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Design and evaluation of solar parabolic trough collector system integrated with conventional oil boiler

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Abstract: In this paper an attempt has been made towards the design and evaluation of a solar parabolic trough collector (PTC) system integrated with a conventional oil boiler (COB) to increase the energy utilization effectiveness and reduce the environmental emission of the existing conventional oil boiler in the Kombolcha textile factory, in Ethiopia. The factory uses 8500 ton/annum of heavy fuel oil to generate 26 ton/hour of pressurized hot water at 140°C temperature which causes an increase in greenhouse gas emissions, so the solar parabolic trough collector hot water generation system will be an appropriate solution for this application. Based on the available annual solar radiation, estimates of the solar fraction, solar energy unit price and system pay-back period have been carried out. The proposed system has the potential to save 1055.9 ton/year of fuel oil. The unit cost of PTC solar energy is estimated to be 0.0088 \$/kWh and the payback period of the plant is five years. Since the unit price of oil energy (0.0424 \$/kWh) is much greater than the unit price of solar energy by a substantial margin (0.033 \$/kWh) in Ethiopia, therefore the water heating system by a solar parabolic trough collector is a feasible alternative to heating by a conventional oil boiler.

Key words: conventional oil boiler, energy, solar parabolic trough

1. Introduction

The Ethiopian population will continue to grow for several decades to come. Energy demand is likely to increase even faster, and the proportion of energy supplied and energy demand is still not balanced. The main sources of energy for industry (fossil fuels: coal, heavy oils and electricity) that we use are believed to be running out. Moreover, these sources of energy (such as heavy oil and coals) can cause harm to our environment [1]. This environmental challenge can be mitigated by looking for alternative clean energy resources along with an adaptation strategy against those environmental consequences that cannot be reversed. Using renewable energy sources has the advantage of no pollution, no greenhouse gas generation and there is no danger to the security of the energy resource. One of these clean and renewable resources is solar energy. Solar thermal power plants are one of the most interesting options for renewable electricity and thermal (steam) energy production. Ethiopia has a huge potential in solar energy particularly in the Southwest where the deserts have some of the best solar resource levels in the world. This sets parabolic trough powerplants as an option for power production in the country [2–4]. With solar energy, solar radiation is used to generate electricity, heat water or other fluids, charge batteries, heat homes through glass windows, generate steam and cook food. Joshua [5] presented a concentrated solar power (CSP) used for generating steam instead of fossil fuels. One of the most well-known solar collectors is a parabolic trough solar collector. A parabolic trough collector is based on mature technologies among the solar thermal ones. The annual average daily solar radiation for Ethiopia is 5.2 kW h/m^2/day [4]. A typical PTC consists of a parabolic trough reflector, which reflects the incident radiation from the coming solar beam radiation onto the absorber. The absorber consists of a steel absorption pipe enveloped inside a glass tube located at the focal line of a parabola. The circulating heat transfer fluid (HTF), which passes through the absorber, is heated up by the radiant energy absorbed. The heat collected is used to produce steam from medium to super-heated at high temperature [6].

The purpose of this paper is to analyze and describe the heat losses (conduction convection and radiation) associated with the heat collection element of a solar PTC. The effect of wind speed, the mass flow rate of a heat transfer fluid, ambient temperature and available solar radiation on thermal losses were investigated. The receiver of the parabolic trough collector is modeled in an engineering equation solver (EES) and with a MATLAB code. Author [7] reported about the direct-absorption parabolic-trough solar collector for the medium to high temperature regime, using a nano-fluid as a heat transfer fluid and evaluated the effect of the mass flow rate, convection heat transfer coefficient, absorption coefficient, and solar irradiance on the collector performance. Author [8] studied the detailed temperature distribution of a PTC receiver using FLUENT software and a MCRT code by considering the heat transfer fluid flow, radiation and conduction heat transfer mechanisms. The outlet temperature or useful energy of a parabolic trough steam generation system is dependent on the wavelength, the glass envelope's absorption of solar radiation energy, inlet temperature and properties of heat transfer fluids. A.A. Hachicha [9] presented a detailed numerical heat transfer model based on the finite volume method. An optical model was developed for calculating the non-uniform solar flux distribution around the receiver.

Evangelos Bellos *et al*. [10] investigated in detail the working fluid for solar parabolic trough collectors, and reported the exergetic and the energetic performance of the PTC, operating with different working fluids such as pressurized water, therminol VP-1, nitrate molten salt, sodium liquid, air, carbon dioxide and helium. Just as the results of pressurized water are the best working medium for temperature levels up to 550 K, carbon dioxide and helium are the only solutions for temperatures greater than 1100 K. El Ghazzani B. *et al*., in [11], have presented the performance of a PTC, the plant efficiency is around 52%, the plant exergy efficiency is about 24% and the solar fraction is around 56%. In this case, it is possible to avoid annually 57% of CO_2 emissions by the implementation of the solar plant.

