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Potential for Solar Industrial Process Heat Systems for Tea Drying Applications – A Case Study

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Abstract **– An increase in energy consumption especially for industrial applications enhances the uptake of fossil fuels since, they are currently the major sources of industrial process heat and electricity. The need for clean energy technologies is therefore critical, in order to meet the rising energy demand using sustainable energy sources. Solar thermal energy technologies have attracted much attention in terms of research and developmental activities worldwide. The present study seeks to explore the viability of adopting solar thermal technologies at Tingamira - Tanganda Tea estate, Zimbabwe. Data on current sources of heat, daily consumption of process heat and required process temperatures was gathered. Systems advisor model (SAM, version-2021.12.2) was applied to analyse feasibility of linear Fresnel (LF) and Parabolic trough (PT) solar thermal technologies for industrial tea drying. LF system is potentially a better option for producing process heat for low temperature applications. It requires smaller aperture area (360 m^2) and a lower initial capital cost of \$ 112 860 which is about 8 % cheaper. Also, it yields more energy at lower levelized cost of heat as compared to PT technology when solar multiple is increased up to 2. Replacing wood fuel would reduce the factory carbon footprint by 114 tonnes CO_2 annually. Also, potential for sensible rock-bed heat storage systems in the tea factory was assessed. Rock bed sensible TES using natural rocks can avail a viable option for heat storage and about 16 m^3 of storage volume would be needed to meet a daily heat demand of 1 MWh.**

Keywords **– Process heat; solar thermal; solar multiple; thermal energy storage.**

Nomenclature	
NREL	National Renewable Energy laboratory
CSP	Concentrated solar power
CTC	Cutting, tearing and curling
HTF	Heat transfer fluid
IRENA	International Renewable Energy Agency
LCOH	Levelised cost of heat (\$)
LF	Linear Fresnel
LTES	Latent Thermal Energy Storage
PT	Parabolic trough
REN21	Renewable Energy policy Network for the 21st century
SAM	Systems Advisor Model software

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SHIP	Solar Heat for Industrial Processes
SM	Solar multiple
SOLTRAIN	Southern Africa Solar Thermal Training and Demonstration Initiative
Subscript, th	thermal
STES	Sensible Thermal Energy Storage
TES	Thermal Energy Storage
UNEP	United Nations Environmental Programme

1. INTRODUCTION

Consumption of thermal energy in various industrial sectors is inevitable due to the pivotal role it plays in different industrial processes. One of the most common needs for process heat is drying, which is involved in many industries including agriculture, textile, paper, auto mobile, rubber, marine, pharmaceutical and tea manufacturing among others [1]. Drying is quite an energy intensive process since it requires heat to reduce the moisture content to recommended levels depending on the type of the products. In the tea manufacturing industry, thermal energy accounts for 85 % of the total net energy, while the other 15 % is required in form of electric energy to power various machinery [2]. Thermal energy is utilised at temperatures ranging from 33 °C to 150 °C, where the lower temperature heat is used for withering process, while temperatures within 90 °C and 150 °C are needed for drying purposes [3].

Most of this thermal energy is coming from the conventional sources of steam boilers which are powered mostly by firewood, coal and gas [4]. These energy sources are not sustainable largely because of their negative environmental effects since they contribute the most towards the global carbon emissions which cause global warming and climate change [5]. The world is currently concerned by the disastrous effects of climate change, and this has forced a global shift towards serious consideration of sustainable and clean sources of industrial process heat [6].

Solar thermal systems are showing a real potential of a viable option for industrial process heat needed in various industrial sectors especially at low temperature range (< 200 °C) including the tea manufacturing industry [7]. Presently, different solar thermal energy technologies are being considered for drying applications in various industrial processes and at varying temperature ranges. Industrial drying processes can be classified according to the required temperatures where, drying at temperatures within 15 °C and 50 °C is regarded as low temperature drying while, for temperatures beyond 50 °C is high temperature drying [8].

Research work and developmental activities are currently ongoing in both classes of drying, as evidenced by various international conferences to discuss and promote sustainable energy sources for industrial applications. Also, there are documented successful and operational solar thermal projects reported around the globe, some of which are summarised in Table 1.

