INVESTIGATION OF SOLAR WATER HEATING SYSTEMS FOR INDUSTRIAL APPLICATIONS IN NORTHERN ETHIOPIA

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1. Abstract

Low temperature water heating for industrial process is one of the ideal applications for solar energy. The paper looks at an investigation of the feasibility of solar water heating systems for industrial applications in Northern Ethiopia. The study was conducted at four factories, namely, a tannery, a particleboard factory, a textile factory and an edible oil factory. The factories use hot water for different processes for the production of their products. The daily hot water consumption is high but most of the processes in the factories require low temperature hot water (<80^0C). The current source of energy for water heating at the factories is mainly furnace oil.

The first part of the study was to conduct measurements on the hourly hot water demand in each factory. The processes demanding hot water, the temperature and volume needed were studied to establish the heat load in each factory. In summary the hot water demand for each factory was: a) Tannery, 141 m^3/day, 35 – 65 ºC, b) Textile, 49 m^3/day, 60 - 80 ºC, c) Edible oil, 24 m^3/day , 70 – 90 ºC, d) Particleboard, 7 m^3/day , 40 – 55 ºC. The hourly hot water demand was found to be mainly during the day time having peak demand around noon.

The second part is on study of the solar energy availability. Ethiopia is one of the countries endowed with plenty of sunshine. However, long term solar radiation data is scarce. Hence, study on solar radiation estimation models was conducted. Data from solar radiation instrumentation recently installed at Mekelle University was used to compare with results of the estimation models. Measurement data were available for one year (July 2010 - June 2011). The comparison indicates that the estimated monthly average solar radiation is close to the measured data for the months of January to April and September to December. For the rainy months of June until August the estimation was higher than the measured data.

The third part is the overall system design and sizing based on the hot water demand of part one and the solar radiation data of part two. Flat plate solar collector with unit collector area of 2 m^2, aluminum absorber, eight copper tubes, single 4 mm thick glass and mineral wood insulation was selected as it is appropriate for such industrial applications. The system sizing results for each factory are: a) Tannery, number of collectors 960 and overall space requirement 3200 m^2 b) Textile, number of collectors 384 and overall space requirement 1500 m^2 c) Edible oil, number of collectors 240 and overall space requirement 800 m^2 d) Particleboard, number of collectors 48 and overall space requirement 300 m^2. All factories have plenty of space to accommodate the solar collector systems.

Finally economic analysis for the implementation of the solar water heating systems was conducted. The current furnace oil cost is estimated at 9 USD cents per kWh. The analysis results on solar water heating indicate that it will cost the factories about 5 USD cents per kWh and the payback period will be 6 – 7 years. In addition to the advantage of using clean energy, the factories can save their energy cost up to 30% by implementing the solar water heating systems.

