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DESIGN AND SIMULATION STUDY

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Modeling and performance analysis of solar parabolic trough collectors for hybrid process heat application in Kenya's tea industry using system advisor model

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Abstract

Among the Concentrated Solar Collector (CSC) technologies, Parabolic Trough Collector (PTC) is the most mature and commercialized CSC technology today. Currently, solar PTC technology is mainly used for electricity generation despite its huge potential for heating, especially in industrial process heat (IPH) applications. Though the technology is well-developed and successfully used in many developed countries, there is barely any development in Kenya. This paper 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 modelled and a yearly simulation performed using System Advisor Model (SAM) software. 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. 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 of 24 h), some months will still require hybridisation with biomass to fully meet the energy demand. TES must also be incorporated in the solar PTC design to maximise on energy production. The hybrid solar–biomass plant with TES provides optimal performance when SM is 1.8 and TES is 24 h. This results in LCOH of 1.85 US cents/kWh, which is 25% cheaper than using biomass only as is the current practice. Furthermore, integration of solar PTC has a positive impact on carbon footprint and considerably reduces annual greenhouse gas (GHG) emissions by 9817 tons of CO_2-eq, and annual fuel wood consumption by 16,462 m^3 (equivalent to 23.51 acres of mature grown trees).

Keywords Concentrated solar collector, Parabolic trough collector, System advisor model, Solar multiple, Thermal energy storage, Hybridisation, Levelised cost of heat, CO_2 mitigation

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Introduction

Depletion of fossil fuels combined with the ever-increasing demand for energy presents a challenge for the future of world energy supply. In this context, clean, efficient and sustainable energy sources and technologies are needed globally if future energy demands are to be realised. From estimations, the potential of different renewable energy sources (RES) is both enormous and adequate to cover an important share on the future mixed electrical energy (Bird et al., 2013). It is estimated that annual solar radiation that reach the Earth's surface is 885 million TWh (Yuzugullu, 2013). This abundant solar energy makes it a promising source for clean energy production (Kabir et al., 2018). Heat is the world's largest energy end use, accounting for almost half of global final energy consumption, significantly more than electricity (20%) and transport (30%). However, most of the emphasis on renewable energy production is still biased towards electricity generation. Industrial processes are responsible for 51% of all the global heat energy consumption (IEA, 2021), and up to two-thirds of industrial energy demand is also heat. As industrial heat demand grows so does its share in energy-related CO_2 emissions, estimated to be 40% of global CO_2 emissions (IEA, 2019). It is therefore critical that sustainable heat energy sources become part of future energy plans and investments to meet the growing demand, especially in the industrial sector (Akello et al., 2022).

At present, Kenya, just like the rest of the world, especially in Sub-Saharan Africa, is facing the challenge of meeting its sustainable energy needs in a cost-competitive manner. The industrial sector in Kenya heavily relies on imported petroleum and wood fuel for heat energy. However, the high costs of petroleum coupled with high levels of industrial heat energy inefficiency continues to contribute to high manufacturing costs, leading to less competitive products witnessed by increased competition from lower-priced imports. Kenya's high fuel costs, which includes electricity tariffs that rank among the highest on the continent, has forced a number of factories, including those in urban setups, to switch to wood fuel and other forms of biomass. However, with time, increased competition for tree products from other sectors has led to increased fuel wood costs and reduced availability of industrial firewood, especially in industries consuming large amounts of firewood like in Kenya's tea sector (Oloo, 2014).

Kenya remains Africa's leading tea producer and third in the world behind India and China. Black tea is the country's leading agricultural foreign exchange earner. For a long time, the tea sector in Kenya has particularly relied on eucalyptus trees for process heat. This poses serious environmental challenges, besides being expensive (one tonne of processed tea requires $8m^3$ of eucalyptus wood). Combustion of eucalyptus is also a source of greenhouse gases (GHG) emissions. Eucalyptus equally require more water (43% more) to grow compared to other trees, thus reducing biodiversity and could promote desertification (Albaugh et al., 2013). It is for this reason that, in South Africa, for instance, eucalyptus plantation forestry is classified in the Water Act as a stream-flow reduction activity.

Concentrated solar thermal technologies have the potential to provide sufficient global energy, and contribute substantially to greenhouse gas emissions mitigation efforts (Quaschning, 2004; Commission of European Communities, 2007). Process heat generation by concentrated solar collectors (CSC) can significantly contribute to the conservation of conventional energy resources, reduction of CO_2 emission, and help mitigate global warming (Odeh & Morrison, 2006). Many CSC designs can be considered for concentrating collectors but generally, concentrators are classified into four main types, namely; Linear Fresnel Reflector (LFR), Parabolic Dish Collector (PDC), Central Receiver Collectors (CRC), and Parabolic Trough Collectors (PTC).

Parabolic trough collector remains the most mature and proven concentrated collector technology and is currently being used in commercial scale to heat fluids for temperatures of up to 500 °C (Jaramillo et al., 2013). The parabolic shape results in high optical efficiency which produces high energy intensity renewable power. This is the reason why almost 90% of all the thermal solar plants in the world are built with a parabolic trough technology and a Rankine cycle scheme (Kalogirou, 2004). Since Kenya geographically stands astride the equator, the country benefits from abundant solar energy throughout the year, lending itself for potential PTC applications. Solar PTC can therefore be a significant sustainable energy solution for the tea industry in Kenya. Besides, the PTC technology requires little space for setup (compared to eucalyptus plantations) and this can free up large spaces from eucalyptus plantations which can then be used to expand tea growing, among other uses.

A major challenge with solar process heat application is system temperature fluctuations witnessed during unsteady state radiation conditions which may significantly cause thermal and operation problems (Odeh & Morrison, 2006). Solar energy also depends on meteorological conditions which often leads to uncertainty on the instantaneous energy supply. At the same time, large shares of unstable solar energy generation contribute to instability and unreliability (Soares et al., 2018). Furthermore, a time mismatch is a common occurrence due to the different time profile for availability of solar energy and heating demand in plants. This necessitates the need for dedicated thermal energy storage (TES) device, such as a water tank. The presence of TES facilitates flexible operation of the system, which then allows the system to compensate for solar energy input fluctuations, thereby increasing capacity factor and dispatchability. However, the use of TES implies a larger solar field and storage tanks leading to additional costs (De Luca et al., 2015). Therefore, in the short and medium term, CSC integration with TES may still require additional reliable energy source, such as biomass, to reduce on overall costs and still be able to meet set environmental goals. This is particularly relevant for tea growing highlands of Kenya which traditionally receive heavy rainfalls and hence prevalent cloudy conditions for a better part of the year, resulting in lesser solar energy availability as compared to other parts of the country.

Biomass is by far the only renewable source that is continuously available on the production side, but the availability and cost of biomass feedstock can be a hinderance to large-scale deployment of biomass technologies (Thomas et al., 2014) on their own. For this reason, renewable hybridization becomes a viable alternative (Peterseim et al., 2014), where different renewable sources in the energy generation portfolio are combined by taking advantage of each technology. This results in a hybrid thermal process with improved performance, relative to the stand-alone counterparts, in addition to being cost-effectiveness, with decreased CO_2 emissions intensity, and/or increased dispatchability (Nathan et al., 2017). In the short-term, such hybrids can reduce the amount of biomass fuel needed to provide firm supply, while in the longer term, they can also lower the cost of carbon–neutral cycles over their stand-alone counterparts (Nathan et al., 2017). Additionally, hybridization of CSC with biomass results in both system stability and reliability (Colmenar-Santos et al., 2015), and has the potential to increase the cost effectiveness of solar TES, since the capacity of the TES can be optimized independent of any commitments to meet supply. This is important not only because of the growing demand for energy storage (IEA, 2014), but that the maximum economic utilization of TES occurs at much smaller storage capacities than that needed to maintain firm supply (Kueh et al., 2015).