Akello *et al*., [11] used a numerical approach to analyse viability of adopting a PT solar collector system for industrial tea drying applications in Kenya. The research considered a hybrid solar-biomass system to mitigate the intermittent nature of the solar resource. Results have shown that, the proposed integrated system with a thermal energy storage system can deliver thermal energy at a levelised cost of heat of 0.018 $/kWh, which is 25 % cheaper than using biomass only. This system would lower the annual consumption of wood fuel by 16.462 m^3 and reduce carbon emissions by 9817 tonnes annually.

TABLE 1. SOME DOCUMENTED OPERATIONAL SOLAR HEAT PLANTS FOR INDUSTRIAL PROCESSES

Company and operational year	Industrial process and temperature ranges, °C	Solar thermal technology
CONA Drying Schwellinger, Germany, 2022 [9]	Drying for agriculture, forestry and fishing, 30 to 60	Solar air collector, Capacity 35 kW_{th}, Gross area 50 m^2
CONA Drying Steinhaus, Austria, 2021 [9]	Drying for agriculture, forestry and fishing	Solar air collector, 168 m^2
Jinan, China, 2021 [9]	Materials drying, 90 to 95	Evacuated tube collector, 1538 m^2
CONA Drying Burgkirchen, Austria, 2021 [9]	Drying for agriculture, forestry and fishing	Solar air collector, 120 m^2
Heinz Daurer and Sohne, Germany, 2019 [9]	Manufacturing, component drying	Evacuated tube collector, 297 m^2
Zacatecas Termosolar, Mexico, 2017 [9]	Fruits and vegetables drying, 55 to 120	Solar air collector, 120 m^2
Surprise SHIP, United States, 2017 [9]	Sewage drying, 90–100	PT solar collector, 151 m^2
RAM Pharmaceuticals producer, Jordan, 2015 (Solar Payback 2017 [9]	Sterilisation, drying, fermenting, 160	Capacity 277 kW, Linear Fresnel collector 396 m^2
Parc Solaire Alain Lemaire, Canada, 2014 [9]	Paper manufacturing – drying, 120–140	PT solar collector, Capacity 800 kW_{th}, Gross area 1490 m^2
Golden Hills Tea Factory in India, 2010 and 1992 [10]	Preheating air for tea drying, 110–150	Glazed flat plate solar air collector, Gross area 264 m^2
FengLi Fruit Drying, China, 2000 [9]	Fruit drying, 50–70	Solar air collector, Capacity 39 kW_{th}, Gross area 55.7 m^2
Malabar Tea Drying, Indonesia, 1994 [9]	Tea drying, 35	Solar air collector, Capacity 420 kW_{th}, Gross area 600m^2

The use of a LF solar collector for phosphate drying applications has been studied in Tunisia [12]. The study indicated that, an aperture area of this solar collector of 100 m^2 can deliver 59.766 kWh of thermal energy annually. Basing on this performance it was estimated that this solar drying system would produce the highest yield of dried phosphate of about 43 tonnes during the summer and this would save about 38.255 kg of carbon emissions.

Famiglietti *et al.*, [13] numerically studied feasibility of using LF collectors to produce hot air (up to 400 °C) for industrial processes. Use of a turbocharger was proposed to enable direct solar air heating without use of another heat transfer fluid. Simulation results revealed that hot air of temperatures between 300 °C and 400 °C can be obtained at mass flow rates ranging from 0.2 kg/s to 0.7 kg/s. The study concluded that, employing this technology has great potential in enabling an energy shift to sustainable solar thermal systems.

A study has been carried out in Lebanon to assess the economic and environmental effects of adopting solar drying systems for food drying applications [14]. The assessment highlighted that; a solar drier can be utilised for about 60 % of the total drying time. Considering a drier of capacity of 120 kg of carrots, employing a solar drier can save up to $ 780 monthly due to reduced fuel costs and this investment would have a payback period of less than a year (10 months). Also, using a solar drier would enable a reduction of 6400 kg of carbon emissions per month.

Amer *et al.*, [15] investigated the performance of an integrated solar drying system. The system uses a solar air heater and an electric powered hot water storage tank as an auxiliary heat source with the two coupled by a heat exchanger. The study shown that, the system can achieve temperatures of 40 °C to 50 °C in the drying chambers but temperature controllers were used to maintain it at required drying temperature of 35 °C for at least 30 hours. It was concluded that, this integrated solar dryer would be ideal for drying herbal tea leaves (chamomile) and other medicinal plants.