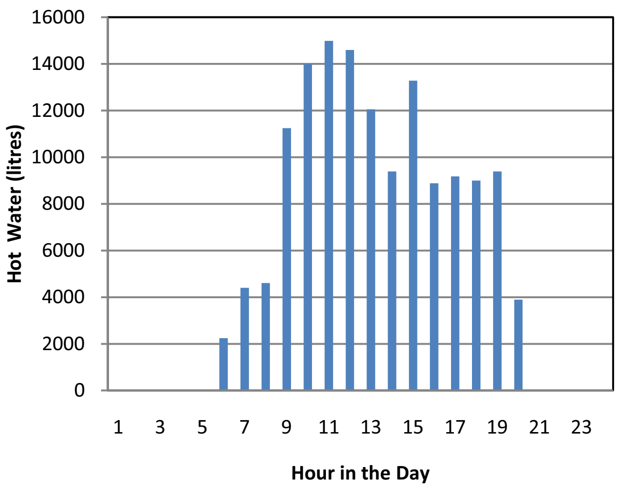
2. Hot Water Demand in the Factories

Many developed countries in the world are applying solar energy for industrial processing. The majority of the projects on solar industrial process heat plants operating worldwide are in the sectors of food and beverage, textile and tannery (IEA, 2004). Developing countries like Ethiopia with plenty of solar energy have yet to harness the potential. With the aim of studying the feasibility of solar water heating for industrial processing, four factories situated in North Ethiopia were selected. The study was conducted at four factories, namely, Sheba Tannery (ST), Maichew Particleboard Factory (MPF), Bahirdar Textile Factory (BTF) and Ashraf Edible-oil Factory (AEF). The factories use hot water for different processes for the production of their products. The hourly hot water demand in each factory was studied as there was no recorded data available. The study was made during regular operation of the factories for one week and includes identifying: i) process demanding hot water, ii) working temperature of the process, iii) hourly consumption of hot water and iv) current source of energy for heating water. The summary of the hot water demand study is shown in Table 1. In summary the hot water demand for each factory was: a) Tannery, 141 m^3/day, 35 – 65 °C, b) Textile, 49 m^3/day, 60 - 80 °C, c) Edible oil, 24 m^3/day , 70 – 90 °C, d) Particleboard, 7 m^3/day , 40 – 55 °C. The energy needed to heat the amount of water per day is estimated to be 14 GJ, 8 GJ, 6 GJ and 1 GJ for the Tannery, Textile, Edible Oil and Particleboard factories, respectively.

Table 1: Summary of the processes and hot water demand in each factory.

No.	Factory	Process	Working Temperature (°C)	Consumption (m^3/day)	Current Source of Energy
1.	Sheba Tannery	Skin Tanning Skin Re-tanning Hide Tanning Hide Re-tanning	35 50 40 65	18.4 66.6 29.3 27.0	Furnace oil for a steam boiler
2.	Maichew Particleboard	Glue preparation Impregnation	40 55	6.0 1.2	Furnace oil, fire wood
3.	Bahirdar Textile	Pre-heater Washing Chemical Preparation	60 70 80	36.0 7.8 5.2	Furnace oil for a steam boiler
4.	Ashraf Edible Oil	Conditioning Degumming Neutralization Washing	85 90 90 70	6.0 5.0 5.0 7.7	Furnace oil for a steam boiler

The hourly variation of the hot water demand was also studied at each factory. All the factories mainly process their products during the day time. The hourly hot water demands averaged during the days of measurement for Sheba Tannery and Maichew Particleboard factories are shown in Figure 1a and 1b. Figure 1a indicates that the peak demand is around noon for the Tannery, which is an advantage for storage size reduction for solar energy application. Figure 1b shows that the demand at the Particleboard factory is intermittent at some interval of hours. The figures also show two different scenarios: large scale hot water consumption reaching 15,000 liters per hour at Sheba Tannery and relatively small scale consumption reaching 1,100 liters per hour at Maichew Particleboard Factory.



a)

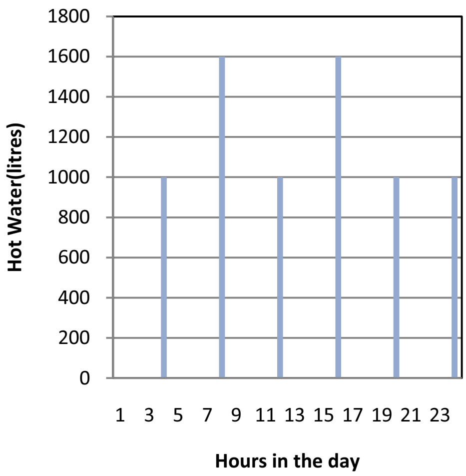


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Figure 1: Hourly hot water demand a) at Sheba Tannery and b) at Maichew Particleboard Factory.

3. Solar Radiation Measurement and Estimation Models

Long term solar radiation data is scarce in the country. Previous studies on solar energy resource assessment available in literature are (Mulugeta and Drake, 1996), (Aregaw, 1996) and (SWERA, 2008). The first two papers discuss about the solar energy resource potential based on solar hour measurements from the National Metrological Agency. The third report is based on satellite data simulation and modeling. The National Metrological Agency has long term monthly average sunshine hour data from many stations around the country (NMA, 2010). Therefore, it was necessary to look into solar radiation estimation models to convert the sunshine hours to daily and hourly data.