This paper analyses the performance of biomass–solar PTC hybrid system configurations for industrial process heat (IPH) generation and utilisation in tea drying, under the meteorological conditions of Kericho, Kenya. The simulation model is developed using System Advisor Model (SAM) software, Version 2021.12.02 (SAM, 2021), developed by the US National Renewable Energy Laboratory (NREL). SAM incorporates the transient system (TRNSYS) simulation tool for modelling and is capable of analyzing diverse renewable energy systems (Blair et al., 2014).

Methodology

Solar PTC performance is modeled in SAM using meteorological and process heat demand data from Toror tea factory, Kericho as the reference site, and SAM is used to examine the performance of the different trough system configurations and the cost of energy generated. The process simulation provides an analysis of the system design parameters and their effects on economic competitiveness of the different trough configurations. SAM combines an hourly simulation model with performance and finance models to calculate energy output and energy costs (Jain et al., 2013). Most SAM inputs can be used as parametric variables to investigate impacts of variations in performance, cost, and financial parameters on model results (SAM, 2009).

A. *Solar resource*

Proper solar resource assessment is of paramount importance mainly due to its intermittent nature and non-uniform availability across the globe. Since diffuse irradiance cannot be optically concentrated, solar resource in CSC systems only consists of the direct normal irradiance (DNI), which is by far the important parameter for energy yield calculation and performance assessment of CSC systems (Janotte et al., 2017). The DNI refers to the amount of solar irradiance that is perpendicular to the unit area received from the incoming sun rays (Mukeshimana et al., 2021).

In this study, DNI data was estimated from 1 year (2021) hourly ground measurements of solar irradiance at Kericho near the reference site, and the monthly mean DNI is presented in Fig. 1 (Akello et al., 2022).

From Fig. 1, the average hourly DNI is 5.25 kWh/m^2/day, a clear indication that though Kericho is found in the highlands, the location has sufficient DNI for industrial CSC operations, since an average daily DNI of 5.0

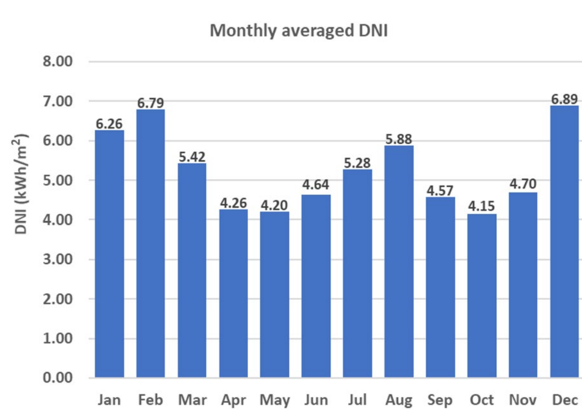

Fig. 1 Mean monthly DNI (kWh/m^2/day) in Kericho

kWh/m^2/day over the year is the recommended minimum DNI for CSC operations (Mashena et al., 2016) and (Wang et al., 2017). Furthermore, the total annual DNI is 1915.59 kWh/m^2 which is acceptable annual DNI threshold value for setting up a CSC project, since typically, for a CSC system to achieve high economic performance, the range of cumulative annual DNI at a site must vary between 1600 and 2000 kWh/m^2/year (Parrado et al., 2016; Wang, 2019).

B. *Heat sink energy*

In SAM, heat sink refers to the plant capacity, which in this context is the thermal energy demand for tea drying. The main data obtained from Toror tea factory included average monthly quantity of Made Tea (MT), corresponding amounts of fuel wood consumption in the drying process, and the cost of the fuel wood. Thermal energy demand is computed from the specific thermal energy consumption (STEC) per Kg of Made Tea (MT) as opposed to fuel wood utilisation due to significant inefficiencies that are witnessed along the biomass combustion value chain in most tea factories. The specific thermal energy consumption for tea drying is 11 MJ/kg in the range of 90–160 °C (Kumar et al., 2021). Using this value to compute monthly energy demand, the annual thermal energy demand for Toror tea factory is approximately 14,285,783 kWh (Table 1), or 14,286 MWh.

C. *System modeling*

The main reason of modeling the solar PTC system is to evaluate the amount of energy it will supply and this helps in designing and optimizing its performance and cost in order to determine the economic viability of the designed system. SAM provides a detailed design along with an hourly simulation for the system. Modelling by SAM requires input to define the features of the physical equipment of the system and estimates the costs of the project (Shirmohammadi et al., 2021). As a first step to modeling, the weather data including hourly DNI data from the reference site are added to the solar resource library of SAM.

The energy demand for the system is also imported as the heat sink power to the SAM. Finally, the solar collector and receiver parameters are configured (solar field design). The system model is established according to the schema illustrated in Fig. 2, which presents how the tools are linked together.

The solar collector field design is critical in developing the predictive model that can characterize the IPH hybrid plant (specifically for tea drying at Toror) and, thus, aid the analysis and evaluation of the plant's performance. The biomass boiler technology is well-established and widely used in Kenya's tea sector, while process heat generation from solar thermal is a relatively new concept. The solar thermal technology is therefore considered as the critical component for the successful implementation of a hybrid biomass–solar PTC plant. Figure 3 illustrates the process flow diagram of the solar PTC system.

The following sub-sections provide details of both technical and financial modeling assumptions used in this study.

Table 1 Thermal energy demand (Toror tea factory)

Months	Made tea (MJ)	Energy demand (MJ)	Energy demand (kWh)
January	360,712	3,967,832	1,102,176
February	315,439	3,469,829	963,841
March	377,022	4,147,242	1,152,012
April	449,614	4,945,754	1,373,821
May	455,771	5,013,481	1,392,634
June	430,581	4,736,391	1,315,664
July	383,847	4,222,317	1,172,866
August	377,100	4,148,100	1,152,250
September	390,743	4,298,173	1,193,937
October	487,485	5,362,335	1,489,538
November	402,075	4,422,825	1,228,563
December	245,008	2,695,088	748,636
Total	4,675,397	51,429,367	14,285,935

Technical parameters

In SAM, the key design point parameters governing the performance of the solar field are design point DNI, design point temperatures (loop inlet and outlet heat transfer fluid (HTF) temperatures) Solar Multiple and TES. The design point DNI represent the DNI at which the plant should achieve the specified thermal rating, and is determined as the weighted average of effective DNI data, since this yield results that correspond with the yearly average efficiency values of the system (Steinfeld et al., 2016). The weighted average of DNI data is 476 W/m^2, which is also the design point value of DNI for this system. In SAM, this design point DNI is equivalent to about 50% value of the PDF/CDF data of annual DNI, as illustrated in Fig. 4.

