THE VIABILITY OF SOLAR ENERGY FOR DOMESTIC WATER HEATING IN ETHIOPIAN CITIES

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ABSTRACT

Investigation of the possible use of solar energy for domestic water heating is conducted for seven representative Ethiopian cities. In this study, the transient performance of the system is computed using a numerical heat transfer model of a flat-plate collector from the input of average annual climatic data and collector parameters. From the annual contribution of solar energy to the heating load and the estimated investment cost, the pay back period of the heating system for each city is calculated. The research result indicates that domestic water heating by solar energy as a viable alternative to electric water heating.

INTRODUCTION

Electricity has been serving as the main source of thermal energy for domestic water heating systems in Ethiopia cities. The inevitable rise of price of electricity or government subsidies for power plants, caused by increased investment cost of power generation, makes the search for an alternative source of thermal energy for domestic water heaters urgent. The use of oil and gas firing water heater is not possible considering the present scarcity of these fuels and relatively high intial cost of such heaters. The sever scarcity of charcoal and wood in cities and the adverse consequence of firing these fuels on the forest, makes their use for this application questionable. The remaining option is to exploit the inexhaustible and freely available solar radiation. The conversion of solar energy in efficient way to thermal energy incurs intial cost. If solar energy has to be used for this purpose, it has to bring economic benefit to the potential user by reducing the cost of water heating.

The viability of solar water heating system to reduce electrical energy consumption for domestic water heating in Ethiopia has not been studied throughly. The absence of locally conducted investigations would force one to accept conclusions made elsewhere for countries having similar climatic conditions. These findings are not fully valid in view of the scarcity of conventional materials like copper and aluminum which are used for fabrication of flat-plate solar collectors and differing costs of fuels and electricity. In order to make technically sound decisions on the adaptation of solar technology, the system performance, availability of raw materials locally, adaptability of the technology to locally existing facilities and manufacturing cost should be examined. The feasiblity of solar water heating system is examined by comparison of fuel or electricity savings with the capital cost of the plant by net present worth or pay-back period methods [1]. The electricity savings are calculated from the annual contribution of solar energy to the heating load. The variation of solar energy from place to place and within a year makes costly experimental monitoring of the system at different stations in predicting long term performance. Hence the procedure of simulating the system by a numerical heat transfer model from the in put of climatic data and collector parameters is adopted in this study [2],[3]. The development of a low cost solar water heater, which can be disseminated widely, requires the use of cheaper materials rather than technically better and locally scarce copper and aluminum. A recent study conducted by dissection of galvanized steel absorber plate and tube flat-plate collectors has indicated that their life can extend up to 15 years, while the efficiency stagnates at 80 % of the intial value after decreasing linearly in the first five years [4].

THERMAL MODEL

In the flat-plate collector shown in Fig.1, the blackened absorber plate absorbs solar radiation and transfers heat to the water in the tube. The transparent cover, which is opaque to infrared radiation, and the insulation at the back trap the collected energy from being lost by radiation and convection. Radiation incident on the collector surface is given by:

