Economically realizable solar process heat solutions in Ethiopian textile industry with demand derived from artificial neural network data

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Abstract: - The possibility of augmenting industrial process using solar and thus reach at an economically realizable solution nictitates knowing the energy demand at a relatively high accuracy. An accurate energy use prediction gives relevant information to make sound decisions such as appropriate technology selection, sizing and performance validation of solar process heat integration. Furthermore, an accurate energy prediction would have huge impact in assessing the economic feasibility of the chosen technology. In this paper, textile industry's thermal energy demand is derived from an artificial neural network (ANN) model. The outputs of this derived thermal model is then coupled to a sun and solar collector steady state model to arrive at an economically realizable solar process heat solutions in a textile industry. To demonstrate the validity and practicality of the proposed solution, a case study was conducted on an Ethiopian textile industry. Payback periods that span from 2.1 to 9.1 years are identified for the various solar collector technologies without subsidy. The payback period is relatively high for parabolic through collector (PTC) that exceeds the typical industry standard of 3-5 years which might create realization barrier. However, as done elsewhere, proper policy to support such renewable solutions would help for the uptake of this technology in Ethiopian industries.

Key-Words: - Artificial neural network (ANN), solar process heat, sun model, solar collector, economically realizable, payback period, textile industry.

1 Introduction

Globally and particularly in developing countries, industries have faced a serious fuel shortage as a result of energy crises. Consequently there is now a clear understanding for energy efficiency improvement need triggered by the escalating energy price. Fig. 1 depicts the industrial energy consumption trend for 2017 and beyond from non-renewable energy sources [1].

This observed trend has set an impulse for energy conservation measures in order to decrease the energy cost. Advancement in technology can lead to this reduction. While it is true that this technology advancement has the potential to effectively reduce energy consumption, it's associated huge capital investment is beyond the reach of many industries in developing countries. Thus demand side energy management, modification of industrial processes and use of alternative energy sources remains as a plausible solutions [2]. However due to the dynamic energy requirement and economic feasibility, a significant improvement in energy conservation maybe possible through the latter option.

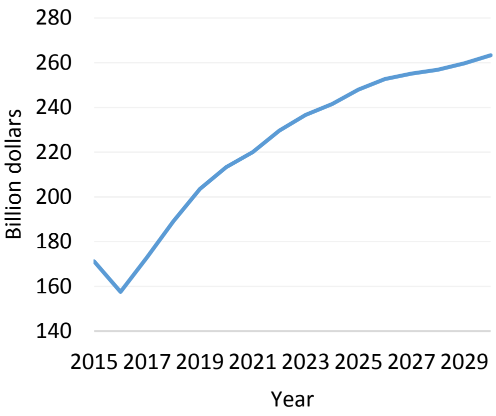


Fig. 1 . Non-renewable energy expenditures in industry (billion 2016 dollars) after [1].

In developing countries where there is a prevalent energy shortage marked by a slow rate of economic growth, utilization of alternative source of energy might be effective. Moreover, given the presence of many low-to-medium industrial processes in this regions, a significant opportunity for solar process heat augmentation exists [3]. One such industry that holds this promise is the textile industry [3-4]. Low absolute energy demand per plant, varying temperature levels of process heat utilization, and high energy cost (especially in times of escalating fuel price) characterizes the textile industry [5]. On the other hand, the uncertainty of available solar radiation and the dynamic energy demand is a challenge for the integration of solar technologies to industrial production processes. Specifically, textile industry's thermal energy determination is difficult since most process involve heating vats and tanks by direct steam injection; and actual energy consumption depend on input fabric, methodology of temperature control, machine type and other process dependent variables [5-6]. In this work a novel method of energy use determination derived from artificial neural network data is utilized. Subsequently, an economically realizable solar process heat solution is investigated for textile washing, bleaching, dyeing and boiler preheating using solar collectors and parabolic through. Data for the case study are from measurements taken at the chosen factory and some are from the solar Keymark [7], SHIP plants [8] and chs India [9] database. The following section will illustrate the aforementioned points by first discussing the Ethiopian textile industry's energy situation then elaborate on various energy generation and demand model and finally demonstrate a case study on economically feasible solar process heat solutions. The approach used for finding economically realizable solar process heat solution in the chosen Ethiopian textile factory is depicted in Fig. 2.