The operating collector loop inlet and outlet temperatures are selected as the temperatures that satisfies the heating application, in this case, tea drying in the range of 90–160 °C. The drying temperature of 110 °C is optimum for good quality black tea (Naheed et al., 2007). The suitable temperature of the HTF at the solar field outlet must be selected at least 15 °C higher than the

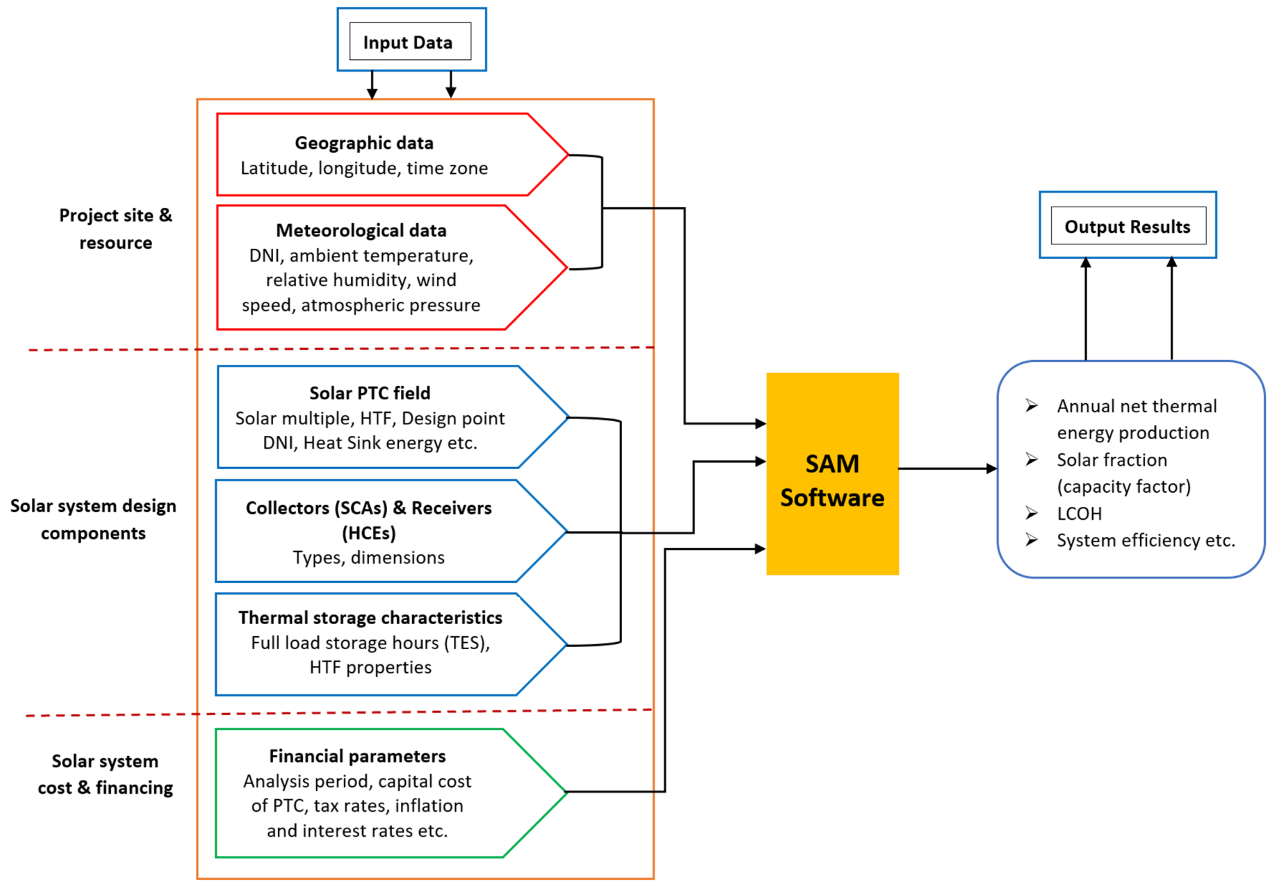

Fig. 2 Solar PTC system flowchart of the simulation in SAM software [adapted from (Mukeshimana et al., 2021)]

demanded steam temperature by the process to be supplied to compensate the thermal loss between the solar field outlet and the drier inlet (Lovegrove & Stein, 2012). The selected final outlet temperature is 130 °C, with the inlet temperature selected to be 40 °C (Fig. 3).

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 (Montes et al., 2009). 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.

TES, on the other hand, specifies the ability of the solar system to store additional heat from the solar collector (Shirmohammadi et al., 2021). 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 through a parametric study to supply a baseload capacity (process heat demand).

Finally, the PTC collector and receiver parameters are configured from SAM library. The solar collector assembly (SCA) selected is EuroTrough ET150 because of the following advantages (Guzman et al., 2014):

- 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 EuroTrough ET150 is used, i.e., 0.871. 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 (Selvakumar et al., 2010). The stow angle (angle that trough have to track in 1 day) is kept at 170°.

This study adopts the use of thermal storage to increase energy efficiency and to satisfy demand requirements

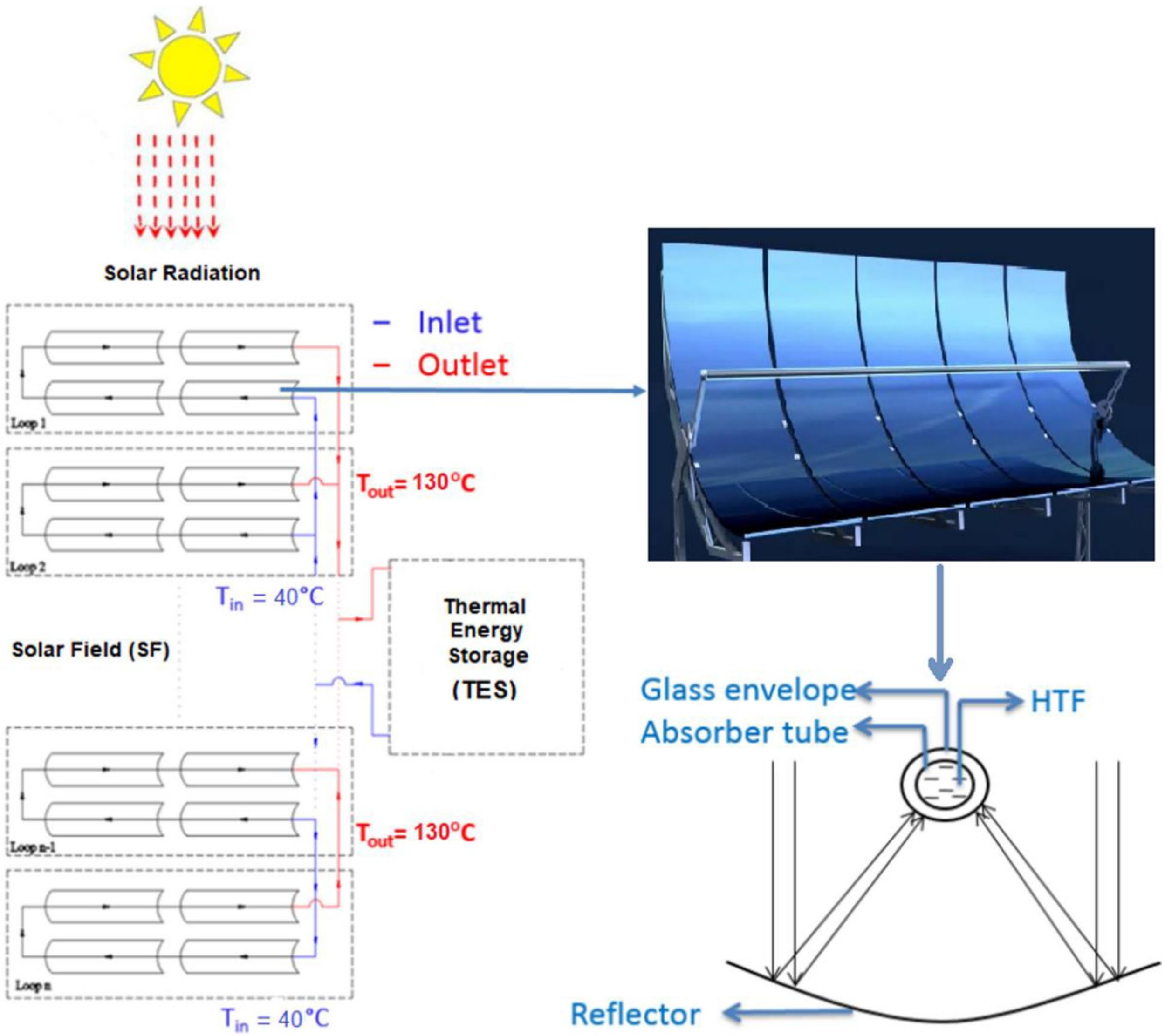

Fig. 3 Process flow diagram of the parabolic trough system [adapted from (Suresh et al., 2019)]

whenever needed. Storage media is pressurised water that is the same for the solar field, so the system only requires one tank for charge and discharge. Water is preferred, because the energy system being modelled operates at a low temperature range, and therefore, no phase change in the storage medium within this range is anticipated. Besides, water is cheaper and more easily obtainable than most other storage media, which can undergo phase change (Ezeanya et al., 2018). For the remaining parameters, default values from SAM software were otherwise used. The details of technical assumptions used in this study are summarised in Table 2.