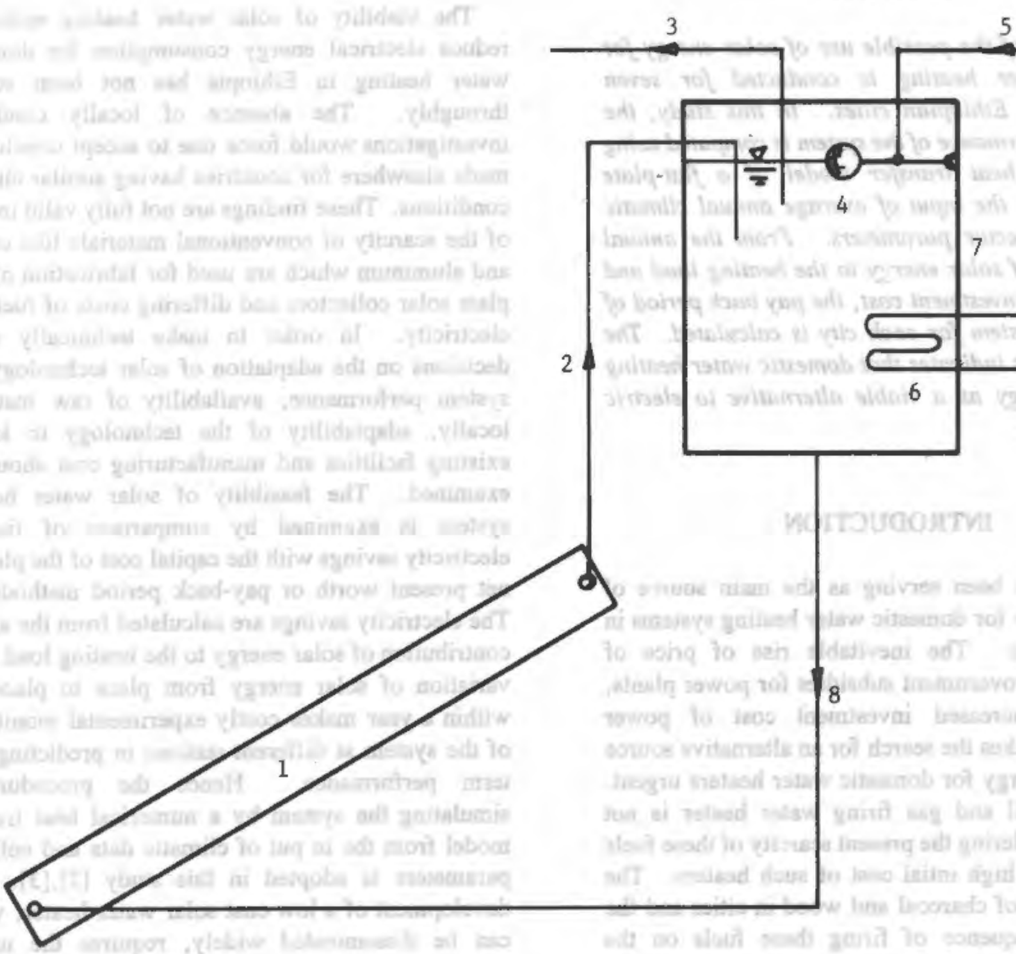
$$I = R_b(G_r - D_r) + 0.5(1.0 + \cos(S))D_r + 0.5\rho(1.0 - \cos(S))G_r \qquad (1)$$

The beam radiation factor R_b is dependent on hour-angle, latitude, azimuth, solar declination, and collector slope. The flux collected per unit time depends on the transmissivity of the cover and absorbtivity of the absorber and is given as:

$$I_c = I\,(\tau\;\alpha) \qquad (2)$$

While most of the energy is transferred to the water, the rest is

- transferred to the surrounding across the glazing and insulation, and
- stored in the absorber plate and glazing.



1. Collector
2. Riser
3. Hot water supply
4. Floot valve
5. Cold water supply
6. Auxilary electric heater
7. Storage tank
8. Downcomer

Fig. 1 Thermosyphon Heating System With a Flat-plate Collector.

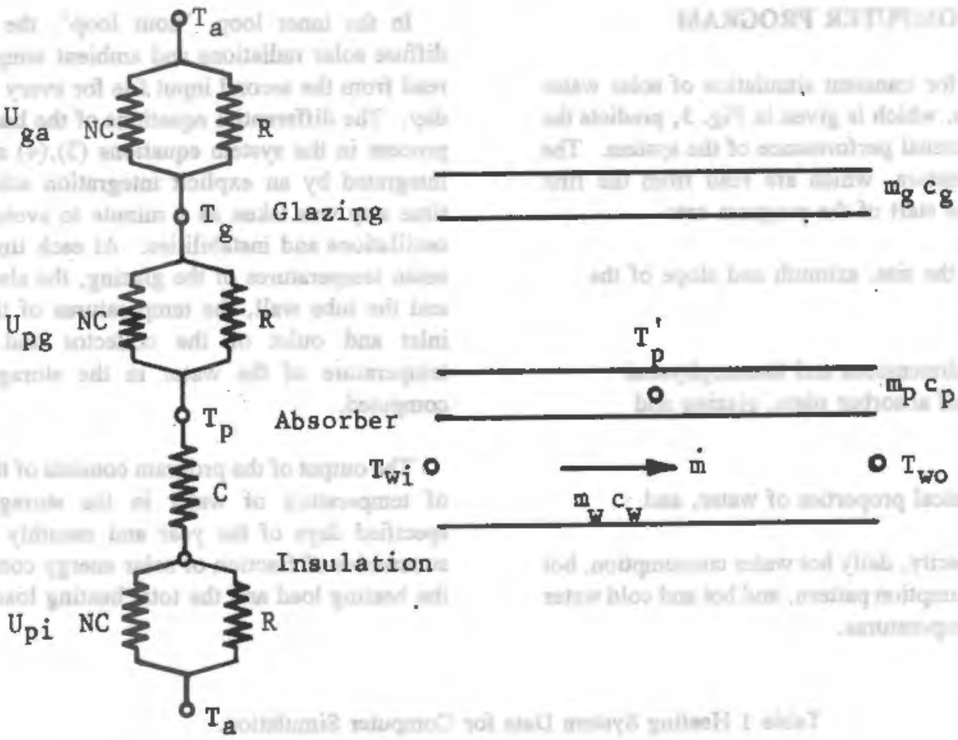


Fig. 2 Thermal Resistance and Capacitance of the Collector

Representing the thermal resistance and capacitance of the simplified collector model as in Fig. 2, makes its possible to define the heat exchange process by the following set of differential equations.

