MASTER OF SCIENCE IN RENEWABLE ENERGY ENGINEERING COHORT 5

RESEARCH PROJECT MODULE

MSc. thesis titled: "FEASIBILITY STUDY AND PERFORMANCE ANALYSIS OF A HYBRID SOLAR-BIOMASS (FIREWOOD) STEAM GENERATION SYSTEM FOR TEA DRYING IN RWANDA BLACK TEA PROCESSING PLANTS"

CASE STUDY: MATA TEA PROCESSING PLANT

By

Student names: NGOMANZIZA EMMANUEL

Registration number: 222022399

College of Science and Technology
African Center of Excellence in Energy for Sustainable Development

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MASTERS OF SCIENCES IN RENEWABLE ENERGY ENGINEERING

In the College of Science and Technology

SUPERVISOR NAMES: Dr. NKURIKIYIMFURA Innocent

Signature:

Date:

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AUTHOR’S DECLARATION

I, **NGOMANZIZA Emmanuel** declare that this thesis is the result of my own work and has not been submitted for any other degree at the University of Rwanda or any other institution.

NGOMANZIZA Emmanuel

Signature:
Date:

SUPERVISOR: NKURIKIYIMFURA Innocent

Signature:

Date:

ABSTRACT

This research thesis aims at the feasibility study, design and performance analysis of using Concentrated Solar thermal technology combined with biomass (firewood) thermal energy technology as a hybrid renewable energy system to supply the process heat requirements in tea drying step for Rwanda black tea processing plants. The hybrid thermal system for tea drying under study is constituted by a solar thermal energy production technology for tea drying and combined with a usual thermal energy production technology with the use of fire tube boilers. The solar thermal system under study is based on the use of Parabolic Trough solar Collector (PTC) as it has high optical efficiency. It outlines the some literatures manifesting the similarities to this research topic and extracts the gaps that my research project expects to overcome. It gives also the basic concepts that outline some theories about solar collectors that include Flat Plate solar collectors (FPC), Concentrated Solar Collectors (CSC), their industrial applications and arbitrary instances, solar thermal energy storage techniques to overcome solar resource intermittency. It has also the simulation part with System Advisor Model (SAM) software version 2023.12.17 offered freely by US National Renewable Energy Laboratory for renewable energy projects simulations. The SAM software requires the simulation key parameters to consider such as site meteorological data, annual thermal energy demand in Mega-watt thermal for Mata tea processing plant, Thermal Energy storage System (TES) hours for system resilience upon solar energy intermittency mitigating, Solar multiple(SM) which is a factor of designing solar field size to optimize the system functionality and feasibilities. It also makes results analysis and discussion then establish the concluding paragraphs and lastly addresses some recommendations to the Rwanda black tea processing plants proprietors.

ACKNOWLEDGMENTS

First of all, I would like to thank the almighty God for providing me my inner willingness to pursue studies in renewable energy engineering, means, and help me to successfully complete my MSc.thesis. I would like to thank all my family members and relatives who have sincerely encouraged me so that I cannot give up. I would like to thank the University of Rwanda through the African Centre of Excellence for Energy for Sustainable Development (ACEESD) for accepting my MSC application.

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God bless you All

Table of content

List of figures

LIST OF ABBREVIATIONS

ABBREVIATION	MEANING
ACEESD	African Center of Excellence in Energy for Sustainable Development
CSC	Concentrated Solar Collectors
DNI	Direct Normal Irradiance
GHG	Green House gas
GL	Green Leaves
HCE	Heat Collector Element
HFC	Heliostat Field Collectors
HTF	Heat Transfer Fluid
IPH	Industrial Process Heat
LCOE	Levelized Cost of Heat
LFR	Linear Fresnel Reflector
MSc	Master of Science
MT	Made Tea
MW-t	Mega Watt- thermal
NREL	National Renewable Energy Laboratory
PTC	Parabolic Trough Collector
RWF	Rwandan Franc
SAM	System Advisor Model software
SCA	Solar Collector Assembly
SM	Solar Multiple
TES	Thermal Energy Storage

1 CHAPTER 1: INTRODUCTION

1.1 Background

Steam generation and utilization in tea processing plants is a crucial step in black tea manufacturing processes as it contributes to tea drying within dryers after passing into the heat exchangers[1]. However, in Rwanda tea processing plants, the steam is obtained while burning firewood into the boilers furnace and thus helps to make water boil and produces steam adiabatically within the boilers tank and this steam can be served wherever needed for tea drying and tea leaves withering[2].

This technique that relies only on firewood burning is associated with some negative environmental challenges like great deforestation, high greenhouse gas emission into the space and in addition high cost of production for 1 kg of black tea[3]. This research topic titled **"Feasibility study and performance analysis of a hybrid solar-biomass steam generation system for tea drying in Rwanda black tea processing plants"** aims at the technical feasibility assessment of solar thermal energy generation system incorporation in Rwandan tea processing plants and the performance analysis of the system to integrate in terms of hybridization percentage or capacity factor, economic viability concerning firewood reduction and money recuperation[3].

During this research, data have to be collected from Mata tea factory as one typical example of firewood reliance tea processing plant among Rwanda tea processing plants. I have to incorporate necessary literatures related to this topic, its simulation with system advisor model software to monitor the feasibility and performance analysis of the system. I have to take account into intermittency of solar energy source while designing thermal energy storage system for nights and cloudy day"s operations. To execute this, I have to collect necessary data by consulting necessary parameters of the current system in the factory and record documents kept by the plant operators / staffs and utilize some literatures about this topic and relate them with my research topic then data will be observed and utilizes to assume the thermal energy that the plant is rated with in the year of the data I was provided and then system sizing about solar steam generation system and afterward conclusion and recommendations will be addressed to the plants proprietors through the management of the plant. Besides, once the system is implemented for one plant, other factories will imitate it accordingly.

1.2 Problem Statement

All tea processing plants in Rwanda are still relying on cut down trees while burning them daily into the fire tube boilers furnace which makes water boil and produces steam useful to execute the step of tea drying within fluidized bed dryers and tea leaves withering[4][5]. It's understandable that there is a high profit. But, according to different literatures, it is a great deforestation in our country which can be the root cause of the problems like environmental degradation or erosion, ecosystem disturbance while cutting down trees, and natural forests resource diminishing.

In addition, the consumption of firewood at bulk quantity generates high greenhouse gas (GHG) emission which implies environmental pollution that can beget climate change. Some factories don't have their own sufficient forests. They use to purchase mature trees from else forest landlords and transport them. The daily firewood handling and arranging is also included. Therefore, firewood is costlier which makes the cost of production to be very high. I can mention the case of Mata Tea Factory [4]. They don't have their own sufficient forest. Therefore, in all tea processing plants of Rwanda, firewood energy is the only one thermal energy resource which is dependable for many years for green leaves to black tea manufacturing while the firewood will be more and more becoming scarce as tea plantations are being augmented and tea factories are being increased in number and as you know the environment does not grow in area [6]. Besides, it is understandable that an alternative adequate solution for fire wood energy assisting like solar thermal energy exploitation. It means cogeneration of steam on the basis of wood and solar energy utilization.

In summary, the tea processing plants in Rwanda heavily relies on firewood thermal energy resource for steam generation to execute the black tea manufacturing, leading to:

Deforestation: increased firewood demand contributes to deforestation, impacting the environment and biodiversity [4].

Environmental degradation: Burning firewood releases greenhouse gases and air pollutants, contributing to climate change and local air quality issues [7].

Rising operating cost: Fluctuations in firewood prices and supply can significantly impact processing plant production costs [1].

Environmental pollution: The tea drying step on the basis of burning Eucalyptus logs is associated with Greenhouse Gas Emission into the surrounding environment [8].

1.3 Main Objective

The main objectives of this research thesis are the following:

- Design and technical feasibility assessment of a solar thermal energy generation system to integrate in Mata tea processing plant for assisting the existing system relying on burning firewood solely and develop an optimized hybrid system that can maximize solar energy utilization while ensuring a reliable, continuous steam supply for tea drying process.
- Performance analysis and optimization while modeling and simulating the thermal performance of the proposed system under variation of plant operational conditions and determine the key performance parameters such as solar multiple that determine percentage of hybridization and system efficiency.
- To justify the economic viability behind the solar thermal energy generation system integration and utilization together with the existing system in Mata tea processing plant.
- To justify that solar thermal energy generation system integration for tea drying in Rwanda tea processing plants is eco-friendly tea drying technique and admit that there exists certain firewood saving associated with GHG emission reduction and justify environmental sustainability.

1.3.1 Specific Objectives

The specific objectives for my research thesis are the following:

- To investigate all helpful parameters such as specific heat for tea drying, temperature range with in tea is dried and the quantity of annual dried black tea during 2023 for Mata tea processing plant to model annual heat sink requirements in mega-watt hour- thermal (MWh-t) and assume the equivalent heat sink power in MW thermal (MW-t) that will further be used in simulation part.
- To investigate geographical and meteorological data of Mata tea processing plant location and assume design point direct normal irradiance, latitude, longitude and Geographical Mean Time (GMT) and use these data in system advisor model source library, simulate and observe that location solar thermal energy production susceptibility.
- To design the solar thermal system for the plant while configuring the system components such as solar collector, Receiver and heat transfer fluid and then take 24hrs as thermal energy storage (TES) hours and solar multiple(SM) varying from 1 to 3 to observe solar field aperture area of the designed system at optimal solar multiple value (SM=1.8) and TES=24hrs for continuous operation. In addition the required steam storage tank volume has to be observed as well as the technical parameters of Parabolic Trough solar collector (PTC) to be used, receiver pipes, and Heat Transfer Fluid (HTF) have to be revealed.
- Performance analysis while varying Solar Multiple and Thermal energy storage and observe the variation of annual thermal energy generated and solar system efficiency and then validate the optimal point the system is aimed to operate. SM=1.8 and TES= 24hrs.

1.4 Significance of the research project

After remarking that all Tea processing factories in Rwanda are some of the biggest consumers of wood biomass which is usually associated with the problems such as deforestation, extinction of some natural animal's species in ecosystem, environmental degradation or erosion , high greenhouse gas emission which implies environmental pollution, high production cost, limitation for tea factories augmentation in number as tea plantation requires large forests area and firewood scarcity in future if all factories grow without forests increasing. I can undoubtedly admit that this project I am researching about is wonderful.

1.5 Scope

This study will focus on the feasibility study and performance analysis of a solar and wood biomass thermal energy generation hybrid system useful for Rwanda tea factories during tea drying process.
Even if the tea factories in Rwanda, burn the firewood biomass into the boilers furnace to heat water for steam generation, this research that I am carrying out regards all black tea manufacturing plants in Rwanda. But as it is easy matter to visit each factory alone, my chosen case of study is Mata Tea factory where I can easily access data and as the principle is the same for all black tea manufacturing plants. The targeted manner for data provision will be the approach of the management at Mata tea company ltd inside the factory, tea processing team makers, boilers operators and tea makers. I will also take observable data relating to steam temperature range for tea drying, steam pressure value and these data will help me to size appropriate solar steam generation system. During this thesis writing, the feasibility study and performance analysis will be assessed using system advisor module software provided freely by United State National Renewable Energy Laboratory (NREL) for renewable energy project simulation. I will use data for the year 2023 as the data were collected before the end of 2024. I will evaluate firewood saving quantity, amount of money to recuperate, capacity factor or hybridization percentage, and Levelized cost of heat at different solar multiple values.

1.6 Thesis Organization

During this thesis writing, I will write while respecting the succession of the following steps:

Chapter 1 outlines the introduction statements that covers the background and expresses the problem statement, objectives of the thesis, and significance of the thesis that signify the feasibility of the thesis, scope and delimitation during thesis writing.

Chapter 2 will outline the literatures review that will include the introduction, steam boilers basics that will focus on the theories related to steam production with the current technologies in Rwanda black tea manufacturing factories, tea drying process overview, challenging effects with the use of firewood solely at the bulk quantity, solar thermal collectors basics and solar steam production that will include non- concentrating solar collectors and concentrating solar collectors , solar thermal energy storage techniques and lastly clarifying the similar works and their useful methodologies and the existing gap that my thesis will ameliorate.

Chapter 3 will be about the research methodologies to be carried out during the research about my spoken topic. It will include the data collection step at Mata tea factory as my study case, system modeling on the basis of annual heat sink power(MW-t) for tea drying and simulation with system advisor model software offered freely by the US National Renewable energy laboratory (NREL).

Chapter 4 will outline the results analysis and discussion.

Chapter 5 will be about conclusion and recommendations to be addressed to the plant managers and proprietors so that the project will be made recognition to higher leadership category of Rwanda as it has numerous benefits for the tea processing plants as well as to be environmental friendly. Lastly, useful bibliography will be manifested by using Mendeley referencing manager software which is online freely available.

2 CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The tea industry faces a growing challenge for balancing production demands with environmental sustainability[2][3]. Traditionally tea factories rely heavily on wood-fired boilers for steam generation, leading to deforestation and greenhouse gas emissions. This literature review explores the potential of combining wood and solar thermal energy generation system for steam generation in Rwanda black tea processing plants, aiming to reduce firewood consumption and promote a more sustainable black tea manufacturing process.

Indeed, the aim of this literature review concerns with reviewing some literatures that includes the steam boilers principles, the literatures with remarkable similarities with my thesis topic of hybrid solar-biomass thermal energy generation systems, steam generation with solar concentrating collectors,

2.2 Steam production with boilers

2.2.1 Steam production with a fire tube boiler

Firewood is burned into the boilers furnace; the fire glue is created and by force passes inside the tubes submerged into water container which heated and steam is generated continuously and stored within the same boilers tank which is adiabatically closed, thermally insulated and has a steam stop valve that can be opened for steam supplying whenever necessary[9][7].

Key Features for a fire tube boiler:

- Fire glow passes through the fire tubes submerged into water.
- Water surrounds the tubes carrying fire glow.
- Simpler design, generally lower cost[7].
- Suitable for lower to medium steam pressures and capacities[9].

The **Figure 2-1** shows schematically the working principle of the fire tube boiler.

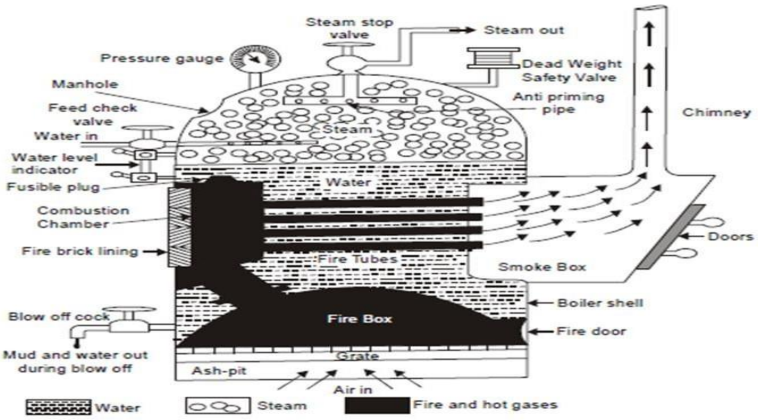


Fig. 5.1. Cochran Boiler.

Figure 2-1: Fire tube boilers parts [7]

The produced steam is harnessed with a steam hose to the radiators heat exchanger concentrated serpentine hoses on which the fan blows air and the outwards air become very hot up to above 150℃ which is required for tea drying. The produced hot wind is blown under the fluidized bed carrying a Tea Dhool from fermentation unity and makes it dry within 15 minutes and thus, tea Dhool becomes black with low moisture content of below 3%[10]. This technology is one which is currently employed during black tea manufacturing in most of Rwanda tea processing plants [11].

2.2.2 Steam production with a water tube boiler

Working Principle: In a water tube boiler, the water flows inside tubes, and the hot gases from combustion pass around the tubes. This heats the water and generates steam. Imagine water flowing through pipes that are heated from the outside [7].

Key Features for a water tube boiler:

- Water flows inside tubes submerged into fire glow [11].
- Fire glow surrounds the tubes.
- More complex design, generally higher cost.
- Suitable for higher steam pressures and capacities [7].

2.3 Steam generation with solar concentrating collectors

Apart from steam production with firewood reliance system, steam can also be produced with the use of environmental friendly means while installing a solar concentrating collectors basis system for steam generation [12]. There exist different types of solar collectors that can be used for thermal energy generation such Parabolic Trough Solar collectors system, Linear Fresnel solar collectors system, Parabolic dish solar collectors system and Center tower solar collector system or Heliostats field based solar collectors system[13]. Therefore, industrial process heat adapts from concentrating solar power [14].

2.3.1 Key components of solar thermal systems

- **Solar collectors:** These devices absorb solar radiation and convert it into heat. They can be flat-plate collectors or concentrating collectors.
- **Heat transfer fluid:** A substance, often water or oil, that circulates through the collector to absorb heat.
- **Storage tank:** A container to store the heated fluid for later use.
- **Heat exchanger:** A device that transfers heat from the heated fluid to another medium, such as air or water [14].

2.3.2 Challenges faced by solar thermal energy generation systems

- **Intermittency:** Solar energy is intermittent, depending on weather conditions [7].
- **High initial cost:** The upfront cost of installing solar thermal systems can be significant [7].
- **Geographic limitations:** Solar thermal systems are most effective in regions with high solar irradiance [7].

There are two basic types of solar collectors and these are usually classified as concentrating and non-concentrating collectors [15].

2.4 Non concentrating solar collectors

There are two main types of non-concentrating collectors: flat plate solar collectors and evacuated tube solar collectors [15].

2.4.1 Flat plate solar collector

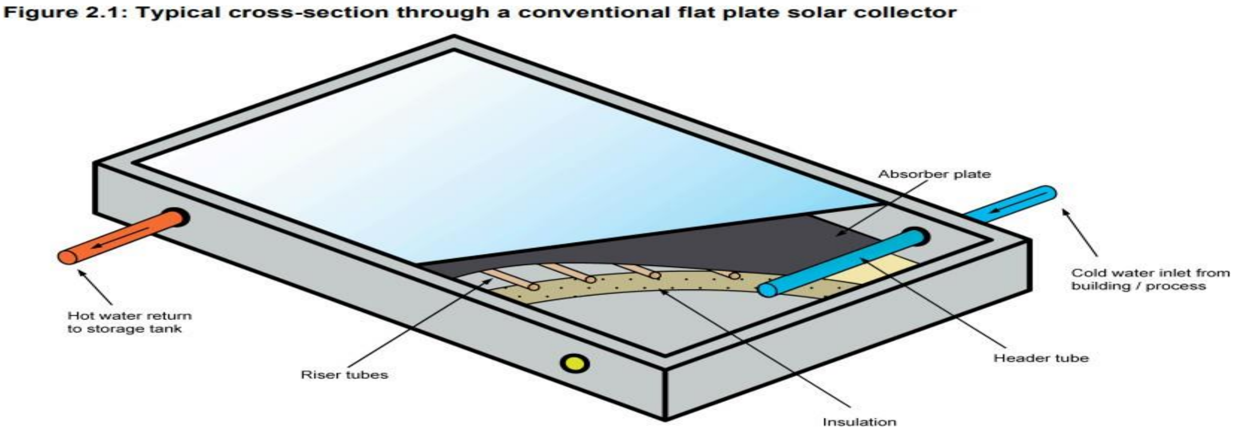


Figure 2-2: Typical cross-section through a conventional flat plate solar collector [15]

- **Working of the FPC system and applications**

An absorber plate, usually metal, is connected to a series of riser tubes (or pipes), which are in turn connected at the top and bottom to larger diameter pipes, called headers. The solar energy incident on the absorber plate is transferred to the fluid flowing through the riser tubes. Cool water enters at the bottom header and warmed water exits from the top header. The absorber is usually contained in an insulated box with a transparent cover. The temperature range of flat plate collectors is approximately 30–80°C [15].

Flat plate collectors can be constructed from a variety of materials and different construction methods are possible. As a result, they may have different performance and costs and be designed for different applications. For example, two layers of glazing are sometimes used to improve thermal performance. Some of the other variations are discussed below. Unglazed collectors have no glazing or insulation, and usually consist of extruded polymer tubes. Their use in Large Scale Thermal System (LSTS) is rare, although they have been used in the horticultural sector for greenhouse heating and swimming pool heating where lower water temperatures are required [15].

2.4.2 Evacuated tube collector (ETC)

There are two common types of evacuated tube collectors: heat pipe and U-tube. Both collector types are formed from an array of evacuated tubes joined to a manifold through which the heat transfer liquid (water or water/glycol) flows [15].

The solar absorber is located inside a double glass tube with a vacuum between the two tubes, similar to an elongated thermos flask. The tubes are connected to a manifold through which the heat transfer fluid is passed. The inner glass tube has a selective surface facing outward to absorb the sun’s energy. The heat is transferred into the inner glass tube and removed by a heat pipe or a copper tube through which the heat transfer fluid flows. The loss of heat from the absorber by natural convection is eliminated by the vacuum and, as a result, high operating fluid temperatures of up to 120ºC can be achieved[15].

The possibility of higher temperatures is of particular importance for solar industrial process heating application because it increases the number of applications where solar energy can be used[15].

A heat pipe evacuated tube collector uses heat pipes to transfer the collected solar heat from the tube into the fluid in the manifold. Heat pipes are made up of copper tubes which contain a very small amount of water in a partial vacuum. The heat pipe is encased in the inner glass tube. As the heat pipe is heated, the small amount of water inside vaporizes and rises to the top of the heat pipe into the heat exchanger in the manifold. The cold water is heated as it flows through the manifold and at the same time cools the vapor inside the heat pipe where it condenses and falls to the bottom of the heat pipe. The process is repeated, thus creating a highly effective method of transferring the sun‟s energy, which strikes the tubes into the fluid. Heat pipe evacuated tube collectors are not suitable for horizontal installation, as inclination should be at least 25° to function[15].

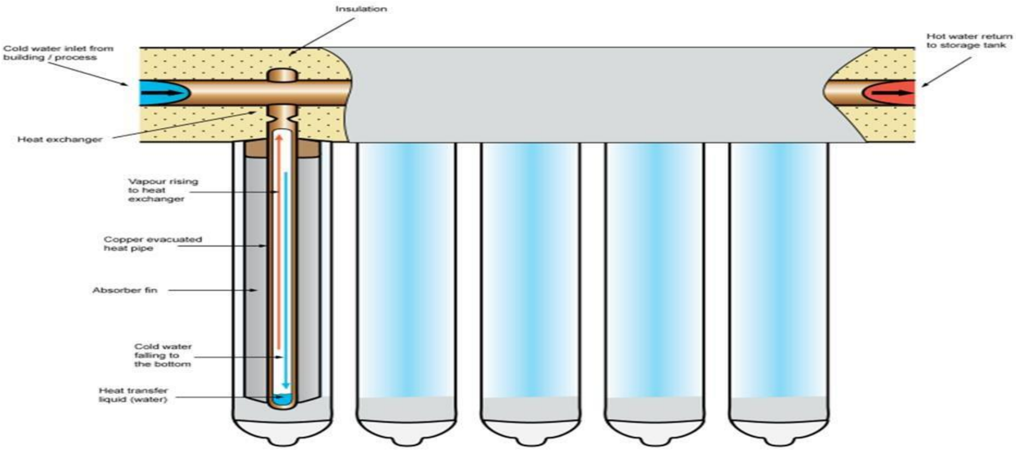


Figure 2-3: Typical heat pipe evacuated tube solar collector [15]

Evacuated U-tube collectors have the fluid heated as it flows through a „U‟ shaped copper pipe inside the glass tubes.

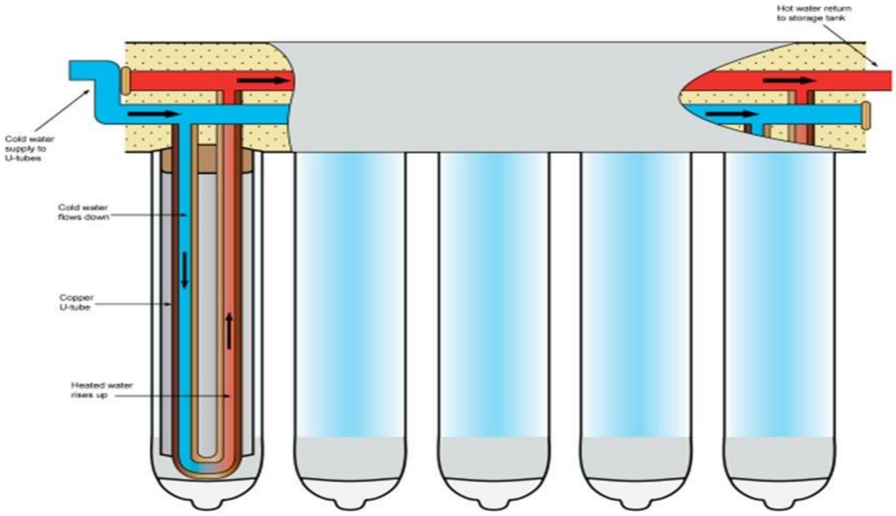


Figure 2-4: Typical evacuated U-tube solar collector [15]

2.5 Concentrating solar collectors

Concentrating collectors are optical reflecting or refracting devices. They usually have a convex, flat or concave surface to intercept and focus the sun‟s beam radiation to smaller receiving area there by increasing the radiation flux. Concentrating collectors are suitable for high temperature applications. Concentrating collectors can operate under beam radiation only. Most of the concentrators need the sun tracking mechanism to follow the sun‟s movement over a day[16].

