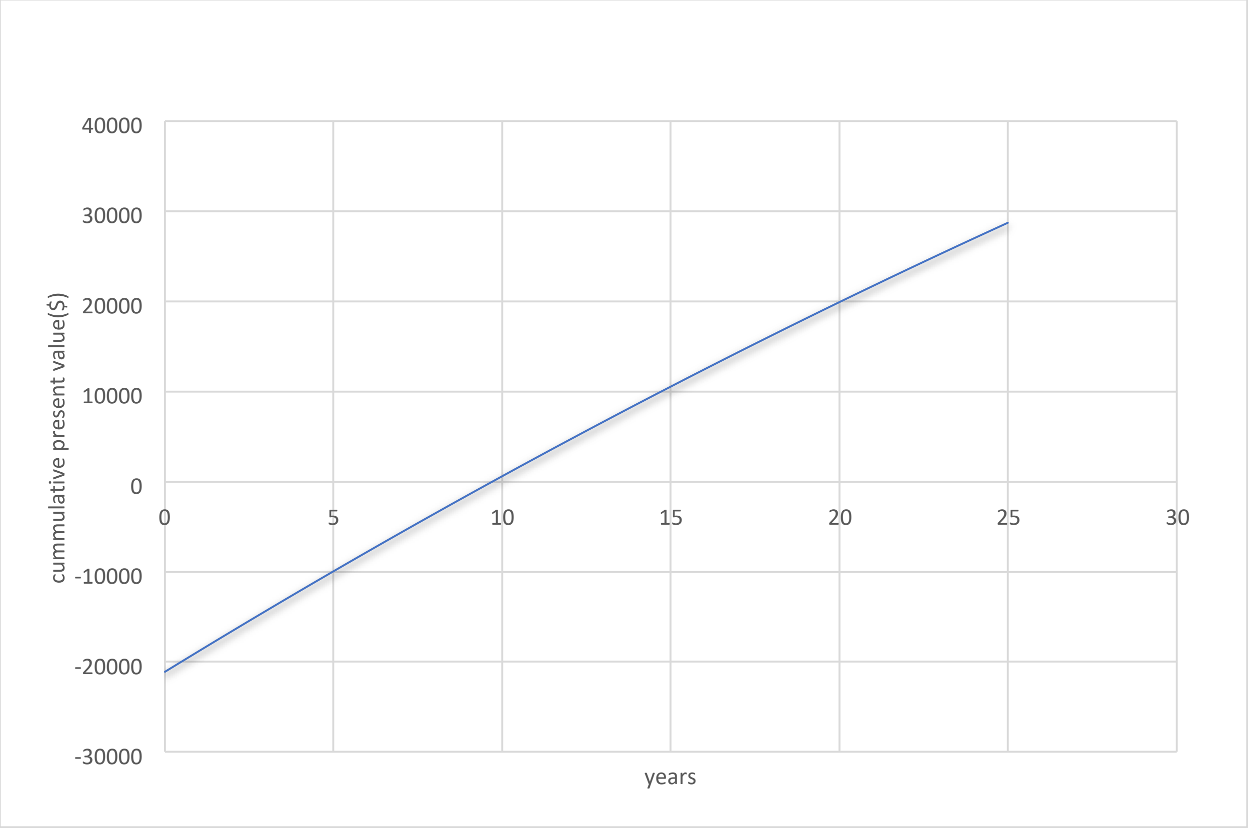


Figure 18: Payback period of the system

Figure 18 shows the payback period of the solar thermal system. The system will take approximately 9 years to pay the money that was initially invested into it at the first place. The payback period acceptance criterion for MMB is less than 5 years so this means the project may not be ideal to them. Regardless of this being the case, the use of solar thermal energy at MMB can still be very beneficial. The payback period range for solar thermal systems is 8 to 11 years[59], the payback period of the system does not greatly deviate from the payback period range.

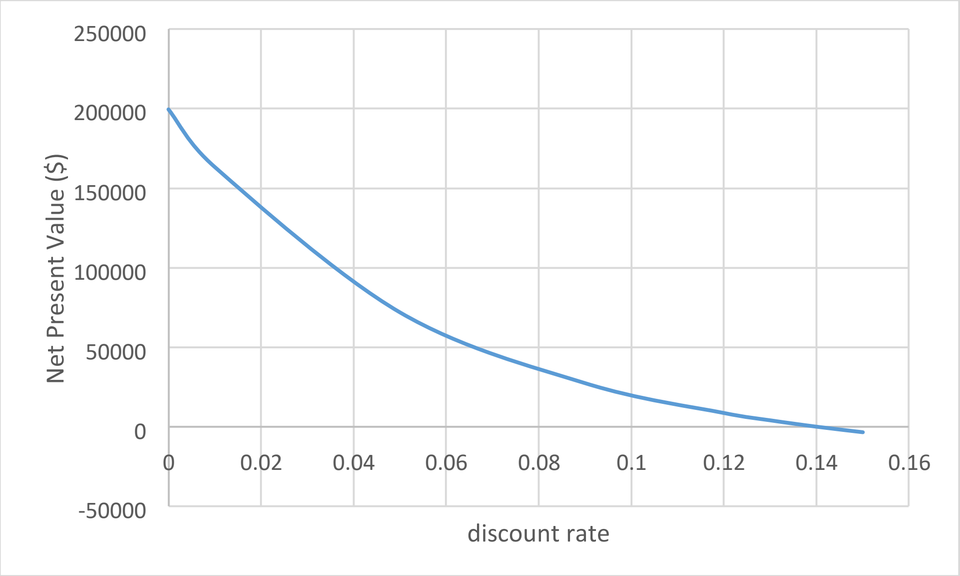


Figure 19: Determination of the internal rate of return(IRR) of the system

The IRR for the project was found to be 14% as shown in Figure 14. It is higher than the interest rate due to the positive NPV. The IRR is greater than discount rate when the NPV is positive[60]. The discount rate and IRR are always positive but if the discount rate is higher that the IRR the NPV is negative[60]. Negative NPVSS means that the project should not be done at all because the investor will run a loss.