$$m_p c_p \frac{dT_p}{dt} = A_c\,[I_c - U_{pg}(T_p - T_g) - U_{pi}(T_p - T_a)] - U_{pw}A_w[T_p - \frac{(T_{wi}+T_{wo})}{2}] \quad (3)$$

$$m_w c_w \frac{dT_{wo}}{dt} = U_{pw}A_w\left[T_p - \frac{(T_{wi}+T_{wo})}{2}\right] - \dot{m}c_w(T_{wo}-T_{wi}) \quad (4)$$

$$m_g c_g \frac{dT_g}{dt} = U_{pg}A_c(T_p - T_g) - U_{ga}A_c(T_g - T_a) \quad (5)$$

Equation (3),(4) and (5) are derived from the energy balance on the absorber plate, water and glazing respectively. The given set of equations are non-linear due to temperature dependent radiant and convective heat transfer coefficients. Hence, the solutions are obtained by an integration scheme which linearises the given equations within the time step.

The temperature of the water at the inlet of the collector is evaluated taking into account the hot water extracted from the storage and heat losses across the storage. In this model, the level of water in the storage tank is to be controlled by a float valve keeping the mass of water in the storage constant. After making energy balance in time interval Δt, the storage tank temperature is evaluated from:

$$T_s = T_{wi} + [\dot{m}\,\Delta t\,c_w(T_{wo}-T_{wi}) - U_sA_s(T_s - T_a) - \Delta m\,c_w(T_s - T_{wo})]\ /\ \rho_w V_s c_w \quad (6)$$

COMPUTER PROGRAM

The Program for transient simulation of solar water heating system, which is given in Fig. 3, predicts the monthly and annual performance of the system. The constant parameters, which are read from the first input file at the start of the program are:

- latitude of the site, azimuth and slope of the collector,
- geometric dimensions and thermophysical properties of absorber plate, glazing and insulation.
- thermophysical properties of water, and
- storage capacity, daily hot water consumption, hot water consumption pattern, and hot and cold water delivery temperatures.

In the inner loop, "hour loop", the global and diffuse solar radiations and ambient temperature are read from the second input file for every hour of the day. The differential equations of the heat exchange process in the system equations (3),(4) and (5), are integrated by an explicit integration scheme. The time step was taken as 1 minute to avoid numerical oscillations and instabilities. At each time step, the mean temperatures of the glazing, the absorber plate and the tube wall, the temperatures of the water at inlet and oulet of the collector and the mean temperature of the water in the storage tank are computed.

The output of the program consists of the variation of temperature of water in the storage tank for specified days of the year and monthly and annual summaries of fraction of solar energy contribution to the heating load and the total heating load.

Table 1 Heating System Data for Computer Simulation.

Heating System Data	
Collector type	Galvanized steel absorber and tube
Collector area	1.8 m^2
Storage tank volume	0.05 m^3
Daily water consumption	0.15 m^3
Hot water supply temp.	60 °C
Make-up water supply temp.	20 °C
Hot water consumption	Constant from 8 - 21 hrs

RESULTS AND DISCUSSION

Seven cities, representative of the climatic conditions of most part of Ethiopia were selected to study the economic viability of solar domestic water heating system with a galvanised steel absorber plate.

CLIMATIC DATA

The absence of recorded hourly values of climatic data has made it necessary to generate estimated values of global radiation, diffuse radiation and ambient temperature, respectively, from

- daily total global radiation,
- daily total diffuse radiation,
- daily maximum and minimum temperatures.

This type of approach gives nearly exact values for a clear sky day [5]. Even for cloudy days, considering the variation of sunshine hours for the same day of the year in different years, the approach is reliable for prediction of long term performance of the heating system. The climatic data used in the system simulation are the average of seven or more years.

In Fig. 4, the monthly average of daily mean and global radiation, daily maximum and minimum temperatures, used in the simulation, are given for four of the seven cities in consideration.