Financial parameters and system costing

The financial assumptions used as input values for the modeling of the solar PTC include the analysis period of the project which has been selected at 25 years. Relevant economic indicators of Kenya were obtained from the Central Bank of Kenya (CBK) and Kenya Revenue Authority (KRA) websites. These include inflation rate at 9.06% and annual interest rate at 12.39% (CBK, 2022). The sales tax or value added tax (VAT) is 16% (KRA, 2022a), while the corporate tax rate is 30% (KRA, 2022b). The annual discount rate and IRR target were also selected as 12% and 15%, respectively, with respect to the recommended values (Aly et al., 2019; Hernández-Moro & Martínez-Duart, 2013). Finally, the cost of solar field

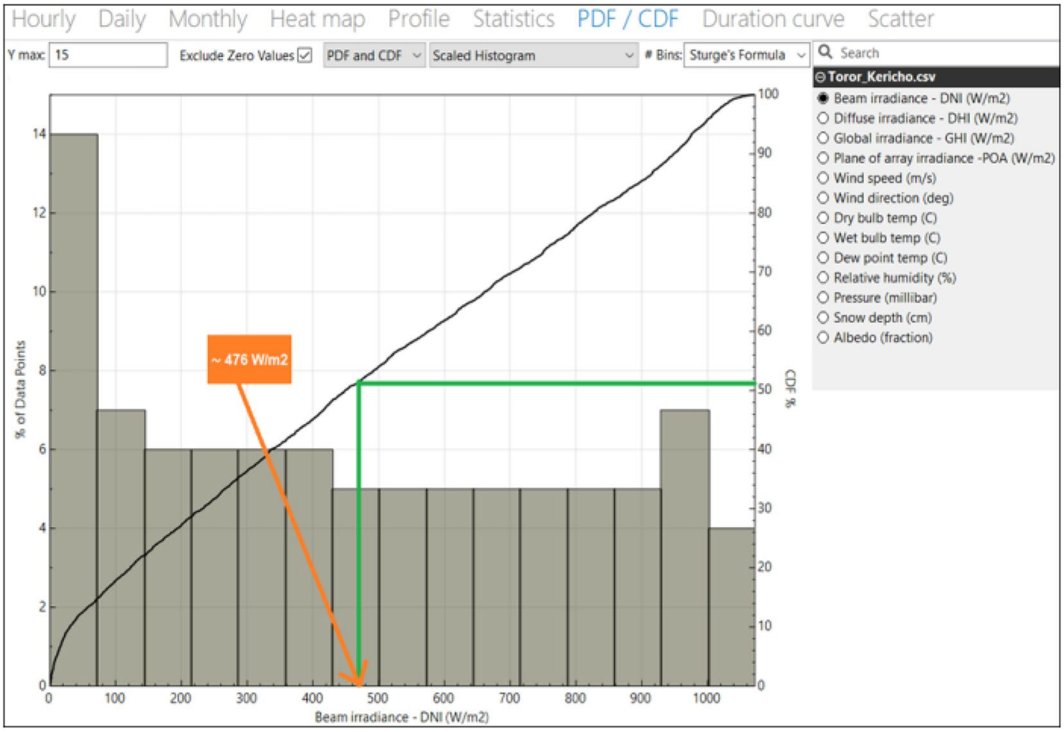

Fig. 4 Design point DNI selection

provided by the EuroTrough ET150 is US$243/m^2, which has been computed as follows (Guzman et al., 2014):

- Solar Field: $161/m^2.
- Mirrors: $28/m^2.
- Site improvement $54/m.^{2}

Thermal storage costs, which has a direct impact on LCOH, are provided by the in-built TES cost model in SAM that estimates the capital cost for sensible heat storage systems as a function of maximum operating temperature, storage medium heat capacity, storage medium cost, number of storage tanks, and storage material cost. (Glatzmaier, 2011). Once the above critical parameters were determined, default values from SAM software were otherwise used for remaining parameters.

Cost of fuel wood

The tea factories currently rely on biomass (fuel wood) as the main source of process heat for tea drying. It is only under rare circumstances when fuel wood supply is insufficient that the factories complement the wood with industrial fuel oil. Due to increasing scarcity of wood and stringent government restrictions on logging, the cost of wood has kept increasing. On average, tea factories pay KES2000 (approximately US$20) per cubic metre of wood. Data provided by KTDA indicated that during the 1-year study period, Toror tea factory consumed 17,797 m^3 of wood. This translates to annual expenditure of US$355,940 on wood to meet the drying energy demand of 14,285,935 kWh (Table 1). Therefore, the levelized cost of heat from wood combustion stands at about 2.49 US cents/kWh.

Results and discussion

The results of the system model described under Methodology and applied to some typical cases are discussed in this section. 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 levelised cost of heat (LCOH) for different IPH system configurations. The results are then used to identify the optimized hybrid system configuration that provide 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 (Ezeanya et al., 2018). Table 3 represents SM equivalence in terms of total collector aperture area,