1.1. Type of solar thermal collector

A solar collector is a special kind of heat exchanger that transforms solar radiant energy into heat. A solar collector differs in several aspects from most conventional heat exchangers. The latter usually accomplishes a fluid to fluid exchange with high heat transfer rates and with radiation as an important factor [12]. There are basically two types of solar collectors.

1.2. Non-concentrating collectors

Stationary collectors do not move and can be further subdivided into flat plate collectors and evacuated tube collectors. Stationary collectors are cheaper and require little maintenance but they can only achieve low to medium temperatures [13].

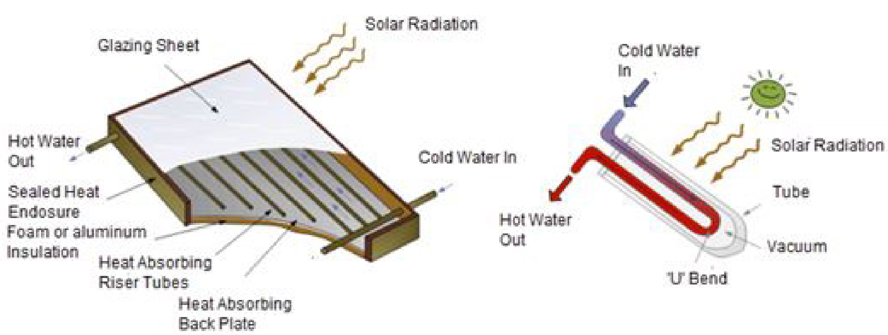

Fig. 1. Model of flat plate collector and evacuated tube collectors

1.3. Concentrating solar collector

CSP collectors usually rotate to track the sun's rays to achieve the maximum available temperatures. But the CSP collectors are more expensive and require more maintenance. They use mirror surfaces to collect sunlight on an absorber called a receiver. They can achieve high temperatures but like evacuated tube collectors, only use direct available beam radiations.

According to Mc. El Jai's [14] expression, the process of concentrating solar energy can be achieved by a system based on concentration of lenses, or reflective mirrors such that the sun rays converge onto a target of a smaller size located at the focal plan of this surface. Generally, solar concentrator technology mainly consists of (i) a focusing device, (ii) an absorber/receiver provided with or without a transparent cover, and (iii) a tracking device for continuously following the sun. CSP technologies are usually categorized in three different concepts; they work as follows [15]:

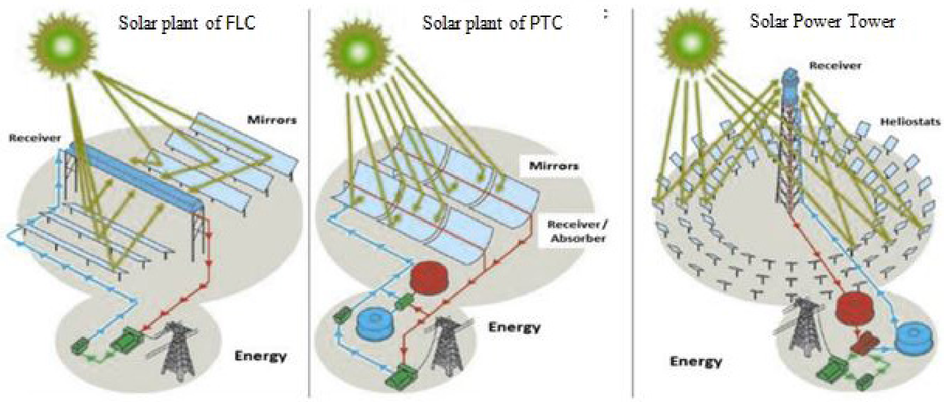

Fig. 2. Different types of solar concentration plants [14]

Today, PTC solar power plants use water as a heat transfer fluid (HTF) that is circulated through absorber tubes. The water is heated till the stated temperature value. The most important factors to make solar power plants to be more commercially viable are to reduce costs, hazards, health problems, reduce environmental impacts and increase thermal efficiency. Kombolcha Textile Share Company (KTSC) uses annually 8 500 tons of fossil fuel to generate a 26 ton/hour mass flow rate of pressurized hot water with a temperature of 140°C, which increases greenhouse gas emissions, so the solar parabolic trough collector water heating system seems to be an appropriate solution for this application. It reduces the fossil fuel consumption, extra cost of fossil fuels and negative environmental impacts. The PTC solar power plant with an oil heat exchanger increases the building cost and decreases the efficiency of the plant. In order to avoid these disadvantages, a direct hot water generation system using a PTC without an oil heat exchanger is an appropriate solution.