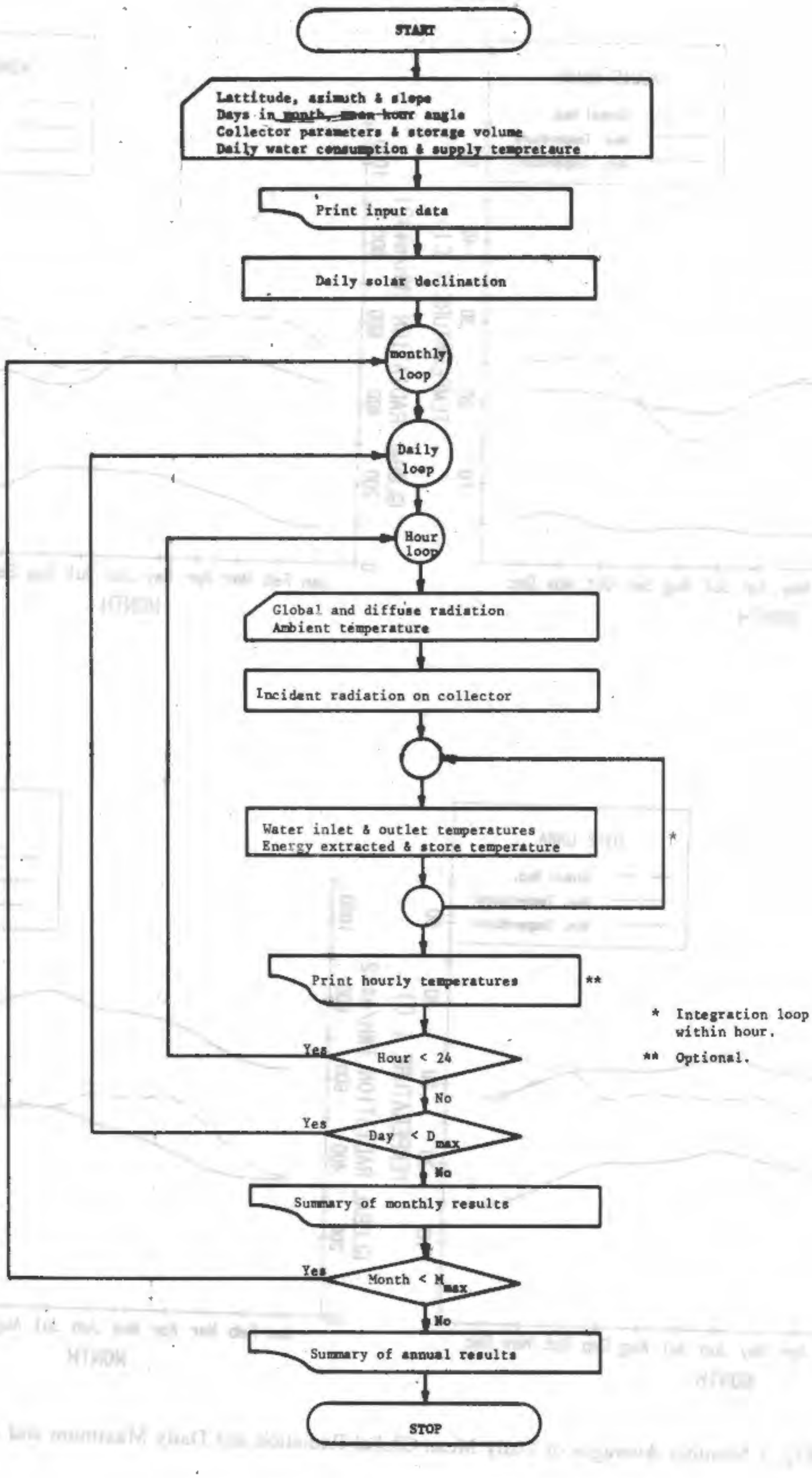


Fig. 3 Flowchart of Simulation Programme.