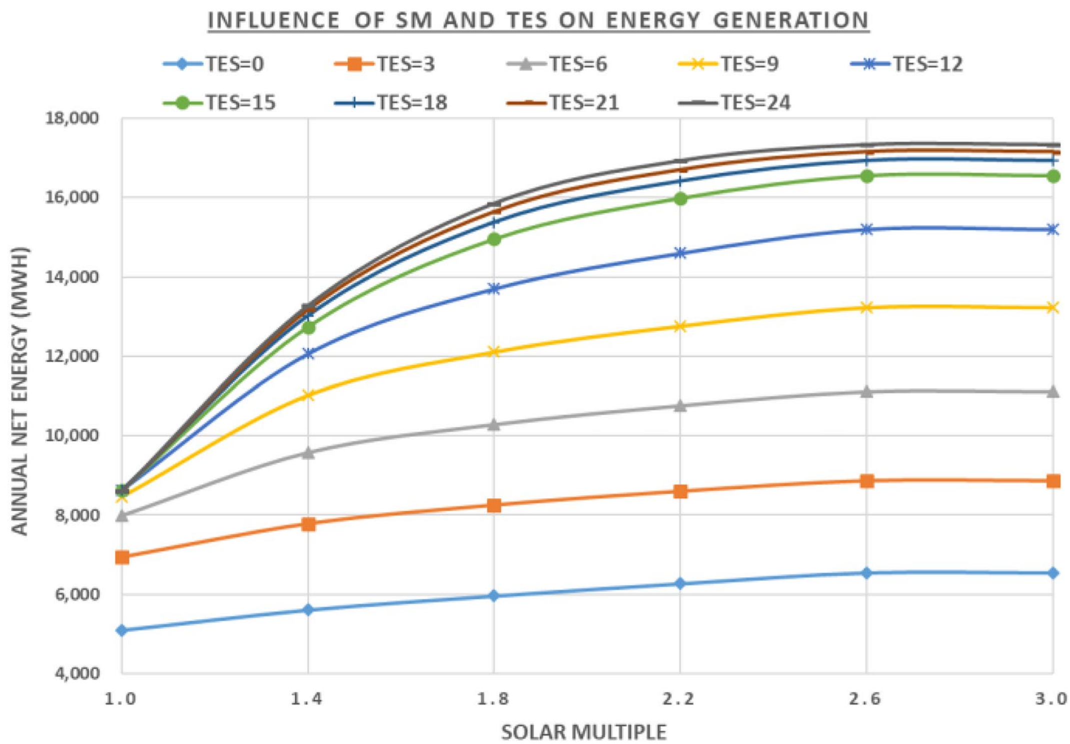

Fig. 5 Influence of SM and TES on energy generation

while Table 4 is the TES hours equivalence in terms of thermal storage capacity.

D. *Performance of* the *Solar PTC System*

Figure 5 shows the influence of SM and TES on annual energy generation by the solar PTC system derived from SAM parametric analysis. It is clear that an increase in both SM and TES values results in corresponding increase in solar energy output. The maximum annual energy output by the system is 17,331 MWh at SM of 2.6 and 3.0, when TES is 24 h. Energy output from the solar system is reduced significantly and way below the energy demand without thermal energy storage (TES = 0). In this case, the maximum annual energy output is 6546 MWh at SM 2.6 and 3.0, hence the need for TES if stand-alone solar PTC system design is under consideration.

E. *The need for hybridisation*

Tea is produced throughout the year in Kenya, and for most tea factories, harvesting of tea leaves takes place throughout the week except on Sundays. Hence, process heat for tea drying must be supplied almost on a daily basis all year round.

Figure 6 shows monthly energy supply from the solar PTC assuming that the system is to designed to its largest capacity, that is, when SM = 3 and TES = 24. The average annual energy output of this system is 17,331 MWh, which is more than the design rated plant capacity of 14,286 MWh. However, from Fig. 6, at least 3 months, that is, April, May and October, will need hybridisation with biomass to fully meet the energy demand. Hybridisation must, therefore, form part of plant design if process heat demand for tea drying is to be met effectively.

The following two sections will now examine the performance of two different configurations of hybrid biomass–solar plant designs.

Case 1: Hybrid solar–biomass plant without thermal storage

The first hybrid configuration analysed in this study is the biomass–solar PTC hybrid system without thermal storage. In this case, TES = 0 and all the energy deficit from the solar PTC generation is supplied by biomass. From Fig. 5, annual energy values increases minimally with increasing SM, from 5089 MWh at SM = 1 to a maximum of 6546 MWh at SM = 3.

Figure 7 shows the solar system efficiency and LCOH at different SM values. In this case, solar system efficiency refers to the proportion of incident thermal energy that is converted by the solar PTC system into heat and

Table 2 Design parameters and considerations

Parameter	Value
Site: Toror tea factory, Kericho Kenya	
Longitude	35.297
Latitude	− 0.318
DNI	5.25 kWh/m^2/day
Solar field	
Design point DNI	476 W/m^2
Total aperture reflective area	10,800 m^2
Target receiver thermal energy	25,667 MWh
Loop temperature at field entrance	40 °C
Loop temperature at field exit	130 °C
Collector (EuroTrough ET150)	
Reflective aperture area	817.5 m^2
Length of collector assembly	150 m
Length of single module	12.5 m
Number of modules per assembly	12
Optical efficiency at design	0.871
Mirror reflectance	0.935
Optical efficiency at design	87.1%
Receiver tube (Schott PTR70)	
Absorber tube inner diameter	0.066 m
Absorber tube outer diameter	0.07 m
Absorptance of absorber tube	0.96
Emittance of absorber tube	0.074
Thermal storage system	
Heat transfer fluid (HTF)	Pressurized water
Loop inlet HTF temperature	40 °C
Loop outlet HTF temperature	130 °C
Heat sink	
Heat sink	14,286 MWh
Pumping energy for HTF through heat sink	0.55 kW/Kg/s

Table 3 Solar multiple in terms of aperture area

Solar Multiple	Area (m^2)	Area (Acres)
1.0	7200	1.78
1.4	10,800	2.67
1.8	10,800	2.67
2.2	14,400	3.56
2.6	18,000	4.45
3.0	18,000	4.45

Table 4 TES hours in terms of thermal capacity

TES (hours)	TES (m^3)	TES (kWh)	TES (MW)
0	0	0	0
6	112	6828	6.83
12	224	27312	27.31
18	336	61452	61.45
24	448	109248	109.25

available for tea drying in the tea dryers. At SM = 1, the system records the highest efficiency of 39.4% and the lowest LCOH of 1.35 US cents/kWh. As SM values become greater than 1, LCOH increases due to increased investment costs to a maximum of 2.47 US cents/kWh at SM = 3. At the same time, system efficiency decreases to a low of 16.9% at SM of 3.0, because the excess solar thermal energy remains unutilized. Since the change in annual energy value is minimal, there's no need to oversize the system. Hence, the optimal configuration for the biomass–solar PTC hybrid system without TES is to have SM = 1. Analysis of monthly energy demand against supply for the optimized configuration (when SM = 1) indicate the need for hybridisation for all the months to meet energy demand (Fig. 8). Cumulative monthly solar fraction for the year is very low at 35.5%, making biomass the predominant energy supply source at 64.5%. Even though the resultant hybrid plant from this configuration will have an LCOH of 2.07 US cents/kWh, which is 16% cheaper than using biomass boilers alone (biomass currently costs 2.49 US cents/kWh), Case 1 is not an ideal option to consider when the main objective is to substantially cut on biomass consumption.

Case 2: Hybrid solar–biomass plant with thermal storage

From Fig. 5, the design rated plant capacity of 14,286 MWh is attained from SM = 1.8 for TES = 15 and beyond. The performance of hybrid solar–biomass plant with TES is, therefore, analysed for SM values of between 1.8 and 3.0, to maximise both solar energy production and share of solar in the hybrid plant.

Figure 9 illustrates the impact of SM and TES on solar system efficiency and LCOH for SM values of between 1.8 and 3.0. For different TES values, the highest system efficiencies and lowest LCOH values are attained when SM = 1.8. System efficiency is reduced beyond SM = 1.8, because most generated heat remains unutilized or is dumped. Lowest efficiency recorded is 35.3% at SM = 2.6 and SM = 3.0, with thermal storage at TES = 15. Similarly, due to higher investment costs that is needed as the system gets larger, LCOH increases beyond SM = 1.8. The maximum LCOH is 2.55 US cents/kWh at TES = 15 and SM = 3.0.