The monthly average sunshine hour for the three cities where the factories under study are situated is shown in Figure 2. The figure shows that the sunshine hour for the cities of Mekelle and Bahirdar are close to each other ranging from minimum of about 4 hours during the rainy season to a maximum of about 10 hours during the dry season. In Maichew the sunshine hour varies from 4 hours in the rainy seasons to about 8 hours in the dry season.

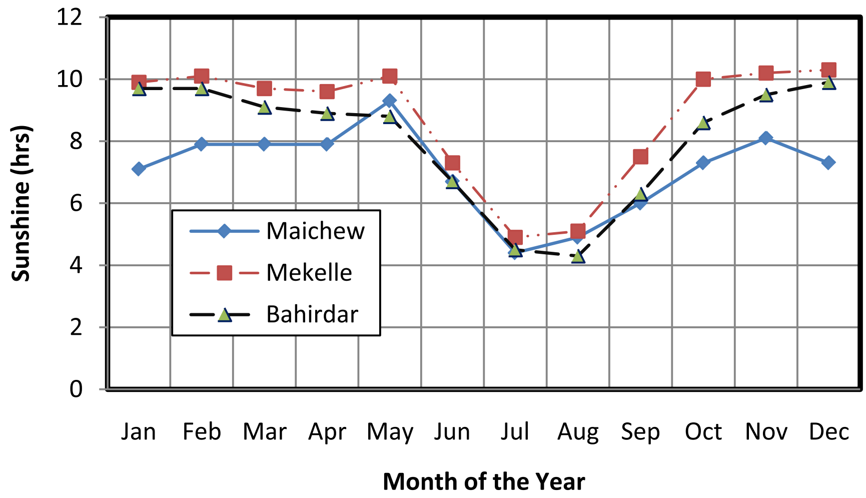


Figure 2: Sunshine hour data for the cities of Maichew, Mekelle and Bahirdar (NMA, 2010).

3.1 Estimation of Monthly Average Daily Global, Diffuse and Beam Radiation from Sunshine Hours

Angstrom's linear model (Duffie and Beckman, 2006a) has been used to estimate the monthly global solar radiation from the sunshine hour data. Similarly the model was used to estimate the diffuse and beam component of the solar radiation. Specific data for each city was applied to find the Angstrom coefficients and the estimated values have been calculated from the model. The results of the model for Mekelle and Maichew are shown in Figure 3 below representing the cities with higher and lower sunshine hours respectively.

3.2 Estimation of Average Hourly Global, Diffuse and Beam Radiation from Daily Radiation

A method proposed by Collares-Pereira and Rabl (Duffie and Beckman, 2006b) based on the disaggregation of daily data in to hourly data has been used. In this method, the hourly global solar radiation is obtained from the daily global solar radiation and the hour angle. Similarly, the diffuse and beam components are obtained from the equation by Liu and Jordan (Duffie and Beckman, 2006b). Plots of results for representative days in the year are shown in Figure 5 in the next section.