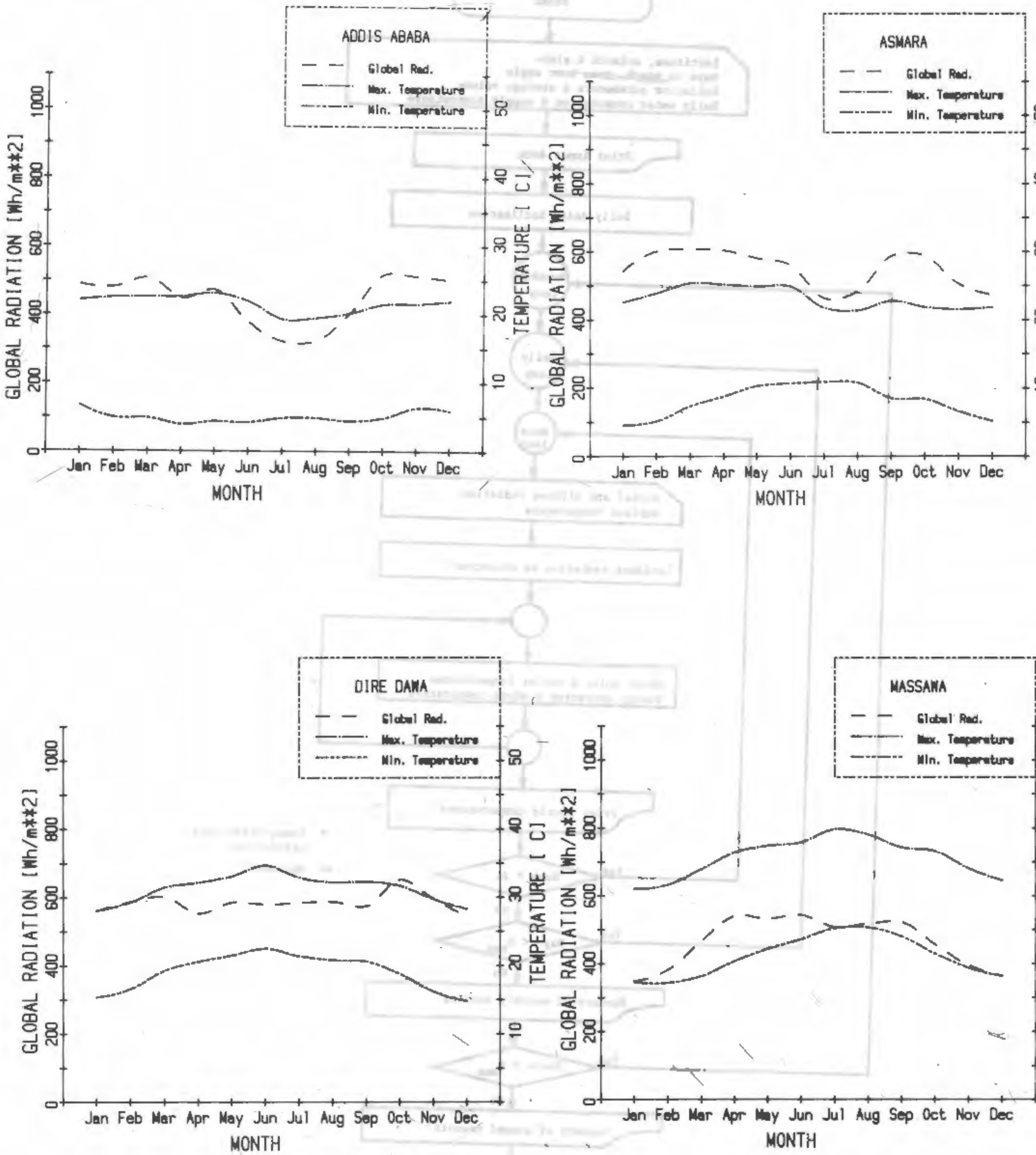


Fig. 4 Monthly Averages of Daily Mean Global Radiation and Daily Maximum and Minimum Temperatures.

SIMULATED PERFORMANCE

The simulation model has provided the monthly and annual contributions of solar energy to the heating load, the total incident energy on collector surface, the collector efficiency and temperature variation of water in the storage tank of typical days of the year from the input of climatic data of each of the seven cities and collector parameters. The type of flat-plate collector, storage volume, daily water consumption, hot water supply temperature and daily hot water consumption pattern used in the simulation of the heating system are given in Table 1. The annual variation of the fraction of heating load supplied by solar energy is illustrated in Fig. 5 for the four cities. In cities where seasonal variations are clearly demarcated, sharp drops of the contribution of solar energy to the heating load are seen. In these cities, the required hot water supply temperature on cloudy days can not be achieved by enlarging the collector area. This problem can, however, be easily overcome by installing a back-up electric immersion heater in the storage tank. The variation of water temperature in the storage tank in given in Fig. 6. In a clear sky day, the water temperature in the storage tank rises to 60 °C just after noon and falls afterwards as the hot water in the tank is diluted by the cold make-up water. This is automatically done by the float-valve which maintains the level of water in the tank constant to avoid interruption of thermosyphon circulation. A concious user, however, can shift most part of the consumption towards the evening and manually controlling the supply of make-up in the evening can reduce the dilution of the hot water in the storage tank.