The highest system efficiency of 50.5% is attained with LCOH of 1.81 US cents/kWh at TES = 24. At the same time, the average annual solar fraction at SM = 1.8 and TES = 24 is 101% (Fig. 10), which is sufficient energy to operate the plant on solar alone for a better part of the year. Therefore, SM = 1.8 and TES = 24 are selected as the

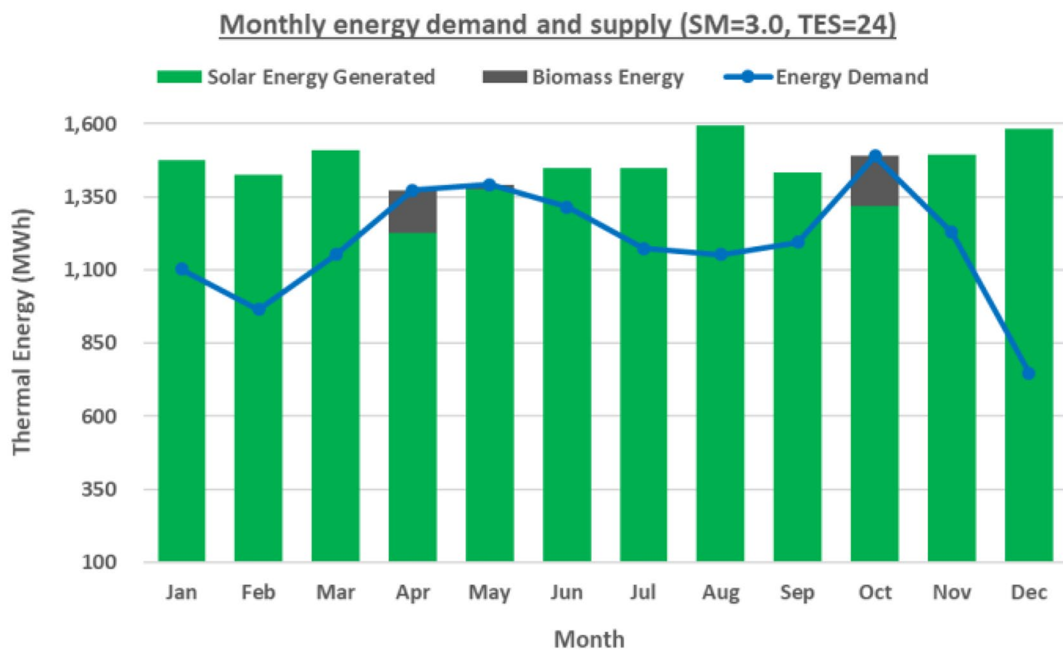

Fig. 6 Monthly energy demand and supply from solar and biomass

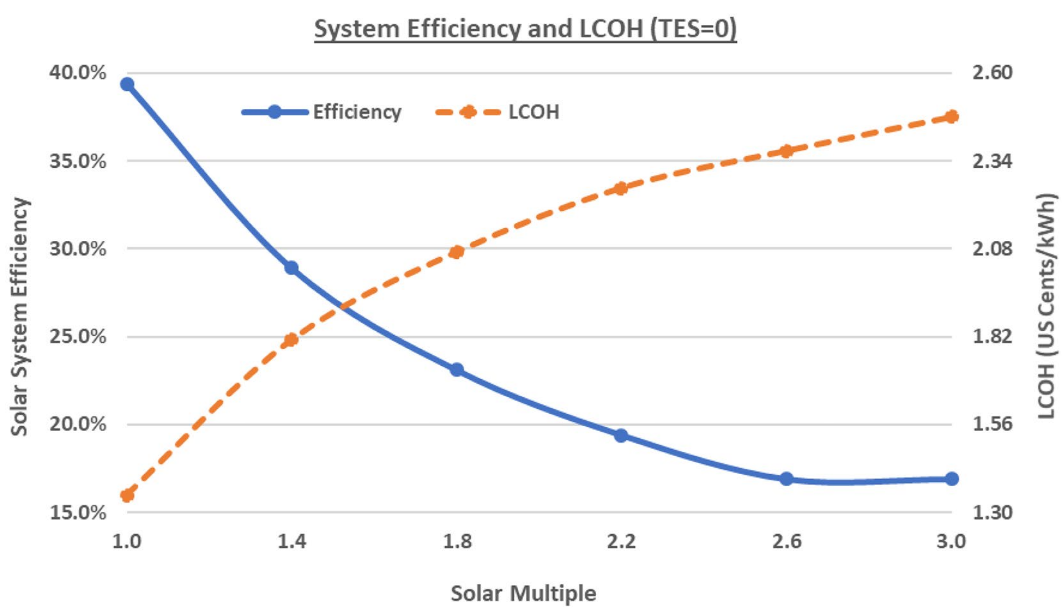

Fig. 7 Influence of SM on solar system efficiency and LCOH

optimal configuration. The cost of heat generation using the optimized solar PTC (1.81 US cents/kWh) is also 27% cheaper than using biomass only as is the current practice.

Monthly distribution of the generated energy for the optimized configuration illustrates availability of sufficient solar thermal energy generation for 8 months. From Fig. 11, only 4 months (April, May, June, October) will need hybridisation with biomass to meet energy demand. In this case, cumulative monthly solar fraction for the year is 92.5%, with only 7.5% thermal energy from biomass required to meet the energy deficit. The resultant hybrid plant from this configuration will have an LCOH of 1.85 US cents/kWh, which is 25% cheaper than using