Kalogirou [16] emphasised the need to incorporate thermal energy storage systems to solar drying systems to achieve uninterrupted industrial drying processes. Suresh *et al.*, [17] assessed different materials and storage systems that can be considered for integration with solar driers. The study explored various materials such as water, sand, natural stones, and phase change materials as well as different heat storage technologies. The study concluded that, natural solid materials are most favourable for heat storage that can be incorporated with industrial solar drying systems due to their cost effectiveness, availability, and harmlessness.

Even though, there are several operational solar thermal systems and a good potential for these sustainable technologies, their uptake is still very low especially for industrial applications due to various hindrance factors which include, intermittent nature of the solar resource. This has promoted research and developmental work on thermal energy storage (TES) technology to enable continuous supply of process heat which is crucial for industrial applications. There are three main types of TES technologies being considered currently including, thermochemical, latent heat and sensible heat storage systems [18].

Sensible thermal energy storage (STES) systems are the most popular in the market largely because of their low cost and maturity [19], but they have the lowest energy densities compared to other TES systems. This technology stores thermal energy as sensible heat in either liquid or solid materials. Water is the most used liquid for heat storage, especially for low temperature applications of less than 100 °C [20]. Thermal oils and molten salts are the other liquids being used, but mainly for high temperature applications especially in solar thermal power plants [21]. Different solid-state media including, natural rocks and some manufactured solid materials such as, metals, ceramics, concrete and bricks are being considered for industrial heat storage applications [22].

Latent thermal energy storage (LTES) systems, which are based on the phase change materials performs better in terms of energy density but at a higher cost [23]. Currently, their uses are mainly limited to low temperature heating applications in buildings [24]. Thermochemical energy storage systems are based on exothermic reactions of some chemical compounds which gives off thermal energy, however this technology is still on the research and developmental stage [25].

Solid state sensible TES based on natural rocks have shown potential as TES medium for industrial process heat storage applications [26]. Besides the fact that, natural stones are locally and readily available which makes them cost effective, they are harmless to the environment [27]. Also, they have good thermal characteristics including, thermal conductivity, specific heat capacity, density and thermal degradation resistance, to perform well as heat storage materials [28]. However, they also have a drawback of low density as compared to other solid materials [19] and this have implications on size of the storage facility.

Kamfa *et al.*, [29] extensively reviewed work on potential for employing concentrating solar technologies for industrial applications. The study highlighted the need for further research on viability of utilising concentrating solar thermal systems for large scale commercial drying processes. Also, a research gap was reported on integrating TES systems with either solar thermal energy systems or hybrid of heating systems which include solar thermal and other existing conventional heating technologies.

It is against this background that, the present study seeks to explore the potential of adopting concentrating solar thermal systems (LF and PT systems) for supplying industrial process heat at Tingamira-Tanganda tea factory in Zimbabwe. Also, the potential of utilising thermal energy systems in the tea factory, shall be addressed.

The following objectives shall be considered to guide this research:

- To establish the daily demand of process heat energy and the ranges of required process temperature.
- To assess the viability of adopting concentrating solar thermal energy systems to meet the process heat for tea drying.
- To estimate size requirements for a cost-effective sensible thermal energy system based on natural stones, to store enough process heat for a daily demand.in the tea factor.

2. Materials and Methods

This assessment of potential for employing solar thermal technologies and thermal energy storage systems is based on a case study. Tingamira – Tanganda Tea estate has been considered for this study and this tea factory is located in the southeastern region of Zimbabwe which receives an average direct solar radiation of more than 5 kWh/m^2/day annually [30]. This solar resource is considered good enough for viable installations of concentrating solar energy technologies and the company has already installed an operational solar photovoltaic (PV) plant with a capacity of 1700 kW of electric power. The plant is delivering surplus electricity to what is required to power all the machinery in the factory. The major industrial processes in this factory include withering, which is the preliminary heating to reduce moisture in fresh leaves from about 80 % to about 66 %. Cutting, tearing and curling is another major process which accounts for major part of electricity. Lastly, tea drying, which is done in three phases is the final main production process which needs thermal energy.

2.1. Data Collection

Data on current source of process heat, daily consumption of thermal energy and the actual process temperature requirements was gathered from the tea factory. This information was used to guide the choice of suitable technical input data for simulations of proposed solar thermal systems.