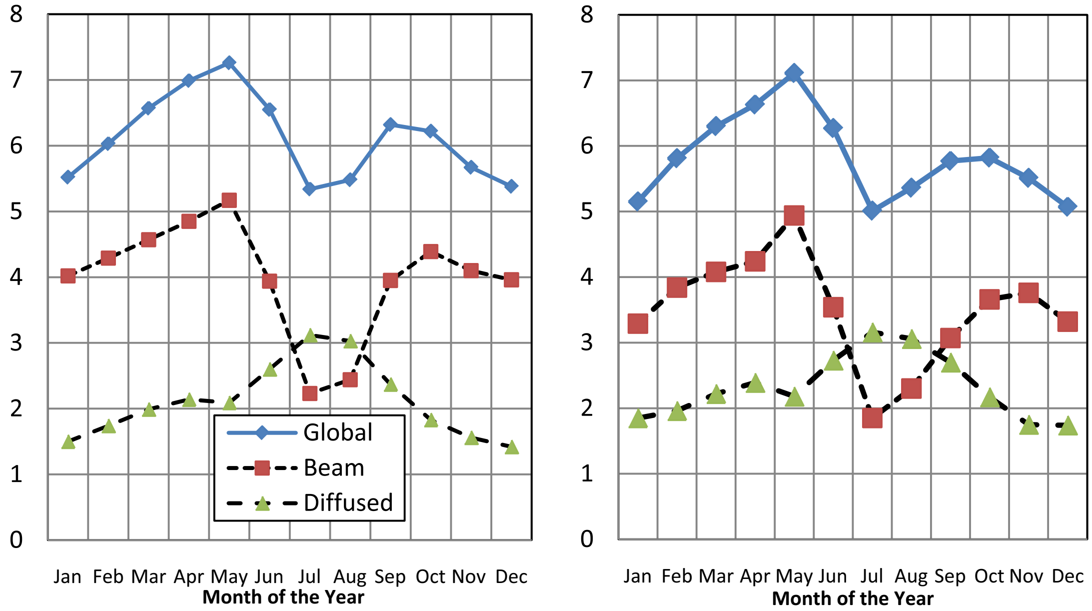


Figure 3: Estimated monthly average solar radiation (kWh/m^2/day) for Mekelle and Maichew.

3.3 Comparison of Measured Solar Radiation with Estimation Results

Solar radiation instruments have been installed at Mekelle University metrological station. The instruments have been recently installed and include pyrheliometer and pyranometer. The data collected so far are for one year. Comparison is made here between the measured data and estimated from the solar radiation models discussed in the previous sections.

Comparison of the global solar radiation measured and estimated is shown in Figure 4 below. The plots show good correlation in the months January to April and November to December. The measured data for the year was lower than the estimated values during the rainy season of June to August. Since the measured data are only for one year (2010/11) it may not be a conclusive observation. It would be necessary to get average values of a number of years of data. But from the data available it seems that the estimation models over estimate the solar radiation during the rainy season.

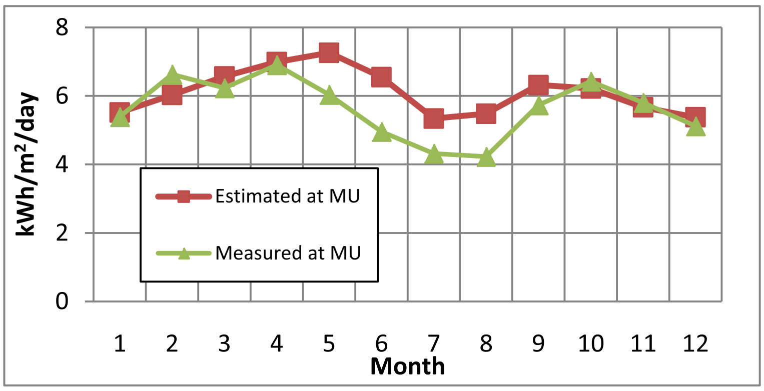


Figure 4 Comparison between measured data and estimated values of global solar radiation.

Comparison of the measured and estimated hourly solar radiation data in the months of August and December are shown in Figure 5 below. The figure shows estimated monthly average, measured monthly average in the months of August and December. There is good correlation in the month of December. In the month of August, a slight difference is observed between the estimation and the measured data. However, the difference observed is not significant to affect the design and sizing of the SWH systems.