4.4.4 Emissions

The other important aspect in every renewable energy project is the environmental impact brought about by the project. The percentage amount of coal reduced was determined and found to be approximately 11%.The CO_2 emission factors for industrial coal was found to be 97% [61] and it was used in determination of the amount greenhouse gas emissions that could be averted by the use of solar thermal energy to substitute 17% of coal used within the boiler house with solar thermal energy. The amount of greenhouse gas emission that could be averted by the use of solar thermal energy at MMB was found to be approximately 57 tons of carbon dioxide per annum.

4.5 System at MMB

There is enough space at MMB in the vicinity of the boiler house to place the collectors of 79.54 m^2 (approximately 80 m^2) and already the roof of the buildings at this place are North facing as seen in Figure 20. The figure also shows a heap of coal in front of the boiler house which is used for heating purposes within the boiler which could be reduced by the use of solar thermal energy at MMB.

Figure 20: Boiler house at MMB with a heap of coal in front of it

The designed solar thermal system for MMB is an active system because it uses pumps for circulation of the working fluid[56]. The system has 7420 Liters storage tank size,1.83kWh/m^2 collector yield, collector area of 80 m^2 with the solar fraction of 54%. A solar water heating system designed for domestic purposes with the water demand of 4800L had the following attributes; 1.25kWh/m^2 collector yield, collector area of 130 m^2 with a solar fraction of 80%[37]. The results were obtained from the AEE design calculation methods[37]. The collector output for the lower collector area is higher than that with the higher collector area because there are less thermal losses when the collector area is low[62].

When comparing the obtained results using the study methodology with the results obtained using [37] methodology there is an error of approximately 20%. This is because the method that was followed for designing the solar thermal system for MMB took into consideration a number of aspects such as losses and sizing the storage tank according the mass balance curve. This was not done for the domestic system, the storage sizing was done according to the daily demand and it could possibly be oversized. A series of calculations were done to obtain the results for MMB unlike for the domestic hot water system which only used average values and estimated values[37].The costs of the systems vary because of the type and brand of collector and storage tank used in the designed.

The aperture area of the selected collector is 2.998 m^2 and when divided into the optimal collector area of 80 m^2, 27 evacuated collectors will be needed. There will be needed 27 collectors to fully service the required collector area, the required collector area is 81 m^2. The storage tank size of the system will be 2500 Liters. 54% of the of the

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions and recommendations on findings

It was realized that MMB uses coal to heat water in their plant and solar thermal energy can be used to replace the coal as the solar radiation in Lesotho was found usable by solar collectors[24].

The boiler is the main source of hot water (where water is heated using coal) that supplies all the processes and the cold make up water reduces the efficiency of the boiler so an opportunity to preheat the water was realized and studied. A retrofitted solar thermal system design was designed for preheating the boiler makeup water. The amount of water that would be preheated was determined and was found to be 7.42 m^3. An Excel based model was made from scratch and was used to design the system and determine its economic and technical viability. The solar radiation available at MMB was modelled using the Excel based model and found that it can be collected by solar collectors and then produce thermal energy. Selection of the collector to employ was done through the energy-per-dollar criteria. Evacuated tube collector with the EPD of 18 kWh/$. The optimal collector area is decided upon by the maximum storage tank temperature of 100 °C. It was found to be 80 m^2. The actual required collector area to be employed was found to be 81 m^2. The storage tank size was determined using the mass balance curve method and it was found to be 2110 Liters, because a tank of such size could not found on the market; a 2500 Liters storage tank was selected. The makeup water makes 12% of the boiler feed water and system was found to be able to preheat 54% of the makeup water. This makes a huge difference as 11% of the coal used would be reduced. The NPVSS of the system was found to be $25044 over 20 years and therefore saving MMB money. The use of solar thermal energy will save MMB money while reducing the greenhouse gas emissions from the company. This study therefore designed the cost-effective solar thermal system for MMB.

This project therefore recommends that MMB taps into the use of solar energy by expanding its capacity to trap and convert the light and ultimately heat its system. It must also offer training to its human resources and ensure that machinery used is both efficient and effective such that it minimizes its emissions. Because this move is green, disposal and fixing of solar panels and machinery should be clearly stipulated such that it does not further endanger the ecology it is in. Moreover, Lesotho is likely to industrialize and MMB to expand its operations in future, it would be beneficial if Lesotho as a country commits itself to ensure companies use green energy and solar energy is the nearest option. Lastly, MMB should over time implement the use of solar energy for all its operations and encourage all depots to look into the same. Whilst the initial installation is costly, the benefits cover those not only economically but also for the planet. These recommendations will not only allow MMB to be greener but also financially relaxed on spending on coal for production of heat.

5.2 Study limitations and future work

The designed system could not reach maximum financial benefit due to the storage tank temperature being higher than 100°C at the optimal collector area. The solar thermal system only reduced 11% of the coal used at MMB so there is still a chance to reduce a larger percentage of coal by a different method of integration of renewable energy resources. There is also an opportunity to reduce the amount of electricity that is used by MMB as the supplier that they are exporting from, uses coal for electricity production, this will aid in the green production which the company wants to venture into.

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