2.2. Viability of Proposed Potential Solar Thermal Technologies

Concentrating solar power (CSP) technologies were suggested as alternative options for production of required process heat in the tea factory which ranges from 35 °C to 150 °C. Linear Fresnel (LF) and parabolic trough (PT) solar thermal systems were suggested for producing heat at about 200 °C and the schematic illustrations of these systems are presented in Fig. 1 and Fig. 2.

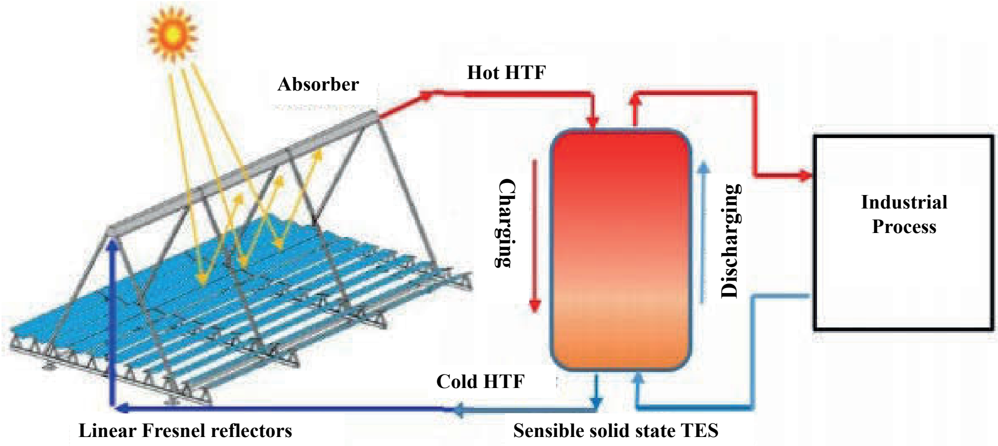

Fig. 1. Linear Fresnel solar thermal system [31].

Linear Fresnel solar thermal collector consists of a number of reflective mirrors which are set up in such a way that they all reflect the direct solar radiation which reaches them to an absorber tube. A heat transfer fluid (HTF) is then pumped through the receiver tube to harness the accumulating high temperature-thermal energy and transfer it either directly to where it is used or to a storage facility.

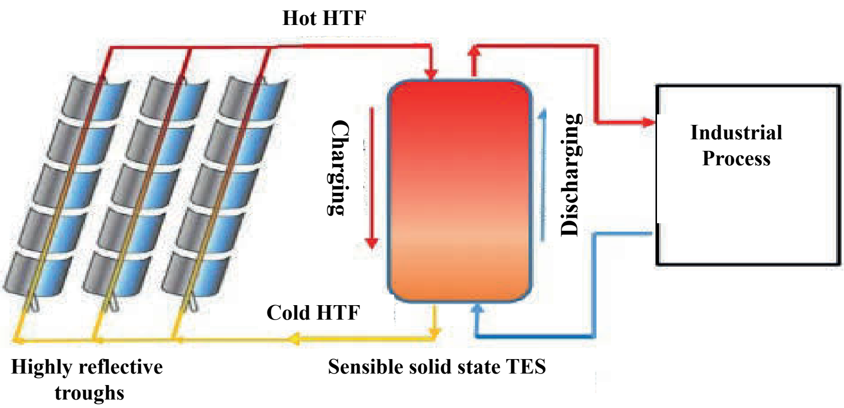

Fig. 2. Parabolic trough solar thermal system [31].

PT solar thermal collector is made up of an array of parabolic troughs with high reflectivity. These troughs reflect direct solar radiation on to the receiver tubes that run along focal lines of the troughs. The concentrated solar radiation heats up the receiver to high temperatures and this heat is transferred to a thermal energy storage system or to an industrial process by pumping a HTF through the receiver tubes.

These proposed solar thermal technologies can be integrated with the existing heating system either at the supply level or process level. For the supply level integration, the solar thermal system is incorporated in such a way that it preheats the water and feeds it into the steam boiler, which will reduce the overall wood fuel consumption. On the other hand, process level integration refers to incorporation of the solar heat system to a specific industrial process. This installation can be done in parallel to the existing heating system and this arrangement will enable the current steam boiler to provide process heat during prolonged periods of no sunlight. Also, process level integration will require the services of a thermal energy storage and a heat exchanger to ensure a constant supply of process heat at the required temperatures.