2. Materials and method

Methodology

The energy demand of the industry has been studied using the primary data collection method. Second, review the literature of applicable materials on parabolic trough collectors and power production systems. Third, collect secondary data from previous and related research studies. Fourth, gather information from existing meteorological data sources like NASA, A.A and Kombolcha city meteorology. Fifth, the system is modeled using MATLAB and EES programs.

These software packages have been chosen for their simplicity and flexibility. Finally, a cost and financial analysis has been performed to predict the pay-back period and unit price.

Location of the study area

The study area is identified by directly visiting the site. Climate data like solar sunshine hours, maximum and minimum ambient temperature and wind velocity have been obtained from the Kombolcha meteorology station office, Ethiopia. All necessary parameters like system working temperature points, the flow rate of hot water, fuel oil and water have been obtained from measurements. The study area is located at a latitude of 11.08° and a longitude of 39.72° at an altitude of 2 000 meters above sea level with an ambient temperature range between 17°C and 28°C [16].

System descriptions and models

The schematic diagram of the proposed power plant, shown at Figure 3, consists essentially of a solar collector field, conventional oil boiler and control systems. When the beam radiation is strong enough to generate hot water temperature, the solar field heats up the water that flows through the solar absorber of the PTCs (see red solid line), so it is continuously supplied to the system. When the beam radiation is reduced in the morning and afternoon, as well as the radiation does not reach the earth due to clouds and the mass flow of an HTF is reduced, the outlet temperature of the HTF still reaches the set point thanks to a temperature and flow rate controller. If the mass flow rate of hot water further reduces or the beam radiation is not sufficiently available, the flow of the HTF changes its direction through the boiler with the help of the flow rate of a fuzzy controller (FC). This controller receives flow rate and temperature signals from flow meter and thermal sensors, respectively. The three-way valve is implemented at the solar field outlet side and is controlled by data logging computer. When the mass flow rate and outlet temperature of the HTF is below a set value, the thermal and flow meter sensors send signals to the controller that commands to open the three-way valve towards the conventional boiler for preheating (see yellow solid line). Finally, if the mass flow rate of hot water further reduces and the outlet water temperature is very low or the beam radiation is not available, the pump fully charges through the conventional oil boiler (see blue solid line). In the system layout, the hidden red line indicates data logger cables that are used to transfer data from the measurement device to the computer and the blue hidden line is also used to transfer the command from the computer to the control device.

The textile industry uses oil boilers for different applications. In the industry, solar energy is used to reduce the amount of fuel material burnt in boilers and greenhouse gas emissions. The following table shows the primary data input and the output value of oil boilers.

Table 1. Primary data input value

Parameter	Unit	Value	Parameter	Unit	Value
Fuel consumption	ton/year	8 50	Water consumption	ton/year	26
Operating hour/day	hour	24	Required temperature	°C	140
Required pressure	bar	4	Water inlet temperature	°C	18

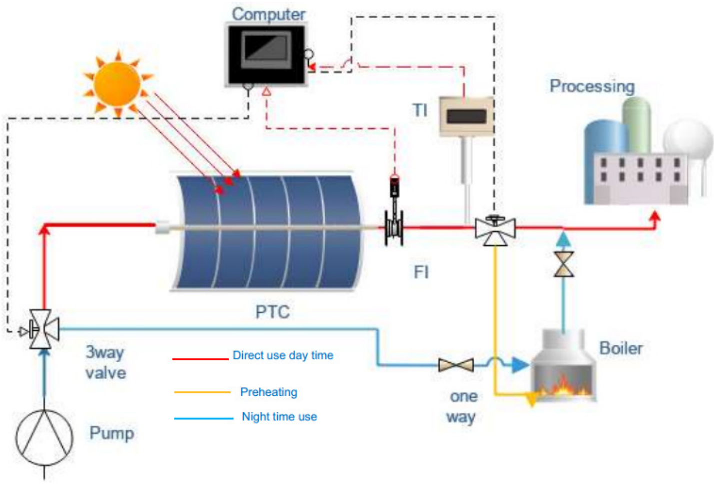

Fig. 3. The scheme of solar PTC system integrated with conventional oil boiler plant

3. Design and evaluation of solar PTC system integrated with COB

Thermal analysis of parabolic trough solar collector

Solar radiation falling on the concentrator is reflected on the absorber tube located at the focal line with a concentric transparent glass cover. As the temperature of the absorber increases, heat transfer processes take place.

The PTC analysis uses the following assumptions to simplify the complexity of each part of the analysis: the heat transfer fluid is an incompressible and steady process, the glass is opaque to infrared radiation, the parabolic shape of the concentrator is symmetrical, solar energy fluxes, temperatures, and other thermodynamic properties are considered uniform around the receiver, finally, the glass envelope surface, as well as the conduction thermal losses, are negligible.