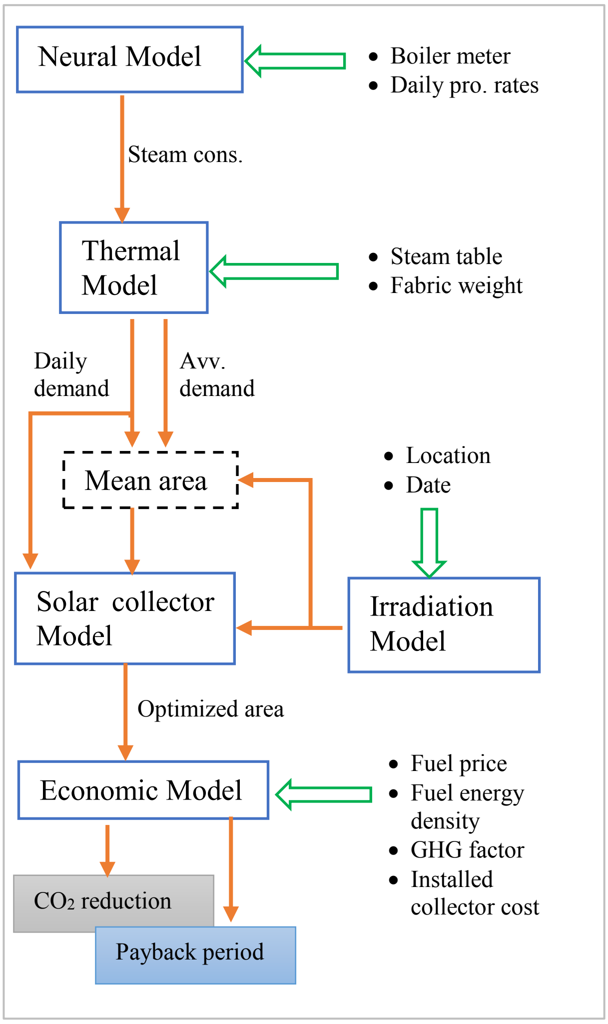


Fig. 2 methodology for economically realizable solar process heat implementation in Ethiopian textile industry.

2 Energy Situation in Ethiopia

As of 2014, Ethiopia's main energy supply is biomass that constitute 92.4% of the total energy consumption followed by oil and hydropower with 5.7% and 1.6% respectively [10]. Out of the total 40,000 GWh final energy produced, 92%, 4%, and 3% are consumed in domestic appliance, transport and industry [11]. Electricity in the country is mainly derived from hydro power (96 %) followed by wind energy (4 %), of which around 11 % is exported [11]. Despite the heavy dependence on traditional fuels and low industrial energy consumption, the 10. 8% annual economic growth since 2005 is one of the fastest growing in the world [12]. This fast trend of economic growth would result in expected rise of energy demand by a rate of 10 - 14 % per year till 2037[13].

As can be seen from table 1, the country is endowed with energy resources but small percentage of the potential is realized.

Table 1 Ethiopia's energy resource potential (after: [13-14])

Energy resource	Potential	Utilized	utilized
Hydropower, MW	45,000	2,100	4.7%
Solar, MW	52	5MW, PV	9.6%
Wind, GW	10000	720	7.2%
Geothermal, MW	5-10,000	7.3	<1%
Coffee residues, tons/year	214,299		
Cotton stalk, tons/year	88,922		
Prosopis juliflora, ha/year	700,000		
Bamboo waste, ha/year	1,000,000		
Natural gas, Billion m3	113	-	0%
Coal, Million tons	>300	-	0%
Oil Shale, Million tons	253	-	0%

As shown in Fig. 3, utilization of solar energy can be quite effective in Ethiopia due to the fact that most regions in the country experience a more or less uniform solar radiation with average daily values of 5.2 kW/h for 5-8 hours for most of the year [15]. As can be seen from Table 1, the solar generation focus, though still small, is on PV for electricity generation. However, as in other developing countries, there are ample opportunities for solar process heat integration for various off-grid industrial applications [3-4].

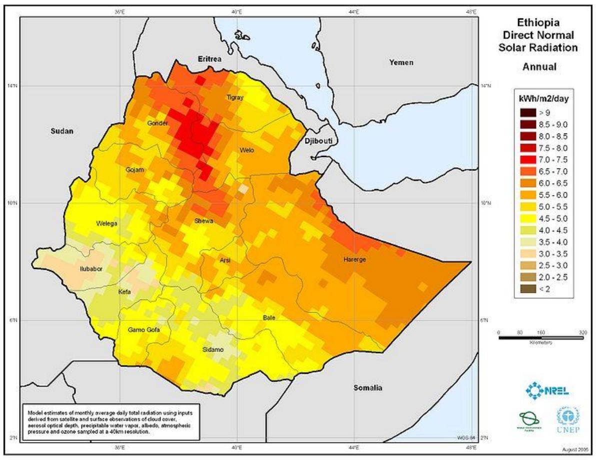


Fig. 3 Ethiopia's annual direct solar radiation potential after [15].