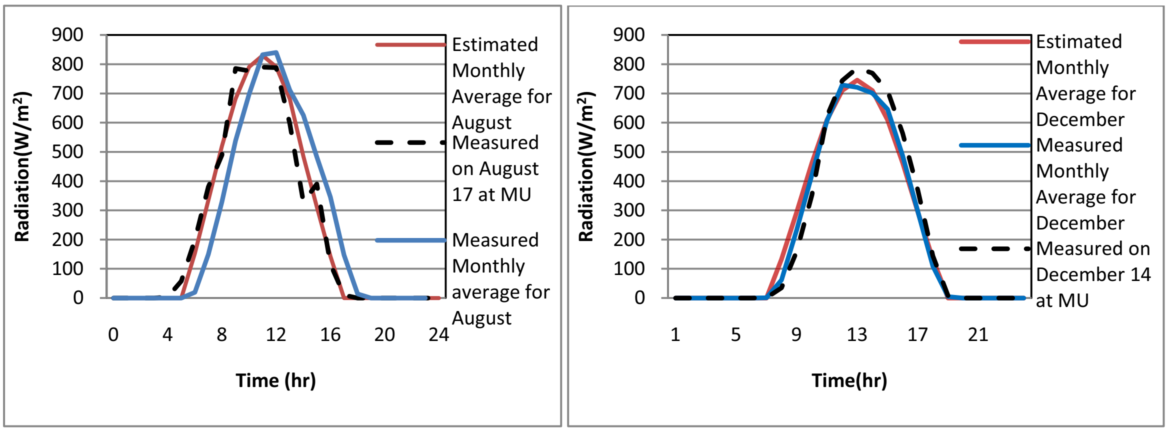


Figure 5 Hourly solar radiation for the months of August and December.

4. Overall Solar Energy System Design and Sizing

Flat-plate solar collectors were found to be appropriate instead of other types for the factories. The main reasons for selecting flat-plate collectors were: i) cost and availability of materials and labor, ii) simple design without any need for tracking mechanism, iii) no significant space limitations in the factories. The overall design and sizing of the SWH systems are discussed below.

4.1 Description of the unit flat-plate collector

A unit flat-plate collector with a collector area of 2 m^2 is assumed in the design. The unit size was selected for ease of fabrication and transportation. The dimensions and materials of the collector selected are shown in Table 2 below. Thermal analysis of the collector was done for assumed mass flow rate of water 0.06 kg/s. The overall heat loss coefficient for the collector (U_c) in the expected temperature range of application was found to be 8.6 $W/m^2\,{}^0C$. Similarly the heat removal factor (F_R) was found to be 0.85.

Table 2 Dimensions and materials for the unit flat-plate collector.

Collector Area (A_c)[m^2]	2	Tube Material	Copper
Collector Perimeter [m]	6	No. of Tubes	8
Depth of the Collector [m]	0.095	Tube Diameter [m]	0.022
Absorber Material	Steel	Insulation Material	Mineral wool
Thickness of the Absorber [m]	0.002	Edge Insulation Thickness[m]	0.025
Number of Glass Cover	1	Back Insulation Thickness[m]	0.05
Glass Thickness [m]	0.004		

The useful heat gain from the unit collector to deliver the required hot water in each hour of the day can be calculated from: [Duffie and Beckman, 2006c]

$$q_u = A_c F_R[(\tau\alpha)I_c - U_c(T_f - T_a)] \quad \text{(eq. 1)}$$

Where I_c is the hourly solar radiation and ($T_f - T_a$) is the temperature difference, which depends on the hot water temperature requirement and ambient temperature in each factory. The total amount of heat gain in the day will be the sum of the calculated values in each hour of the day. Calculations were made for the month of May based on the monthly average hourly solar radiation from the estimation models discussed in the previous section. The design daily useful heat gain was found to be 12, 11, 13.5 and 15 MJ/m^2 for ST, MPF, BTF and AEF respectively. The detail calculations may be referred in [Robel, 2011].