In this study, a parabolic trough collector type ET150 is investigated by using MATLAB and EES codes in order to analyze the thermal efficiency and hot water outlet temperature at a given condition. An ET150 parabolic solar collector is a high geometric mirror, with which accuracy could be reached. The mirror has a multilayered structure. The first layer below the glass is the reflective layer, with silver as a coating material. The thickness of the complete mirror amounts to 4 to 5 mm.

Direct solar radiation rays are reflected by high reflectance (ρ) material or collectors to concentrate on the receiver tube. During this process the concentrated solar radiation flux is transmitted through the glass envelope, and falls on the absorber tube. During this process, a large part of the concentrated solar radiation energy is transmitted through the glass envelope due to the used high transmittance (τ) materials. The absorber tube absorbs the concentrated solar radiation flux through the selective coating which is plated on the outer surface of the absorber. The selective coating has high absorptance (α) for radiation in the solar energy spectrum, and low emittance in the long wave energy spectrum to reduce thermal radiation losses. In general, a large part of the coming beam solar radiation energy is reflected by the reflector, transmitted by

Table 2. Characteristic parameters of parabolic trough solar collector [18]

Euro trough model	Luz3	ET150
Focal length	1.71 m	1.71 m
Aperture width	5.76 m	5.77 m
Aperture area	545 m^2	817.5 m^2
Collector length	99 m	148.5 m
Absorber tube diameter	0.07 m	0.07 m
Number of modules per drive	8	12
Geometric concentration ratio	82	82
Rim angle (degree)	80	80
Module length	12 m	12 m
Number of glass facets	224	336
Number of absorber tube (4.1 m)	24	36
Mirror/collector reflectivity (ρ)	93%	94%
Transmittivity of glass envelope (τ)	0.96	0.965
Absorptivity factor of absorber (α)	0.96	0.96
Intercept factor	0.95	0.95

the glass envelope and absorbed by selective coating absorbers. The selective coating absorbs the concentrated solar radiation flux and converts it into heat [8, 18].

The trough collector models are made up of identical 12 m long collector modules with a total length of 148.5 m long ET150 SCA per drive and an aperture area of 817.5 m^2 [17, 18] (Fig. 4).

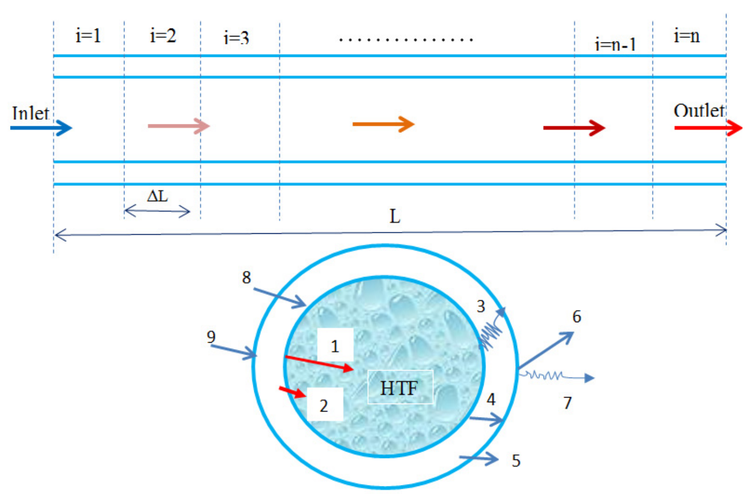

Fig. 4. Schematic of the 2D heat transfer model

The resistance network that represents the model shown in Figure 5 is:

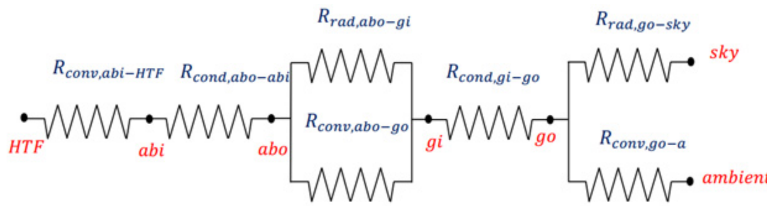

Fig. 5. Thermal resistance network

Where: the *HTF* is the heat transfer fluid, *abi* is the absorber inner surface, *abo* is the absorber outer surface, *gi* is the glass envelope inner surface, *go* is the glass envelope outer surface.

Convection heat transfer from the absorber to the HTF

The receiver is consisting of two concentric pipes. The inner one is made of metallic pipe and the outer pipe is made of glass. Vacuum is created between them in order to avoid convention and conduction thermal losses [19].