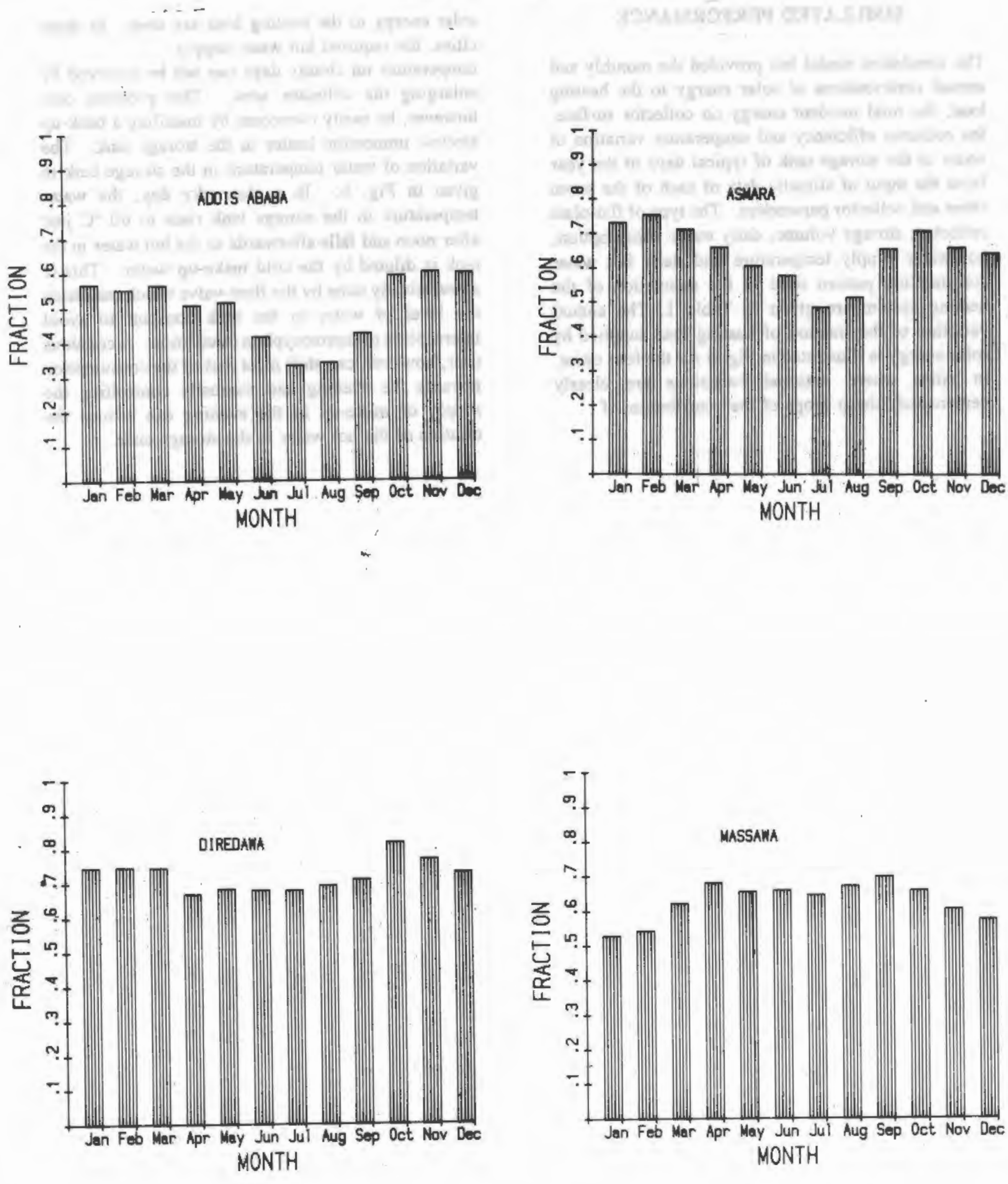


Fig. 5 Simulated Monthly Fraction of Solar Energy Contribution to the Heating Load.