Both LF and PT solar thermal systems were designed using Systems Advisor Model (SAM version: 2021.12.2). This is a popular modelling tool which is often used to simulate performance of different solar thermal systems. A flowchart shown in Fig. 3 was used for simulation of both LF and PT solar thermal systems.

Weather data including direct normal irradiance, ambient temperature, humidity, wind speed among others, was applied. Solar field data was also supplied, with desired inlet and outlet temperatures of 90 °C and 170 °C being considered for both systems. Pressurised water was used for heat transfer fluid for both LF and PT systems. Dimensions and types of solar collectors and receivers were also specified as provided by the software and for the PT system, Luz LS-2 and Schott PTR80 were used for the collector and receiver respectively. Also, financial input data including inflation rate, tax rate, interest rate and internal rate of return were specified. SAM was then run to give the estimated technical and financial performance of the solar thermal systems.

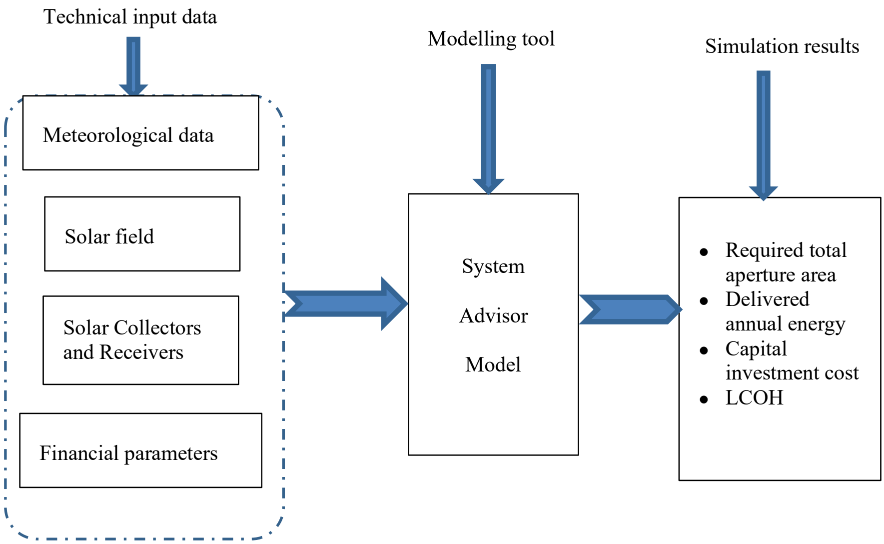

Fig. 3. Simulation flowchart.

In this assessment, both PT and LF solar systems are considered to have same power capacity (220 kW) and produce equal thermal energy annually of about 320 MWh which is equivalent to estimated energy content of wood fuel consumed in a year. The two technologies were compared based on the main output parameters including annual energy output, LCOH, collector area requirements and initial capital investments. SM of the solar thermal systems was varied to assess the performance impact of producing excess energy for storage purposes to provide back up and stabilize thermal output during moments of insufficient and fluctuating solar resource. SM is a factor which specifies the extent of oversizing the solar field and is defined as a ratio of produced thermal energy to required process heat, and in this case, it was varied from 1 up to 2.

2.3. Determination of Solid-State Thermal Energy Storage Unit

Average thermal capacity per unit temperature C_{th}, (~ 0.7 kWh/m^3/K) of heat storing natural rocks [19] was used to estimate volumetric thermal energy density (E_v) by also considering, the temperature range (ΔT) within which, the TES unit is discharging usable process heat as given in Eq. (1).

$$E_v = C_{th} \cdot \Delta T (\text{kW/m}^3) \tag{1}$$

Volume, (V_{TES}) of the required TES facility was then determined, using thermal energy density and daily demand of process heat (Q_{th}) as defined in Eq. (2).

$$V_{TES} = \frac{Q_{th}}{E_v} \tag{2}$$

3. RESULTS AND DISCUSSIONS

3.1. Current Scenario of Industrial Process Heat Demand at the Tea Factory

A steam boiler which is fired by firewood produces super-heated steam which is used to produce hot air for withering tea leaves and drying of processed tea in three different drying chambers at different temperature ranges. Details of heat consumption are given in Table 2.