The convection heat transfer from the inside surface of the absorber pipe to the HTF is:

$$Q_{\text{conv\_}p\_f} = \pi D_i h_{\text{conv\_}p\_f} \left(T_p - T_f\right).$$

A convective heat transfer coefficient is found from the Dittus–Boelter correlation.

$$h_{\text{conv},p-f} = \text{Nu}_{Di} \frac{k_f}{D_i}.$$

The Nusselt number is estimated as: if Ref > 2 300.

$$\text{Nu}_{Di} = 0.023\,(\text{Re})^{0.8}\,(\text{Pr})^{0.4}.$$

Otherwise,

$$\text{Nu}_f = 4.364,$$

$$\text{Re} = \frac{\rho_f V D_i}{\mu_f},$$

$$\text{Pr} = \frac{c_p \mu_f}{k_f}.$$

Conduction heat transfer through the absorber wall

The temperature distribution and the heat flux for the long hollow cylinder; for one dimensional and steady state conditions [19–21]. Fourier's law of conduction through a hollow cylinder:

$$q\_cond; p\, 0 = 2\pi kp \left(T_{pi} - T_{po}\right) / \ln\left(D_o/D_i\right) \quad \text{(W/m)}, \tag{1}$$

where kp is the thermal conductance of the absorber at the average temperature of the absorber

$$\left(\frac{T_{pi} - T_{po}}{2} w/mk\right).$$

Convection heat transfer from absorber to glass envelop

The inner tube is the absorber and the outer tube is the glass cover. Between them there is a vacuum, approximately pressure near to Pa, in fact, that leads to negligible heat convection losses between the absorber and cover tube [21].

Radiation heat transfer from the absorber to the glass envelop

Thermal radiation transference from the outer surface of the metallic pipe to the inner wall of the glass cover is calculated as [19]:

$$Q_{\text{rad\_}p-g} = \pi D_o h_{r,p-g} \left(T_p - T_g\right). \tag{2}$$

The radiation coefficient between the receiver and the cover is given as [6,22,23]:

$$h_{r,p-g} = \frac{\sigma\left(T_p^2 + T_g^2\right)\left(T_p + T_g\right)}{\dfrac{1}{\varepsilon_g} + \dfrac{1-\varepsilon_g}{\varepsilon_g}\dfrac{D_o}{d_i}}. \tag{3}$$

The heat transfer rate from the outer surface of the pipe to the glass wall and from the glass wall to the ambience is equivalent, which implies:

$$A_g\left(h_{r,g-a} + h_w\right)\left(T_g - T_a\right) = A_p h_{r,p-g}\left(T_p - T_g\right), \tag{4}$$

$$T_p = \frac{A_g}{A_p}\frac{\left(h_{r,g-a} + h_w\right)\left(T_g - T_a\right)}{h_{r,p-g}} + T_g. \tag{5}$$

Conduction heat transfer through the glass wall

The thermal conductivity of the insulated material of the glass wall is very low relative to the high thermal conductivity materials. Thus, it is one of the reasons to neglect the conduction heat transfer through the glass wall.

Convection heat transfer from envelop to atmosphere

$$Q_{\text{conv},g-a} = h_w A_g\left(T_g - T_a\right), \tag{6}$$

where the convective heat transfer coefficient (hw) between the external surface of the glass cover and the ambient air is:

$$h_w = \frac{\text{Nu}_{\text{air}} k_a}{d_0}. \tag{7}$$

The Nusselt number can be estimated as [22,23]:

$$\begin{aligned}&\text{if } 0.1 < \text{Re}_{\text{air}} < 1000\\ &\qquad \text{Nu}_{\text{air}} = 0.4 + 0.54\,\text{Re}_{\text{air}}^{0.52}.\\ &\text{if } 1000 < \text{Re}_{\text{air}} < 5000\\ &\qquad \text{Nu}_{\text{air}} = 0.3 + 0.54\,\text{Re}_{\text{air}}^{0.6}.\end{aligned}$$

The dimensionless Reynolds number of the air over the outer wall of the glass covers is [19,23]:

$$\text{Re}_{\text{air}} = \frac{\rho_{\text{air}} d_o V_{\text{air}}}{\mu_{\text{air}}}. \tag{8}$$

Radiation heat transfer from glass envelop to atmosphere

Sky temperature

The effective temperature of the sky has been calculated from the following simple empirical relation [11, 19, 23]:

$$T_{\text{sky}} = T_a - \sigma, \tag{9}$$

$$Q_{\text{rad},g-a} = \varepsilon_g A_g \sigma \left(T_g^4 - T_{\text{sky}}^4\right). \tag{10}$$

Overall heat loss coefficient (U_L)