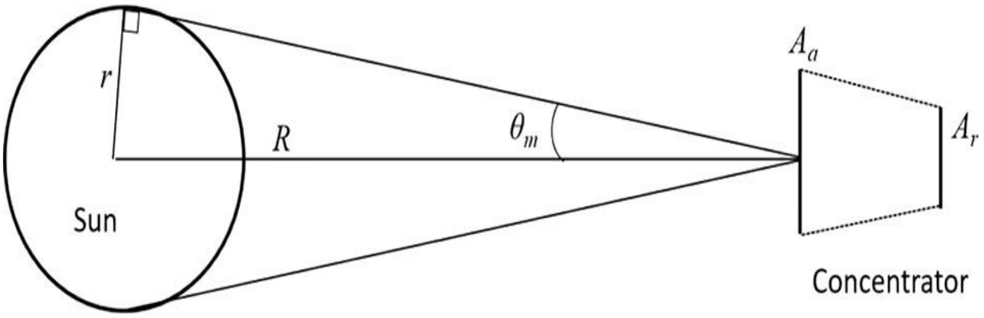


Figure 2-5: Sun, solar collector and receiver graph showing aperture and receiver area[16]

$$\text{Concentration ratio} = \frac{aperture\ area}{receiver\ area} = \frac{A_a}{A_r}$$

θ_m: Acceptance half angle of the concentrator

R: Distance of the concentrator from the Centre of the sun

r: Radius of the sun

A_a: Aperture area of the concentrator

A_r: Receiver area

If the sun and concentrator are both considered to be the blackbodies at temperature T_S and T_r, then the amount of radiation emitted by the sun is given by

$$Q_s = (4\boldsymbol{\pi}r^2)T_s^4 \qquad \textbf{(1)}[17]$$

A fraction of this radiation is intercepted by the concentrator, given by

$$\mathbf{F}_{s-r} = \frac{A_a}{4\boldsymbol{\pi}R^2} \qquad \textbf{(2)}$$

Therefore, the energy radiated from the sun and received by the concentrator is

$$Q_{s-r} = a\frac{4\pi r^2}{4\boldsymbol{\pi}R^2}\boldsymbol{\sigma}T_s^4 \qquad \textbf{(3)}$$

A black body receiver radiates equal to $A_rT_r{}^4$ and a fraction of this reaches the sun, given by

$$Q_{r-s} = A_r\mathbf{F}_{s-r}\boldsymbol{\sigma}T_s{}^4 \qquad (4)[17]$$

Under this idealized condition the maximum temperature of the receiver is equal to that of the sun. According to the second law of thermodynamics it is true only when

$$Q_{s-r} = Q_{r-s} \qquad \textbf{(5)}\ [17]$$

Therefore, from the equation (3) and (4)

$$\frac{A_a}{A} = \frac{R^2}{2}\mathbf{F}_{r-s} \qquad \textbf{(6)}[17]$$

The maximum value of F_{r-s} is equal to 1, thus the maximum concentration ratio C_{max} for three dimensional concentrators is **(with** $r/R = sin\theta_m$**)**

$$C_{max} = \frac{1}{sin^2(\theta m)} \qquad \textbf{(7)}\quad [17]$$

The higher the concentration ratio, higher is the temperature obtained in the collector at the same time tracking requirements become stringent, increasing the cost of the system[13]. There exist different types of concentrating solar collectors that are illustrated in the section below.

2.5.1 Parabolic trough collector (PTC)

A parabolic trough collector is a type of solar thermal collector that is straight in one dimension and curved as a parabola in the other two, lined with a polished metal mirror. The sunlight which enters the mirror parallel to its plane of symmetry is focused along the focal line, where the objects are positioned that intended to be heated. The trough is usually aligned on north-south axis, and rotated to track the sun as it moves across the sky each day[16]. The **Figure 2-6** shows a typical drawing of a parabolic trough solar collector. .

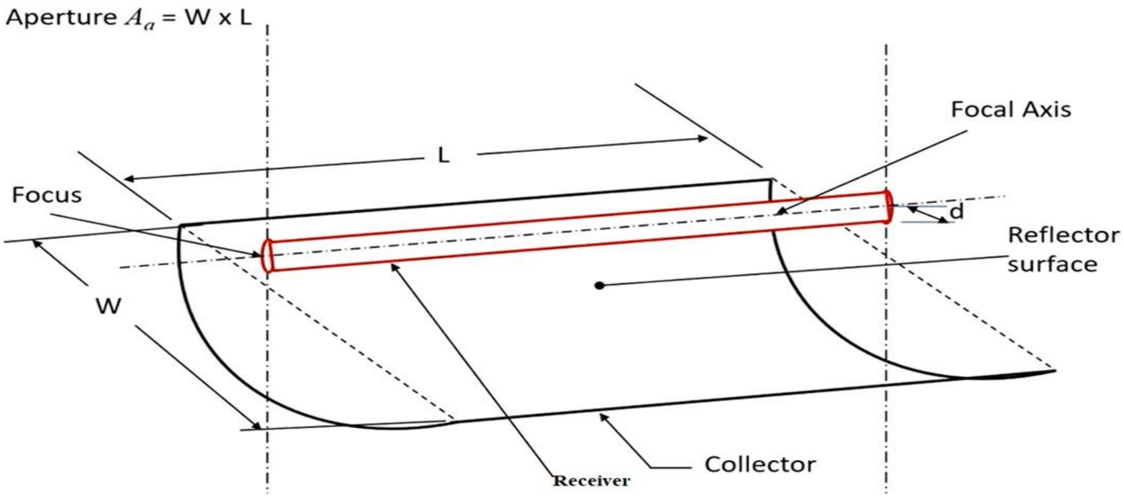


Figure 2-6: Parabolic solar collector design with its focal line graph [16]

2.5.2 Parabolic collectors and Industrial process heat (IPH) applications of parabolic trough solar collectors

PTCs can be used to provide heat for industrial processes, such as food processing, chemical manufacturing, and oil and gas production[18]. The **Figure 2-7** indicates the scheme of the parabolic solar collector.

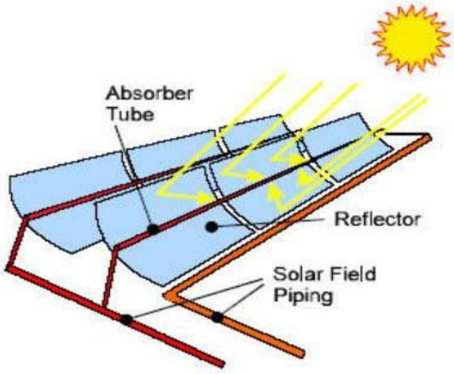


Figure 2-7: Scheme of parabolic trough solar collector

The **Figure 2-8** indicates the typical example of PTC industrial process heat application in a dairy processing plant in Mexico. The **Figure 2-8** shows a typical application of PTC in a diary processing plant in Mexico**.**

Figure 2-8: Application of PTC in a dairy processing plant in Mexico [18]

2.5.3 Parabolic dish solar collector and applications

Parabolic dish systems consist of a parabolic shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver mounted at the focal point.

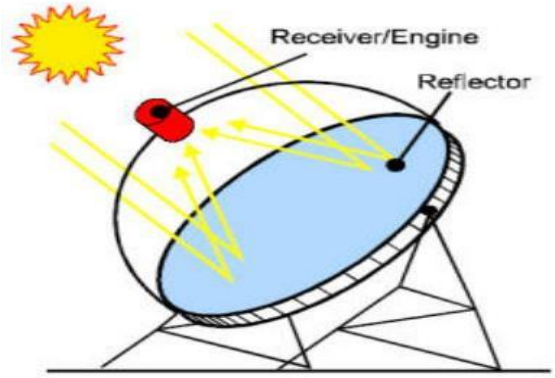


Figure 2-9: Scheme of Parabolic Dish solar collector[16]

The **Figure 2-10** shows the parabolic dish solar collector and its industrial processing heat application in a diary industry in India.

Figure 2-10: Application of parabolic dish in a dairy industry in India [18]

2.5.4 Centre tower solar power receiver/ Heliostat Field Collectors (HFC)

The central tower solar power receiver, also known as a heliostat receiver, is the heart of a central receiver solar power plant (CSP plant) utilizing tower technology. These power plants use a vast array of flat, mirrored panels called heliostats to concentrate sunlight onto a single focal point at top a centrally located tower[19]. This system can be applied for industrial process heat applications instead of concentrated solar power application[18].

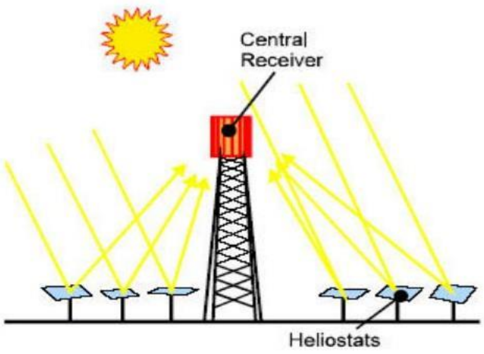


Figure 2-11: Center receiver, Heliostats field [19]

2.5.5 Linear Fresnel reflector (LFR)

Linear Fresnel Collector/Reflector by geometry is a line focusing system which is most appropriate for the medium range temperature applications like process heat. The other line focusing concentrators like Parabolic Line focusing system or “Trough” system can satisfy these requirements better. However, this particular project promotes the Fresnel type of solar thermal technology considering the lower capital investment and the simplicity of fabrication and installation if compared to other CSP technologies [20]. The Fresnel technology uses series of long flat mirrors reflecting the beam radiation to the line of fixed receiver. Every single mirror line is equipped with individual tracking drivers and rotates along its own axis. For a given instance they should be at different angles to point the receiver. All these rotating axes are parallel with each other while the line of focus where the receiver is placed is also parallel with these rotating axes[20].

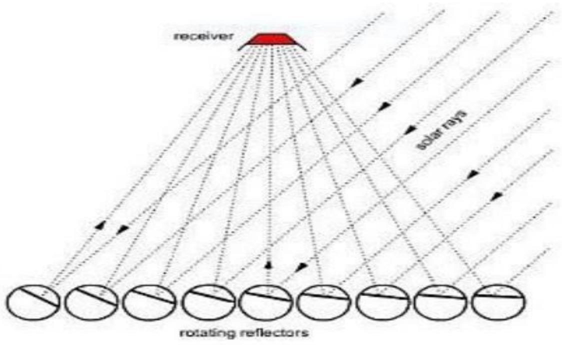


Figure 6: *Geometrical view of Linear Fresnel Collector*

Figure 2-12: Geometrical view of Linear Fresnel solar collector [19]

Table 1: CSC status, absorber type, concentration ratio and indicative temperature it can produce

Collector type	Absorber type	Concentration ratio	Indicative temperature (℃)
Flat Plate Collector(FPC)	Flat	1	30-80
Evacuated Tube Collector(ETC)	Flat	1	50-200
Compound Parabolic Collector(CPC)	Tubular	1-5 5-15	60-240 60-300
Linear Fresnel Reflector(LFR)	Tubular	10-40	60-250
Cylindrical Trough Collector(CTC)	Tubular	15-50	60-300
Parabolic Trough Collector(PTC)	Tubular	10-85	60-400
Parabolic Dish Reflector(PDR)	Point	600-2000	100-1500
Heliostats field collector(HFC)	Point	300-1500	150-2000

2.6 Tea drying processes

The high pressure and temperature steam harnessed from the boiler is forced to pass into radiator serpentine hoses on which a ventilated cold wind is blown and exchange heat with this steam at the outer surface of these concentrated hoses such that the forced wind becomes hot up to above 150℃ temperature is reached[21]. This very hot wind is used within fluidized bed dryer for tea drying process

There are two main objectives in regard to the drying process. The first is to halt the oxidation process, in order to prevent further chemical changes. The second objective is to reduce the moisture content of the leaf for a stable final product with a good storage quality. The end results, meaning the remaining humidity of the leaves depends on the black tea‟s desired properties. The **Figure 2-13** indicates the tea drying brain storming scheme.

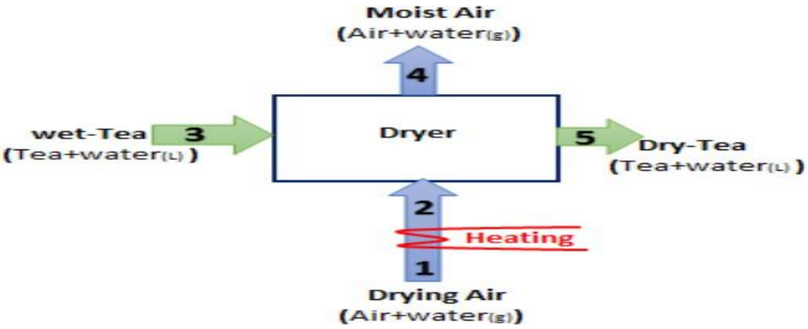


Figure 2-13: Tea dryer operation brain storming [1]

According to the literature [22], there are many different configurations in practice, but a representative system of a fluidized bed tea dryer is shown in the **Figure 2-14**. The tea dhool(macerated and fermented tea shoots) is fed into one end of the machine, and then dry tea escapes over a weir at the opposite end. The weir height is often adjustable and will regulate the bed loading, and hence the residence time. The air supply is split into three sections, with the hottest air meeting the dhool. The exhaust temperature will rise as the tea dries, despite the lower inlet temperature at the dry end. The aim is to avoid tea particle temperatures, and thus exhaust temperatures, of greater than 90℃[22][23]

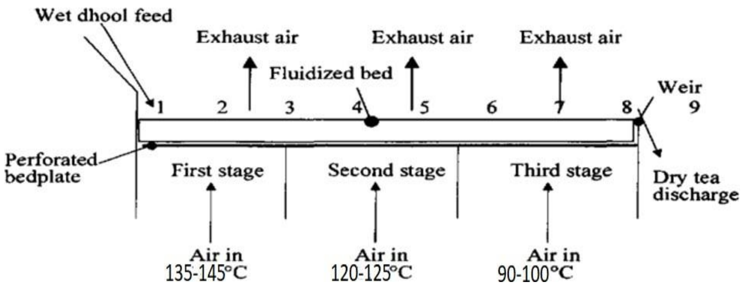


Figure 2-14: Air temperature requirement during tea drying[24]

2.6.1 Thermal energy and mass flow for typical up-country and low-country tea factory

According to the data retrieved from Sri-Lanka Tea research institute, in up or mid altitude country, during withering, 4.50kg of green leaves (G.L.) loses 2.28kg moisture and becomes 2.22kg of withered leaves after consuming 9.0MJ of thermal energy and in drying process, the obtained 2.22kg of withered leaves loses 1.22kg of moisture and become 1kg of made tea (MT) after consuming 13MJ of thermal energy[25]. But, in low altitude country, during withering, 4.50kg of green leaves (G.L.) loses 2.12kg moisture and becomes 2.38kg of withered leaves (WL) after consuming 9.0MJ of thermal energy and in drying process, the obtained 2.38kg of withered leaves loses 1.38kg of moisture and becomes 1kg of made tea (MT) after consuming 13.7MJ of thermal energy[25].

2.6.2 Key Thermal Energy Performance Indicators

According to KTDA [4], the target for thermal Energy Efficiency is as follows

- 3.5 – 4 Kg.Steam / Kg.MT (drying alone)
- Boiler Efficiency: 1800 Kg. steam/m^3- Firewood boiler
- 18.79 MJ/Kg.MT – Steam energy
- Firewood 1 m^3 = 5170 MJ => 1800 Kgs of steam/m^3

According to KTDA[4], specific heat for tea drying is 18.79 MJ/Kg of Made Tea(MT) at 20% of firewood moisture content**(MC)** whereas according to Sri-lank tea research institute, From the above the total average thermal energy usage in tea processing (withering and drying) could be taken as **22.4** MJ/kg of Made Tea[25]. As already stated most tea factories depend on fuel wood for thermal energy requirements. The moisture content of fuel wood used varies from 20to 25% and depending on this, fuel wood demand for tea processing varies from 1.8 to 2.2 kg fuel wood/kg made tea at fuel wood moisture contents of 20 to 25% respectively[4].

2.7 Similar literatures

Modeling and performance analysis of solar parabolic trough collectors for hybrid process heat application in Kenya‟s tea industry using system advisor model[26].

2.7.1 Review of the similar literature

According to the abstract of the first literature[26], among the Concentrated Solar Collector (CSC) technologies, Parabolic Trough Collector(PTC) is the most mature and commercialized CSC technology today[26]. Currently, solar PTC technology is mainly used for electricity generation, despite its huge potential for heating, especially in industrial process heat (IPH) applications[26]. Though the technology is well-developed and successfully used in many developed countries, there is barely any development in Kenya[26]. This literature studies the techno-economic feasibility of a solar PTC- assisted tea drying process in one tea factory that currently relies on biomass for process heat in the tea producing area of Kericho, Kenya. The plant integrating parabolic troughs is modeled and a yearly simulation performed using System Advisor Model(SAM) software[26]. The weather data are derived from ground measurements at Kericho meteorological weather station. SAM is used to model the impact of the principal design parameters, i.e., Solar multiple(SM), thermal energy storage (TES) and hybridization percentages, on solar- biomass plant configurations, and to reveal the optimum case[26]. The studied impacts are linked to the annual energy production and the optimal size which minimizes the Levelized Cost of Heat (LCOH). Analysis of monthly variations of energy production by the solar PTC reveals that even when the solar system is designed to its maximum capacity(SM of 3 and TES=24h). Some months will still require hybridization with biomass to fully meet the energy demand[26]. TES must also be incorporated in the solar PTC design to maximize on energy production. The hybrid solar-biomass plant with TES provides optimal performance when SM is 1.8 and TES is 24h[26]. This results in LCOH of 1.85 US cents/kWh, which is 25% cheaper than using biomass only as is the current practice[26].

Levelized Cost of Energy (LCOE) is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net energy generated by that plant over its operating life.

Furthermore, integration of solar PTC has a positive impact on carbon footprint and considerably reduces annual greenhouse gas (GHG) emissions by 9817 tons of CO2-eq, and annual fuel wood consumption by 16,462 m^3 equivalent to 23.51 acres of mature grown trees[26].

2.8 Previous methodologies

2.8.1 Solar Resource assessment

The tea factory is located in Kericho, Kenya, which receives sufficient direct normal irradiance (DNI) to support a solar PTC system. They have executed the hourly ground measurements of Direct Normal Irradiance at Kericho, Kenya (reference site) for one year (2021) and they obtained 5.25 kWh/m²/day. This value meets the minimum recommended DNI (5.0 kWh/m²/day) for industrial heat applications.

By calculus annual DNI: 1915.59 kWh/m², exceeding the typical threshold (1600-2000 kWh/m²/year) for high economic performance**.**

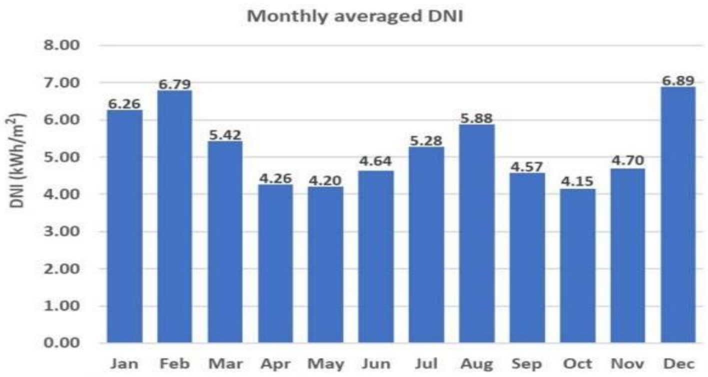


Fig. 1 Mean monthly DNI (kWh/m^2/day) in Kericho

Figure 2-15: Mean monthly DNI (kWh/m2/day) in Kericho

2.8.2 Heat Demand assessment

The factory's thermal energy demand for tea drying is estimated based on fuel wood consumption data.

- ✓ Specific Thermal Energy Consumption (STEC): A STEC value of 11 MJ/kg was used to represent the energy required to dry one kilogram of Made Tea. This value is within the typical range of 90-160°C for tea drying processes.
- ✓ Energy Demand Calculation: The monthly quantity of Made Tea was multiplied by the STEC value to determine the monthly thermal energy demand.
- ✓ Annual Energy Demand: The sum of the monthly energy demands resulted in an annual thermal energy demand of approximately 14,286 MWh for Toror tea factory.

2.8.3 System Modeling

SAM software is used to simulate the PTC system's performance under various configurations. Key parameters include design point DNI, collector loop temperatures, solar multiple (SM), and thermal energy storage (TES) hours.

1) Software

System Advisor Model (SAM) software which is free offered by US renewable energy laboratory for simulation of renewable energy project, was utilized to evaluate the amount of energy the solar PTC system will supply for design, optimization, and economic viability assessment.

Steps:

- Add hourly DNI data from the reference site to SAM's solar resource library.
- Import energy demand as heat sink power to SAM.
- Configure solar collector and receiver parameters (solar field design).

2) Technical Parameters

- Euro Trough ET150 parabolic solar collector was configured.
- Pressurized water for thermal storage was chosen.
- Design Point DNI was 476 W/m² for which the plant achieves the specified thermal rating[26].
- Operating Collector Loop Temperatures:

Inlet: 40 °C and Outlet: 130 °C (selected to compensate for thermal loss between solar field outlet and tea drier inlet)[26].

- Solar Multiple (SM): Ratio between thermal energy produced at the design point and thermal energy required by the plant (1.0 to 3.0 ranges analyzed)[26].
- Thermal Energy Storage (TES): Ability of the system to store additional heat from the solar collector (0 to 24 hours analyzed)[26][27].
- PTC Collector and Receiver:

Collector: EuroTrough ET150 (selected for low cost, easy installation, rigid structure, high optical performance, and less specific weight).
Receiver: Schott PTR70 (selected for high absorptance and low emittance).
Stow Angle: 170° (angle the trough needs to track in a day).

- Thermal Storage Media: Pressurized water (due to operating temperature range and availability).

3) Performance analysis of the Solar PTC System

They studied the impact of variations in Solar Multiple(SM) and Thermal Energy Storage (TES) on the physical parameter like annual thermal energy generated, solar system efficiency, fraction of hybridization and Levelized cost of heat (LCOH).

By analysis, they remarked that even with the largest designed system (SM = 3, TES = 24 h), some months (April, May, October) require biomass to meet the full energy demand[27].

4) Results and Discussion

Increasing SM and TES generally leads to higher annual solar energy generation.

Thermal storage is crucial for a stand-alone solar PTC system to meet year-round demand.

However, increasing SM beyond a certain point results in diminishing returns due to unutilized heat[26]

2.8.4 Gap

They have not use the capacity factor to estimate for economic viability evaluation whereas for my case, I will use it to estimate firewood quantity to suppress and amount of money to recuperate.

2.9 The second similar literature

Solar - Biomass hybrid system for process heat supply in medium scale hotels in Sri- Lanka[12].

2.9.1 Review of the previous work

According to the abstract of the second literature, this study aimed at evaluating and demonstrating the feasibility of using Concentrated Solar Thermal technology combined with biomass energy technology as a hybrid renewable energy system to supply the process heat requirements in small scale industries in Sri Lanka. Particularly, the focus was to apply the concept to the expanding hotel industry, for covering the thermal energy demand of a medium scale hotel. Solar modules utilize the rooftop area of the building to a valuable application. Linear Fresnel type of solar concentrator is selected considering the requirement of the application and the simplicity of fabrication and installation compared to other technologies. Subsequently, a wood-fired boiler is deployed as the steam generator as well as the balancing power source to recover the effects due to the seasonal variations in solar energy. Bioenergy, so far being the largest primary energy supply in the country, has a good potential for further growth in industrial applications like small hotels. When a hotel with about 200-guests capacity and annual average occupancy of 65% is considered, the total annual CO2 saving is accounted as 207 tons compared with an entirely fossil fuel (diesel) fired boiler system. The annual operational cost saving is around $ 40,000 and the simple payback period is within 3-4 years. The proposed hybrid system can generate additional 26 employment opportunities in the proximity of the site location area. This solar-biomass hybrid concept mitigates the weaknesses associated with these renewable technologies when employed separately. The system has been designed in such a way that the total heat demand of hot water and process steam supply is managed by renewable energy alone. It is thus a self-sustainable, non-conventional, renewable energy system. This concept can be stretched to other critical medium temperature applications like for example absorption refrigeration. The system is applicable to many other industries in the country where space requirement is available, solar irradiance is rich and a solid biomass supply is assured[12].