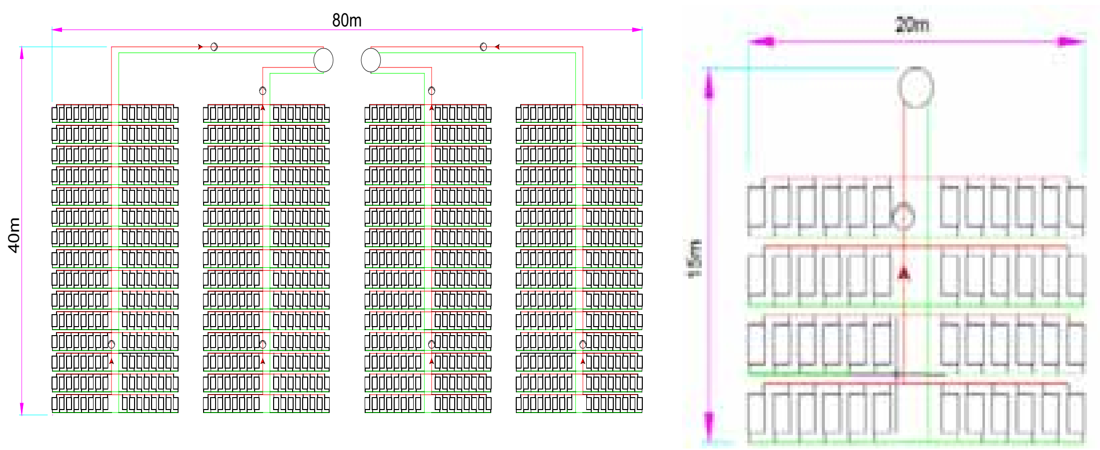
The solar fraction for each month with respect to the design month of May for each factory was then determined. The annual average solar fraction was found to be 0.66 for ST, 0.63 for BTF and AEF, and 0.76 for MPF. The solar fraction indicates the percentage of the hot water demand that can be satisfied by the SWH systems. The remaining fraction has to be satisfied with auxiliary system. The existing boilers in the factories will be used as auxiliary systems.

4.2 Determination of size of the SWH systems and hot water storage tanks.

Based on the unit size of the collector and the hot water demand discussed in section 2, the number of collectors needed and the space requirement were calculated. The hot water storage tank, the overall system layout and the space requirements needed for each factory were estimated. The calculation results for each factory are summarized in Table 3. The overall system layout for the Tannery and the Particleboard factory are shown in Figure 6. The figure is an indicative diagram to show the arrangement of the collectors, the storage tanks, the pipelines and location of pumps.

Table 3 Summary of the SWH systems for each factory.

Factory	Energy Demand (GJ)	Useful Heat Gain Unit Collector (MJ/m^2)	Number of Collectors	Space requirement (m^2)	Storage Tank (m^3)
ST	11.2	12	960	3200	2x50
BTF	5.2	13.5	384	1500	1x24
AEF	3.6	15	240	800	1x15
MPF	0.5	11	48	300	1x3.2



a) ST **b) MPF**

Figure 6 Overall system layouts of the SWH systems.

5. Economic Analysis of the Solar Energy Systems

Solar Water Heating systems have high initial investment but can run for a number of years with very low operational cost. SWH systems have the advantage that the source is renewable with no contribution to environmental pollution. In addition to the environmental benefit, industries would be encouraged to implement if the SWH systems are economically feasible. The methods of payback period and life cycle cost are used to check the feasibility of the systems for the implementation in the factories under the study.

5.1 Cost of Energy for the Current Furnace Oil

The factories in the study use mainly furnace oil for heating water. The heating value of furnace oil is about 35 MJ/liter and the price during the study period was USD 0.69 per liter. This means, assuming no losses, the cost of energy is 0.07 USD/kWh. The way the furnace oil is used to heat water has significant heat losses. The furnace oil is fed to a boiler to generate steam. The steam is then used to heat cold water circulated through heat exchanger. Therefore, it is expected that there will heat loss due to combustion and at the heat exchanger. Actual efficiency of the systems in the factories was not available during the study. However, an overall efficiency of 0.8 was assumed, which is typical combustion efficiency of steam boilers. The cost of energy including the assumed efficiency becomes 0.09 USD/kWh.

5.2 Cost of Energy for the SWH

The cost of energy includes: i) investment cost for the SWH collectors, storage tanks, pumps and pipelines, ii) manufacturing and labor cost, iii) operation and maintenance cost. The basic assumptions that were made for the feasibility calculations are shown in Table 5. Based on the assumptions and the design discussed in the previous section, the costs are calculated for each factory as shown in Table 6.