The heat loss from the collector in terms of an overall heat loss coefficient is expressed. The parameter of the overall heat loss U_L can be determined by [15]:

$$U_L = h_w + h_r + h_c\,, \tag{11}$$

$$U_L = \left[\frac{A_p}{A_g\left(h_{c,g-amb} + h_{r,g-amb}\right)} + \frac{1}{h_{r,p-g}}\right]^{-1}. \tag{12}$$

Overall heat transfer coefficient and factors

The next step is estimating the overall heat transfer coefficient between the surroundings and the fluid. The overall heat transfer coefficient (U_0) is given as:

$$U_0 = \left[\frac{1}{U_L} + \frac{D_0}{h_{fi} D_i} + \frac{D_0 \ln\left(\frac{D_0}{D_i}\right)}{2k_f}\right]^{-1}. \tag{13}$$

Rate of useful energy

The difference between the absorbed solar radiation and the thermal loss is useful energy that is given by [23, 24]:

$$Q_u = A_a \eta_0 I_b - A_p U_L \left(T_p - T_{am}\right). \tag{14}$$

After rearrangements of the above equation we get:

$$q_u' = F' \frac{A_a}{L}\left[\eta_0 I_b - \frac{A_p}{A_a} U_L \left(T_f - T_a\right)\right]. \tag{15}$$

Collector efficiency factor is given by:

$$F' = \frac{\frac{1}{U_L}}{\frac{1}{U_L} + \frac{D_0}{h_f D_i} + \frac{D_o}{2k}\ln\left(\frac{D_0}{D_i}\right)}. \tag{16}$$

The actual useful energy collected by the fluid is given by [15, 23, 24]:

$$Q_{act} = \dot{m} C_{pf}\left(T_{f,o} - T_{f,i}\right). \tag{17}$$

The outlet temperature of the HTF is calculated as:

$$T_{f,o} = T_{f,i} + \frac{q'_u}{\dot{m}C_{pf}}. \tag{18}$$

The thermal efficiency of the collector is:

$$\eta_{th} = F_R \left[\eta_o - \frac{U_L \left(T_{f,i} - T_{amb} \right)}{I_b C} \right]. \tag{19}$$

The exit fluid temperature $T(f,o)$ is:

$$T_{f,o} = T_{f,i} + \frac{\eta_{th} I_b A_a}{\dot{m}C_p}. \tag{20}$$

The mass flow rate through the parabolic trough solar collector and the total useful solar energy rate depend on the arrangement type between solar collectors. The parallel arrangements between parabolic trough collectors increase the total flow rate entering the system and the series arrangements increase the outlet temperature of the fluid or water with a constant mass flow rate. The following equation is used to estimate the total number of solar collectors:

$$N_c = \frac{\text{TSCR}}{\text{SPRPC}} = \frac{26\ \text{ton/h}}{1.89\ \text{ton/h}} = 14\ \text{collector},$$

where: TSCR is the total water consumption rate, SPRPC is the hot water production rate per collector.

A solar field land area is calculated as follows:

$$\text{solar field area} = \frac{A_{\text{aperture}}}{W} \times L_{\text{spacing}} \times (N_c - 1) + W,$$

where a solar field land area is the land area required for the solar collectors including the space between the collectors, and W is the aperture width (m).

Costs of solar process systems

The delivered price of equipment such as collectors, pumps and controls, pipes, deriving devices and central controllers, and all other equipment associated with the solar installation should be considered. The cost of the fuel should consider additional costs like transportation and tax.

Installed costs of solar equipment can be shown as the sum of two terms, one proportional to the collector area and the other independent of the collector area [25–27].

$$C_I = C_A A_C + C_E.$$

The life cycle cost of a parabolic trough heating system is determined from the investment cost, the present value of maintenance (3%) and the pumping cost distributed over the life areas follow [5, 16]:

$$L_{cc} = C_I + C_m \frac{1}{i} \left(1 - \frac{1}{(1+i)^n} \right). \tag{21}$$

Table 3. Cost estimations for parabolic trough solar collector and oil

Parameter	**Units**	**Total**
Interest rate (%)	7	7
Inflation rate (%)	10.4	10.4
Life time (year)	25	25
PTC direct capital cost ($/m^2)	200	2 289 000
Indirect cost (%)	25	572 729.83
Fuel cost ($/Kg)	0.4577	–
Pump ($/piece)	705.88	1411.76
Fuel consumption (ton/annualy)	8 500	–
Flex.hos ($/ton)	400	53.7
Elbow ($/piece) (16)	1.56	24.96
Pipe ($/ton) (85 m)	350	428.917

The life cycle saving of a solar PTC is the energy cost saved due to the replacement of conventional energy by solar energy.