2.9.2 Previous methodologies

The project starts with a literature survey which is continued throughout the project to get a thorough knowledge and to get updated the available technology on the subject. The technological findings over this literature survey are discussed in initial chapters which is useful in the analysis process in the following chapters[12];

- The energy survey related to the hotel industry was carried out to assess the system requirement correctly and to identify the practical issues. Information gathered through surveys was analyzed in order to provide foundation for model design and for design proceedings in comparison with the available standards and design practices[12];
- Data surveys on the solar potential and on the biomass potential in Sri Lanka were carried out through the information available with the sources and publications of government regulatory bodies, research publications from relevant organizations and with information available from on-going projects[12];

Designing of a proper hybrid system that meets the requirement of the application unit (hotel) was done based on the information gathered during this study and further possibilities of optimizing the system was considered by varying the solar-biomass combination (i.e., varying the weight of the energy contribution to the application by solar energy and by bioenergy)[12].

- A computer program specific to this system was developed in the process of this optimization and the improvements of the system parameters. Repeated calculations by varying the input parameters of this solar-biomass hybrid combination can be done by using this specific program to evaluate the results and limitations for finding better alternatives[12].
- Results of the optimization process were evaluated against the technical and economic considerations to find out the best options. Financial feasibility was investigated with basic indicators in comparison with a fossil fuel system[12].
- Environmental and social benefits of this hybrid renewable application were assessed over the weaknesses associated with the fossil fuel system[12].

2.10 Gap

It was a small scale system compared to my case study as it was modeled for hot water supply and steam supply for laundry in Sri–lank hotel.

It is a small scale project compared to my study case of industrial process heat for tea drying.

1 CHAPTER 3: METHODOLOGY

The research methodology is the systematic method to solve a research problem through data collection with various techniques; data interpretation and utilization for system modeling.

In this case, this study will employ a mixed-methods approach, combining quantitative and qualitative research approach to model the MW-t of the required solar thermal energy generation system for Mata tea processing plant and together with solar resource data, it is possible to use these two data in system advisor model software for system design and simulation such that the required system's solar field size, receiver size, heat transfer fluid and thermal energy storage hours will be configured as system's technical parameters and recognize their optimal size. In results analysis and discussion, I will observe the system's capacity factor variation upon the variation of direct normal irradiance and design point direct normal irradiance, influence of solar multiple on the capacity factor, thermal energy storage versus capacity factor variation and thermal energy storage versus its thermal capacity, solar multiple variation versus solar field size and validate the optimal solar multiple and solar field size for the system under design for the processing plant in my case study. Lastly, I have to assume the susceptible firewood quantity to be suppressed and the money to save based of the capacity factor.

2.11 DATA COLLECTION

According to both quantitative and qualitative information, the following information is necessary:

- Solar resource data Mata tea factory location while consulting some literatures and employing Google map or photovoltaic geographical information website (PVGIS.com).
- Received annual tea green leaves quantity during 2023 and corresponding annual made black tea.
- Coefficient of transformation
- Firewood quantity utilized for tea drying during 2023 and firewood moisture content value.
- Firewood calorific value corresponding to that moisture content value
- Firewood thermal energy generated during 2023
- Made tea per cubic meter of firewood
- Specific heat for tea leaves withering
- Specific heat for tea drying within driers
- Withering temperature range
- Tea drying inlet and outlet temperatures at driers sections indicated by digital temperature indicators
- Thermal energy calculus for withering during 2023
- Thermal energy calculus for drying during 2023

- Overall thermal energy employed for black tea manufacturing during 2023
- Firewood price per cubic meter
- Firewood cost
- Summary of annual heat sink requirements for Mata tea processing plant during 2023
- Heat sink power requirements in MW thermal during 2023

2.11.1 Solar resources assessment at Mata tea factory location

First of all, according to the literature of academic assessment undertaken in partnership with the MININFRA Department of meteorology in 2007 used a meteorological data set to estimate monthly average global radiation. This was found to vary between 4.3 and 5.25kWh per m^2 per day over all region of Rwanda [2]. Another research regarding solar energy stated that Rwanda is located 2° South of Equator receiving 4.3 to 5.25 kWh per m^2/day in almost all regions of Rwanda (Mininfra, ESSP, 2018). With such high level of solar energy resource, Rwanda is naturally suitable for development and application of solar energy as one of viable energy sources for tea processing [8].

Secondly, according to global solar atlas map data, the assumption of the above literature is correct. So I will use Direct Normal Irradiance (DNI) retrieved from PVGIS.com map, Google map or Global Solar Atlas.com website [28].

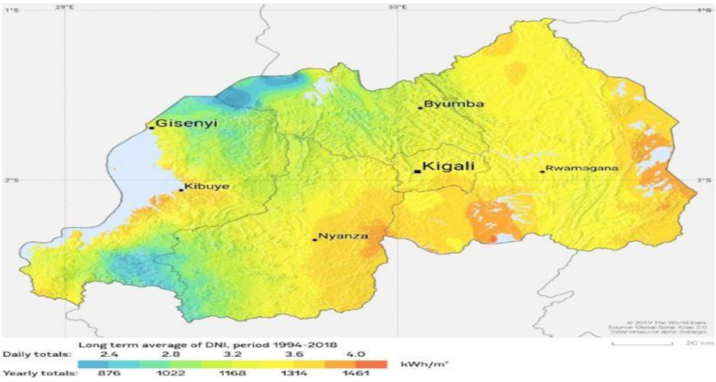


Figure 0-1: DNI of Rwanda according to Global Solar Atlas.com[8]

I have to conduct a thorough site assessment about solar radiation resource availability and assume the insolation per m^2. This can be executed while using data retrieved from PVGIS map, google map or global solar atlas.com. I will consider the Direct Normal Irradiance(DNI) only as the diffuse component of the solar radiation cannot be generally reflected or concentrated by solar concentrating collectors.[26]. The **Figure 0-2** indicates the Mata Tea Factory location.

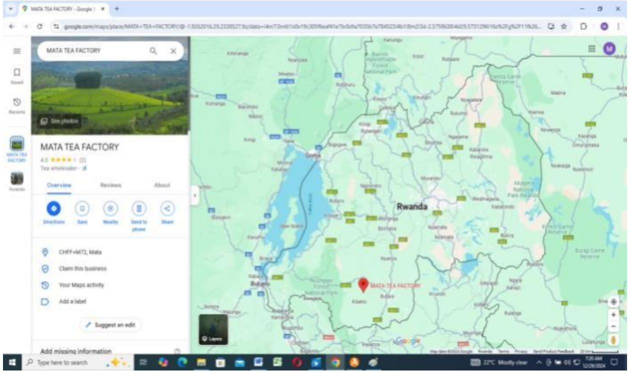


Figure 0-2: Geographical location of Mata tea factory on the earth globe

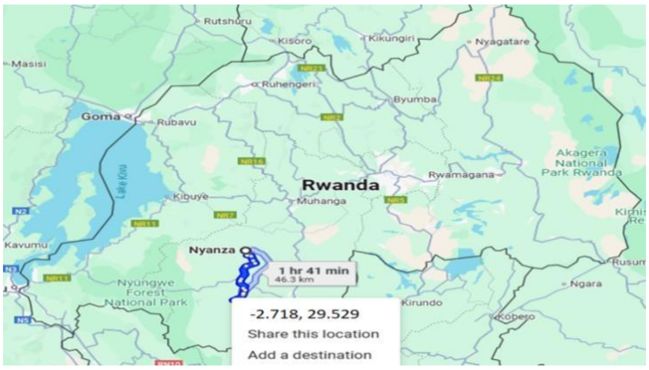


Figure 0-3: Mata tea factory location on the earth globe

According to the map shown in the Figure28, Mata tea factory is located on the earth globe at Latitude -2.718 south and 29.529 longitude East. In southern province of Rwanda, Nyaruguru District, Mata Sector.

2.11.2 Annual Thermal energy supply and Demand evaluation for tea processing in Mata tea factory during 2023

According to the data provided from tea making team at Mata Tea factory, the **Table 2** shows the tea Green Leaves (GL) and corresponding Made Tea (MT) as well as the data for Firewood quantity utilized during 2023. These data help us to evaluate the amount of thermal energy demanded by the tea factory, thermal energy dissipated by made tea and firewood thermal energy during 2023.

Table 2: Tea Green Leaves, Made Tea and firewood consumption data at Mata Tea Factory during 2023

Month	GL(kg)	Expected GL(kg)	MT(kg)	Expected MT(kg)	Firewood (m^3)	Expected (m^3)	m^3/ MT	GL/MT	Expected GL/MT
JANUARY	1,506,225	1,183,018	361,018	295,755	1,120	828	3.1	4.17	4
FEBRUARY	1,135,137	1,170,444	275,807	292,611	709	583	2.57	4.12	4
MARCH	1,554,361	1,375,479	365,933	343,870	1,139	963	3.11	4.25	4
APRIL	1,428,380	1,368,408	334,913	342,101	1,149	958	3.43	4.26	4
MAY	1,848,555	1,294,083	429,098	323,521	1,411	906	3.29	4.12	4
JUN	1,369,879	1,012,450	341,959	253,113	1,125	709	3.29	4.01	4
JULY	523,264	677,418	149,285	169,355	382	474	2.56	3.51	4
AUGUST	298,272	651,350	88,348	162,837	185	456	2.09	3.24	4
SEPTEMBER	336,386	844,041	88,997	211,010	196	591	2.2	3.78	4
OCTOBER	1,105,800	1,173,364	273,350	293,341	757	821	2.77	4.05	4
NOVEMBER	1,493,421	1,481,207	350,363	370,302	1,104	1,037	3.15	4.26	4
DECEMBER	1,213,479	1,459,105	279,476	364,776	876	1,021	3.13	4.34	4
TOTAL	**13,813,159**	**13,690,367**	**3,338,547**	**3,422,592**	**10,153**	**9,347**			
MONTHLY AVERAGE	1,151,097	1,140,864	278,212	285,216	846	779	3	4	4
DAILY AVERAGE	37844.2712	37507.8542	9146.70411	9376.9642	27.816438	25.608595			

2.11.3 Green leaves versus made tea during 2023

The **Table 3** indicates the Green Leaves and Made tea.

Table 3: Green Leaves (GL) vs. Made Tea (MT) in 2023

Month	GL(kg)	MT(kg)
JANUARY	1,506,225	361,018
FEBRUARY	1,135,137	275,807
MARCH	1,554,361	365,933
APRIL	1,428,380	334,913
MAY	1,848,555	429,098
JUN	1,369,879	341,959
JULY	523,264	149,285
AUGUST	298,272	88,348
SEPTEMBER	336,386	88,997
OCTOBER	1,105,800	273,350
NOVEMBER	1,493,421	350,363
DECEMBER	1,213,479	279,476
TOTAL	**13,813,159**	**3,338,547**
MONTHLY AVERAGE	1,151,097	278,212
DAILY AVERAGE	37844.2712	9146.70411

The **Figure 0-4** indicates the corresponding graphs for GL and MT.

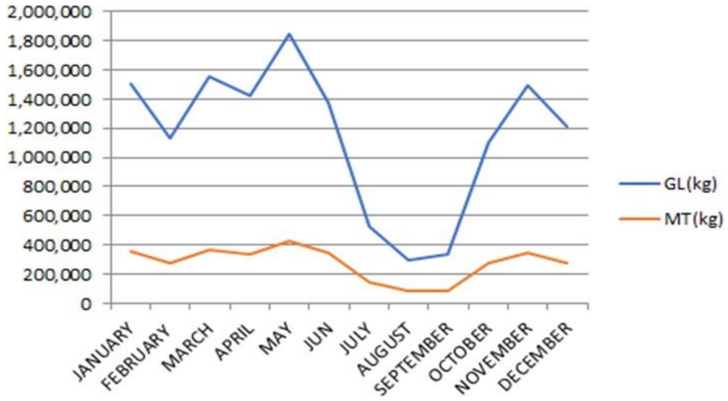


Figure 0-4: GL VS. MT graph during 2023

2.11.4 Made tea versus firewood consumed during 2023

Table 4: Made Tea and Firewood correspondence table during 2023

Month	MT(kg)	Firewood(m^3)
JANUARY	361,018	1,120
FEBRUARY	275,807	709
MARCH	365,933	1,139
APRIL	334,913	1,149
MAY	429,098	1,411
JUN	341,959	1,125
JULY	149,285	382
AUGUST	88,348	185
SEPTEMBER	88,997	196
OCTOBER	273,350	757
NOVEMBER	350,363	1,104
DECEMBER	279,476	876
TOTAL	**3,338,547**	**10,153**
MONTHLY AVERAGE	278,212	846
DAILY AVERAGE	9146.70411	27.81643836

2.11.5 Made tea per cubic meter of firewood during 2023

Table 5: Made Tea (MT) per cubic meter of firewood

Month	MT(kg)	Firewood(m^3)	kg.MT/m^3
JANUARY	361,018	1,120	322.3375
FEBRUARY	275,807	709	389.0084626
MARCH	365,933	1,139	321.2756804
APRIL	334,913	1,149	291.4821584
MAY	429,098	1,411	304.1091425
JUN	341,959	1,125	303.9635556
JULY	149,285	383	389.7780679
AUGUST	88,348	185	477.5567568
SEPTEMBER	88,997	196	454.0663265
OCTOBER	273,350	757	361.0964333
NOVEMBER	350,363	1,104	317.3577899
DECEMBER	279,476	876	319.0365297

TOTAL	**3,338,547**	**10,154**	
MONTHLY AVERAGE	278,212	846	354.2557003
DAILY AVERAGE	9146.70411	27.81917808	

The **Table 5** indicates the made tea per cubic meter of firewood.

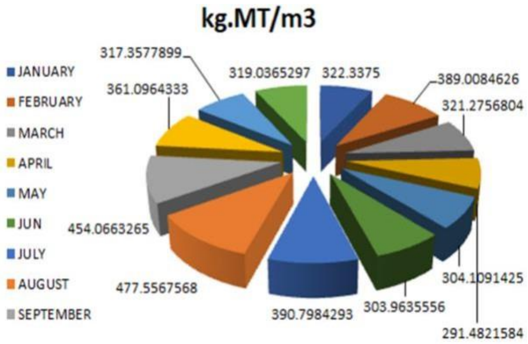


Figure 0-5: Kg of Made Tea per cubic meter

2.11.6 Firewood cost for Mata Tea Factory during 2023

According to the data provided by the storekeeper for Mata Tea Company, one cubic meter of firewood is costlier as it can cost at least 27000RWF including transport, handling cost and disposing cost. In this way, the table 7 indicates the amount of money in RWF spent on firewood by Mata Tea Company during 2023.

Table 6: Firewood cost in RWF for Mata tea factory during 2023

Month	Firewood(m^3)	RWF/m^3	FIREWOOD COST(RWF)
JANUARY	1,120	27000	30240000
FEBRUARY	709	27000	19143000
MARCH	1,139	27000	30753000
APRIL	1,149	27000	31023000
MAY	1,411	27000	38097000
JUN	1,125	27000	30375000
JULY	382	27000	10314000
AUGUST	185	27000	4995000
SEPTEMBER	196	27000	5292000
OCTOBER	757	27000	20439000
NOVEMBER	1,104	27000	29808000
DECEMBER	876	27000	23652000
TOTAL	**10,153**		**274131000**
MONTHLY AVERAGE	846		22844250
DAILY AVERAGE	27.81643836		751043.8356

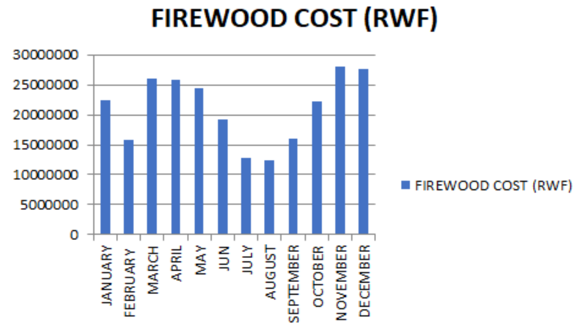


Figure 0-6: Firewood monthly cost in RWF

As we see in the above data, firewood is costlier. This cost of firewood for Mata tea factory, includes the purchase cost, the transportation cost and firewood daily handling cost and disposal.

2.11.7 Thermal energy supply subdivision in Mata Tea Factory

As the figure below summarizes the thermal energy generation and harnessing to the usage section in the factory, In Mata Tea processing plant, thermal energy is utilized for green leaves withering in three floors withering chambers equipped with 59 troughs on which tea leaves are displayed during withering process and tea drying within three dryers with thee drying sections for each dryer.

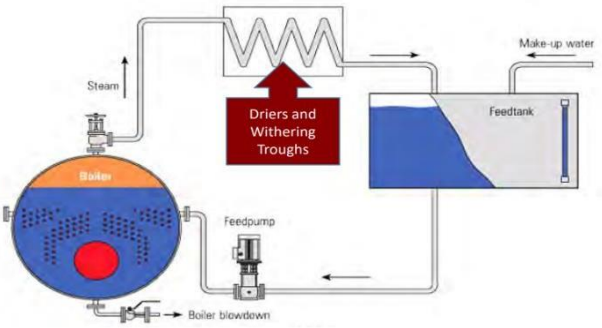


Figure 0-7: Thermal energy demand subdivision in Mata Tea Factory[4]

2.11.8 Thermal energy calculus for Tea Green Leaves (GL) withering during the year 2023

The moisture content of harvested tea green leaf is in the range of 70-80% (wet basis) and in withering operations moisture content is reduced to a level that lends itself to the unit operations of rolling and roll breaking. At this stage the accepted level of moisture depends on the method of manufacture adopted being 54±1.5% (wet basis) for high/mid-grown teas having liquoring characteristics; 59±2% (wet basis) for low grown manufactured for leaf style to suit markets in the Middle East; and 70 ±2% (wet basis) for CTC teas to suit markets requiring small leaf grades having thick color liquors. According to Kenya Tea Development Agency (KTDA) literature, withering section consumes normally 30% of the thermal energy generated from the boilers. For this data, the table below indicates the quantity of thermal energy supplied to withering section in Mata Tea factory during 2023.

Table 7: Thermal energy supplied for tea leaves withering in Mata Tea Factory during 2023

MONTH	MT(kg)	Thermal energy dupply(MJ)	Thermal energy supply(MWh)	Withering MWh supplied(30%)
JANUARY	361,018	7730240	2147.288889	644.1866667
FEBRUARY	275,807	4893518	1359.310556	407.7931667
MATCH	365,933	7861378	2183.716111	655.1148333
APRIL	334,913	7930398	2202.888333	660.8665
MAY	429,098	9738722	2705.200556	811.5601667
JUNE	341,959	7764750	2156.875	647.0625
JULY	149,285	2636564	732.3788889	219.7136667
AUGUST	88,348	1276870	354.6861111	106.4058333
SEPTEMBER	88,997	1352792	375.7755556	112.7326667
OCTOBER	273,350	5224814	1451.337222	435.4011667
NOVEMBER	350,363	7619808	2116.613333	634.984
DECEMBER	279,476	6046152	1679.486667	503.846
TOTAL	**3,338,547**	**70076006**	**19465.55722**	**5839.667167**
MONTHLY Average	278,212	**5839667.167**	**1622.129769**	486.6389306
DAILY AVERAGE	9146.70411	**191989.0575**	53.33029376	18.6570836

Hence, the thermal energy supplied for withering during 2023 is equivalent to **5839.667167MWh** which is 30% of total thermal energy supplied according to KTDA literature[4].

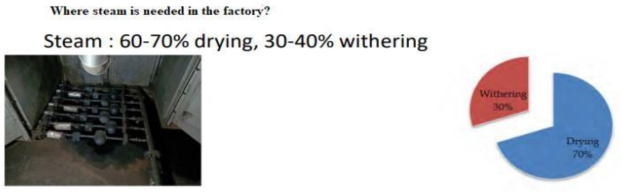


Figure 0-8: Percentage proportion of thermal energy in tea processing factory [4]

2.11.9 Dissipated thermal energy for green leaves withering during 2023

According to the literature of tea research institute of Sri Lank, in up country (high altitude), 4.5kg of green leaves dissipate theoretically 5.6MJ of thermal energy to obtain 2.22kg of withered leaves[25]. Therefore, the calorific value for green leaves withering is estimated as follows:

$C_v = \frac{5.6MJ}{4.5kg} = \mathbf{1.24MJ/kg}$[25]

Hence, the thermal energy dissipated by GL during 2023 is evaluated as follows:

MJ dissipated by green leaves=$GL(kg) x C_v(MJ/kg)$=13813159kgx1. 24MJ/kg =**17189709MJ=4775MWh** thermal

2.11.10 Thermal energy demand estimation for tea drying and withering during the year 2023

Mata tea factory has 3 dryers comprising one MACROY engineering model dryer and 2 Marshall Fowler engineering model dryers. Each dryer has three stages through which tea dhool passes during tea drying processes and thus consumes thermal energy during their working. The **Figure 2-1**, shows the dryer sections and corresponding temperature range for tea drying.

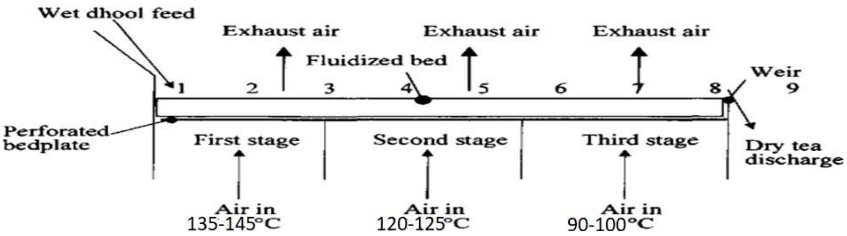


Figure 0-9: Tea dryers sections at Mata Tea Factory

Table 8: Drying inlet and exhaust air temperatures ranges at Mata tea factory

	INLET AIR T(°C)	**TEA DHOOL T(°C)/ Exhaust air**
FIRST STAGE	**135-145**	**40-45**
SECOND STAGE	**120-125**	**60-70**
THIRD STAGE	**90-100**	**80-90**

Rolled leaves after the fermentation process (essentially enzymic oxidation/ polymerization of tea polyphenols) is subjected to the unit operation of drying[4]. In this operation the moisture content is reduced to 3% in Fluidized Bed Driers supplied with hot air from air radiators. Drying needs at least **8bars** pressure steam. Withering of green tea leaves needs **4 bars** pressure steam. It means that 60-70% of steam is used for tea drying[4]. In our case, let us consider 70% of thermal energy supplied for tea drying and 30% for withering during 2023 at Mata Tea Factory. The table below computes the thermal energy supplied for withering and drying during 2023[4].

Table 9: Thermal energy supply for tea drying and withering during 2023 at Mata tea factory

MONTH	MT(kg)	Thermal energy supply(MJ)	Thermal energy supply(MWh)	Withering MWh supplied (30%)	Drying MWh supplied(70%)
JANUARY	361,018	7730240	2147.288889	644.1866667	1503.102222
FEBRUARY	275,807	4893518	1359.310556	407.7931667	951.5173889
MATCH	365,933	7861378	2183.716111	655.1148333	1528.601278
APRIL	334,913	7930398	2202.888333	660.8665	1542.021833
MAY	429,098	9738722	2705.200556	811.5601667	1893.640389
JUNE	341,959	7764750	2156.875	647.0625	1509.8125
JULY	149,285	2636564	732.3788889	219.7136667	512.6652222
AUGUST	88,348	1276870	354.6861111	106.4058333	248.2802778
SEPTEMBER	88,997	1352792	375.7755556	112.7326667	263.0428889
OCTOBER	273,350	5224814	1451.337222	435.4011667	1015.936056
NOVEMBER	350,363	7619808	2116.613333	634.984	1481.629333
DECEMBER	279,476	6046152	1679.486667	503.846	1175.640667
TOTAL	**3,338,547**	**70076006**	**19465.55722**	**5839.667167**	**13625.89006**
MONTHLY Average	**278,212**	**5839667.167**	**1622.129769**	**486.6389306**	**1135.490838**
DAILY average	**9146.70411**	**191989.0575**	**53.33029376**	**18.6570836**	**37.33120563**

Hence, according to KTDA literature, thermal energy supplied to dryers‟ sections during 2023 at Mata Tea Factory, is estimated to **13625.89006MWh thermal** which is 70% of total thermal energy supplied whereas that for tea leaves withering is **5839.667167MWh** thermal which is 30%. The total annual thermal energy supplied for tea processing is assumed to be **19466MWh** thermal.