TABLE 2. INDUSTRIAL PROCESS HEAT CONSUMPTION IN THE TEA FACTORY

Heat source	**Process and required temperature ranges**	**Daily consumption**	**Total supplied energy daily**	**Estimated annual heat demand**
Firewood	Withering: 33 °C Drying in three different drying chambers: Wet: 125–140 °C Intermediate: 95–110 °C Dry: 90–100 °C	About 250 kg (average calorific value of 4 kWh/kg)	1000 kWh	320 MWh (considering the factory is operational for 320 days per)

3.2. Simulation Results and Discussions

Parabolic trough and Linear Fresnel solar thermal systems were designed and optimized with a target of meeting annual thermal energy demand of 320 MWh at equal power capacity of 220 kW. In this study, the main performance variables used for comparative assessment of the two technologies are aperture area, capital investment, annual thermal energy yield and LCOH which are discussed in the following sections.

3.2.1. Solar Collector Area and Capital Investment for Parabolic Trough and Linear Fresnel Systems and the Effects on Solar Multiple

Solar multiple (SM) was varied between 1 and 2 for both parabolic trough and linear Fresnel solar systems and effects on aperture area and capital costs are summarized in Table 3.

TABLE 3. VARIATION OF APERTURE AREA AND CAPITAL INVESTMENT WITH SOLAR MULTIPLE

SM	Aperture area, m^2		Initial capital investment, US$	
	Linear Fresnel	Parabolic trough	Linear Fresnel	Parabolic trough
1.0	360	376	112 860	123200
1.2	418	450	135 432	147 840
1.4	486	520	158 004	172 480
1.6	555	600	180 576	197 120
1.8	624	674	203 148	221 760
2.0	695	740	225 720	246 400

An increase in SM resulted expectedly in the enlargement of the solar collector area and a rise in the capital costs for both solar systems which agrees with the findings by [11]. This is due to the need for additional space to oversize the solar field and the related extra investment. Results for the solar systems when they are not oversized (SM = 1) show that parabolic trough system requires more aperture area and is relatively more expensive as was also reported by [32] and [33]. The general layout and space requirements for parabolic trough solar collector assembly makes it occupy more area than the packed nature of the solar collector for linear Fresnel systems. On the other hand, lower capital costs for linear Fresnel technology are attributed to cheaper flat plane mirrors which are used as the reflective materials as compared to the parabolic troughs for parabolic trough systems. Also, linear Fresnel systems uses lighter structural materials which enables cost effective small sun tracking engines.

3.2.2. Expected Delivered Annual Energy and LCOH for Varying Values of Solar Multiples

Simulation results on effects of SM on annual energy delivered by the solar thermal systems are presented in Fig. 4.

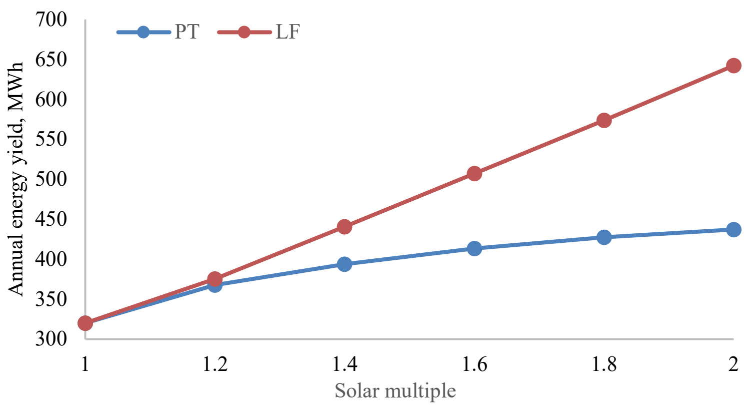

Fig. 4. Effects of SM on annual energy delivered by PT and LF solar systems.

Thermal energy output delivered annually increases as the SM increases. This is expected since larger values of SM implies over sizing the solar field which enables more process heat to be generated by both solar thermal systems. Similar trends were also observed by [11] and [34]. However, Fig. 4 reveals that for SM values ranging between 1 and 2, energy output from LF technology is increasing by higher magnitude such that the energy yield can double at SM values between 1.8 and 2.

Observations of how LCOH varies with changes in SM for both PT and LF solar thermal systems are presented in Fig. 5.