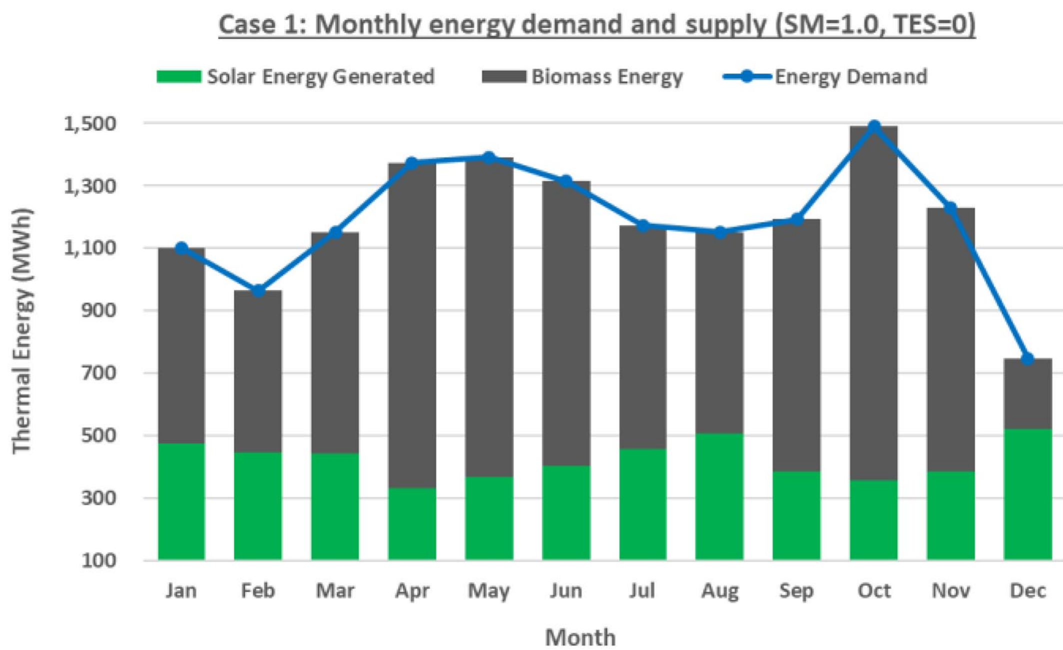

Fig. 8 Monthly energy demand and supply after optimisation

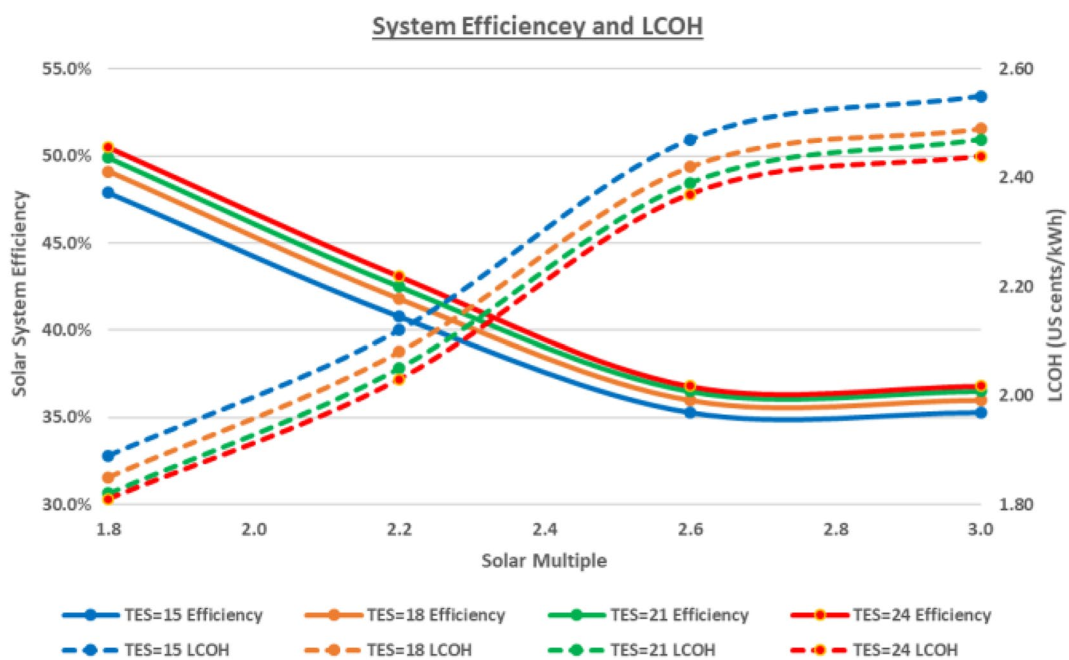

Fig. 9 Influence of SM and TES on system efficiency and LCOH

biomass boilers as the only source of process heat for tea drying operations.

F. *Solar PTC operation on a typical day*

To study the variations of different flows of thermal energy that come into play during the operation of the optimised hybrid solar–biomass plant, we chose 1 day of the year (June 21st). On this day (Fig. 12), DNI starts becoming available at 0700 h with a value of 339 W/m^2.

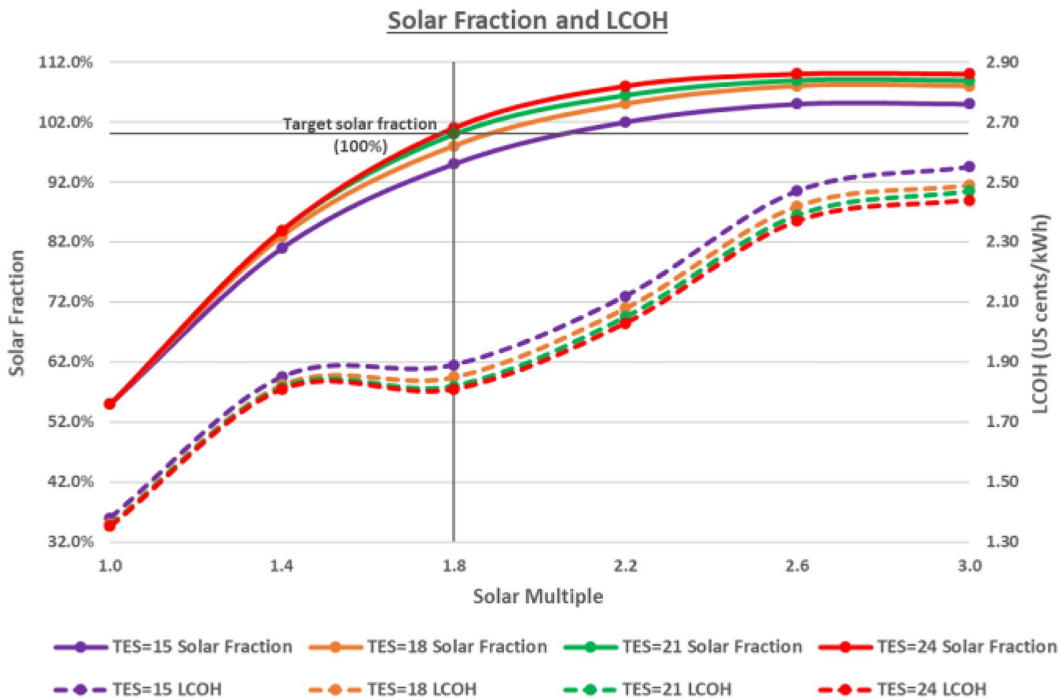

Fig. 10 Influence of SM and TES on solar fraction

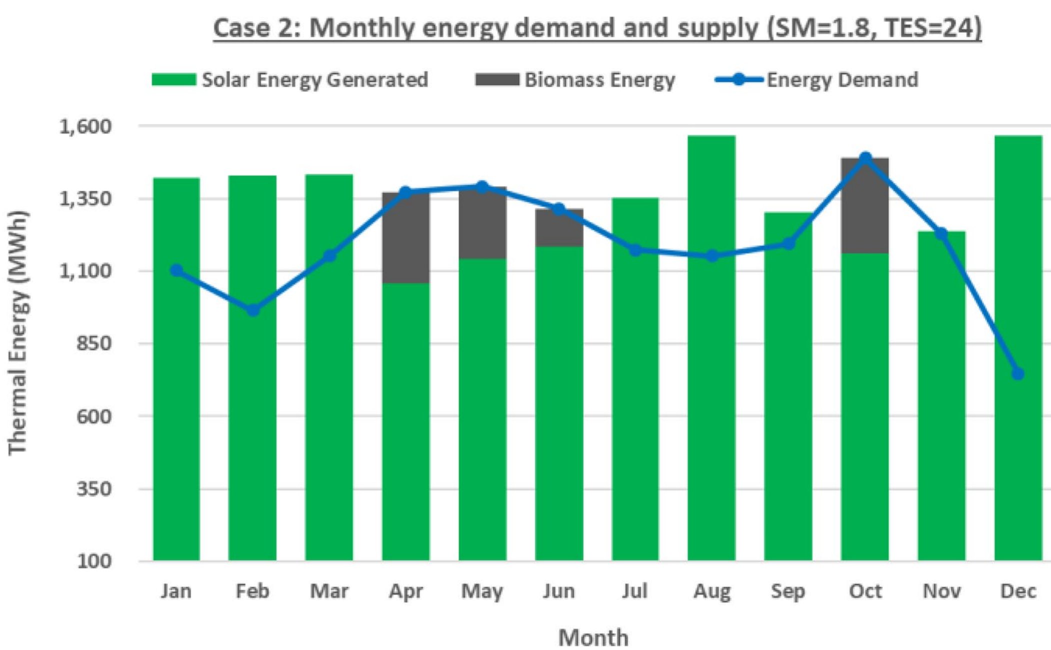

Fig. 11 Monthly energy demand and supply for optimized system

The maximum value was obtained at 1200 h (1021 W/m^2). After sunset at 1900 h, the available solar energy vanishes, with the last DNI recorded at 1800 h (320 W/m^2).