2.11.11 Dissipated thermal energy by manufactured tea within dryers

According to the Sri-Lank tea research institute, 4.5kg of Green Leaves (GL) give 2.22kg of Withered Leaves (WL). It implies that 13813159kg of GL gives 6814492kg of withered leaves (WL).

As 2.22kg of WL dissipate 10.6MJ to be transformed into 1 kg of black tea, the dissipated thermal energy for manufactured black tea during 2023 can be evaluated as follows:

MJ dissipated during tea drying $=WL(kg)xC_V\left(\frac{MJ}{kg}\right)=6814492kgx\ \frac{10.6MJ}{2.22kg}$ **=32537663MJ=9038MWh**

2.11.12 Firewood thermal energy calculus at Mata tea factory

According to KTDA literature[4], **1m^3** of eucalyptus firewood with **20%** of moisture content(MC), dense with **493kg/m^3** and is susceptible to produce **6902MJ** of thermal energy and its calorific value (CV) is assumed to **14MJ**. This analogy is the same for Mata tea factory as the moisture content of their dry eucalyptus wood logs that they burn into the boilers furnace is also **20%.**

- Firewood measurement

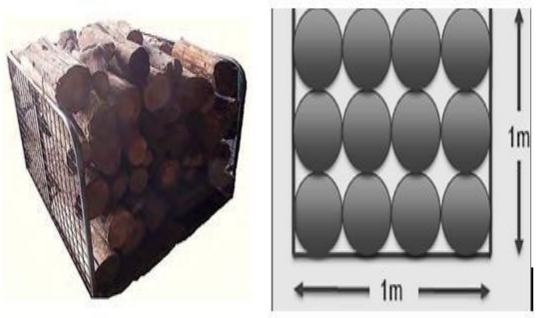


Figure 0-10: One cubic meter of Eucalyptus firewood[4]

According to KTDA[4], the denser cubic meter of Eucalyptus firewood has the following characteristics At 20% Moisture Content:

- Density: 493Kg/m^3
- Calorific value: 14MJ/Kg
- Energy: 6902MJ
- Firewood 1 m^3 = 5170 MJ => 1800 Kgs of steam/m^3

In addition, according to the mentioned literature, as the moisture content (MC) of the firewood decreases, the calorific value increases with respect to the table below:

Table 10: Firewood moisture content VS. Calorific value[4] [5]

MC%	CV(MJ/kg)
0	18
10	16
20	14
30	12
40	10
50	8

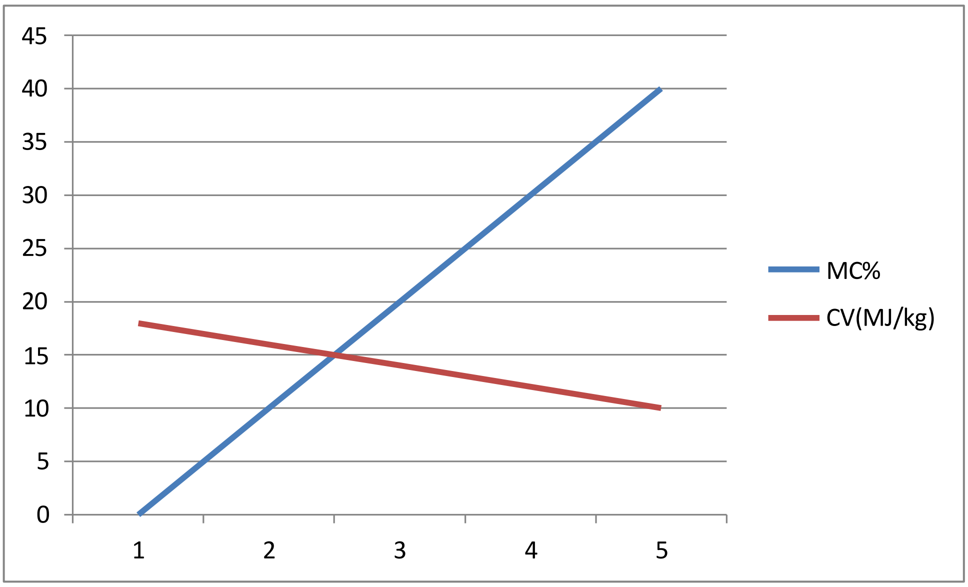


Figure 0-11: Firewood moisture content VS. Calorific value [5]

While considering the above firewood parameters, the table below includes the total thermal energy generated by all firewood consumed during the year 2023 for tea manufacturing in Mata tea factory.

Table 11: Thermal energy supply for tea manufacturing in Mata tea factory during 2023

Month	**Firewood(m^3)**	**MC(%)**	**CV(MJ/kg)**	**Density(kg/m^3)**	**MJ supply**
JANUARY	1,120	20	14	493	7730240
FEBRUARY	709	20	14	493	4893518
MARCH	1,139	20	14	493	7861378
APRIL	1,149	20	14	493	7930398
MAY	1,411	20	14	493	9738722
JUN	1,125	20	14	493	7764750
JULY	382	20	14	493	2636564
AUGUST	185	20	14	493	1276870
SEPTEMBER	196	20	14	493	1352792
OCTOBER	757	20	14	493	5224814
NOVEMBER	1,104	20	14	493	7619808
DECEMBER	876	20	14	493	6046152
TOTAL	**10,153**				**70,076,006**
MONTHLY AVERAGE	846				5839667.167
DAILY AVERAGE	27.81643836				191989.0575

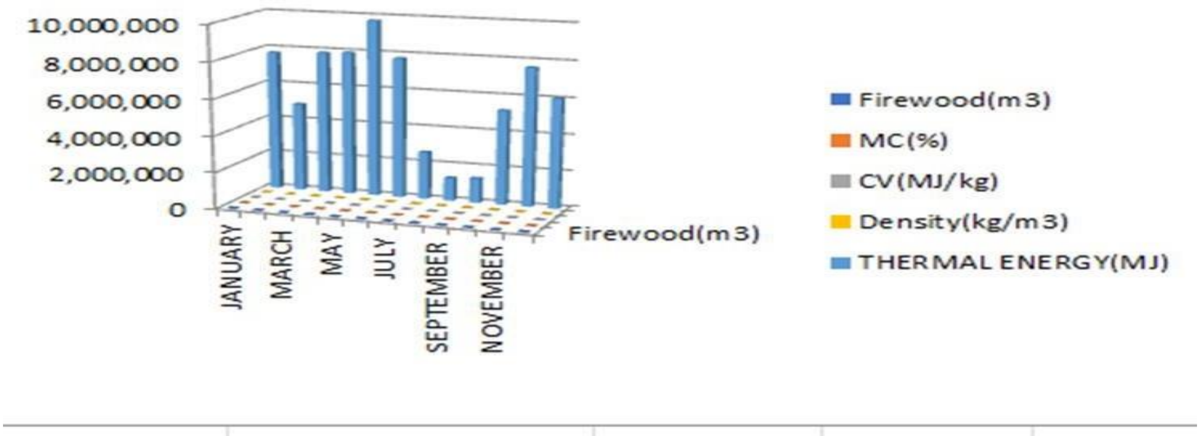


Table 12: Annual thermal energy (MJ) supply from firewood

According to the data provided in the above table, the quantity of firewood utilized at the boilers during the year 2023 is equivalent to **10153m^3**.

The heat capacity (capacity value) for tea drying at Mata tea factory is equivalent to 14MJ/kg as the moisture content (MC %) of the firewood they utilize is 20%. Hence, the thermal energy generated can be assumed to **70076006** MJ. The firewood annual thermal energy supplied for tea withering and drying during 2023 is estimated to **70076006MJ**

Table 13: Thermal energy consumed for tea processing during 2023

Month	GL(kg)	MT(kg)	MJ/kg.MT	MJ demand
JANUARY	1,506,225	361,018	18.79	6783528.22
FEBRUARY	1,135,137	275,807	18.79	5182413.53
MARCH	1,554,361	365,933	18.79	6875881.07
APRIL	1,428,380	334,913	18.79	6293015.27
MAY	1,848,555	429,098	18.79	8062751.42
JUN	1,369,879	341,959	18.79	6425409.61
JULY	523,264	149,285	18.79	2805065.15
AUGUST	298,272	88,348	18.79	1660058.92
SEPTEMBER	336,386	88,997	18.79	1672253.63
OCTOBER	1,105,800	273,350	18.79	5136246.5
NOVEMBER	1,493,421	350,363	18.79	6583320.77
DECEMBER	1,213,479	279,476	18.79	5251354.04
TOTAL	**13,813,159**	**3,338,547**		**62,731,298**
MONTHLY AVERAGE	1,151,097	278,212		5,227,608
DAILY AVERAGE	37844.27123	9146.70411		200419.4828

According to the data provided in the table above, the thermal energy demand during the year 2023 is equivalent to **62731298.13MJ=17425.89006MWh.**

Table 14: Thermal energy supplied vs. thermal energy utilized during 2023

Month	MJ supply	MJ demand
JANUARY	7730240	6783528.22
FEBRUARY	4893518	5182413.53
MARCH	7861378	6875881.07
APRIL	7930398	6293015.27
MAY	9738722	8062751.42
JUN	7764750	6425409.61
JULY	2636564	2805065.15
AUGUST	1276870	1660058.92
SEPTEMBER	1352792	1672253.63
OCTOBER	5224814	5136246.5
NOVEMBER	7619808	6583320.77
DECEMBER	6046152	5251354.04
TOTAL	**70,076,006**	**62,731,298**
MONTHLY AVERAGE	5839667.167	5,227,608
DAILY AVERAGE	191989.0575	200419.4828

2.11.13 Thermal energy supplied and dissipated during 2023 by Mata tea factory

Table 15: Annual thermal energy supply and demand (MWh)-thermal for Mata Tea Factory during 2023

Month	MJ supply	MJ demand	MWh supply	MWh Demand
JANUARY	7730240	6783528.22	2147.288889	1884.313394
FEBRUARY	4893518	5182413.53	1359.310556	1439.559314
MARCH	7861378	6875881.07	2183.716111	1909.966964
APRIL	7930398	6293015.27	2202.888333	1748.059797
MAY	9738722	8062751.42	2705.200556	2239.653172
JUN	7764750	6425409.61	2156.875	1784.836003
JULY	2636564	2805065.15	732.3788889	779.1847639
AUGUST	1276870	1660058.92	354.6861111	461.1274778
SEPTEMBER	1352792	1672253.63	375.7755556	464.5148972
OCTOBER	5224814	5136246.5	1451.337222	1426.735139
NOVEMBER	7619808	6583320.77	2116.613333	1828.700214
DECEMBER	6046152	5251354.04	1679.486667	1458.709456
TOTAL	**70,076,006**	**62,731,298**	**19465.55722**	**17425.36059**
MONTHLY AVERAGE	5839667.167	5,227,608	1622.129769	1452.113383
DAILY AVERAGE	191989.0575	200419.4828	62.19027867	55.67207857

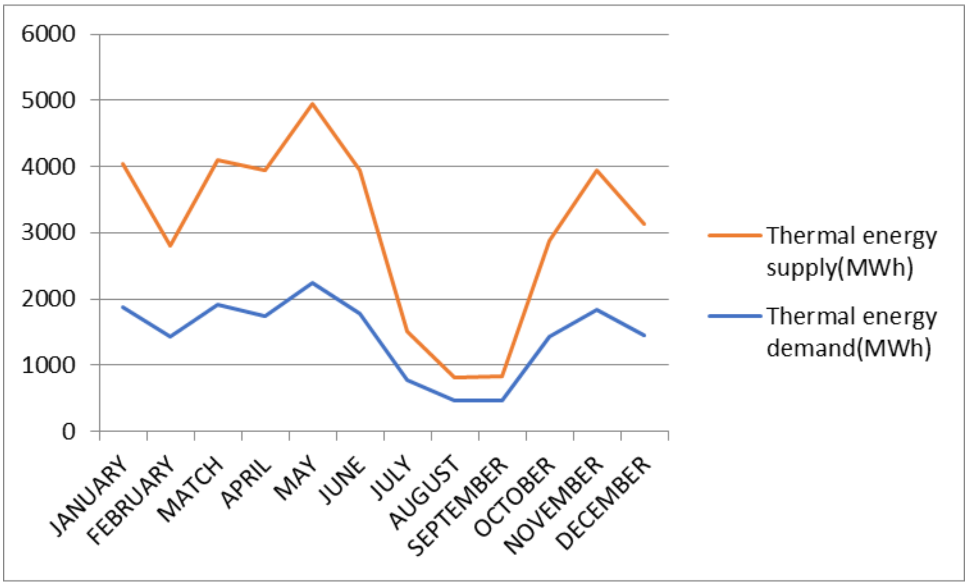


Figure 0-12: Thermal energy supply and demand curve for Mata tea factory during 2023

2.11.14Summary for heat sink requirements for Mata tea factory during 2023

- Total annual thermal energy supply for the tea factory during 2023 is equivalent to 70076006MJ= 19466MWh thermal and total thermal energy dissipated during 2023 was equivalent to 17425.89006MWh thermal.
- Withering thermal energy supplied during 2023 is equivalent to =5839.667167MWh thermal and thermal energy dissipated by the GL is estimated to 4775MWh thermal.
- Drying thermal energy supplied during 2023 is equivalent to 13625.89006MWh thermal and thermal energy dissipated by the manufactured black tea is evaluated as 9038MWh thermal.

2.11.15Thermal power (MW) supply and consumption during 2023

Let us recall that the energy (E) can be expressed in Joule (J) or Watt-second (Ws) and the power (P) can be expressed in Watt (W). Secondly, **1hour=3600seconds** and **1year=8760h**

1Joule=1Watt x1second

- 19466MWh=$\frac{19466\text{MWh}}{8760\text{h}}$=2.222MW thermal which will further be used for simulation with SAM software as it is the rated plant capacity achievable from SM = 1.8 according to the data given by the literature.
- 17425.89006MWh=$\frac{17425.89006\text{MWh}}{8760\text{h}}$=1.9892MW for black tea manufacturing in general(both withering and drying)
- 5839.667167MWh=$\frac{5839.667167\text{MWh}}{8760\text{h}}$=0.666MW for withering stages
- 13625.89006MWh=$\frac{13625.89006\text{MWh}}{8760\text{h}}$=1.555MW thermal for dryers.

2.12 SYSTEM MODELING AND SIMULATION

To model the solar thermal system for tea drying, let‟s consider the heat sink power employed by Mata tea processing plant during 2023 as the required solar thermal system to integrate in and use this MW thermal power in system advisor model software and simulate to observe the required solar field aperture area and storage tank size for continuous thermal energy supply.

2.12.1 Simulation software

I will use System Advisor Model (SAM) software, version 2023.12.17 offered freely by US National Renewable Energy Laboratory (NREL) for simulating renewable energy projects.

2.12.2 Design point Direct Normal Irradiance (DNI)

Even if the direct normal irradiance of the location varies time to time, the data retrieved from PVGIS.COM for the Mata Tea Factory location is equivalent to 5.43W/m^2. I will use this value during simulation as design point.

2.12.3 Solar Collectors loop temperatures

The operating collector loop inlet and outlet temperatures are selected as the temperatures that satisfies the heating application, in this case, tea drying process undergoes in the range of 90–160 °C. The drying temperature of 110 °C is optimum for good quality black tea. The suitable temperature of the HTF at the solar field outlet must be selected at least 15 °C higher than the steam temperature by the process to be supplied to compensate the thermal loss between the solar field outlet and the drier inlet. The selected final outlet temperature is 130 °C and the inlet temperature selected to be 40 °C.

The inlet temperature of the collector field is 40℃ and the outlet temperature of the collector field is 150℃.

2.12.4 Solar multiple (SM)

The solar Multiple (SM) is a factor for designing solar field size and is the ratio between thermal energy produced at design point and thermal energy required by the plant at nominal conditions. The value of the SM controls the size of the solar collector, i.e., increasing the SM results in a solar fraction with a larger reflective area that can provide more heat.

SM=1.8 is the optimum value for solar thermal systems design for Industrial Process Heat applications. It can vary from 1 to 3 and the system behavior can be observed.

2.12.5 Thermal energy storage (TES) hours

Thermal Energy Storage, on the other hand, specifies the ability of the solar thermal system to store additional heat from the solar collector. In this study, the impact of different values of SM and TES are assessed on solar PTC system to determine the benefits and drawbacks of a hybrid biomass–solar PTC plant[26].

Therefore, a suitable solar thermal system for Mata tea processing plant should be designed at annual tea drying heat sink power (MW-t), optimal Solar multiple and 24hrs of TES for continuous thermal energy supply.

2.13 Step to follow and key steps follow diagram

2.13.1 Step to follow

- Use geographical data and meteorological data retrieved from PVGIS.com.
- Use hourly DNI data from the reference site to SAM's solar resource library.
- Solar PTC field design parameters configuration
- Solar collector arrays(SCAs) parameters configuration
- Receiver(HCEs) parameters configuration
- Thermal storage characteristics configuration

2.13.2 Key steps follow diagram

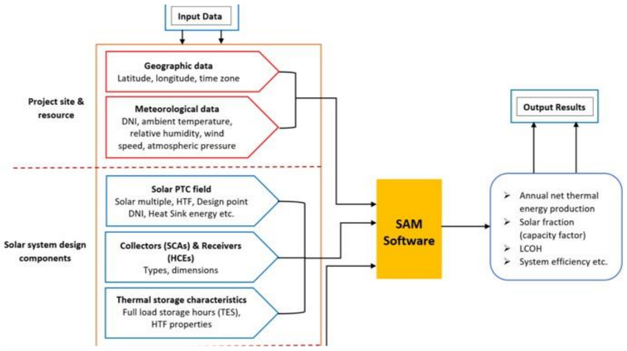
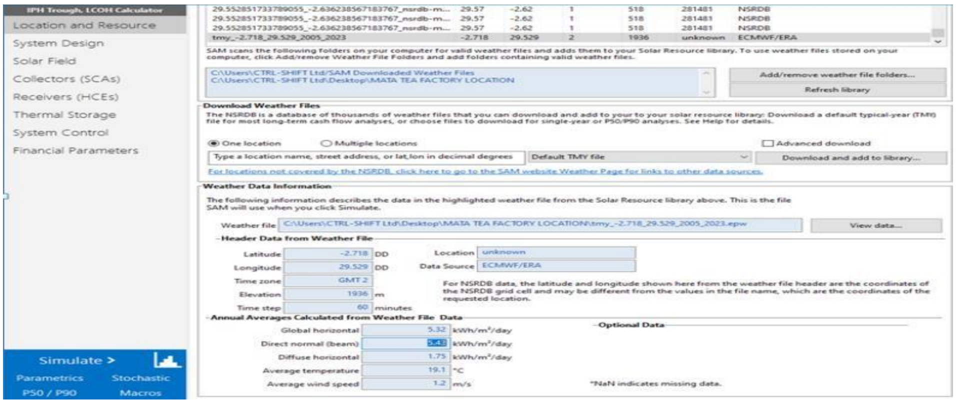


Figure 0-13: SAM's source library inputs and outputs

2.13.3 Location latitude and longitude entering in the SAM

Figure 0-14: On map location of Mata tea factory in Nyaruguru District

This map manifests the latitude and longitude location of Mata Tea Factory location.



29.552851733789055_-2.636238567183767_nsrdb-m...	29.57	-2.62	1	518	281481	NSRDB
29.552851733789055_-2.636238567183767_nsrdb-m...	29.57	-2.62	1	518	281481	NSRDB
29.552851733789055_-2.636238567183767_nsrdb-m...	29.57	-2.62	1	518	281481	NSRDB
tmy_-2.718_29.529_2005_2023	-2.718	29.529	2	1936	unknown	ECMWF/ERA

SAM scans the following folders on your computer for valid weather files and adds them to your Solar Resource library. To use weather files stored on your computer, click Add/remove Weather File Folders and add folders containing valid weather files.

C:\Users\CTRL-SHIFT Ltd/SAM Downloaded Weather Files
C:\Users\CTRL-SHIFT Ltd\Desktop\MATA TEA FACTORY LOCATION

Download Weather Files

The NSRDB is a database of thousands of weather files that you can download and add to your to your solar resource library: Download a default typical-year (TMY) file for most long-term cash flow analyses, or choose files to download for single-year or P50/P90 analyses. See Help for details.

● One location ○ Multiple locations ☐ Advanced download

Type a location name, street address, or lat,lon in decimal degrees | Default TMY file

For locations not covered by the NSRDB, click here to go to the SAM website Weather Page for links to other data sources.

Weather Data Information

The following information describes the data in the highlighted weather file from the Solar Resource library above. This is the file SAM will use when you click Simulate.

Weather file: C:\Users\CTRL-SHIFT Ltd\Desktop\MATA TEA FACTORY LOCATION\tmy_-2.718_29.529_2005_2023.epw

Header Data from Weather File

Latitude: -2.718 DD
Longitude: 29.529 DD
Time zone: GMT 2
Elevation: 1936 m
Time step: 60 minutes
Location: unknown
Data Source: ECMWF/ERA

For NSRDB data, the latitude and longitude shown here from the weather file header are the coordinates of the NSRDB grid cell and may be different from the values in the file name, which are the coordinates of the requested location.

Annual Averages Calculated from Weather File Data

Global horizontal: 5.32 kWh/m²/day
Direct normal (beam): 5.43 kWh/m²/day
Diffuse horizontal: 1.75 kWh/m²/day
Average temperature: 19.1 °C
Average wind speed: 1.2 m/s

Optional Data

*NaN indicates missing data.

Figure 0-15: Geographic data and DNI in SAM for the study case of Mata tea factory

According to PVGIS data, in typical meteorological year 2015-2023, Mata tea factory is located in Southern province of Rwanda, Nyaruguru District, Mata Sector at Longitude: 29.529 and latitude: -2.718, 1936m elevation of altitude and GMT=2 as the **Figure 0-15** indicates. This location has abundant Direct Normal Irradiance (DNI) as the design point parameter which is visualized on the Figure 0-16 during simulation.

Analysis:

- Average DNI at Mata tea factory location: 5.43 kWh/m²/day as mentioned on the **Figure 0-15**
- Meets the minimum recommended DNI (5.0 kWh/m²/day) for industrial process heat operations as it was spoken in the literature.
- Total annual DNI: 1981.59 kWh/m², exceeding the typical minimum threshold (1600-2000 kWh/m²/year) for high economic performance. Besides, this site is susceptible for industrial heat processes (IPH) applications employing concentrated solar collectors (CSC) for tea drying. In this case, parabolic trough solar collectors (PTC) are appointed to be employed in the solar thermal system for tea drying as they have high optical performance.

2.13.4 DNI visualization graphs at clear sky during 2023

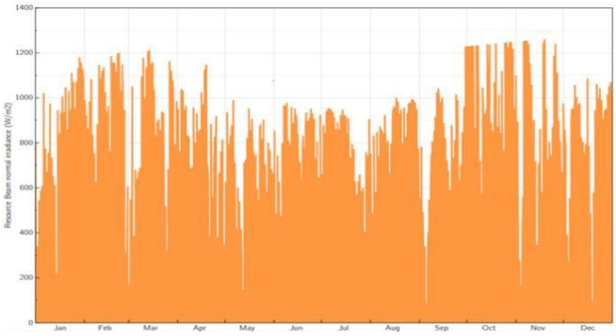


Figure 0-16: Resource beam normal irradiance visualization for all months during 2023

The **Figure 0-16** retrieved from simulation in system advisor model software, clarifies that at Mata tea factory location there is abundant insolation with average value of 494w/m^2 and the maximum can attain 950w/m^2 as the simulation software manifests in the Figure 0-17 and Figure 0-18.

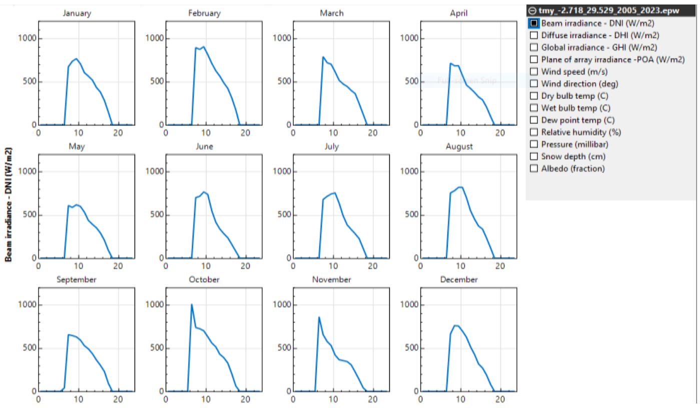


Figure 0-17: Per month magnitude of Direct Normal Irradiance for the study site

The Figure 0-17 above manifests that Southern province of Rwanda, Nyaruguru District, Mata Sector at Longitude: 29.529 and latitude: -2.718, 1936m elevation of altitude and GMT=2 has sufficient beam irradiance for every month according to the simulation in SAM software.