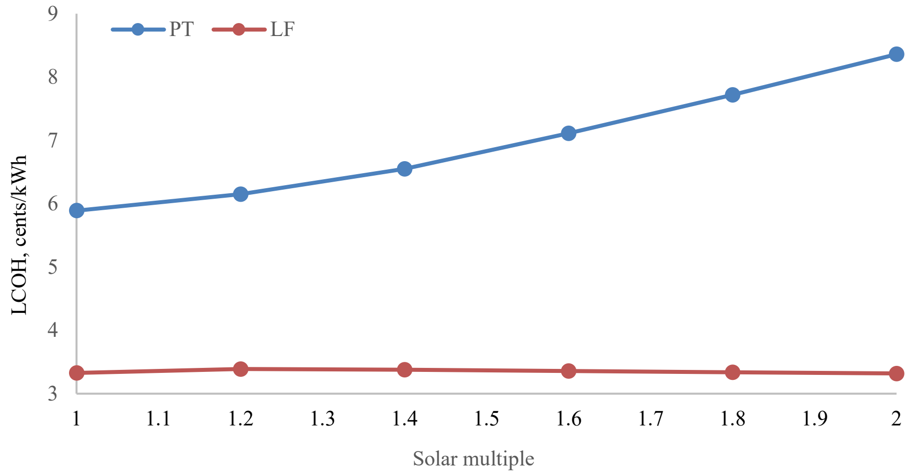

Fig. 5. Variations of LCOH from PT and LF solar systems with SM.

LCOH for the PT solar system is generally increasing as the SM is rising. Akello *et al.* observed the same relationship and this can be explained by the higher investment cost associated with over sizing the solar thermal system. Contrary, for LF system, values of LCOH were seen to be slightly reducing as SM is increased up to a value of 2 and similar results were obtained by [34]. LCOH is largely influenced by capital costs and the delivered annual energy as applied in the SAM software and is defined in Eq. (3).

$$\text{LCOH} = \frac{(\text{FCR} \cdot \text{Capital\_investment}) + \text{FOC}}{\text{Annual\_energy} + \text{VOC}}, \tag{3}$$

where FCR is a factor called fixed charge rate, FOC is fixed operation cost and VOC is variable operation costs.

When SM is increased both capital investment and annual energy increase, but if annual energy yield increases by a higher fraction as compared to that of capital investment, LCOH can reduce, and this accounts for the observed decreasing trend of LCOH for SM varying between 1 and 2.

3.2.3. Potential of Sensible TES System for Tea Drying Solar Multiples

Considering that, the TES unit can discharge from a maximum temperature of 180 °C to a minimum of 90 °C (ΔT = 90 °C), then its thermal energy density is about 63 kWh/m^3. This translates to a storage size of about 16 m^3 for a 1000 kWh$_{th}$ storage capacity required for a day's production in the factory. In addition, a TES system can improve efficiency of the existing heating system by enabling heat recovery which can be used for preheating before entering the boiler and this can also, reduce consumption of wood fuel.

Using the emission factor for dry wood (78.4 gCO_2/MJ^{-1} [35], it implies that, substituting a daily consumption of 200 kg of wood fuel would give an annual saving of carbon emission of about 114 tonnes of CO_2. This saving is huge enough to significantly reduce the carbon footprint of the tea factory.

4. Conclusion

Current consumption of process heat at the Tingamira-Tanganda Tea factory was established, viability of adopting solar thermal technologies was assessed by considering two options, PT or LF systems and potential for thermal energy storage systems in the tea manufacturing factory were analysed. The results revealed that, both technologies can deliver the required process heat at required temperatures and that, LF technology can equally compete with the matured PT technology in delivering process heat for low temperature-industrial applications. Space requirements for the solar thermal collectors to yield required thermal energy output can be easily accommodated, with the LF type offering a smaller solar collector area of 360 m^2 which is about 5 % smaller than that of the PT system.

The effect of increasing the SM of both solar thermal systems resulted in higher aperture area and annual energy yield. Doubling SM value can enable LF system to produce thermal energy output to meet the demand as well as to fully charge a backup TES system, while a PT system can only upgrade its yield by about 37 %. On the other hand, raising the value of SM between 1 and 2 can slightly reduce the LCOH generated by a LF solar system, while that of PT system is expected increase.

Sensible TES system using natural rocks can be adopted for storage of process heat for backup and heat recovery applications to enhance efficiency conventional heating systems. Solar thermal technologies together with TES systems can indeed reduce the carbon footprint of the tea factory by 114.5 tonnes of CO_2 annually if wood fuel is completely replaced.

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