Annual energy saving is:

$$E_{\text{save}} = f_{\text{save}} \times h_r Q_a .$$

The life cycle saving of energy is calculated by:

$$L_{\text{save}} = P_e E_{\text{save}} \frac{1+i_f}{1-i_f} \left[1 - \left(\frac{1+i_f}{1+i} \right)^n \right] . \tag{22}$$

The life cycle cost saving of the solar collector during its life time is calculated by:

$$L_C = f_{\text{save}} \times m_f \times LHV \times h_r \times C_f .$$

Payback period of the plant is calculated by:

$$N_P = \frac{\ln \left[\dfrac{C_l i_f}{E_{\text{save}} C_{Fl}} + 1 \right]}{\ln \left(l \cdot i_f \right)} . \tag{23}$$

4. Result and discussion

For the present study, the heat flux of a parabolic trough collector is evaluated. Annual solar radiation calculation results for beam diffuse and global radiation have been obtained using a MATLAB code, shown in Figure 6.

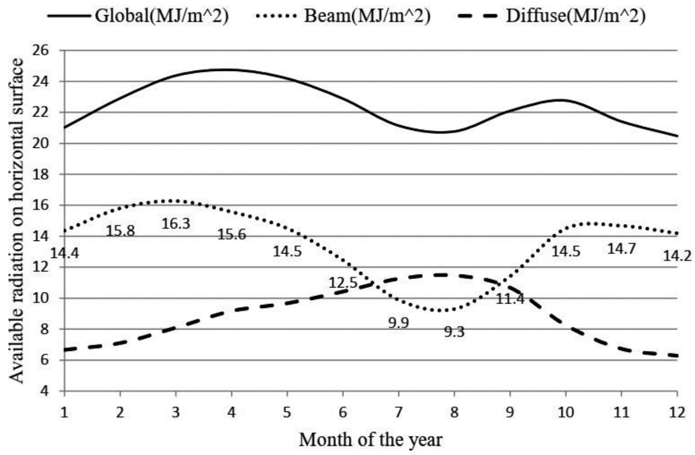

Fig. 6. Estimated monthly average daily radiation on horizontal surfaces

As can be seen in the graph, the solar radiation reaches its maximum in March, the value is close to 16.63 MJ/m^2 and the minimum solar radiation occurs around 9.82 MJ/m^2 in August. The average direct normal radiation is 13.97 MJ/m^2 throughout the year.

An analysis of the hourly solar beam radiations, HTF outlet temperature and the thermal efficiency for the given location was carried out and shown in Figure 7.

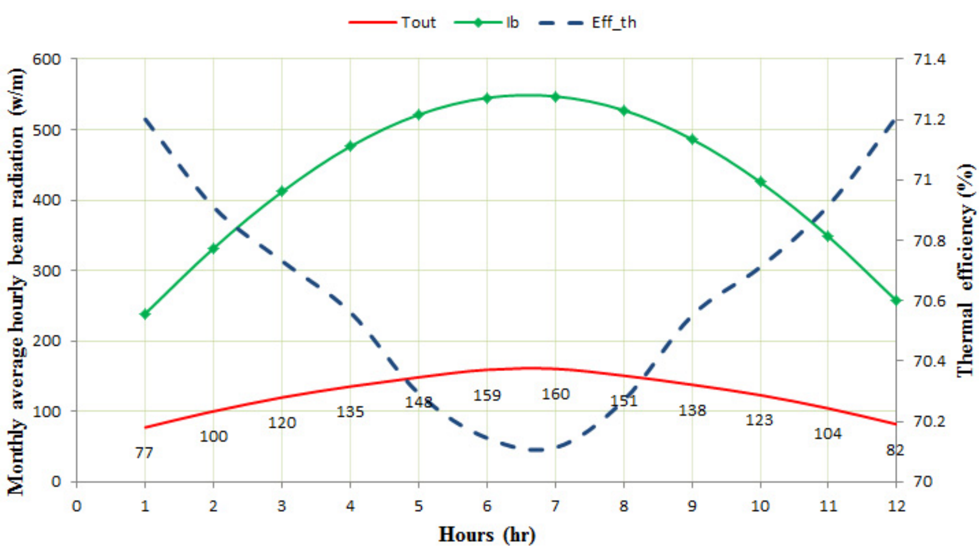

Fig. 7. Estimated hourly thermal efficiency and heat transfer fluid outlet temperature

The solar collector HTF outlet temperature increases gradually with time until reaching peak values. The outlet temperature of water also increases linearly in the range of 77.2 to 160.4°C.

The thermal efficiency of the solar collector decreases with time, which varies from 7:00 am to 1:00 pm, the corresponding value of the PTC thermal efficiency varies from 71.2 to 70.11%.