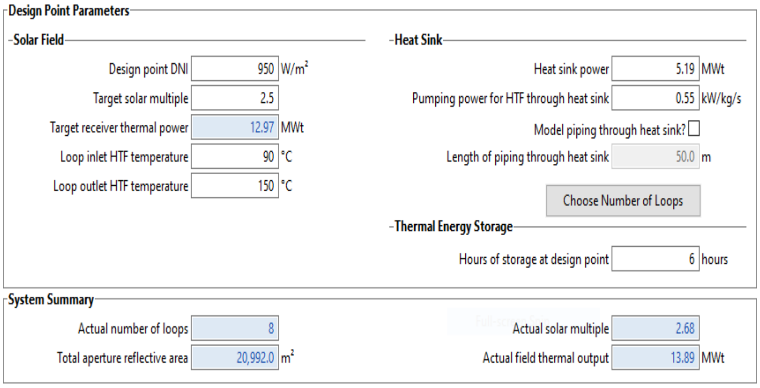
2.13.5 DNI susceptibilities in terms of thermal energy production potential

After first simulation, the System Advisor Model software manifests that the DNI for the study case of Mata tea factory exhibits the following susceptibilities in solar thermal energy production:

Table 16: DNI thermal energy susceptibilities at Mata Tea factory

Metric	**Value**
Annual energy (year 1)	23,050,016 kWh-t
Capacity factor	51%
Annual Water Usage	176 m^3
LCOH Levelized cost of heat	5.80 ¢/kWh-t

According to the SAM software, the location site under study has the sufficient insolation that can attain 950W/m^2 and can produce at least 5.19MWt with a temperature range of 90℃ to 150℃ which is the proof that it can intervene for industrial process heat application such as tea drying purpose with **Thermal Energy Storage hours**=6hrs. The susceptible system can be summarized also in the figure below. These parameters can be changed to observe the solar thermal system summary behavior. In the table above, it is observable that the susceptible capacity factor for the solar thermal system to integrate in with the spoken system‟s characteristics is 51%.



Design point DNI 950 W/m^2
Target solar multiple 2.5
Target receiver thermal power 12.97 MWt
Loop inlet HTF temperature 90 °C
Loop outlet HTF temperature 150 °C
Heat sink power 5.19 MWt
Pumping power for HTF through heat sink 0.55 kW/kg/s
Model piping through heat sink? ☐
Length of piping through heat sink 50.0 m
Hours of storage at design point 6 hours
Actual number of loops 8
Total aperture reflective area 20,992.0 m^2
Actual solar multiple 2.68
Actual field thermal output 13.89 MWt

Figure 0-18: solar energy susceptibility at Mata Tea Factory

Table 17: Solar fraction susceptibility for thermal energy production at Mata Tea Factory

MONTH	Wood energy supply(MWh)	Solar fraction (51%) in MWh	Thermal energy demand(MWh)	MT(kg)	MJ/kg.MT	Thermal energy dupply(MJ)	Thermal energy demand(MJ)
JANUARY	2147.288	1073.644	1884.313	361,018	19	7730240	6783528.22
FEBRUARY	1359.310	679.655	1439.559	275,807	19	4893518	5182413.53
MATCH	2183.716	1091.858	1909.966	365,933	19	7861378	6875881.07
APRIL	2202.888	1101.444	1748.059	334,913	19	7930398	6293015.27
MAY	2705.200	1352.6002	2239.653	429,098	19	9738722	8062751.42
JUNE	2156.875	1078.4375	1784.836	341,959	19	7764750	6425409.61
JULY	732.378	366.189	779.184	149,285	19	2636564	2805065.15
AUGUST	354.686	177.343	461.127	88,348	19	1276870	1660058.92
SEPTEMBER	375.775	187.887	464.514	88,997	19	1352792	1672253.63
OCTOBER	1451.337	725.668	1426.735	273,350	19	5224814	5136246.5
NOVEMBER	2116.613	1058.306	1828.700	350,363	19	7619808	6583320.77
DECEMBER	1679.486	839.743	1458.709	279,476	19	6046152	5251354.04
TOTAL	**19465.557**	9732.778	**17425.360**	**3,338,547**		**70076006**	**62731298.13**
MONTHLY Average	**1622.129**	811.064	**1452.113383**	**278,212**		**5839667.167**	**5227608.178**
DAILY AVERAGE	**47.7407**	26.665	**53.33029376**	**9146.70411**		**191989.0575**	**171866.5702**

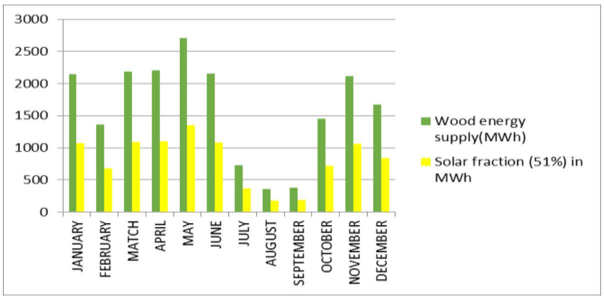


Figure 0-19: Solar thermal energy susceptibility share for Mata tea factory

- Susceptibility for money saving

Table 18: Firewood cost cut share

Month	Firewood(m^3)	RWF/m^3	FIREWOOD COST	m^3 to suppress(51%)	RWF to save(51%)
JANUARY	1,120	27000	30240000	571.2	15422400
FEBRUARY	709	27000	19143000	361.59	9762930
MARCH	1,139	27000	30753000	580.89	15684030
APRIL	1,149	27000	31023000	585.99	15821730
MAY	1,411	27000	38097000	719.61	19429470
JUN	1,125	27000	30375000	573.75	15491250
JULY	382	27000	10314000	194.82	5260140
AUGUST	185	27000	4995000	94.35	2547450
SEPTEMBER	196	27000	5292000	99.96	2698920
OCTOBER	757	27000	20439000	386.07	10423890
NOVEMBER	1,104	27000	29808000	563.04	15202080
DECEMBER	876	27000	23652000	446.76	12062520
TOTAL	**10,153**		**274,131,000**	**5,178**	**139,806,810**
MONTHLY AVERAGE	846		22,844,250		11,650,568
DAILY AVERAGE	32.43769968		875817.8914	16.54322684	446667.1246

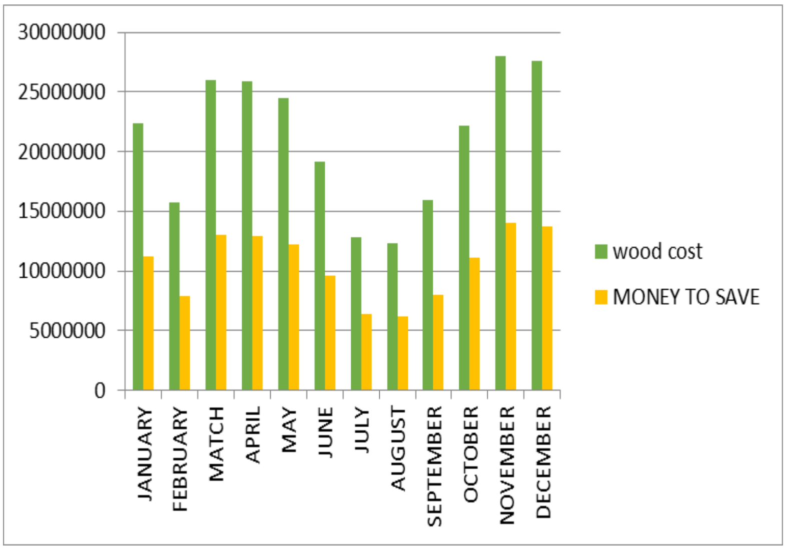


Figure 0-20: Wood cost and cost to suppress with solar fraction

- Susceptibility for firewood consumption suppression

Table 19: Susceptibility for firewood consumption suppression

Month	Firewood(m^3)	RWF/m^3	FIREWOOD COST(RWF)	Firewood m^3 to suppress(51%)	RWF to save(51%)
JANUARY	1,120	27000	30240000	571.2	15422400
FEBRUARY	709	27000	19143000	361.59	9762930
MARCH	1,139	27000	30753000	580.89	15684030
APRIL	1,149	27000	31023000	585.99	15821730
MAY	1,411	27000	38097000	719.61	19429470
JUN	1,125	27000	30375000	573.75	15491250
JULY	382	27000	10314000	194.82	5260140
AUGUST	185	27000	4995000	94.35	2547450
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NOVEMBER	1,104	27000	29808000	563.04	15202080
DECEMBER	876	27000	23652000	446.76	12062520
TOTAL	**10,153**		**274,131,000**	**5,178**	**139,806,810**
MONTHLY AVERAGE	846		22,844,250		11,650,568
DAILY AVERAGE	27.81643836		751043.8356	14.18638356	383032.3562

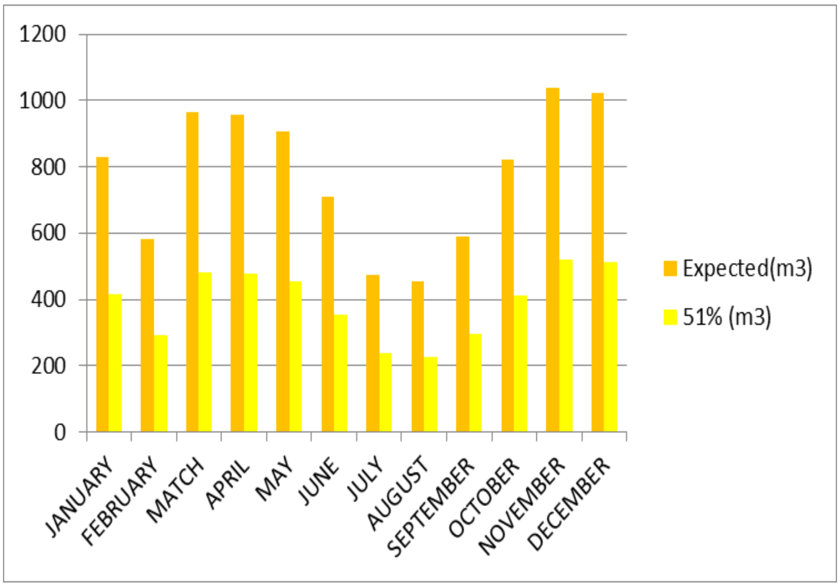


Figure 0-21: Firewood consumed and firewood to be suppressed by solar fraction in the system

The tea factories currently rely on biomass (fuel wood) as the main source of process heat for tea drying. On average, Mata tea factory spends **27,000RWF** per cubic meter of wood. During the 1-year study period, Mata tea factory consumed **10153m^3** of wood. This translates to annual expenditure of **274,050,000RWF** on wood to meet the drying energy demand of **19,466,000kWh**. Therefore, the levelized cost of heat from wood combustion stands at about **14RWF/kWh**

2.14 System design and simulation

2.14.1 Design parameters and considerations

Table 20: design parameters and considerations

Site: Mata tea factory, Nyaruguru District, Mata Sector, Murambi cell

PARAMETER	VALUE
Latitude	-2.718
Longitude	29.529
GMT	2
Elevation	1936m
DNI	5.43kWh/m^2/day
SOLAR FIELD	
Design point Direct Normal Irradiance(DNI)	494W/m^2
Total aperture area	13080m^2
Target receiver thermal energy	4.0MWt
Loop temperature at field entrance	40°C
Loop temperature at field exit	150°C
PTC	**EURO TROUGH ET150**
Reflective aperture area	13080m^2
Length of the collector assembly	150
Length of single model	12.5
Number of model per assembly	12
Optical efficiency at the design	0.871
mirror reflectance	0.935
Receiver tube	**Schott PTR70**
Absorber tube inner diameter	0.066m
Absorber tube outer diameter	0.07m
Absorptance of absorber tube	0.96
Thermal storage system(TES)	
Heat Transfer Fluid(HTF)	Pressurized water
Loop inlet HTF temperature	40°C
Loop outlet HTF temperature	150°C
Heat demand/Heat sink	
Heat sink power	**2.22MW**
Pumping energy of HTF through heat sink	0.55Kw/kg/s

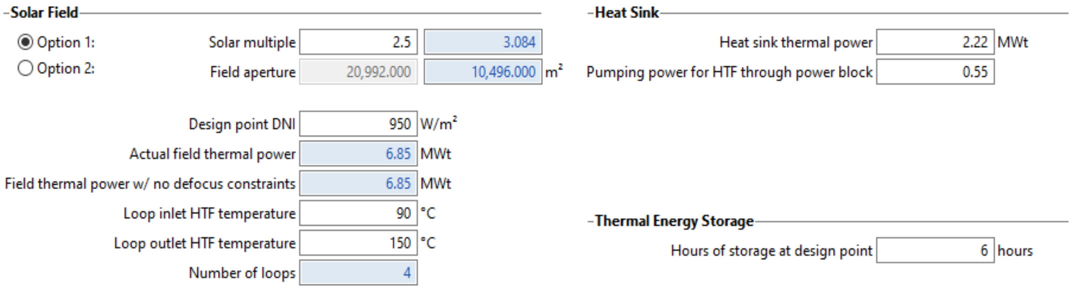
As we have seen by excel calculus, the annual thermal heat sink power requirements at Mata Tea Processing plant was **2.22MW**-thermal (**MW-t)** during the year 2023. This thermal power is one which I will use for system design in simulation.

2.14.2 System design

2.14.3 The system is designed while considering the following parameters:

- Annual Thermal power=2.22MW
- Solar Multiple (SM)=1.8
- Direct Normal Irradiance(DNI)=494W/m^2
- Thermal Energy Storage Hours (TES)=24hrs
- Loop inlet Heat Transfer Fluid(HTF) temperature=40℃
- Loop outlet Heat Transfer Fluid(HTF) temperature=150℃

2.14.4 Case of 2.22MW for Mata Tea processing plant



Solar Field

● Option 1: Solar multiple 2.5 | 3.084

○ Option 2: Field aperture 20,992.000 | 10,496.000 m²

Design point DNI 950 W/m²

Actual field thermal power 6.85 MWt

Field thermal power w/ no defocus constraints 6.85 MWt

Loop inlet HTF temperature 90 °C

Loop outlet HTF temperature 150 °C

Number of loops 4

Heat Sink

Heat sink thermal power 2.22 MWt

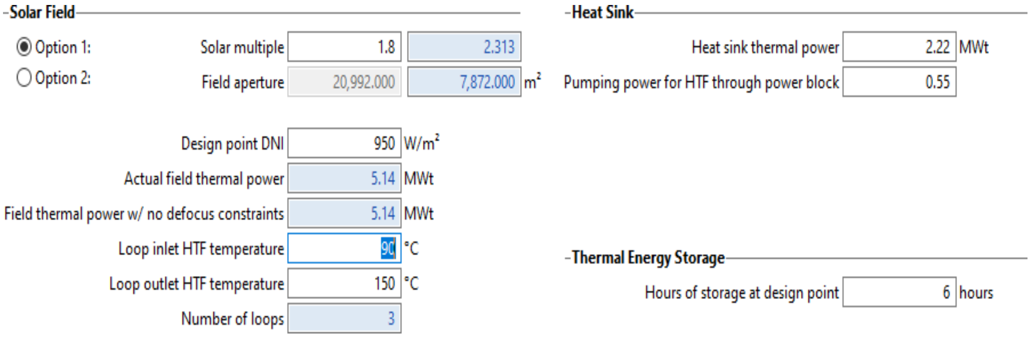
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 6 hours

Figure 0-22: system behavior when the tea processing plant is rated at 2.22MW thermal

2.14.5 Case of SM=1.8



Solar Field

● Option 1: Solar multiple 1.8 | 2.313

○ Option 2: Field aperture 20,992.000 | 7,872.000 m²

Design point DNI 950 W/m²

Actual field thermal power 5.14 MWt

Field thermal power w/ no defocus constraints 5.14 MWt

Loop inlet HTF temperature 90 °C

Loop outlet HTF temperature 150 °C

Number of loops 3

Heat Sink

Heat sink thermal power 2.22 MWt

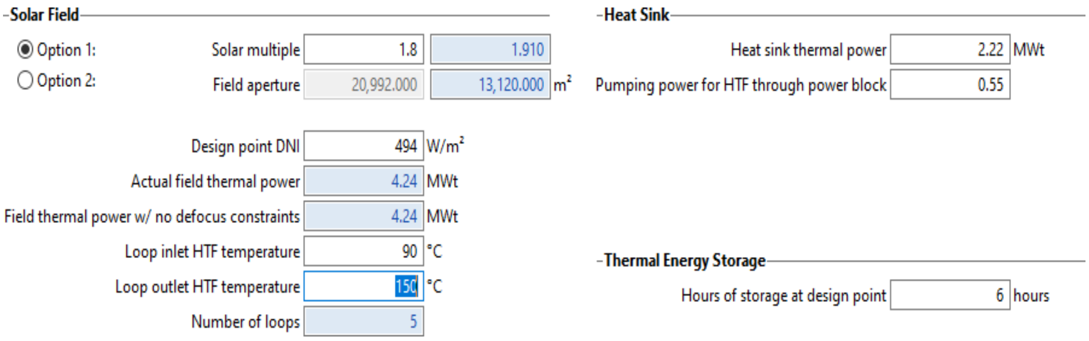
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 6 hours

Figure 0-23: system behavior when solar multiple is 1.8

2.14.6 Case of DNI=494W/m^2



Solar Field

● Option 1: Solar multiple 1.8 1.910

○ Option 2: Field aperture 20,992.000 13,120.000 m^2

Design point DNI 494 W/m^2

Actual field thermal power 4.24 MWt

Field thermal power w/ no defocus constraints 4.24 MWt

Loop inlet HTF temperature 90 °C

Loop outlet HTF temperature 150 °C

Number of loops 5

Heat Sink

Heat sink thermal power 2.22 MWt

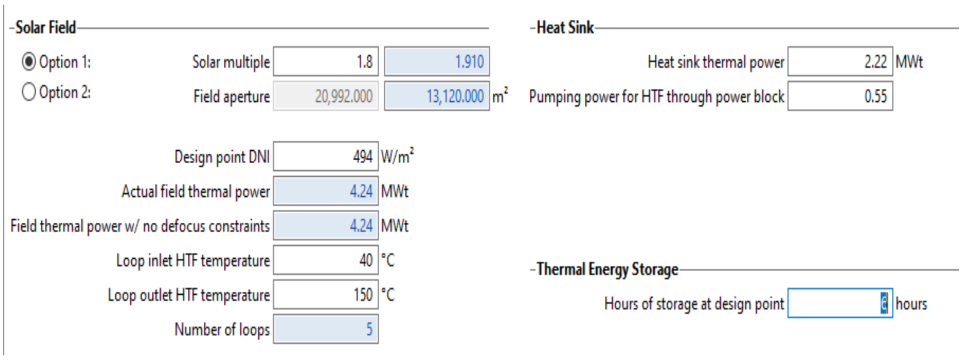
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 6 hours

Figure 0-24: System behavior when DNI is 494W/m^2

2.14.7 Case of Loop inlet HTF Temperature=40℃



Solar Field

● Option 1: Solar multiple 1.8 1.910

○ Option 2: Field aperture 20,992.000 13,120.000 m^2

Design point DNI 494 W/m^2

Actual field thermal power 4.24 MWt

Field thermal power w/ no defocus constraints 4.24 MWt

Loop inlet HTF temperature 40 °C

Loop outlet HTF temperature 150 °C

Number of loops 5

Heat Sink

Heat sink thermal power 2.22 MWt

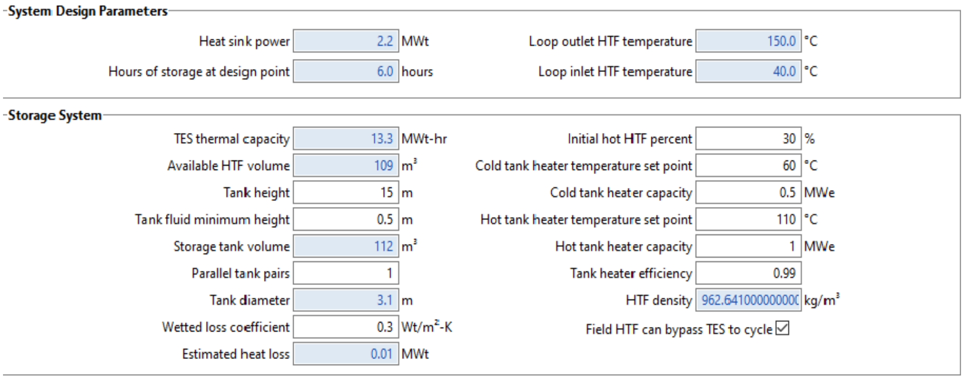
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 6 hours

Figure 0-25: system behavior when loop inlet temperature is degree Celsius

2.14.8 Thermal Energy Storage tank for TES of 6hrs of operation:



System Design Parameters

Heat sink power 2.2 MWt

Hours of storage at design point 6.0 hours

Loop outlet HTF temperature 150.0 °C

Loop inlet HTF temperature 40.0 °C

Storage System

TES thermal capacity 13.3 MWt-hr

Available HTF volume 109 m^3

Tank height 15 m

Tank fluid minimum height 0.5 m

Storage tank volume 112 m^3

Parallel tank pairs 1

Tank diameter 3.1 m

Wetted loss coefficient 0.3 Wt/m^2-K

Estimated heat loss 0.01 MWt

Initial hot HTF percent 30 %

Cold tank heater temperature set point 60 °C

Cold tank heater capacity 0.5 MWe

Hot tank heater temperature set point 110 °C

Hot tank heater capacity 1 MWe

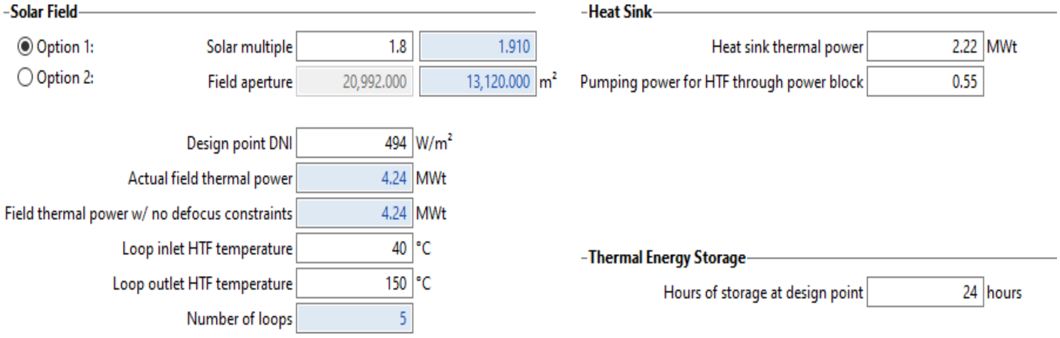
Tank heater efficiency 0.99

HTF density 962.641000000000 kg/m^3

Field HTF can bypass TES to cycle ☑

Figure 0-26: Storage tank size when TES is 6hrs

2.14.9 Thermal Energy Storage tank for TES= 24hrs



Solar Field

● Option 1: Solar multiple 1.8 1.910

○ Option 2: Field aperture 20,992.000 13,120.000 m²

Design point DNI 494 W/m²

Actual field thermal power 4.24 MWt

Field thermal power w/ no defocus constraints 4.24 MWt

Loop inlet HTF temperature 40 °C

Loop outlet HTF temperature 150 °C

Number of loops 5

Heat Sink

Heat sink thermal power 2.22 MWt

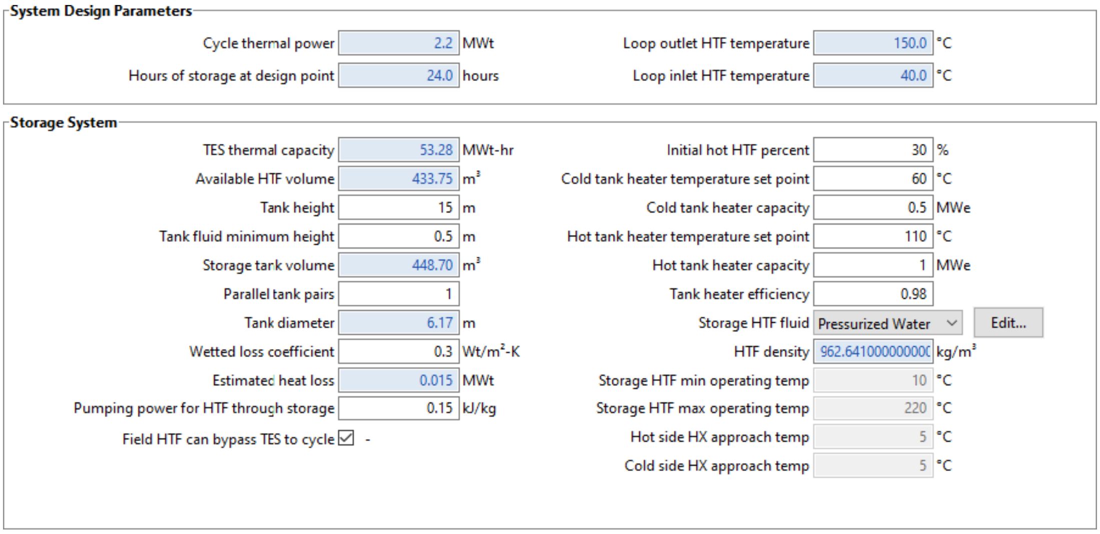
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 24 hours

Figure 0-27: System behavior when TES is 24hrs, SM=1.8

In this case, it is observable that the solar thermal energy generation designed for tea drying at Mata tea factory for continuous steam supplies at location irradiance can have solar field aperture area of 13,120.00 m^2.