3 Overview of the Ethiopian textile industry

Textile industry has always held a central attention in all of Ethiopian industrial policy and development phases. In 2011 ranking of top ten manufacturing exports in the country, share from textile and appeal was 11.49% of the total [16]. There is a growing trend in the expansion of new textile industries and capacitating the existing one. One indication is the fact that Ethiopian export value of textile industry showed a 55% growth in just one year from 2010 to 2011[16]. As of 2010, contribution of Ethiopian textile industries in terms of GDP and industrial output by value terms is 1.6% and 12.4% respectively [17]. Table 2 and Fig.4 show the distribution of these textile sectors in the country and their production capacity.

Most Ethiopia's textile processing units use non-fossil boilers which consume furnace, diesel or coal as a source of energy with the exception of two factories which partially run electric boilers. Currently about 8,112,000 tons of coal, 10,256,803 liter of furnace oil are utilized every year by the sixteen processing units in the country. In addition about 70,607,459 kilowatt of power and 35,344,417 m^3 of water was consumed by the sub-industry in 2011[18].

High share of heat demand in the low-to-medium temperature range is found in textile factory. This heat demand can be complemented using different solar collector technologies [3-4]. The following sections of this paper will take on this concept to further expand it to arrive at an economically realizable solar process heat solution in existing Ethiopian textile industry. It will do that by first deriving heat demand from an artificial neural network model [19]. Next appropriate solar technology mapping with associated collector model will be done. Finally an economic analysis together with the co_2 emission reduction potential of the modeled solar collector technologies will be addressed.

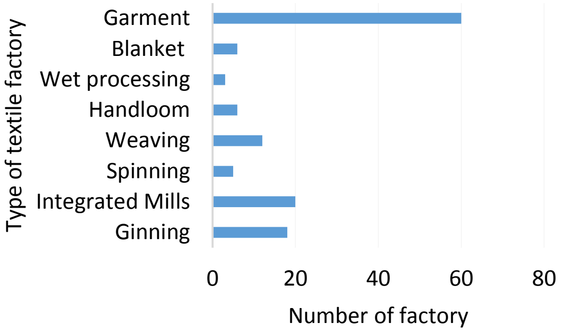


Fig. 4 Textile sector distribution in Ethiopia

Table 2 annual textile production in Ethiopia

Textile product	Annual prod.
Yarn (thousand tones)	102
Woven fabric (million meters)	207
Knitted fabric (million kilograms)	50
Woven garment (million pcs)	91

4 Energy generation and consumption models

4.1 Thermal demand model

The identified suitable solar process heat in textile industry are bleaching, dyeing and washing [3-4]. Even though steam is used for these industrial processes, actually the temperature requirement is below 100°C. Steam is used because it is an effective way of generating and transporting thermal energy. This implies that it is possible to use appropriate solar technologies to supply hot water to these industrial processes. However, before sizing of these solar technologies, the thermal demand has to be determined as accurately as possible. Hence, for this task, the previous work of the authors [19] is used. The methodology uses artificial neural network model to predict the steam consumption of these processes given the daily production rates and steam output as training data. Fig. 5 illustrates the methodology used.