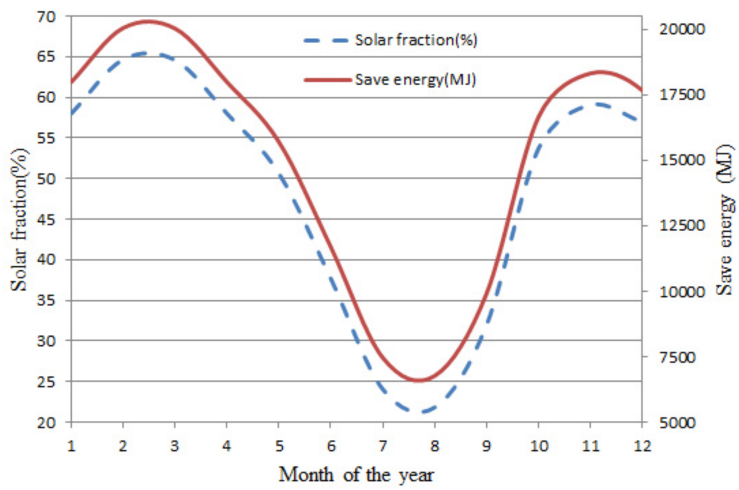

Fig. 8. A diagram of variation of solar fraction and saving of energy (MJ) with each month

As shown in Figure 8, the maximum and minimum value of the monthly average daily total solar fraction was observed to be 64.6% and 21.8% in February and August, respectively, while the maximum and minimum saved energy due to the PTC system integrated with the conventional oil boiler was recorded to be 20047.5 MJ/day and 6766.7 MJ/day for the same months.

Solar fraction is directly proportional to the solar field area but the average solar fraction of the system is satisfied in 37.86%.

The following table shows the final analysis results of solar parabolic trough collectors integrated with conventional oil boiler water heating systems.

Table 4. Summary of annually calculated result of solar parabolic trough collector integrated with conventional oil boiler water heating systems

	Annually produce (before)	Annually emission (reduced)	Emission reduction (Kg/h)
CO_2 (Kg)	2.649E7	3.29E6	2.77
SO_2 (Kg)	255E3	31.678E3	0.7967
	Annually used	Annually saved	Saved cost ($)
HFO (ton)	8 500	1 055.9	483 005
Energy (MWh)	91 699.3	11 391.4	
Solar energy unit price	Payback (year)	Solar fraction (%)	Fuel saved (Kg/h)
0.0088 ($/kWh)	4.85	37.86	26.6/coll

As shown in Figure 9, the unit price and the life cycle cost of solar parabolic trough collector systems varies throughout the life cycle year.

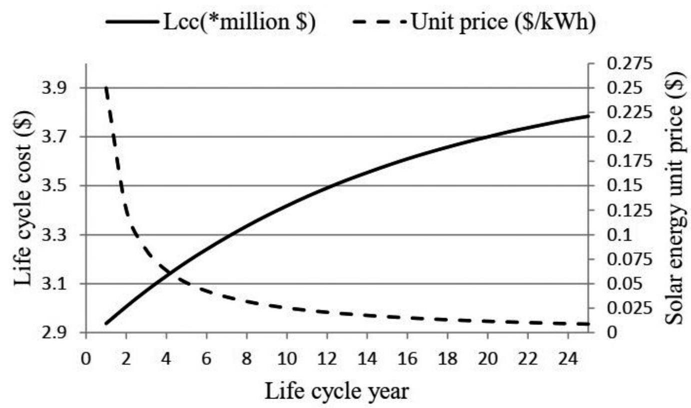

Fig. 9. Unit price of the system

According to Dejen [27] studies in Addis Ababa Tikur Anbesa Hospital, the payback period of a Luz-2 solar collector (uses 47 collectors) is 7 years at the earliest, but the present result shows that the maximum payback period is 5 years with the same HTF outlet temperature and different location, which indicates that an ET150 solar PTC hot water generation system is more feasible.

5. Conclusions

The design and evaluation of a solar parabolic trough collector system integrated with a conventional oil boiler have been done for hot water production for industrial application. The total cost of the proposed hot water generation system is estimated at $2 863 649.17. This reduces heavy fuel oil consumption, operating cost, improves the working condition and addresses environmental problems. The technology implemented will create awareness among the workforce towards clean and renewable energy systems and also will lead to reduction in CO_2, CO and SO_2 emissions due to decrease in overall fuel consumption throughout the year. It is observed that the maximum possible reduction in CO_2 and SO_2 emissions are 82.77 and 0.7967 kg/h, respectively. Hence, the result shows that a parabolic trough solar collector (ET150) is found to be more economical with a payback period of 5 years relative to conventional oil boilers. The result of this work shows that the solar fraction of a parabolic trough collector field accounts for 37.86% of the daily energy consumption and saves 1055.9 tons of heavy fuel oil each year, with annual cost saving reaching $483.005.

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