System Design Parameters

Cycle thermal power 2.2 MWt

Hours of storage at design point 24.0 hours

Loop outlet HTF temperature 150.0 °C

Loop inlet HTF temperature 40.0 °C

Storage System

TES thermal capacity 53.28 MWt-hr

Available HTF volume 433.75 m³

Tank height 15 m

Tank fluid minimum height 0.5 m

Storage tank volume 448.70 m³

Parallel tank pairs 1

Tank diameter 6.17 m

Wetted loss coefficient 0.3 Wt/m²-K

Estimated heat loss 0.015 MWt

Pumping power for HTF through storage 0.15 kJ/kg

Field HTF can bypass TES to cycle ☑ -

Initial hot HTF percent 30 %

Cold tank heater temperature set point 60 °C

Cold tank heater capacity 0.5 MWe

Hot tank heater temperature set point 110 °C

Hot tank heater capacity 1 MWe

Tank heater efficiency 0.98

Storage HTF fluid Pressurized Water

HTF density 962.64100000000 kg/m³

Storage HTF min operating temp 10 °C

Storage HTF max operating temp 220 °C

Hot side HX approach temp 5 °C

Cold side HX approach temp 5 °C

Figure 0-28: Storage tank size when TES is 24hrs

Up to now all parameters have just been set into SAM source library. Let us simulate and observe the graphs showing the system‟s physical parameters variation.

2.14.10 Hourly heat sink thermal power graph overview

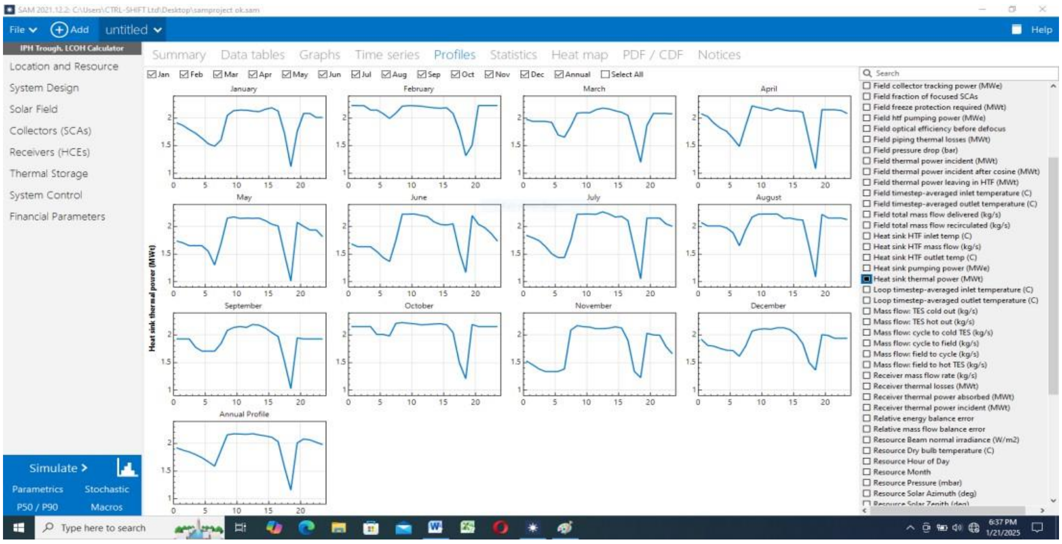
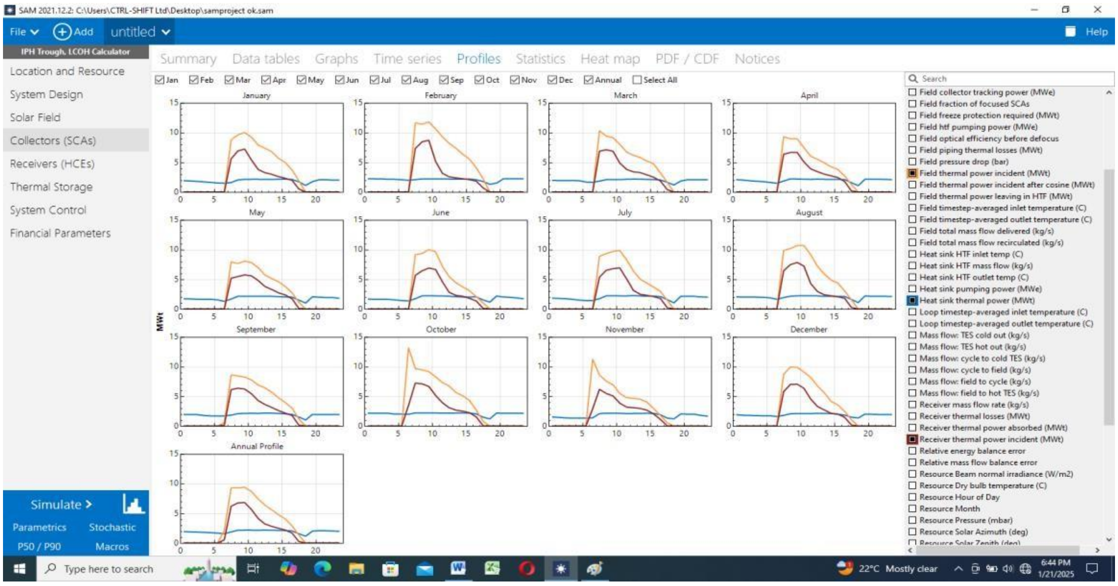


Figure 0-29: Hourly heat sink thermal power graph overview

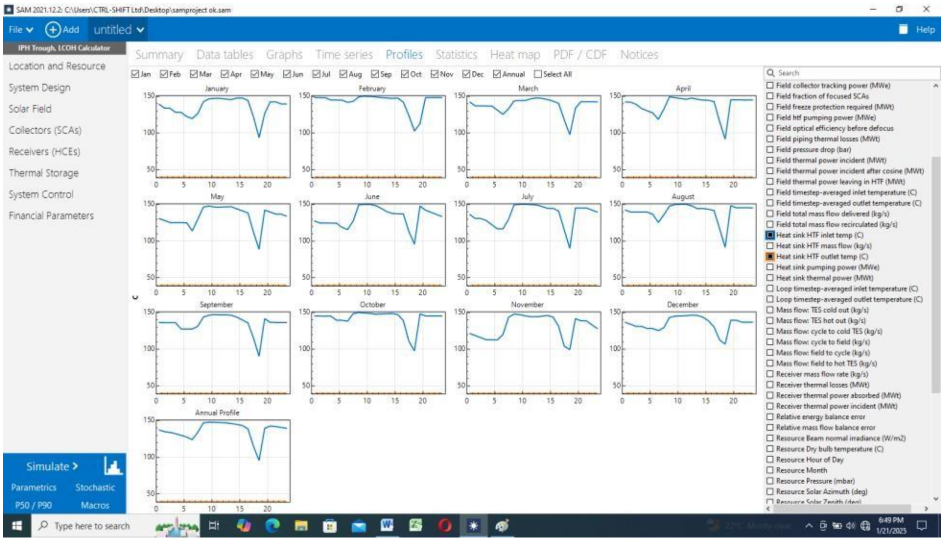
2.14.11 Field thermal power incident, receiver thermal power incident and heat sink thermal power



☐ Field collector tracking power (MWe)
☐ Field fraction of focused SCAs
☐ Field freeze protection required (MWt)
☐ Field htf pumping power (MWe)
☐ Field optical efficiency before defocus
☐ Field piping thermal losses (MWt)
☐ Field pressure drop (bar)
☑ Field thermal power incident (MWt)
☐ Field thermal power incident after cosine (MWt)
☐ Field thermal power leaving in HTF (MWt)
☐ Field timestep-averaged inlet temperature (C)
☐ Field timestep-averaged outlet temperature (C)
☐ Field total mass flow delivered (kg/s)
☐ Field total mass flow recirculated (kg/s)
☐ Heat sink HTF inlet temp (C)
☐ Heat sink HTF mass flow (kg/s)
☐ Heat sink HTF outlet temp (C)
☐ Heat sink pumping power (MWe)
☑ Heat sink thermal power (MWt)
☐ Loop timestep-averaged inlet temperature (C)
☐ Loop timestep-averaged outlet temperature (C)
☐ Mass flow: TES cold out (kg/s)
☐ Mass flow: TES hot out (kg/s)
☐ Mass flow: cycle to cold TES (kg/s)
☐ Mass flow: cycle to field (kg/s)
☐ Mass flow: field to cycle (kg/s)
☐ Mass flow: field to hot TES (kg/s)
☐ Receiver mass flow rate (kg/s)
☐ Receiver thermal losses (MWt)
☐ Receiver thermal power absorbed (MWt)
☑ Receiver thermal power incident (MWt)
☐ Relative energy balance error
☐ Relative mass flow balance error
☐ Resource Beam normal irradiance (W/m2)
☐ Resource Dry bulb temperature (C)
☐ Resource Hour of Day
☐ Resource Month
☐ Resource Pressure (mbar)
☐ Resource Solar Azimuth (deg)

Figure 0-30: Field thermal power incident, receiver thermal power incident and heat sink thermal power

2.14.12 Heat Transfer Fluid temperature variation overview



☐ Field collector tracking power (MWe)
☐ Field fraction of focused SCAs
☐ Field freeze protection required (MWt)
☐ Field htf pumping power (MWe)
☐ Field optical efficiency before defocus
☐ Field piping thermal losses (MWt)
☐ Field pressure drop (bar)
☐ Field thermal power incident (MWt)
☐ Field thermal power incident after cosine (MWt)
☐ Field thermal power leaving in HTF (MWt)
☐ Field timestep-averaged inlet temperature (C)
☐ Field timestep-averaged outlet temperature (C)
☐ Field total mass flow delivered (kg/s)
☐ Field total mass flow recirculated (kg/s)
☑ Heat sink HTF inlet temp (C)
☐ Heat sink HTF mass flow (kg/s)
☑ Heat sink HTF outlet temp (C)
☐ Heat sink pumping power (MWe)
☐ Heat sink thermal power (MWt)
☐ Loop timestep-averaged inlet temperature (C)
☐ Loop timestep-averaged outlet temperature (C)
☐ Mass flow: TES cold out (kg/s)
☐ Mass flow: TES hot out (kg/s)
☐ Mass flow: cycle to cold TES (kg/s)
☐ Mass flow: cycle to field (kg/s)
☐ Mass flow: field to cycle (kg/s)
☐ Mass flow: field to hot TES (kg/s)
☐ Receiver mass flow rate (kg/s)
☐ Receiver thermal losses (MWt)
☐ Receiver thermal power absorbed (MWt)
☐ Receiver thermal power incident (MWt)
☐ Relative energy balance error
☐ Relative mass flow balance error
☐ Resource Beam normal irradiance (W/m2)
☐ Resource Dry bulb temperature (C)
☐ Resource Hour of Day
☐ Resource Month
☐ Resource Pressure (mbar)
☐ Resource Solar Azimuth (deg)

Figure 0-31: Heat Transfer Fluid temperature variation overview

2.14.13 Receiver thermal power absorbed and thermal losses observation

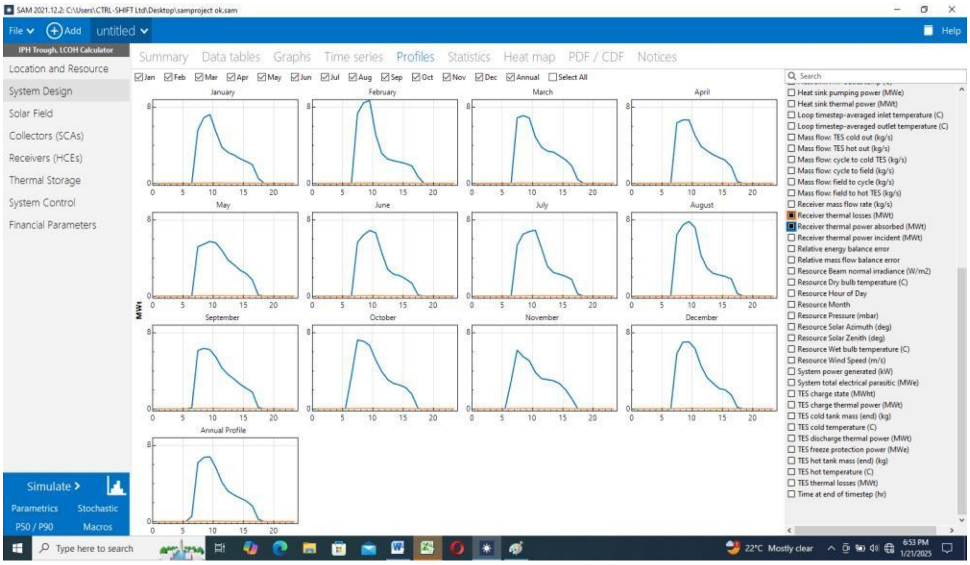
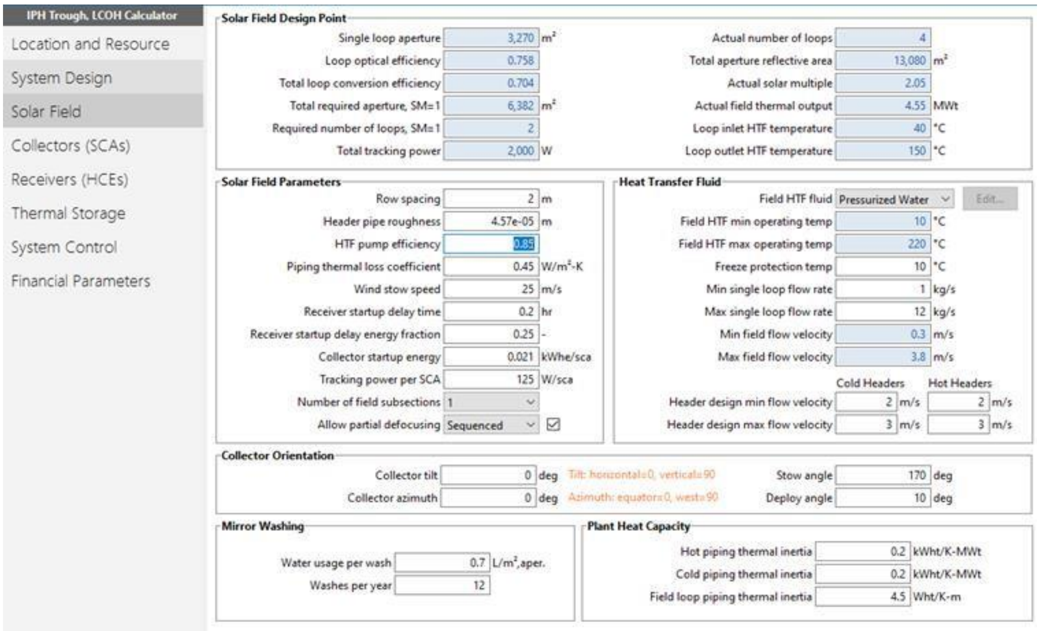


Figure 0-32: Receiver thermal power absorbed and thermal losses observation

2.14.14 Solar field design parameters observation



Solar Field Design Point

Single loop aperture 3,270 m²
Loop optical efficiency 0.758
Total loop conversion efficiency 0.704
Total required aperture, SM=1 6,382 m²
Required number of loops, SM=1 2
Total tracking power 2,000 W
Actual number of loops 4
Total aperture reflective area 13,080 m²
Actual solar multiple 2.05
Actual field thermal output 4.55 MWt
Loop inlet HTF temperature 40 °C
Loop outlet HTF temperature 150 °C

Solar Field Parameters

Row spacing 2 m
Header pipe roughness 4.57e-05 m
HTF pump efficiency 0.85
Piping thermal loss coefficient 0.45 W/m²-K
Wind stow speed 25 m/s
Receiver startup delay time 0.2 hr
Receiver startup delay energy fraction 0.25 -
Collector startup energy 0.021 kWhe/sca
Tracking power per SCA 125 W/sca
Number of field subsections 1
Allow partial defocusing Sequenced ☑

Heat Transfer Fluid

Field HTF fluid Pressurized Water
Field HTF min operating temp 10 °C
Field HTF max operating temp 220 °C
Freeze protection temp 10 °C
Min single loop flow rate 1 kg/s
Max single loop flow rate 12 kg/s
Min field flow velocity 0.3 m/s
Max field flow velocity 3.8 m/s

	Cold Headers	Hot Headers
Header design min flow velocity	2 m/s	2 m/s
Header design max flow velocity	3 m/s	3 m/s

Collector Orientation

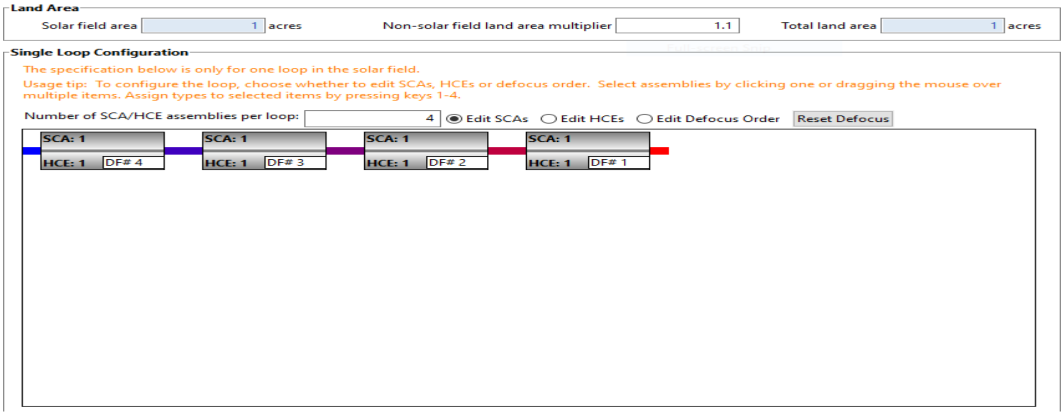
Collector tilt 0 deg Tilt: horizontal=0, vertical=90
Collector azimuth 0 deg Azimuth: equator=0, west=90
Stow angle 170 deg
Deploy angle 10 deg

Mirror Washing

Water usage per wash 0.7 L/m²,aper.
Washes per year 12

Plant Heat Capacity

Hot piping thermal inertia 0.2 kWht/K-MWt
Cold piping thermal inertia 0.2 kWht/K-MWt
Field loop piping thermal inertia 4.5 Wht/K-m



Land Area

Solar field area: 1 acres

Non-solar field land area multiplier: 1.1

Total land area: 1 acres

Single Loop Configuration

The specification below is only for one loop in the solar field.

Usage tip: To configure the loop, choose whether to edit SCAs, HCEs or defocus order. Select assemblies by clicking one or dragging the mouse over multiple items. Assign types to selected items by pressing keys 1-4.

Number of SCA/HCE assemblies per loop: 4 ● Edit SCAs ○ Edit HCEs ○ Edit Defocus Order

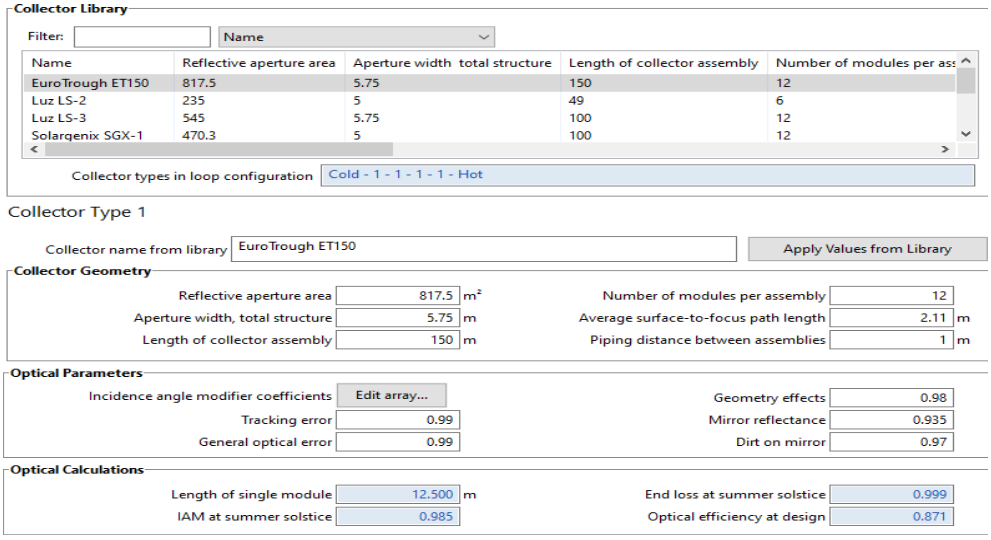
Figure 0-33: solar field design parameters configuration

2.14.15 Solar Collectors Assembly and receivers technical parameters configuration

The PTC collector parameters are configured from SAM library. The solar collector assembly (SCA) selected is **Euro Trough ET150** due to the following advantages it exhibits:

- ❖ Low cost.
- ❖ Easy to install.
- ❖ Has rigid structure.
- ❖ Has high optical performance.
- ❖ Less specific weight.

The optical performance of a parabolic trough collector mainly depends on the reflectance of the collector mirror material and absorptance of absorber tube. Reflectance value of **Euro Trough ET150** is **0.871**.



Collector Library

Filter:

Name	Reflective aperture area	Aperture width total structure	Length of collector assembly	Number of modules per ass
EuroTrough ET150	817.5	5.75	150	12
Luz LS-2	235	5	49	6
Luz LS-3	545	5.75	100	12
Solargenix SGX-1	470.3	5	100	12

Collector types in loop configuration: Cold - 1 - 1 - 1 - 1 - Hot

Collector Type 1

Collector name from library: EuroTrough ET150

Collector Geometry

Reflective aperture area: 817.5 m²

Aperture width, total structure: 5.75 m

Length of collector assembly: 150 m

Number of modules per assembly: 12

Average surface-to-focus path length: 2.11 m

Piping distance between assemblies: 1 m

Optical Parameters

Incidence angle modifier coefficients

Tracking error: 0.99

General optical error: 0.99

Geometry effects: 0.98

Mirror reflectance: 0.935

Dirt on mirror: 0.97

Optical Calculations

Length of single module: 12.500 m

IAM at summer solstice: 0.985

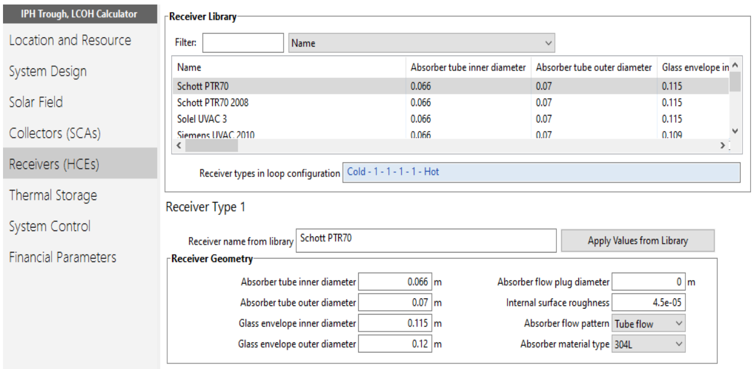
End loss at summer solstice: 0.999

Optical efficiency at design: 0.871

Figure 0-34: parabolic trough solar collector configuration

2.14.16 Receivers parameters configuration

The receiver tube, or heat collecting element (HCE) selected is **Schott PTR70** which has high absorptance of 0.96 and very low emittance of 0.074 at a temperature of about 150 °C. The receiver is also 2% more efficient than other commercial tubes. The stow angle (angle that trough have to track in 1 day) is kept at 170°.