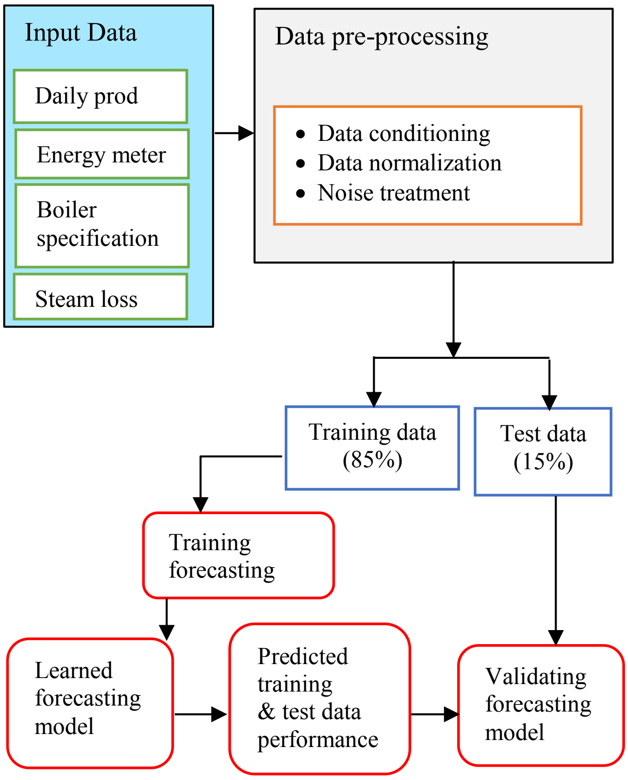


Fig. 5 proposed neural model for steam consumption prediction

The implemented neural model is a variant of the basic back propagation (BP) algorithm known as resilient gradient method. Fig. 6 shows the neural model used. In this algorithm, the neural weight is adapted as

$$w_{ij}(t+1) = w_{ij}(t) + \delta w_{ij}(t) \qquad (1)$$

Where wij is the neural network weight connection from j to i and δwij is the weight update value which is given by

$$\delta w_{ij} = -sign\left(\frac{\partial E}{\partial w_{ij}}(t)\right)\delta_{ij}(t) \qquad (2)$$

Where sign (.) is either +1 or-1 depending on whether its argument is positive or negative and E is the neural network error.

In equation 2, δ_{ij} is initiated to a constant value δ_o and is updated for each weight individually as given in [19]. Table 3 depicts the result of the trained neural model.

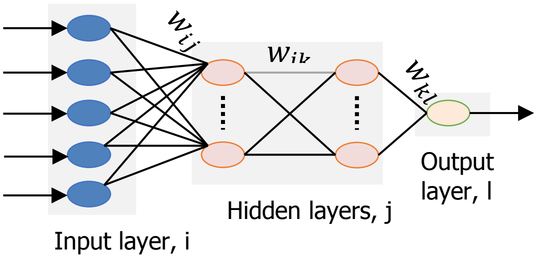


Fig. 6 Multi-layer neural network model

Table 3 Textile steam consumption (kg/kg) after [19]

Industrial process	Steam consumption (kg/kg)
Bleaching	0.6-0.9
Washing	0.7-1.1
Calendaring	0.8-1.4
Jigger	1.2-4.5
Sizing	7.8-9.0

The steam consumption in Table 3 has a range of values (due to the random weight initialization of the neural network and the stochastic steam distribution loss). To get a relatively precise neural output, the steam distribution loss is kept constant and the network response is analyzed to see where the majority of the input data lie in the output space. Fig.7 illustrate the result for the jigger machine. From this, it is clear to see that the mean steam consumption value is around 1.8 kg. Similar analysis for the bleaching and washing machine result in mean steam consumption values of 0.9 and 1.0 kg.

Next step is to find the equivalent steam energy transferred to the various vats and tanks for the bleaching, washing and dyeing textile processes. For that, a heat balance is used where the initial heat content in the tank plus the extra heat supplied by the steam amounts to the final process heat content. The heat balance for the processes can be described by:

$$mh_1 + m_s h_g = (m + m_s)h_2 \qquad (3)$$

Where,

- m and m_s are the initial mass of water and mass of steam injected in kg.
- $h_1$and h_2 are the heat in water at the initial and final temperature in kJ/kg, and
- hg is the total enthalpy of steam supplied, kJ/kg

Equation 3 can be written as

$$m_s(h_g - h_2) = m(h_2 - h_1) \qquad (4)$$

Where the right hand side of this equation is equivalent to the total heat delivered to the process. Thus the net thermal energy delivered, Q_{del}, can be determined from

$$Q_{del} = m_s(h_g - h_2) \qquad (5)$$

In the above equation the heat enthalpy can be found from standard steam table at the given steam supply pressure which in this case is about 2.6 bar.

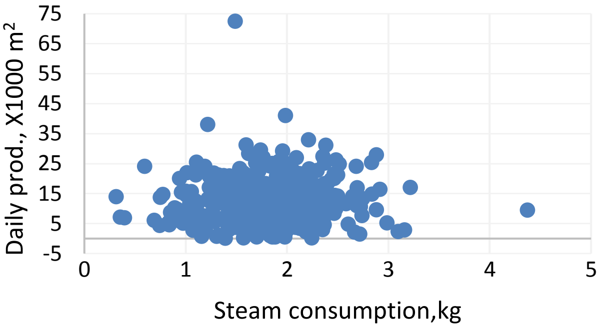


Fig. 7 scattered plot of stem consumption vs daily production rate of textile Jigger machine