Table 5 Basic cost assumptions.

Assumption	Value
Unit cost of 2 m^2 collector	USD 250
Life of the SWH system	15 years
Manufacturing and labor cost	10%
Operation and Maintenance	2%
Interest rate	10%

Table 6 Estimated cost of the SWH system in each factory.

No.	Cost item	Estimated cost in USD			
		ST	AEF	BTF	MPF
1	Collectors	240,000	96,000	60,000	12,000
2	Storage tanks, pipelines and fittings	14,000	2,500	3,000	1,000
3	Manufacturing and Labor	30,000	12,000	8,000	1,600
	Total	**284,000**	**110,500**	**71,000**	**14,600**

5.3 Payback Period (PP), Life Cycle Cost (LCC) and Cost of Energy(CoE)

Payback period is one type of economic feasibility method that determines the number of years required to recover an initial investment through project returns. The basis of the payback method is that the more quickly the cost of an investment can be recovered, the more desirable is the investment. Based on the investment cost estimated in the previous section and an interest rate of 10%, the payback period calculated for the SWH system is found to be 6-7 years.

The Life Cycle Cost (LCC) of the SWH system is the total cost of investment and the cost of operation and maintenance over the entire life of the system. LCC of the SWH system can then be compared to the total cost of fuel that could be saved to check its feasibility. The Life Cycle Saving can then be calculated to quantify the benefit obtained due to the implementation of the SWH. In similar manner, the unit cost of energy of the SWH system can be calculated to compare with the unit cost of fuel that was already found in section 5.1 above.

In all the above calculations the solar energy fraction has to be included. The annual average solar energy fraction was 60% as already determined in section 4. Therefore, the SWH system will require an auxiliary energy supply of 40%. The auxiliary system will be the existing boiler with furnace oil as a fuel. The cost of the fuel for the auxiliary system is therefore included in the economic calculations. The results of the calculations are shown in Table 7 below. The table shows the LCC and LCS for the SWH systems in each factory. The costs of energy in USD/kWh for the case of the SWH system and the existing situation of using furnace oil are also included. As indicated in the table the percentage saving ranges from 26-33 %.

Table 7 Results of the economic feasibility analysis.

Factory	SWH LCC (USD)	SWH LCS (USD)	Cost of Energy (USD/kWh)		Percentage Savings
			SWH	Current Furnace Oil only	
ST	293,873	105,250	0.05	0.09	26%
AEF	118,496	58,480	0.05	0.09	33%
BTF	76,666	28,463	0.05	0.09	27%
MPF	15,875	6,652	0.05	0.09	30%

6. Conclusions and Recommendations

6.1 Conclusions

The study found that there is very high hot water demand in tanneries and edible oil factories, medium demand in textile factory and low demand in particle board factory. In all the factories under study the major hot water consumptions is during the day time which is an advantage for the solar energy application. Based on the demand study and solar energy data, it was possible to design SWH systems for each factory.

The analysis results on solar water heating indicate that it will cost the factories about 5 USD cents per kWh and the payback period will be 6 – 7 years. In addition to the advantage of using clean energy, the factories can save their energy cost by 26-33% by implementing the solar water heating systems. The above results were for conservative estimates. If an optimized SWH system is considered, the savings can even be higher. It is evident from this result that the SWH system is economically feasible for the factories.

6.2 Recommendations

The solar radiation measurements should continue in order to have long time data for future analysis. It is recommended that a database of the solar radiation data be established to organize the data to be shared by researchers seeking measured solar radiation data.

It is recommended that the factories in the study take the work done in this research in to implementation. It is suggested that some detail design and optimization be carried out. Implementation can be phase by phase, starting with small amount of share of the solar energy and then developing it in to full capacity. It is suggested also that capacity building in local manufacture of the collectors is essential. There are small enterprises in the cities where the factories are situated that can be trained to manufacture the collectors.

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