Receiver Library

Filter: Name

Name	Absorber tube inner diameter	Absorber tube outer diameter	Glass envelope in
Schott PTR70	0.066	0.07	0.115
Schott PTR70 2008	0.066	0.07	0.115
Solel UVAC 3	0.066	0.07	0.115
Siemens UVAC 2010	0.066	0.07	0.109

Receiver types in loop configuration: Cold - 1 - 1 - 1 - 1 - Hot

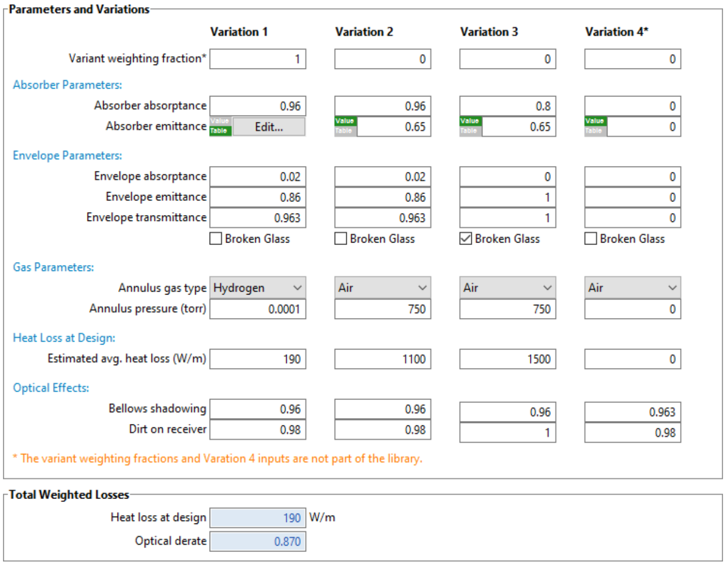
Receiver Type 1

Receiver name from library: Schott PTR70

Receiver Geometry

Absorber tube inner diameter: 0.066 m
Absorber tube outer diameter: 0.07 m
Glass envelope inner diameter: 0.115 m
Glass envelope outer diameter: 0.12 m
Absorber flow plug diameter: 0 m
Internal surface roughness: 4.5e-05
Absorber flow pattern: Tube flow
Absorber material type: 304L

Figure 0-35: Heat collecting elements configuration



Parameters and Variations

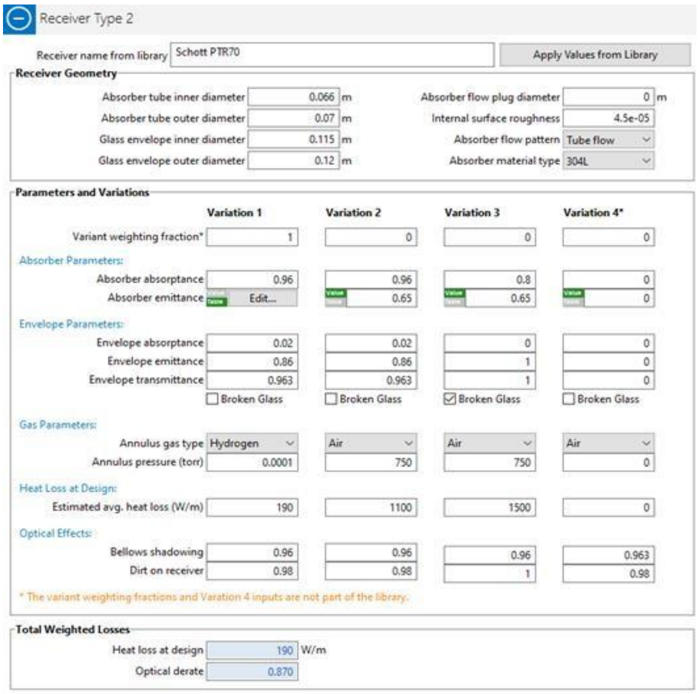
	Variation 1	Variation 2	Variation 3	Variation 4*
Variant weighting fraction*	1	0	0	0
Absorber Parameters:				
Absorber absorptance	0.96	0.96	0.8	0
Absorber emittance	Edit...	0.65	0.65	0
Envelope Parameters:				
Envelope absorptance	0.02	0.02	0	0
Envelope emittance	0.86	0.86	1	0
Envelope transmittance	0.963	0.963	1	0
	☐ Broken Glass	☐ Broken Glass	☑ Broken Glass	☐ Broken Glass
Gas Parameters:				
Annulus gas type	Hydrogen	Air	Air	Air
Annulus pressure (torr)	0.0001	750	750	0
Heat Loss at Design:				
Estimated avg. heat loss (W/m)	190	1100	1500	0
Optical Effects:				
Bellows shadowing	0.96	0.96	0.96	0.963
Dirt on receiver	0.98	0.98	1	0.98

* The variant weighting fractions and Varation 4 inputs are not part of the library.

Total Weighted Losses

Heat loss at design: 190 W/m
Optical derate: 0.870

Figure 0-36: HCE parameters configuration



Receiver Type 2

Receiver name from library: Schott PTR70

Receiver Geometry

Absorber tube inner diameter: 0.066 m
Absorber tube outer diameter: 0.07 m
Glass envelope inner diameter: 0.115 m
Glass envelope outer diameter: 0.12 m
Absorber flow plug diameter: 0 m
Internal surface roughness: 4.5e-05
Absorber flow pattern: Tube flow
Absorber material type: 304L

Parameters and Variations

	Variation 1	Variation 2	Variation 3	Variation 4*
Variant weighting fraction*	1	0	0	0
Absorber Parameters:				
Absorber absorptance	0.96	0.96	0.8	0
Absorber emittance	Edit...	0.65	0.65	0
Envelope Parameters:				
Envelope absorptance	0.02	0.02	0	0
Envelope emittance	0.86	0.86	1	0
Envelope transmittance	0.963	0.963	1	0
	☐ Broken Glass	☐ Broken Glass	☑ Broken Glass	☐ Broken Glass
Gas Parameters:				
Annulus gas type	Hydrogen	Air	Air	Air
Annulus pressure (torr)	0.0001	750	750	0
Heat Loss at Design:				
Estimated avg. heat loss (W/m)	190	1100	1500	0
Optical Effects:				
Bellows shadowing	0.96	0.96	0.96	0.963
Dirt on receiver	0.98	0.98	1	0.98

* The variant weighting fractions and Varation 4 inputs are not part of the library.

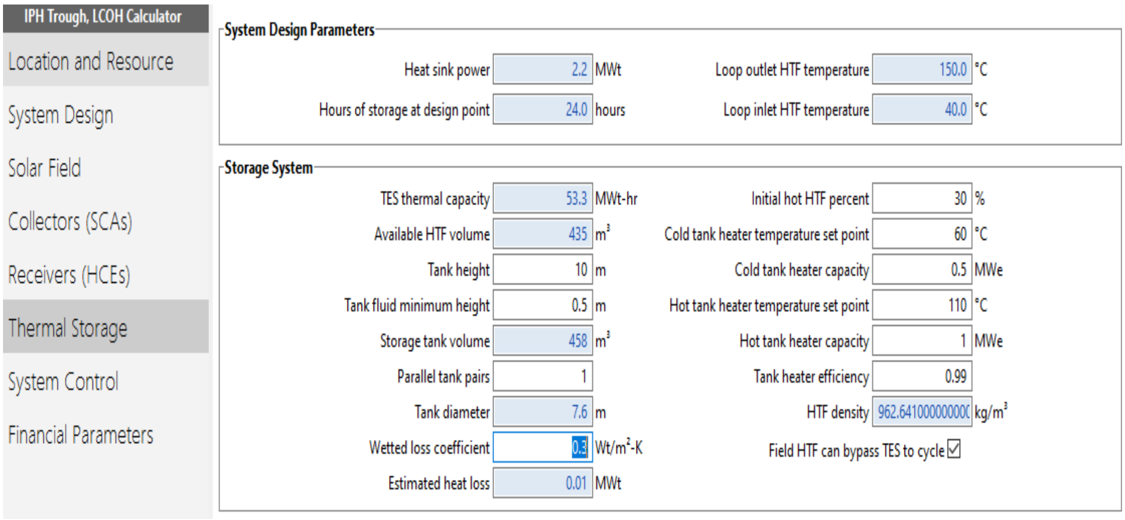
Total Weighted Losses

Heat loss at design: 190 W/m
Optical derate: 0.870

Figure 0-37 HCE parameters configuration

2.14.17 Thermal energy storage (TES) characteristics

This study adopts the use of thermal storage to increase energy efficiency and to satisfy demand requirements whenever needed. Storage media is pressurized water that is the same for the solar field, so the system only requires one adiabatic tank for charge and discharge. Water is preferred, because the energy system being modeled operates at a low temperature range. Therefore, the TES for the solar thermal system under study exhibits the following characteristics:



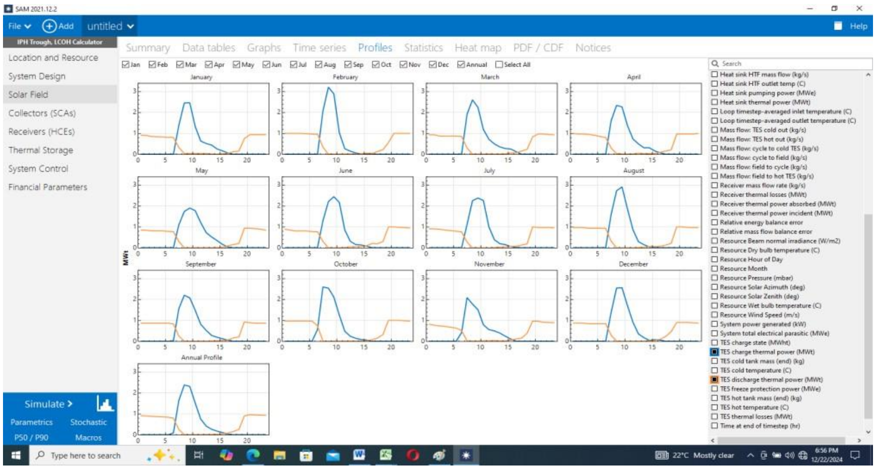
System Design Parameters

Heat sink power: 2.2 MWt
Hours of storage at design point: 24.0 hours
Loop outlet HTF temperature: 150.0 °C
Loop inlet HTF temperature: 40.0 °C

Storage System

TES thermal capacity: 53.3 MWt-hr
Available HTF volume: 435 m³
Tank height: 10 m
Tank fluid minimum height: 0.5 m
Storage tank volume: 458 m³
Parallel tank pairs: 1
Tank diameter: 7.6 m
Wetted loss coefficient: 0.3 Wt/m²-K
Estimated heat loss: 0.01 MWt
Initial hot HTF percent: 30 %
Cold tank heater temperature set point: 60 °C
Cold tank heater capacity: 0.5 MWe
Hot tank heater temperature set point: 110 °C
Hot tank heater capacity: 1 MWe
Tank heater efficiency: 0.99
HTF density: 962.64100000000 kg/m³
Field HTF can bypass TES to cycle ☑

Figure 0-38: thermal storage configuration and characteristics



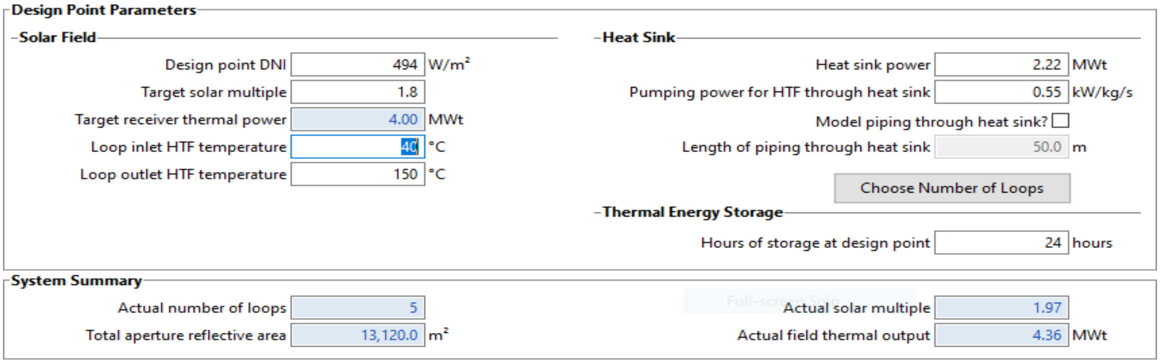
☐ Heat sink HTF mass flow (kg/s)
☐ Heat sink HTF outlet temp (C)
☐ Heat sink pumping power (MWe)
☐ Heat sink thermal power (MWt)
☐ Loop timestep-averaged inlet temperature (C)
☐ Loop timestep-averaged outlet temperature (C)
☐ Mass flow: TES cold out (kg/s)
☐ Mass flow: TES hot out (kg/s)
☐ Mass flow: cycle to cold TES (kg/s)
☐ Mass flow: cycle to field (kg/s)
☐ Mass flow: field to cycle (kg/s)
☐ Mass flow: field to hot TES (kg/s)
☐ Receiver mass flow rate (kg/s)
☐ Receiver thermal losses (MWt)
☐ Receiver thermal power absorbed (MWt)
☐ Receiver thermal power incident (MWt)
☐ Relative energy balance error
☐ Relative mass flow balance error
☐ Resource Beam normal irradiance (W/m2)
☐ Resource Dry bulb temperature (C)
☐ Resource Hour of Day
☐ Resource Month
☐ Resource Pressure (mbar)
☐ Resource Solar Azimuth (deg)
☐ Resource Solar Zenith (deg)
☐ Resource Wet bulb temperature (C)
☐ Resource Wind Speed (m/s)
☐ System power generated (kW)
☐ System total electrical parasitic (MWe)
☐ TES charge state (MWht)
☒ TES charge thermal power (MWt)
☐ TES cold tank mass (end) (kg)
☐ TES cold temperature (C)
☒ TES discharge thermal power (MWt)
☐ TES freeze protection power (MWe)
☐ TES hot tank mass (end) (kg)
☐ TES hot temperature (C)
☐ TES thermal losses (MWt)
☐ Time at end of timestep (hr)

Figure 0-39: TES charge and discharge thermal power

3 CHAPTER 4: RESULTS ANALYSIS AND DISCUSSION

The result of the first simulation in has manifested that at Mata tea factory, the susceptibility of solar resource in thermal energy production for tea drying can exhibits the capacity factor of 51% which is the hybridization percentage or solar fraction of solar thermal energy that can assist for tea drying in Mata Tea Processing plant. It means that solar energy at that geographical location has the potential of suppressing 51% of thermal energy obtaining from firewood burning provided that solar energy is efficiently exploited with Parabolic Trough solar Collectors (PTCs) at 950W/m^2 of DNI. According to this assumption, 51% of firewood can be suppressed if solar energy is thermally converted in high efficient manner. From this point of view, we can also calculate the amount of money that can be saved accordingly. As we saw that the levelized cost of annual heat energy production with firewood solely is 252,372,711RWF and the money that would have been suppressed is 51% of 252,372,711 RWF =128,710,082.61 RWF during the year 2023. But the system in this case is very expensive as solar field aperture area is very large.

Let us remember that the system was designed with the following design points:



Design Point Parameters

Solar Field

Design point DNI: 494 W/m²
Target solar multiple: 1.8
Target receiver thermal power: 4.00 MWt
Loop inlet HTF temperature: 40 °C
Loop outlet HTF temperature: 150 °C

Heat Sink

Heat sink power: 2.22 MWt
Pumping power for HTF through heat sink: 0.55 kW/kg/s
Model piping through heat sink? ☐
Length of piping through heat sink: 50.0 m

Thermal Energy Storage

Hours of storage at design point: 24 hours

System Summary

Actual number of loops: 5
Total aperture reflective area: 13,120.0 m²
Actual solar multiple: 1.97
Actual field thermal output: 4.36 MWt

Table 21: system design points

The performance of the solar PTC system is assessed by investigating the impact of variations of SM (for a range of 1 to 3) and TES (from 0 to 24 h) on the annual thermal energy generated, solar system efficiency, fraction of hybridization and levelized cost of heat (LCOH) for different industrial process heat (IPH) system configurations. The results are then used to identify the optimized hybrid system configuration that provides the best technical, economic and environmental performances. Given that SM and the hours of TES significantly influences the values of LCOH, it is important to design the system, such that the values of SM and TES selected are those that helps to minimize the energy cost (LCOH). A lower LCOH, in this context, should result in more profitable project characterized by more energy produced at a lower cost. Table 21 represents SM equivalence in terms of total collector aperture area, while Table 22 is the TES hours equivalence in terms of thermal storage capacity However, in solar thermal system design, we used SM= 1.8 as according to the literature as it is the optimal design point for sizing with cost optimization.

To optimize tea drying system operation, the thermal energy required for tea drying and temperature range must be kept constant. For this assumption, let us vary design parameters such as design point Direct Normal Irradiance (DNI), Solar Multiple(SM), solar Thermal Energy Storage hours (TES) thus we observe the behavior of the solar thermal system we are designing for tea drying.

3.1 Solar Multiple (SM) in terms of Aperture area

Table 22: Solar multiple in terms of aperture area

SM	$A(m^2)$
1	7872
1.4	10496
1.8	13120
2.2	15744
2.6	18363
3	20992

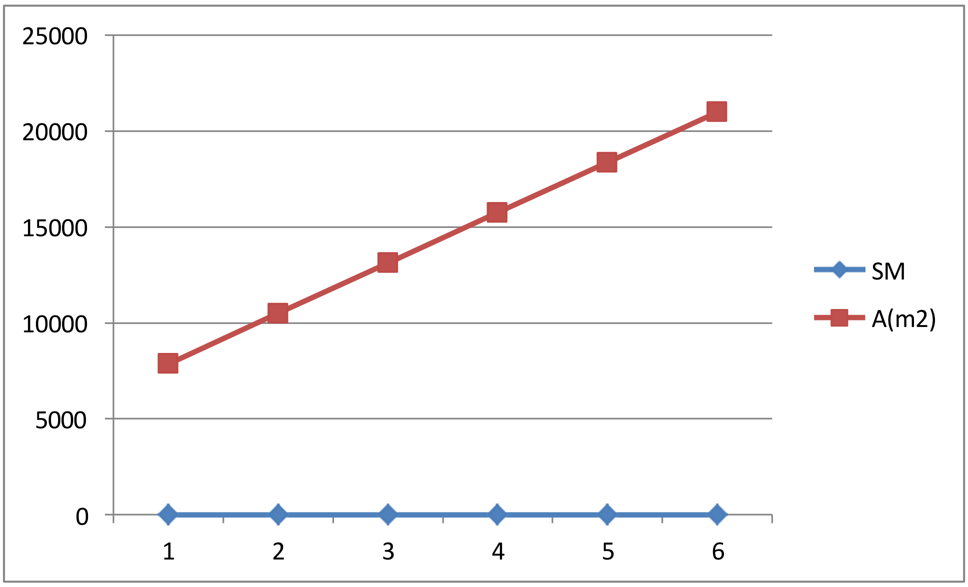


Figure 3-1: Solar multiple vs. Aperture area

The Figure 3-1 show that the value of solar multiple controls the size of the solar collector as increasing the solar multiple results in a solar fraction with a large reflective area that provides more heat. It means that as solar multiple increases, aperture area increases and more solar thermal energy can be generated.

3.2 Influence of solar multiple on the capacity factor

Table 23: Influence of solar multiple on the capacity factor

Irradiance(W/m^2)	SM	TES(hours)	CF(%)	$A(m^2)$
494	1	0	35.9	9810
494	1.2	24	69.9	9810
494	1.5	24	83.4	13080
494	1.8	24	83.4	13080
494	2.2	24	87.2	16350

494	2.4	24	87.2	16350
494	2.6	24	80.3	19620
494	3	24	82.6	22890

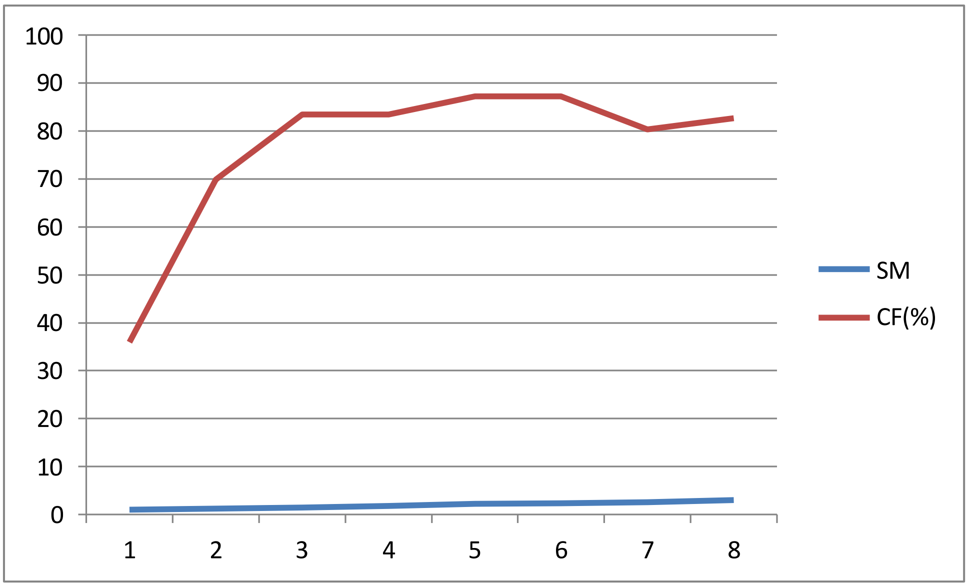


Figure 3-2: Influence of SM on the CF

As solar multiple increases, the capacity factor of the plant increases as the curve on the Figure 3-2 clarifies. However, the design point chosen for the plant is where SM=1.8 so that the system may not be oversized to avoid wastage of thermal energy and system‟s initial cost optimization. No excess of SCAs.

3.3 Thermal Energy Storage hours in terms of thermal capacity

Table 24: TES hours in terms of thermal capacity

SM	TES(hrs)	TES(m^3)	TES(MWh-t)	TES(MW-t)
1	0	0	0	0
1.8	6	112.18	47.952	13.32
1.8	12	216.87	95.904	26.64
1.8	18	325.31	143.856	39.96
1.8	24	433.75	191.808	53.28

The Table 24 indicates that when TES hours increases, the thermal capacity rises also.

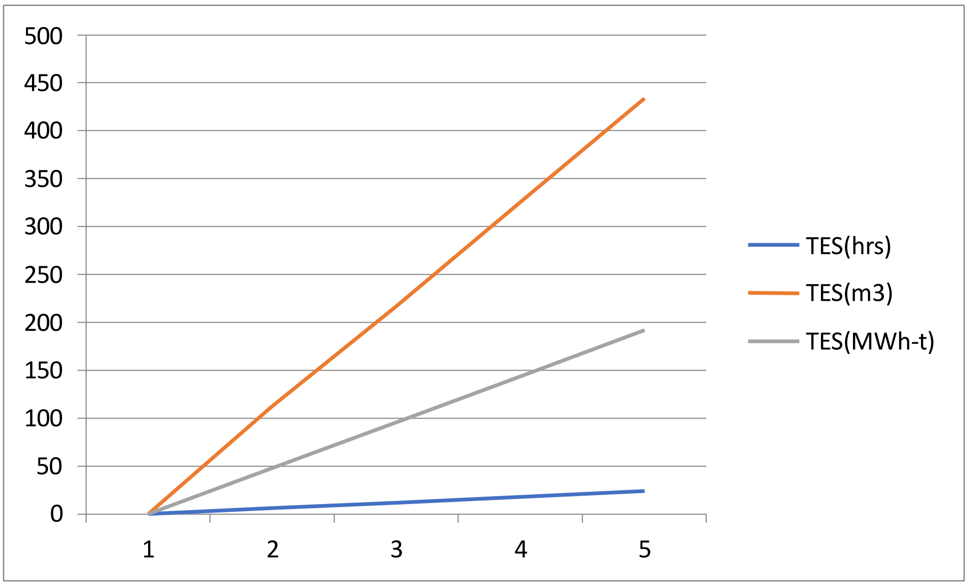


Figure 3-3: influence of thermal storage on thermal capacity

The Figure 3-3 indicates that the thermal energy storage tank and the storage capacity increase as the TES hours increases with respect to the lines in the figure mentioned.

