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Analysis of Sustainable Hot Water Supply for Domestic Application in Yenagoa, Bayelsa State

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ABSTRACT

Due to the high cost of tariff of the public grid system, the maintenance and running cost of the isolated generators, it was necessary to look at an alternative source of providing hot water supply for domestic and other applications. The enormous potential of solar radiation in Nigeria is a viable option for the use of photo voltaic and solar thermal systems to convert the solar energy to solve our growing energy needs. The paper therefore, is aimed at analyzing and designing a solar thermal system for an average domestic building hot water requirement for a family of five using the parameters of an evacuator tube solar collector in Yenagoa city, Nigeria. From the analysis, the hot water requirement for the building load was estimated at 30 litres for rainy and 20 litres for dry season. Due to the high solar intensity the load was increased to 50 litres to maintain the average temperature. The assumed constant temperature of the main water supply was 18°C and 22°C (rainy and dry seasons). With a collector area of 2.1m ^{2} and the hot water supply temperature at 65°C, and the load of the building was estimated to be 29.5MJ for the rainy seasons and 54MJ for the dry seasons. From the design it was observed that the design results satisfied the maximum temperature limit of the storage tank and satisfied the hot water need for a household.

Keywords: *Evacuator Tube, Solar Thermal Energy, Photovoltaic Cell, Collector Area, Solar Radiation.*

1. INTRODUCTION

Energy is considered as the life blood of every nation's economic development. Its usage has increased in the last decade, due to increase energy demand and depletion of conventional energy sources. Global warming and environmental issues are continuously driving the world towards alternative sources of energy [1]. Renewable energy technologies such as photovoltaic and solar thermal water heating systems are seen as solutions for our energy needs. Solar thermal hot water systems are developing and there are several research studies on the design of solar thermal technology and application for hot water production [2-5]. African cities with enormous solar radiation can diversify its energy needs by using solar thermal systems for their hot water needs. For countries within 3200km of the equator, use of such energy could be economically significant. According to [6] solar energy reaching the earth in tropical zones is about 1kWh/m^2 giving approximately 5 to 10 kWh/m^2 per day. Solar energy plays an important role for sustainable development and will represent a large-scale alternate energy employment, especially regarding the use of water heating for domestic use [7]. Jon Cooks [8] reveals that the capital city (Yenagoa) of Bayelsa State has its annual global horizontal radiation of 4.61 kWh/m^2/day (averaged over 22 years). Monthly data shows that radiation peaks is 5.69 kWh/m^2/day in February and is lowest in July at 3.49 kWh/m^2/day. This corresponds with the region's dry and rainy seasons. The need for solar energy application is to address our energy needs and also play a role to reduce the effect of Climatic change on the environment, human and aquatic life.

Therefore, is an increased interest in renewable solar thermal system because it is cost effective and environmentally friendly? This paper provides a solution through the analysis of domestic hot water supply for a family of five in Yenagoa city, Bayelsa state, using the evacuator tube solar collectors because of the increasing domestic, commercial, and industrial demand for hot water.

2. EVACUATOR TUBE SOLAR COLLECTOR

Solar water heaters are made up of solar collectors and there are basically three types namely flat plate solar collectors, evacuator tubes solar collectors and concentrating solar collectors. In this paper, evacuator tube solar collector parameters are used for analysis. Evacuator tube solar collectors are made from borosilicate glass and are connected in row of parallel, transparent glass tubes [9 – 12]. Each tube consists of an outer and inner tubes or an absorber covered with selective coating that absorbs solar energy from the sun. The outer tube has very low reflectivity and very high transmisivity that radiation can pass through. The inner tube has a layer of selective coating that maximizes absorption of solar energy and minimizes the reflection, thereby locking the heat [12 – 14]. When the inner and outer tubes of the evacuator collectors are connected together with the copper header as shown in fig. 1 and a vacuum is created. When air is evacuated from the space between the tubes, it eliminates both convective and conductive heat loss. Evacuator tube solar collectors are suitable for applications requiring energy delivery at moderate temperatures such as domestic hot water heating, space heating and process heating applications mainly 60°C to 80°C. There are basically two form of evacuator tubular absorbers namely single glass enveloping metal-fin-in vacuum type and the all glass-glass evacuated tube type [10]. The working of solar thermal system, its method of application and the storage tank is illustrated in fig. 2.