4.2 Solar model

The maximum possible sunshine duration S_0 can be calculated as [21]

$$S_o = \frac{2}{15} arccos(-\tan(\varphi)\tan(\delta) \qquad (6)$$

Where φ and δ are latitude of the location and declination angle. The latter is given by

$$\delta = 23.45^0 sin\left(\frac{n + 284}{365} x360^0\right) \qquad (7)$$

The direct normal irradiance, Ib, can be approximated by [22]

$$I_b = Aexp(-\frac{P}{P_o}\frac{B}{\sin(\beta_1)} \qquad (8)$$

Where the term, $\frac{P}{P_o} = \exp(-0.0000361h)$ quantify the relative pressures to the altitude, h. The coefficients A and B are extraterrestrial solar intensity (W/m2) and atmospheric extinction whose values are given in [22]. β_1 is the solar altitude angle determined from the relation

$$\sin(\beta_1) = \cos(\varphi)\cos(\delta)\cos(H_a) + \sin(\varphi)\sin(\delta) \qquad (9)$$

Where Ha is the hour angle calculated as

$$H_a = \frac{(solar\ time\ - 720)mins}{4\,{}^{min}/_{deg}} \qquad (10)$$

Solar time designates the apparent angular motion of the sun across the sky and is different from clock time. Thus conversation from clock time to solar time as given in [20] is necessary for the solar calculations.

Finally the diffused radiation is given by

$$I_{coll,d} = CI_b\left(\frac{1+\cos(\beta_2)}{2}\right)$$

Where C and β_2 are the ratio of diffuse to the normal irradiation and collector tilt angle [22].

4.3 Solar collector model

Before modeling and optimal sizing of the solar collectors, a collector technology mapping for the textile boiler preheating, bleaching, jigger and washing processes were consulted from literature. Accordingly, flat plate solar collector (FPC), evacuated tube collector (ETC), and parabolic through collector (PTC) were identified as appropriate solar technologies for the textile industry. The rest of solar technologies such as linear Fresnel are not chosen due to the economics and their large installation area requirements.

The steady state thermal energy, Q, collected from flat plate and evacuated tube collector can be represented as:

$$Q(t) = \eta_0 k_{\theta b}(\theta) I_b + \eta_0 k_{\theta d}(\theta) I_d - a_1(T_{coll} - T_{amb}) - a_2(T_{coll} - T_{amb})^2 \qquad (11)$$

Where

- η is collector efficiency,
- I_b and I_d are the direct and diffused solar radiations with associated incident angle modifiers $k_{\theta b}$, $k_{\theta d}$ respectively
- a_1 and a_2 heat loss constants in W/m^{2}K and W/m^{2}K^2 respectively
- The diffused angle modifier is considered zero in flat plate collector model.

The steady state useful thermal energy, Q, gained by the thermal heat transfer fluid of a parabolic through solar collector is given by

$$Q = F_R A_a \left[S - \frac{U_L}{C}(T_{in} - T_{amb})\right] \qquad (12)$$

Where

- A_a is the shading factor
- S is the absorbed solar energy, W/m^2
- F_R is efficiency of receiver tube
- C is the concentration ratio
- U_L is the thermal loss coefficient

Here, the concentration ratio is given by

$$C = {}^{(w_a - D_{oa})}/_{\pi D_{oa}} \qquad (13)$$

Where, w_a and D_{oa} represent the aperture area and outside diameter of the receiver tube of the parabolic through collector. The absorbed solar energy is given by

$$S = \eta_o I_b \qquad (14)$$

Where, η_o and I_b are the optical efficiency and solar radiation respectively.

Parameters for the selected collectors are from the solar key mark database for the flat and evacuate tube collector [7]. The solar keymark database list only collectors which have been tested according to the standard EN12975. For the parabolic trough collector the model parameters were taken from Indian government database for concentrated solar collector heat (chs India) [9].

5 Economic analysis

In the economic analysis, consideration is given for the replication potential of solar in displacing furnace oil (FO) in existing steam boilers. As discussed in the overview section, except two textile factories, the majority obtain their thermal industrial need either from coal or FO boilers. Due to the volatile and escalating nature of FO in the world market, high replication potential of solar is anticipated for this fuel. The methodology used as depicted in Fig.2 is illustrated by the following steps:

1. Determine average heat demand form daily production rates, steam consumption and derived thermal model (Section: 4.1).
2. Calculate the average solar irradiation on the site (Section: 4.2).
3. Analyze the mean solar collector area using steps 1 and 2 above and including the loss.
4. Optimize the solar collector area using the steady state collector models and the daily solar irradiation values (Section 4.2, 4.3).
5. Determine solar energy delivery form this optimized system and calculate the fuel and emission saved by the solar energy
6. Calculate investment cost and determine the economics of the solar system by calculating the payback period.