3.4 Influence of SM and TES on thermal energy generation

Table 25: Influence of SM and TES on thermal energy generated

SM	TES(hours)	MW-t	System design MW-t	TES(MW-t)
1	0	3.33	2.22	1.11
1.8	12	4.44	2.22	2.22
2.2	16	5.55	2.22	3.33
2.6	22	6.66	2.22	4.44
3	24	7.77	2.22	5.55

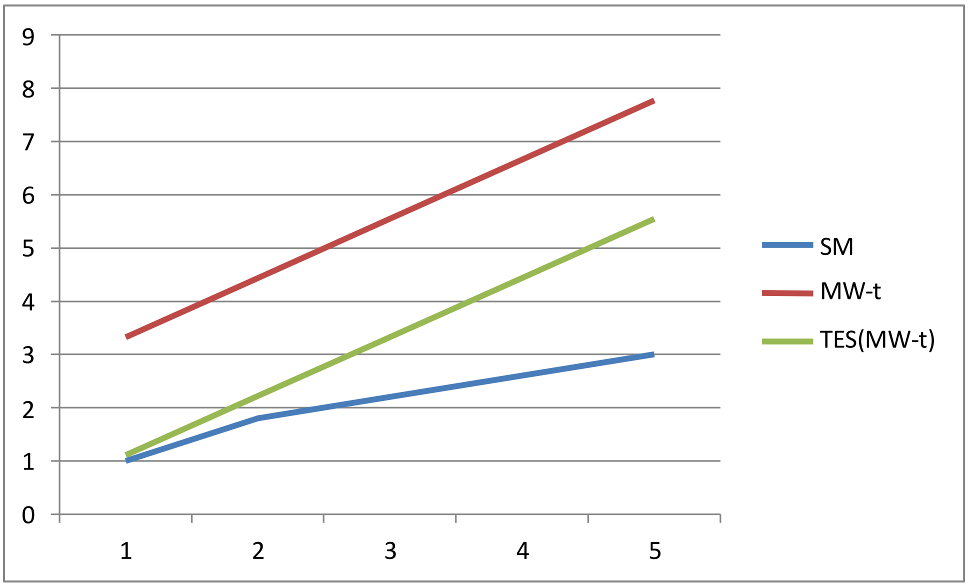


Figure 3-4: Solar multiple thermal energy generated and energy to store

As solar multiple increases, more thermal energy can be generated and energy to store is also supplemented.

3.5 Influence of solar multiple on Levelized Cost of thermal Energy

Table 26: Influence of solar multiple on the LCOE

	LCOE(€/kWh-t)
1	6.89
	6.89
	6.58
	6.93
	8.28
	8.79

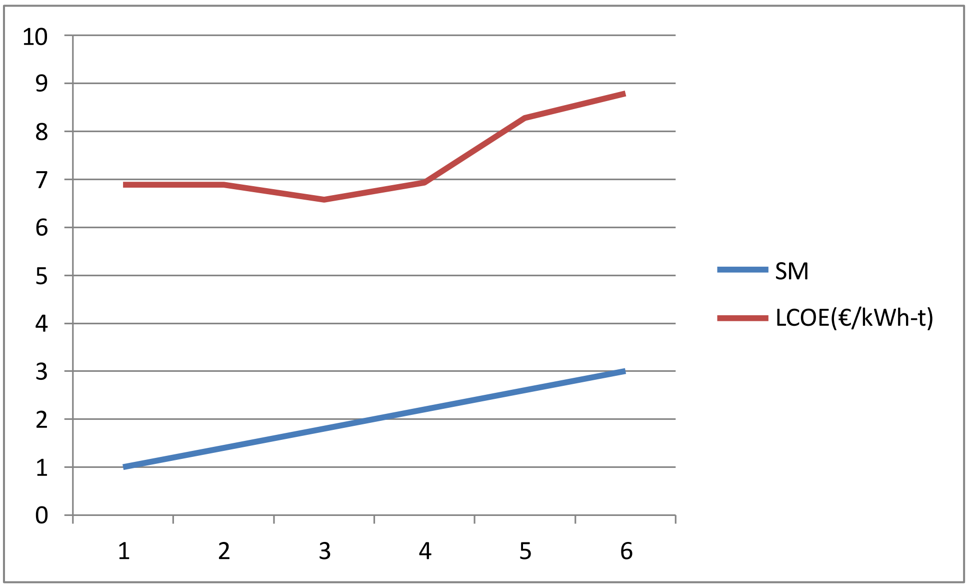


Figure 3-5: SM versus LCOE

3.6 Fuel wood conservation, land preservation and CO2 mitigation

Integration of renewable energy system such as solar PTC into biomass-fired tea factories can help to conserve firewood, land preservation and result in CO2 reduction. During modeling and performance analysis of the parabolic trough solar collectors for hybrid process heat application in Kenya‟s tea industry using system advisor model software, the plant under study was designed as solar thermal energy system expected to supply 17331MWh-t while the factory supposed to demand 14286MWh-t. The firewood reduction due to solar fraction integration contribution, land preservation and CO2 mitigation data in that case are given in the Table 27 for a hybrid plant with and without TES[7].

Table 27: Yearly reductions in CO2 emissions, wood and land use for KTDA Tea factory studied

	Hybrid plant without TES	Hybrid plant with TES
Rated of the plant	14286MWh thermal	17331MWh thermal
Fuel wood conservation	6318m^3	16462m^3
Land preservation	9.02acres	23.51acres
CO_2 mitigation	3768 tons CO_2-eq	9817tons CO_2-eq

In our case, with the same analogy let us apply the proportionality and assume the CO_2 mitigation and land preservation susceptibilities for Mata Tea Company if this project is implemented.

Table 28: Yearly reductions in CO2 emissions, wood and land preservation at Mata Tea Factory

	Hybrid plant without TES	Hybrid plant with TES
Rated of the plant	19465MWh thermal	23614MWh thermal
Fuel wood conservation	8608m^3	22430m^3
Land preservation	12.29acres	31.47acres
CO_2 mitigation	5134 tons CO_2-eq	13375tons CO_2-eq

3.7 Hybrid solar biomass (firewood) without thermal storage

This option is not ideal as it requires significant biomass even with the lowest LCOE (Levelized Cost of Heat)[27]. With TES =0hrs, SM=1, the capacity factor is 33.2%. I this case, Aperture area of the system can be 7872m^2 at the capacity factor of 33.2% implying that 33.2% thermal energy generated from firewood can be saved. Let us now calculate the thermal energy and firewood quantity to save as well as the amount of money to recuperate in this case.

Table 29: solar fraction in terms of thermal energy when TES=0

MONTH	Thermal energy supply(MWh)	Solar fraction (33.2%) in MWh
JANUARY	2147.288889	712.8999111
FEBRUARY	1359.310556	451.2911044
MATCH	2183.716111	724.9937489
APRIL	2202.888333	731.3589267
MAY	2705.200556	898.1265844
JUNE	2156.875	716.0825
JULY	732.3788889	243.1497911
AUGUST	354.6861111	117.7557889
SEPTEMBER	375.7755556	124.7574844
OCTOBER	1451.337222	481.8439578
NOVEMBER	2116.613333	702.7156267
DECEMBER	1679.486667	557.5895733
TOTAL	**19465.55722**	**6462.564998**
MONTHLY Average	**1622.129769**	538.5470831
DAILY AVERAGE	**53.33029376**	17.70565753

The Table 29 manifests that when TES=0, SM=1 the system can operate but no energy storage system.in this case, **6462.564998MWh** which is 33.2% of the thermal energy can be supplied by the solar thermal system.

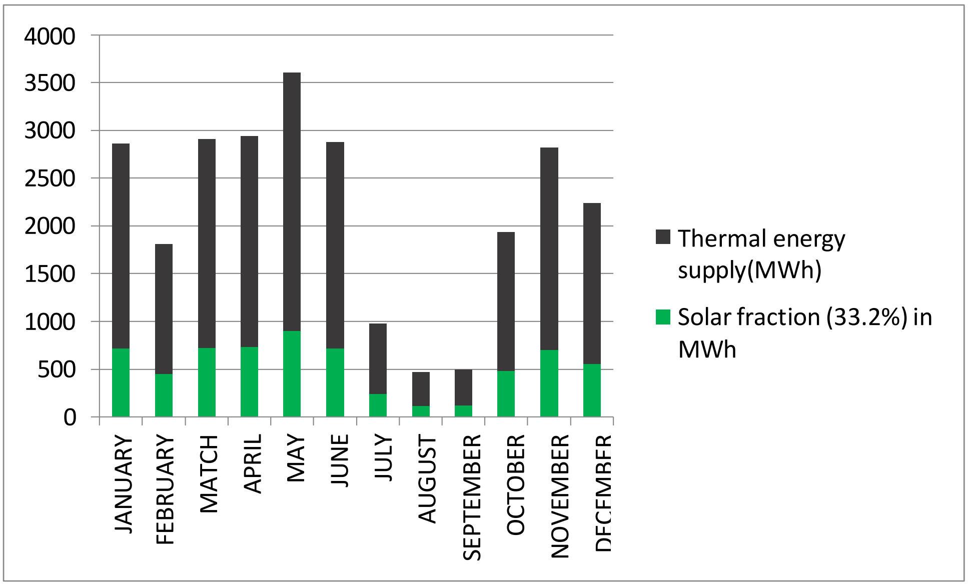


Figure 3-6: Solar fraction thermal energy share when TES=0, SM=1

As the **Table 29** indicates, **6462.564998MWh** thermal can be annually saved in this case of TES=0, SM=1, CF=33.2% when we design while using the data for 2023. Let us also calculate the firewood quantity to suppress as well as the money to recuperate in this case.

Table 30: Firewood quantity and amount of money to save when TES =0

MONTH	**Money to save(RWF)**	**Firewood COST(RWF)**	**Firewood(m^3)**	**33.2% (m3)**	**RWF/m^3**
JANUARY	7422192	30240000	1,120	371.84	27000
FEBRUARY	5226012	19143000	709	235.388	27000
MATCH	8632332	30753000	1,139	378.148	27000
APRIL	8587512	31023000	1,149	381.468	27000
MAY	8121384	38097000	1,411	468.452	27000
JUNE	6355476	30375000	1,125	373.5	27000
JULY	4250662.466	10314000	382	126.824	27000
AUGUST	4087089.725	4995000	185	61.42	27000
SEPTEMBER	5297724	5292000	196	65.072	27000
OCTOBER	7359444	20439000	757	251.324	27000
NOVEMBER	9295668	29808000	1,104	366.528	27000
DECEMBER	9152244	23652000	876	290.832	27000
TOTAL	83787740.19	274131000	**10,153**	**3,371**	
MONTHLY Average	6982311.683	22844250	846	259	
DAILY AVERAGE	229555.452	875817.891	32.437	8.502	

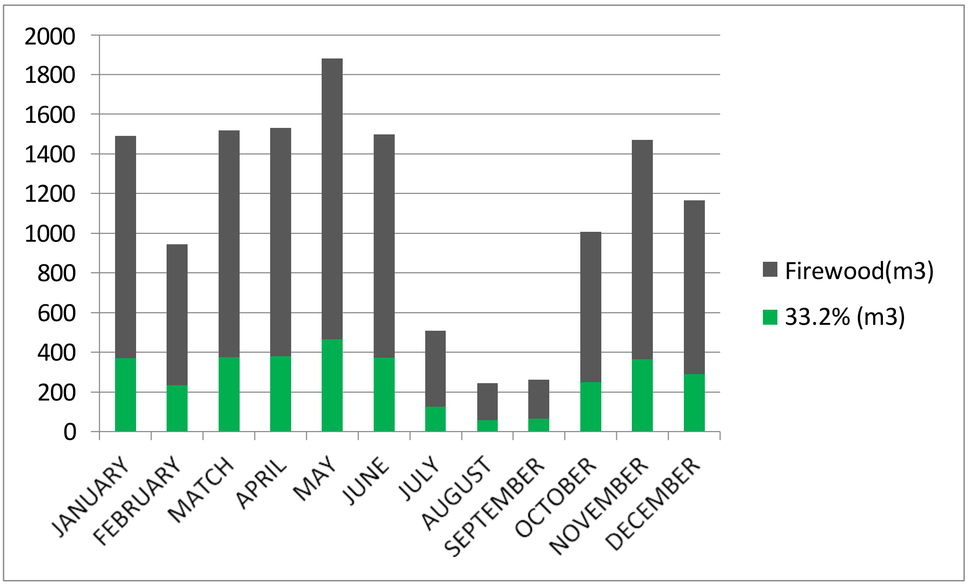


Figure 3-7: firewood to save in case TES=0

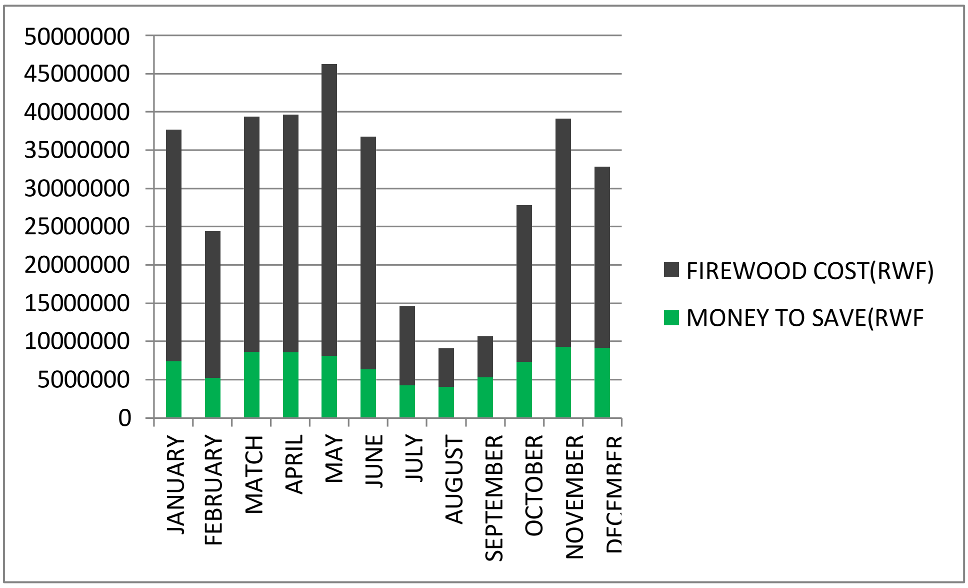
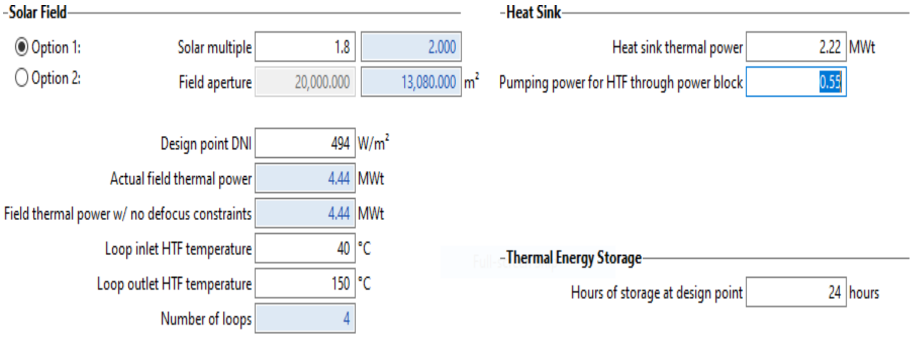


Figure 3-8: Money to save when TES=0

3.8 Hybrid solar–biomass plant with thermal storage

TES allows for a higher solar fraction and reduces biomass dependence. The optimal configuration is SM=1.8 and TES=24 hours.[26][27].


Solar Field

● Option 1: Solar multiple 1.8 2.000
○ Option 2: Field aperture 20,000.000 13,080.000 m²
Design point DNI 494 W/m²
Actual field thermal power 4.44 MWt
Field thermal power w/ no defocus constraints 4.44 MWt
Loop inlet HTF temperature 40 °C
Loop outlet HTF temperature 150 °C
Number of loops 4

Heat Sink

Heat sink thermal power 2.22 MWt
Pumping power for HTF through power block 0.55

Thermal Energy Storage

Hours of storage at design point 24 hours

Figure 3-9: Thermal storage of 24 hours

After simulation, it is observable that the capacity factor increases and becomes 83.4%. Let us also calculate the firewood quantity to suppress as well as the money to recuperate in this case of SM=1.8 and TES=24hours.

Table 31: Solar fraction contribution when SM=1.8, TES=24hrs

MONTH	Firewood Thermal energy supply(MWh)	Solar fraction (83.4%) in MWh when TES=24
JANUARY	2147.288889	1790.838933
FEBRUARY	1359.310556	1133.665004
MATCH	2183.716111	1821.219237
APRIL	2202.888333	1837.20887
MAY	2705.200556	2256.137264
JUNE	2156.875	1798.83375
JULY	732.3788889	610.8039933
AUGUST	354.6861111	295.8082167
SEPTEMBER	375.7755556	313.3968134
OCTOBER	1451.337222	1210.415243
NOVEMBER	2116.613333	1765.25552
DECEMBER	1679.486667	1400.69188
TOTAL	**19465.55722**	**16234.27472**
MONTHLY Average	**1622.129769**	538.5470831
DAILY AVERAGE	**53.33029376**	17.70565753

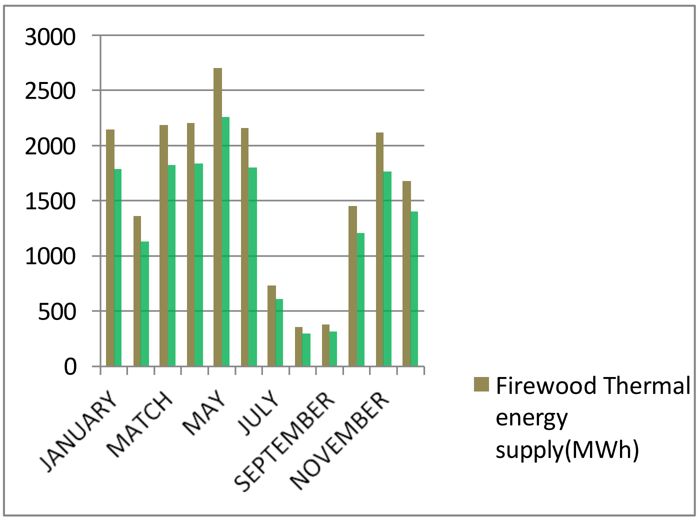


Figure 3-10: Solar fraction contribution when TES=24HRS, SM=1.8

Table 32: money to save when SM=1.8, TES=24hrs

Month	Firewood cost (RWF)	Firewood cost saving share (83.4%) in RWF
JANUARY	22356000	18644904
FEBRUARY	15741000	13127994
MARCH	26001000	21684834
APRIL	25866000	21572244
MAY	24462000	20401308
JUN	19143000	15965262
JULY	12803200.2	10677868.97
AUGUST	12310511.22	10266966.36
SEPTEMBER	15957000	13308138
OCTOBER	22167000	18487278
NOVEMBER	27999000	23351166
DECEMBER	27567000	22990878
TOTAL ANNUAL	**252372711.4**	**210478841.3**
MONTHLY AVERAGE	21031059.29	17539903.44
DAILY AVERAGE	691432.0861	576654.3598

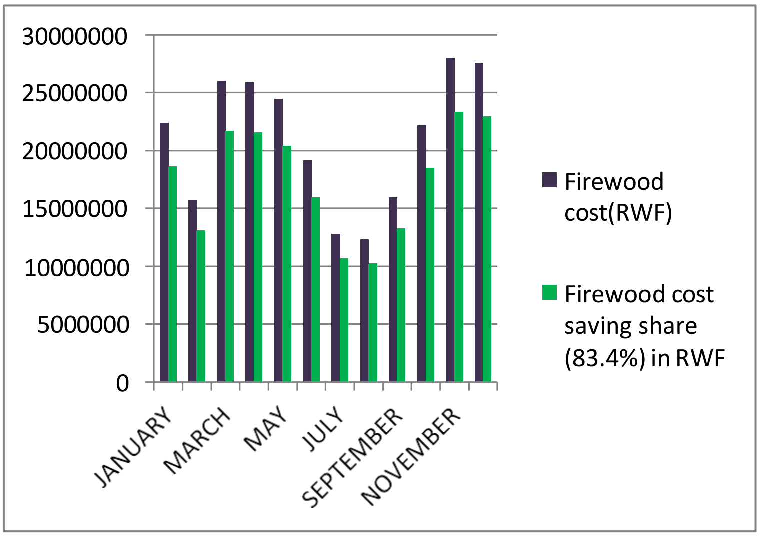


Figure 3-11: Money to save when SM=1.8, TES=24hrs

Table 33: Firewood reduction when SM=1.8, TES=24hrs

Month	**Expected(m^3)**	Firewood saving share(83.4%) in m^3
JANUARY	828	690.552
FEBRUARY	583	486.222
MARCH	963	803.142
APRIL	958	798.972
MAY	906	755.604
JUN	709	591.306
JULY	474	395.4766284
AUGUST	456	380.2580132
SEPTEMBER	591	492.894
OCTOBER	821	684.714
NOVEMBER	1,037	864.858
DECEMBER	1,021	851.514
TOTAL ANNUAL	**9,347**	7795.512642
MONTHLY AVERAGE	779	649.6260535
DAILY AVERAGE	25.60859578	21.35756888

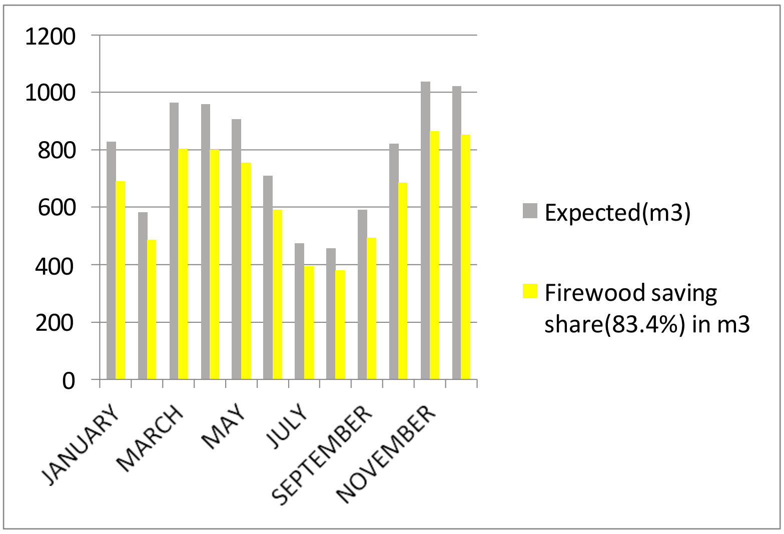


Figure 3-12: Firewood reduction when SM=1.8, TES=24hrs

4 CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

4.1 CONCLUSSION

This research topic titled” **Feasibility study and performance analysis of a hybrid solar-biomass (firewood) steam generation system for tea drying in Rwanda black tea processing plants**” investigated the technical feasibility and performance analysis of a hybrid solar-biomass steam generation system for tea drying in Rwanda's black tea processing plants. The proposed system aims to address the challenges associated with firewood use solely for tea drying, such as high thermal energy consumption which implies firewood utilization at bulk quantity, negative environmental impacts such as deforestation, erosion, environmental degradation and ecosystem disharmony.

The findings demonstrate the feasibility and potential benefits of the hybrid approach exist. While integrating solar thermal parabolic trough solar collectors with the existing biomass (firewood) boiler, the system can effectively utilize renewable energy sources (solar thermal), reducing reliance on wood firewood only and minimizing greenhouse gas emissions. Furthermore, the hybrid system offers improved energy efficiency, reduced tea manufacturing costs as firewood purchasing can be greatly reduced by a particular percentage depending on the solar fraction integrated.

Therefore, the hybrid solar-biomass steam generation system presents a promising solution for sustainable and efficient tea drying for black tea processing plants in Rwanda. By implementing this innovative approach, the tea industry can enhance its environmental performance while minimizing deforestation, diminishing environmental degradation, tea extension lands preservation instead of large area forests, reducing greenhouse gas emission, improve economic viability as it was remarked in this thesis, and contribute to the sustainable development of the country.

4.2 RECOMMENDATIONS

4.2.1 Recommendations to the tea processing plants proprietors:

- Rwanda tea processing plants proprietors should seriously consider adopting hybrid solar-biomass steam generation systems for tea drying. These systems offer a sustainable and economically viable alternative to traditional firewood-based methods solely for tea drying[3].
- Rwanda mountain tea processing plants proprietors should engage themselves in comprehensive feasibility studies that assess the specific site conditions (solar irradiance, biomass availability), tea drying requirements, and economic viability of the hybrid system.
- Rwanda mountain tea landlords should investigate well where this technology is being utilized in abroad countries and then make on sight visit.

- Investigate available funding opportunities, incentives, and subsidies offered by the Rwandan government and international organizations for renewable energy projects and sustainable development initiatives.

- Work with experienced engineers and consultants to optimize the design of the hybrid system based on local climate conditions, available biomass resources, and the specific needs of the tea processing plant. This includes sizing the solar collectors, biomass boiler, and steam distribution network.
- Tea processing plants owners should support the renewable energy engineering lecturers and researchers for renewable energy projects related to solar industrial processes heat application especially for tea sectors so that this project will be further implemented as it in more environmental friendly.

4.2.2 Recommendations to the government of Rwanda:

- **Develop Supportive Policies:** The Rwandan government should develop supportive policies and regulations that incentivize the adoption of renewable energy technologies in the tea industry, such as feed-in tariffs and tax breaks for example.
- **Promote Research and Development:** Invest in research and development to further optimize hybrid solar-biomass systems for tea drying and address specific challenges related to local conditions.
- **Facilitate Access to Finance:** Facilitate access to finance for tea processing plants to invest in renewable energy projects through dedicated loan programs and guarantee schemes.

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