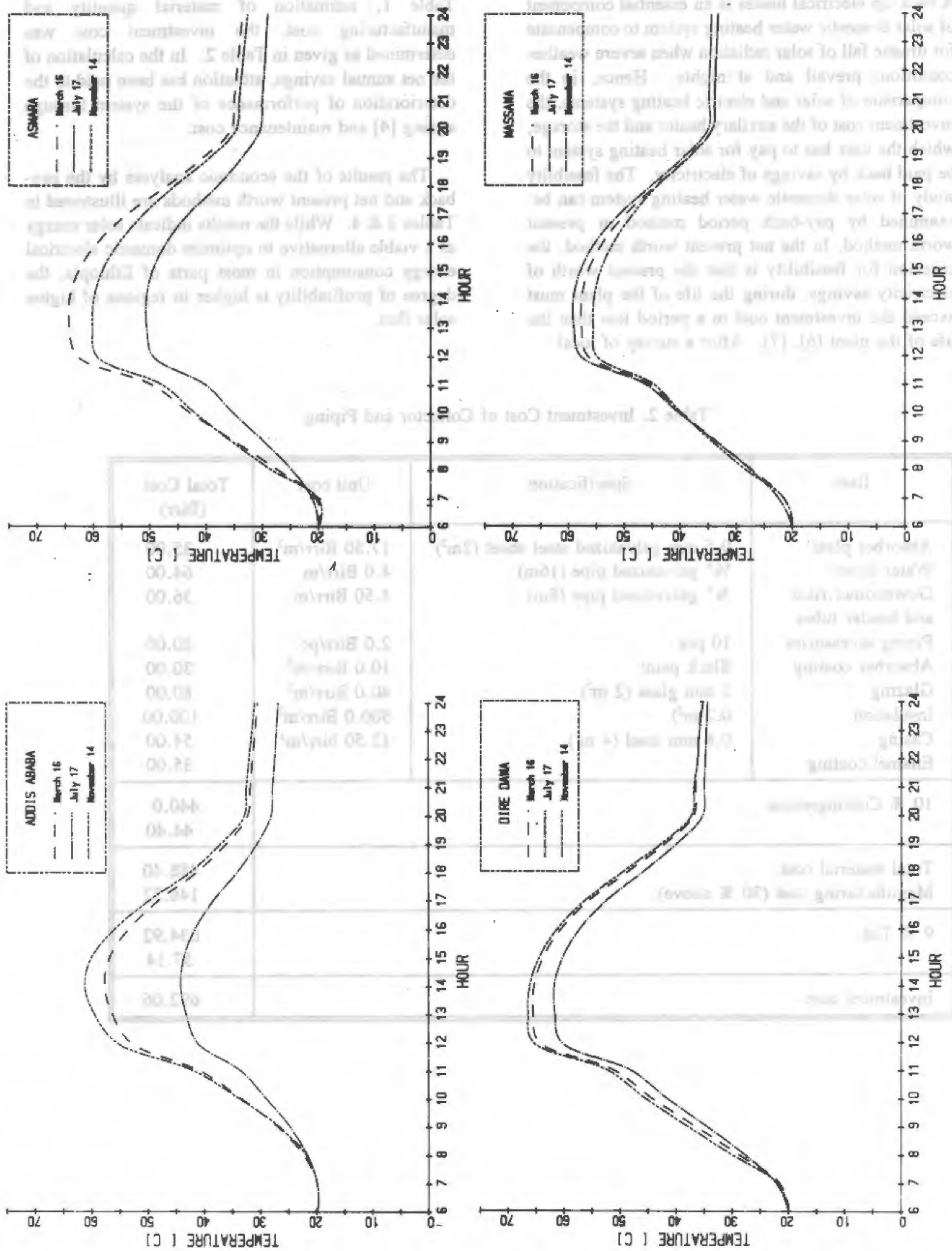


Fig. 6 Simulated Hourly Variation of Temperature of Water in Storage Tank

Economic Analysis

A back-up electrical heater is an essential component of solar domestic water heating system to compensate for drastic fall of solar radiation when severe weather conditions prevail and at nights. Hence, in the comparison of solar and electric heating systems, the investment cost of the auxilary heater and the storage, which the user has to pay for solar heating system to be paid back by savings of electricity. The feasiblity study of solar domestic water heating system can be examined by pay-back period method or present worth method. In the net present worth method, the criterion for feasibility is that the present worth of electricity savings, during the life of the plant must exceed the investment cost in a period less than the life of the plant [6], [7]. After a survey of local prices of materials necessary for the fabrication of solar collector for the heating system data given in Table 1, estimation of material quantity and manufacturing cost, the investment cost was determined as given in Table 2. In the calculation of the net annual savings, attention has been paid to the deterioration of performance of the system through ageing [4] and maintenance cost.

The results of the economic analyses by the pay-back and net present worth methods are illustrated in Tables 3 & 4. While the results indicate solar energy as a viable alternative to optimize domestic electrical energy consumption in most parts of Ethiopia, the degree of profitability is higher in regions of higher solar flux.