Table 4 illustrated all parameters used for the economic analysis.

Table 4 Economic data after [8-9, 23-25]

Pipe and storage loss, %	20	
Weight of fabric, kg/m^2	0.16	
Steam pressure at load, bar	2.6	
FO energy content, kwh/liter	9.87	
FO co$_2$ content, kg/liter	2.52	
FO cost, €/liter	0.48	
Collector cost, €/m^2	FPC	111.11
	ETC	171.66
	PTC	287.3
Mean daily production, m^2	Bleach	10,691
	Jigger	9,149
	Wash	11,664
Mean steam consumption, kg/kg fabric	Bleach	0.9
	Jigger	1.8
	Wash	1.0

6 Results and discussion

The chosen Ethiopian textile industry is Bahir Dar textile factory located at 11°36′N 37°24′E. The factory's key features which are relevant for this work are listed in Table 4.

The optimized neural model performance for the steam consumption in the chosen factory is depicted in Fig.8-10. As can be seen from these figure, the performance is very good as the correlation coefficient (R) is close to one and the mean square error(MSE) is around 0.053. As can be seen from Fig. 9, the MSE fluctuated during the first half of the iteration time but it eventually settled down to a stable value. Moreover, from Fig.10 it is possible to see that the trained neural model closely resembles the actual test data.

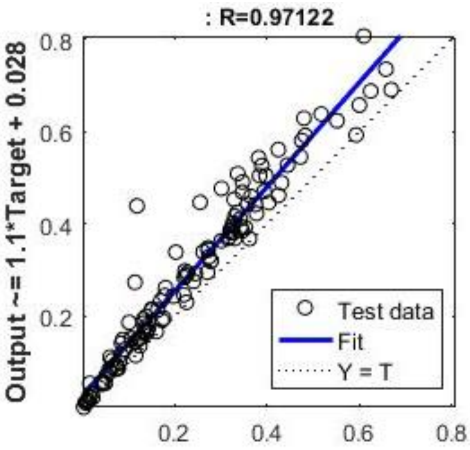


Fig. 8 R value for the optimized neural model

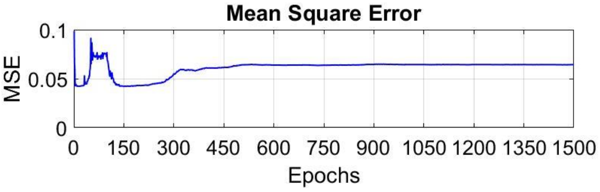


Fig. 9 MSE of the optimized neural model

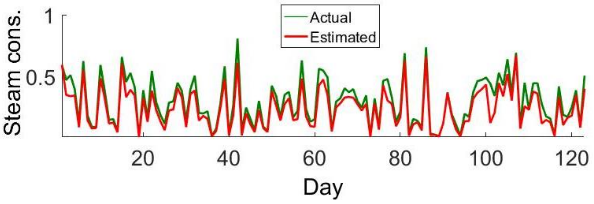
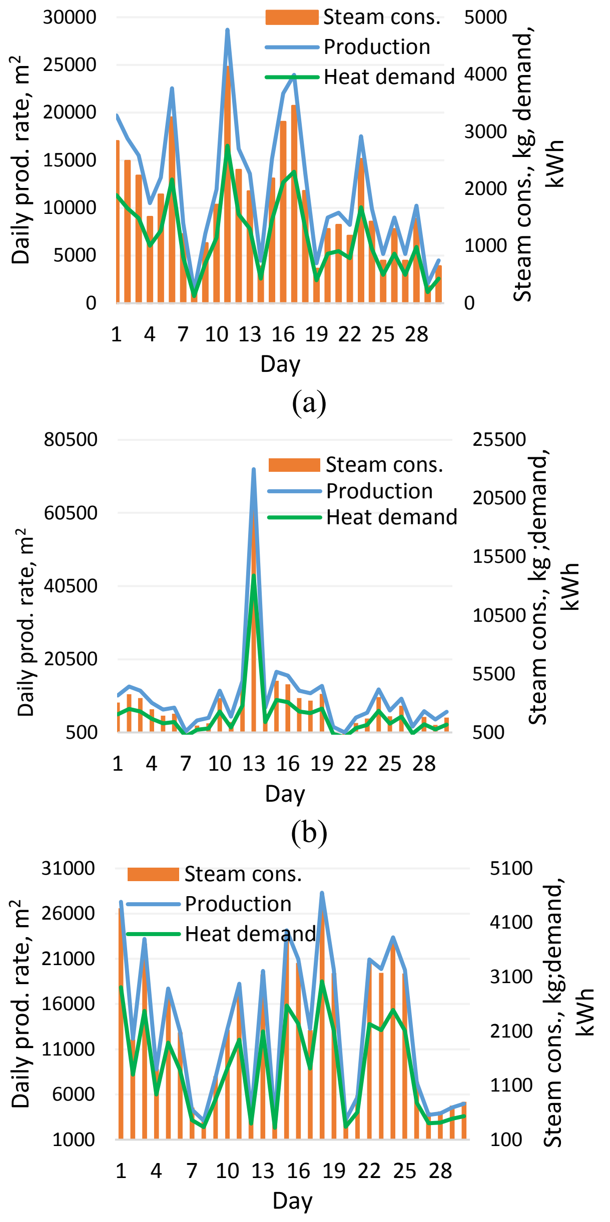