The quantities of thermal energy output of solar field vary simultaneously with DNI. Thermal energy incident at 0600 h is 4.88 MWh and the maximum is 14.91 MWh at 1200 h. Assuming tea drying session

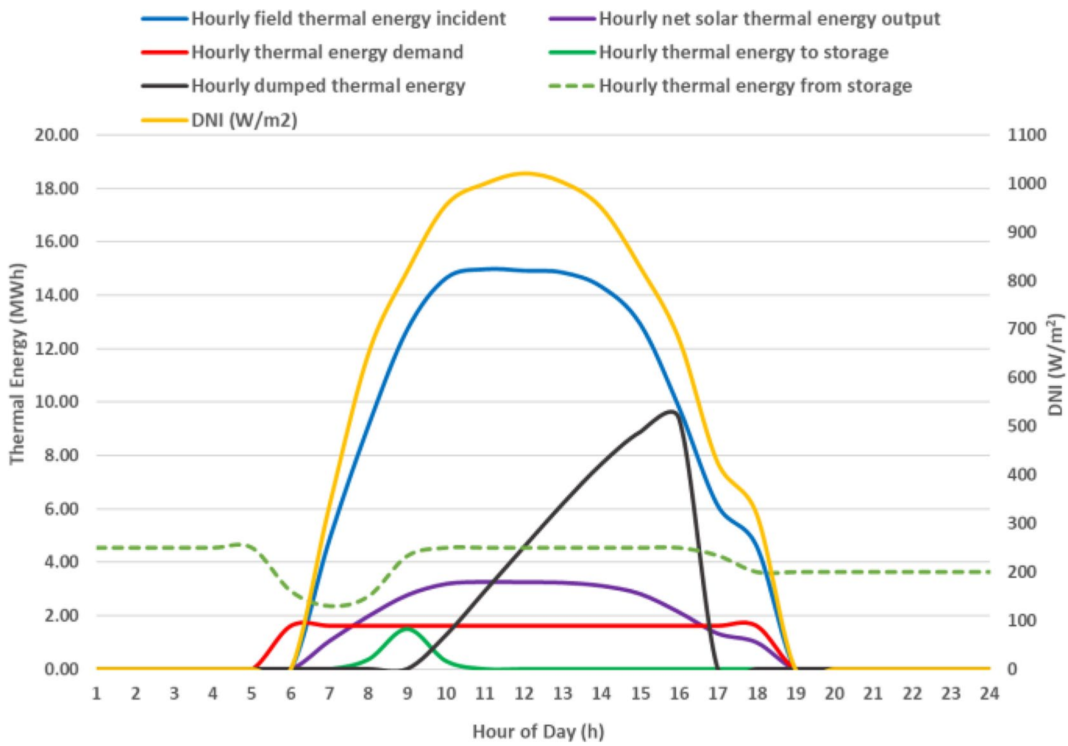

Fig. 12 Performance of Solar PTC on a typical day

taking place between 0600 and 1800 h and that the system starts from full storage capacity of 4.55 MWh, the energy demand at 0600 h (1.63 MW per hour) is initially supplied from storage. At 0700 h, net solar thermal energy output is 1.07 MWh, and the deficit is also supplied from storage. Between 0800 and 1600 h, the solar PTC generates sufficient energy to meet the drying demand, with excess energy returned back to storage. Once the thermal storage capacity of 4.55 MWh is restored at 1000 h, the excess energy of 1.27 MWh is dumped. Dumping takes place for the next 6 hours until 1600 hours when 9.39 MWh is dumped. Between 1700 hours and 1800 hours, the solar PTC system generates insufficient energy for tea drying and the energy deficit is met from storage. Finally, at the end of the day, when drying ceases, system storage capacity is left at 3.46 MWh, which is readily available to assist in the drying processes the following day. The graphs, 'hourly thermal energy to storage' and 'hourly thermal energy from storage', shows the phases of charging and discharging of the storage system respectively.

G. Fuel wood conservation and CO_2 mitigation

Integration of renewable energy such as solar PTC into biomass-fired tea factories can help to conserve wood, save on land and result in CO_2 reduction. Currently, Toror tea factory consumes approximately 17,797 m^3 of wood annually. One mature tree produces 1.0 m^3 of wood and an acre has about 700 trees (KTDA, 2019). Therefore, Toror tea factory consumes 17,797 trees per year, which requires 25.4 acres/year to grow. In Kenyan tea factories, total GHG emissions due to fuel wood combustion is 2.27 kg of CO_2-eq/kg of Made Tea (Azapagic, 2013; Taulo & Sebitosi, 2016). Toror produces 4,675,397 kg of MT, which generates annual emission of 10,613 tons of CO_2-eq. Table 5 shows the annual reductions in CO_2 emissions, wood consumption and land use for the considered two hybrid plant configurations.

Table 5 Yearly reductions in CO_2 emissions, wood and land use

	Hybrid plant without TES	Hybrid plant with TES
Fuel wood conservation	6318 m^3	16,462 m^3
Land preservation	9.02 acres	23.51 acres
CO_2 mitigation	3768 tons CO_2-eq	9817 tons CO_2-eq

Conclusion

This study has used the system advisor model (SAM) to model the impact of solar multiple, thermal energy storage and hybridization percentages (the principal design parameters) on the levelized cost of energy and annual energy production for two different solar–biomass hybrid system configurations—one with TES and another without TES. Thermal energy storage and hybridization are specifically considered to enhance the utility of solar PTC plant investigated for industrial tea drying operations in Kericho, Kenya. For the configuration without TES, the optimal SM is 1. Even though the resultant hybrid plant has LCOH of 2.07 US cents/kWh, which is 16% cheaper than using biomass boilers alone, this configuration provides low cumulative monthly solar fraction of only 35.5%. Employment of solar energy also results in annual reduction of GHG emissions by 3,768 tons CO_2-eq, and fuel wood consumption by 6,318 m^3, which requires 9.02 acres/year to grow. On the other hand, the hybrid solar–biomass plant with TES provides optimal performance when SM = 1.8 and TES = 24. The optimised hybrid configuration provides the least LCOH of 1.85 US cents/kWh, which is 25% cheaper than using biomass only as is the current practice.

When sunlight is insufficient during the rainy seasons, the solar system cannot provide adequate thermal energy for drying. For example, the storage system never reaches its maximum capacity in April, May, June, and October. This reduces the annual solar solar fraction of the plant to about 92.5%. Since 92.5% of the thermal energy required is supplied by the solar system, the fuel wood consumption and CO_2 emissions are reduced by 16,462 m^3 and 9817 tons CO_2-eq, respectively. Furthermore, reduction in fuel wood consumption also means that 23.51 acres of land required annually to grow the trees is spared. Yet the solar field only requires 2.67 acres of land for the project duration of 25 years.

The desired hybrid configuration should be guided by set objectives of the system which includes the desired solar fraction, cost of production reduction targets as well as emissions reduction targets. As already discussed, regardless of the objective for hybridisation, TES must be incorporated in the solar PTC design to adequately meet the desired energy demand.

The implementation of optimal configuration of the biomass–solar PTC hybrid plant is a viable solution for tea drying operations in Kenya's tea factories compared to the current use of biomass alone. The hybrid plant can ensure reliable and firm energy supply, in addition to providing cost-effective CO_2 mitigation and considerable reduction in fuel wood consumption and related land degradation from tree planting and harvesting. Energy output from the solar PTC can be maximized by synchronizing tea drying hours to take place during the day when there's sunlight. Furthermore, a lower LCOH of the system can be obtained when local manufacturing of the PTC is considered, instead of exporting troughs manufactured abroad. At the same time, excess heat generated especially during the hotter months can be used for other processes in the tea factory, especially tea withering, further reducing the cost of production.

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Authors' contributions
P.O.O. Akello analyzed and interpreted all the data in the study. C.O. Saoke and P.O.O. Akello performed system modelling using System Advisor Model. J.N. Kamau and J.O.H. Ndeda determined the methodology adopted for research presentation and environmental analysis in the study. All authors read and approved the final manuscript.

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Availability of data and material
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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