Table 2. Investment Cost of Collector and Piping

Item	Specification	Unit cost	Total Cost (Birr)
Absorber plate	0.5 mm galvanized steel sheet ($2m^2$)	17.50 Birr/m^2	35.00
Water tubes	⅛" galvanized pipe (16m)	4.0 Birr/m	64.00
Downcomer, riser and header tubes	¾" galvanized pipe (8m)	4.50 Birr/m	36.00
Piping accessories	10 pcs	2.0 Birr/pc.	20.00
Absorber coating	Black paint	10.0 Birr/m^2	20.00
Glazing	3 mm glass (2 m^2)	40.0 Birr/m^2	80.00
Insulation	0.2 m^2)	500.0 Birr/m^3	100.00
Casing	0.8 mm steel (4 m^2)	13.50 birr/m^2	54.00
Enamel coating			35.00
10 % Contingencies			440.0 44.40
Total material cost Manufacturing cost (30 % above)			488.40 146.52
9 % Tax			634.92 57.14
Investment cost			692.06

Table 3. Economic Analysis of the System for Asmara

Year	Electricity Birr	Maintenance Birr	Net Saving Birr	Present Worth Birr
1	226.2	17.5	208.7	191.5
2	227.8	19.3	208.6	175.6
3	229.0	21.2	207.9	160.5
4	229.8	23.3	206.5	146.3
5	230.1	25.6	204.4	132.9
6	229.8	28.2	201.6	120.2
7	247.5	31.0	216.5	118.4
8	259.8	34.1	225.7	113.3
9	272.8	37.5	235.3	108.3
10	286.5	41.3	245.2	103.6
Net present worth				670.5
Pay-back period			4 years and 2 months	

Table 4. Results and Data of Economic Analysis

City	Latitude	Solar Energy Contribution [kW-hr]	Net Present Worth [Birr]	Pay-back
Addis Ababa	9.02	1275.0	332.0	5 years 11 months
Asmara	15.17	1635.0	671.0	4 years 2 months
Awassa	7.04	1507.0	550.0	4 years 8 months
Bahr Dar	11.36	1513.0	556.0	4 years 8 months
Dire Dawa	9.36	1839.0	862.0	3 years 7 months
Jimma	7.40	1362.0	414.0	5 years 4 months
Massawa	15.37	1598.0	636.0	4 years 3 months

Data Economic Analysis	
Collector area	1.8 m^2
Heating system data	Table 1
Investment cost of collector	700 Birr
Life of the plant	10 years
Inflation rate of electricity tariff	5 %
Electricity tariff	0.12 Birr/kWh
Efficiency of electric water heater	90 %
Inflation rate of material cost	10 %
Interest rate	9 %
Maintenance cost	2.5 % of investment

CONCLUSION

In this work, the feasibility of solar domestic water heating system is quantitatively demonstrated. Attention should be paid to lay the necessary prequisities for the establishment of small-scale solar collector manufacturing industry. Towards this end, the research in this area should continue in the following directions;

. determination of optimum collector area and storage tank volume for different cities,

. identification of alternative materials,

. development of a low cost batch heater, which can be installed by a larger number of urban dewellers,

. manufacturing and testing of different prototypes, and

. exploring possible areas of application in industrial and agricultural sectors.

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NOMENCLATURE

A_c = Collector area [m^2]
A_s = Surface area of storage tank [m^2
A_w = Surface area of tube [m$_2$]
c_g = Specific heat of glazing [kJ/kg K]
c_p = Specific heat of absorber plate [kJ/kg K]
c_w = Specific heat of water [kJ/kg K]
D_r = Diffuse radiation on horizontal surface [Wh/m^2]
G_r = Global radiation on horizontal surface [Wh/m^2]
I = Solar radiation on tilted surface [Wh/m^2]
$\dot{m}$ = Flow rate of water [kg/s]
m_g = Mass of glazing [kg]
m_p = Mass of absorber plate [kg]
m_w = Mass of water in collector tubes [kg]
R_b = Mass of water in collector tubes [kg]
S = Collector slope [degree]
• = Ambient temperature [°C]
T_g = Mean glazing temperature [°C]
T_p = Mean absorber plate temperature [°C]
T'_p = Tube-plate contact temperature [°C]
T_s = Water temperature in the storage tank [°C]
T_{wi} = Water temperature at collector inlet [°C]
T_{wo} = Water temperature at collector outlet [°C]
T_w = Make-up water supply temperature [°C]
U_{ga} = Glass to air heat transfer coefficient [kW/m^2]
U_{gi} = Heat transfer coefficient across insulation [kW/m^2]
U_{pg} = Plate to glazing heat transfer [kW/m^2]
U_{pw} = Absorber plate tp water heat transfer coefficient [kW/m^2]
V_s = Storage tank volume [m^3]
α = Absorptance of absorber plate [1]
Δm = Hot water consumed in time Δt [kg]
Δt = Integration step [s]
ρ = Ground reflectance [1]
$\rho\omega$ = Density of water [kg/m^3]
γ = Transmittance of glazing [1]

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