Fig. 10 actual and trained neural model output using test data

Next, the textile bleaching, jigger and washing machine heat energy demand which is derived from the above neural model is shown in Fig. 11

Two interesting thermal energy demand variation patterns are observed with in the machine and among the machines. These variations have direct implication for demand side energy management in the textile factory. Load shaving and shifting schemes that match the solar energy generation can be implemented. The result of this would be increased solar energy utilization through decreased storage loss that would improve the solar gain of the system. Moreover, this scheme helps the textile industry to have an economical solar storage capacity that is able to respond to a dynamical load which is in line with the solar energy generation.



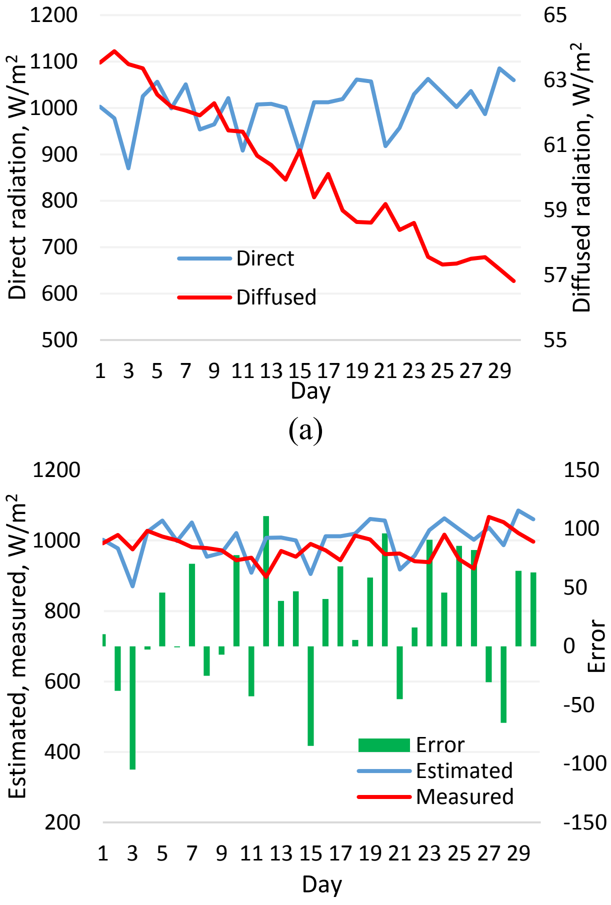
(a)

(b)

(c)

Fig. 11 derived textile process thermal load (a) bleaching; (b) jigger; (c) washing that shows the potential for demand side energy management for 11/2016

To determine the daily solar collector energy outputs, a sun model from solar calculations was used. The result of this s model is depicted in Fig. 12 for November 2010. This model was verified against measurements from the Webel Solar (Grid) 3960Wp project using CMP11 Pyranometer in Bahir Dar University. Fig. 12(b) depicts actual and estimated values with the associated error for the same month. As can be seen from this figure, most of the estimated values deviate from the actual measurements with in a ±50 W/m^2 range. This indicate that the implemented solar energy forecasting method is suitable to be used in the solar collector models. Fig. 13 summarizes the yearly solar irradiation trend for the sun model.



(a)

(b)

Fig. 12 (a) sun model direct and diffused irradiation output for 2016/17; (b) estimated and measured irradiation values for October 2010

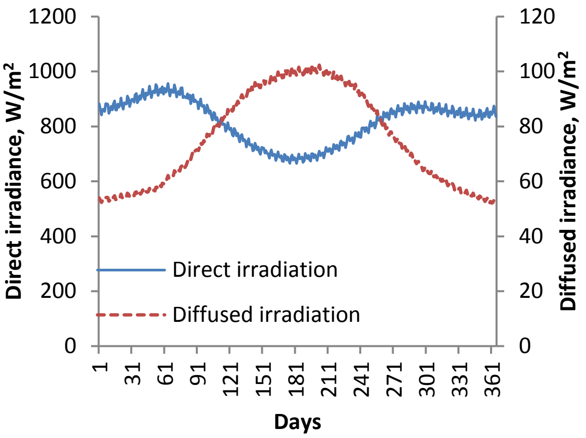


Fig. 13 yearly estimated direct and diffused solar irradiation trend.

Before optimal sizing of the solar collectors, a collector technology mapping for the textile boiler preheating, bleaching, jigger and washing processes were consulted from Literature. The selection criteria use the textile process temperature requirement and the solar collector energy efficiency. Accordingly, flat plate solar collector (FPC), evacuated tube collector (ETC), and parabolic through collector (PTC) were identified as appropriate solar technologies as given in Table 5. Subsequently, simulations were performed to find the optimal collector size for these specific textile thermal loads. Fig. 14 shows the daily collector energy output trends for the various solar technologies for 10/ 2016.

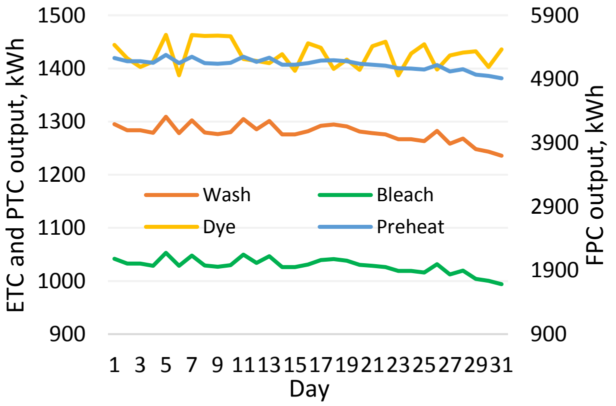


Fig. 14 daily solar energy output from FPC, ETC and PTC for October, 2016.

The optimized collector area values and data given in Table 4 are used to carry out the economic analysis and associated co2 emission reduction potentials. The outcome of this analysis is depicted in Table 5.

Table 5 economic and co$_2$ reduction potential of identified solar process heat solutions

	Boiler preheat	Bleach	Wash	Dye
Collector type	FPC	ETC	ETC	PTC
Collector area, m^2	1,954	366	455	1,056
Solar fraction, %	63.7	75.3	75.3	78.2
Payback period, years	2.1	3.2	3.2	9.1
Co$_2$, ton/year	517	114	142	202

As can be seen from Table 5, payback periods that span from 2.1 to 9.1 years were identified for the various solar collector technologies. The payback period is relatively high for PTC that exceeds the typical industry standard of 3-5 years which might create realization barrier. However, as done elsewhere [26], proper policy to support such renewable solutions would help for the uptake of this technology in the industries.

7 Conclusion and outlook

This work focused on the feasibility of solar process heat solution in textile industries in Ethiopian context. The work comprises three models and an economic analysis. The first model is about determining the thermal energy requirement which was derived form an artificial neural network model based on the previous work of the authors. The second model is a solar model which was based on a solar calculations. The output of this model was compared to actual measurements at the chosen textile factory. The result showed acceptable performance that indicated its potential for use in solar simulations. Following these, a steady state solar collector model was formulated for FPC, ETC, and PTC. Lastly, economics of the proposed solution based on the payback period and emission reduction potential was carried out.

The investigation carried out in this work showed that solar integration for boiler feed water, bleaching and washing industrial process has a low payback period that is below 3.5 years. Particularly, FPC, due to its mature technology and low market price, has the lower payback period of about 2.1 years. This shows its potential use for solar preheat solutions. On the other hand, the anticipated payback period for PTC is slightly higher than 9 years indicating the barrier such technology would find in industrial applications. However, with favorable policy from the government, it is expected that this technology would serve as an industrial heat solution for augmenting the Ethiopian industrial process.

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