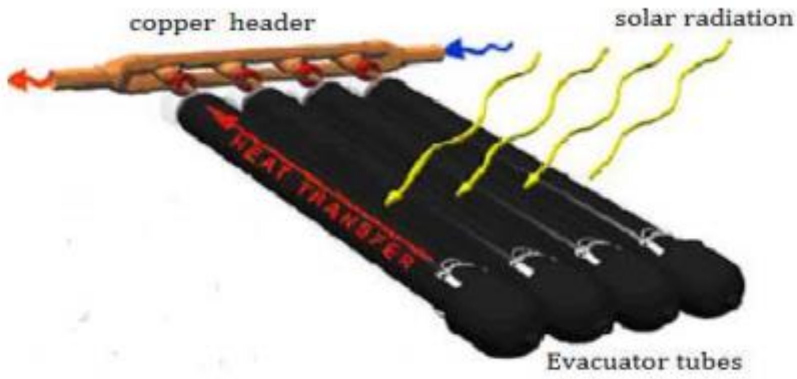

Fig. 1: Application and working principle of Evacuator tubes

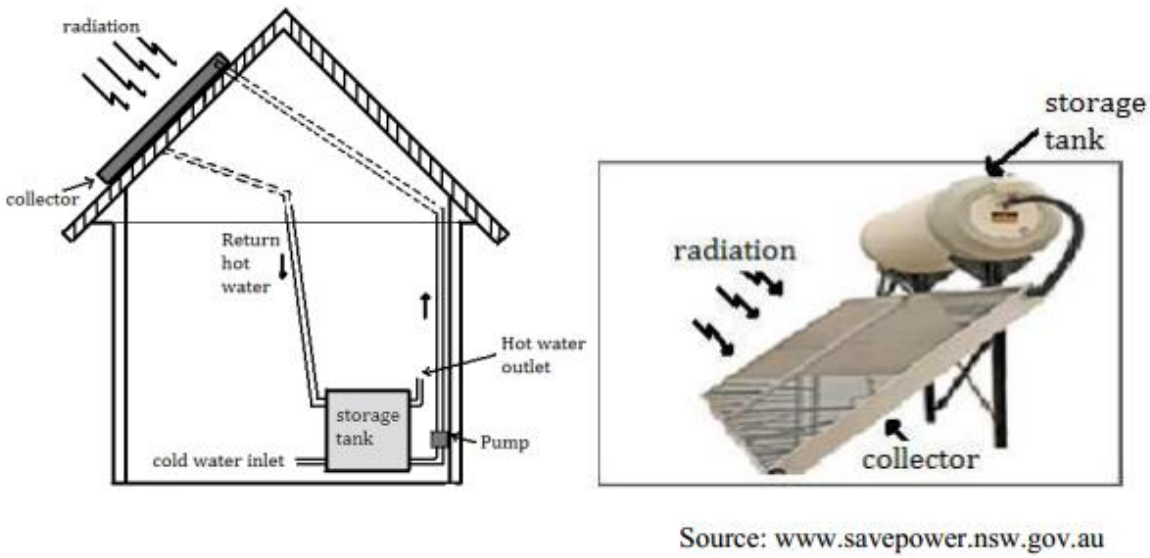

Fig. 2: Schematics of solar thermal system for domestic hot water applications

3. SOLAR RADIATION ON AN INCLINE SURFACE IN YENAGOA CITY

The solar radiation in Yenagoa was calculated on an incline surface of 45 degree using [15, 16] and the following climatic data given in table 1, and then using equation 1.

$$H_T = H_b R_b + H_d(1 + \cos\beta/2) + H\rho(1 - \cos\beta/2) \qquad (1)$$

Where ρ is given as ground reflectivity which varies from 0.3 to 0.8, H_d is diffuse radiation, R_b is beam radiation on tilt plane (β) and the average beam radiation is given in equation 2.

When the solar hour angle is less than 81.4° and Kt lies in between 0.3 and 0.8

$H_d/H = 1.391 - 3.56Kt + 4.189Kt^2 - 2.137Kt^3$ and when solar hour angle is greater than 81.4 and Kt lies in between 0.3 and 0.8 we use this equation $H_d/H = 1.311 - 3.022Kt + 3.427Kt^2 - 1.821Kt^3$

Therefore the average beam radiation;

$$H_b = H - H_d \qquad (2)$$

Table 1: Climatic Data of Yenagoa

Symbol	Description	Standard Values
δ	Declination	*
β	Tilt Angle	45
γ	Surface Azimuth	0
ϕ	Latitude	4.43N
Ꝁ	Clear Index	0.65

The result of solar radiation (H_T) was estimated in the month of January in the dry season and July in the rainy season of 2011 and the estimated radiation was used to calculate the storage tank temperature in section 4. The daily estimated radiation is assumed to be the monthly average and the same was done for every other month of the year. The values are shown in fig. 3 and fig. 4.

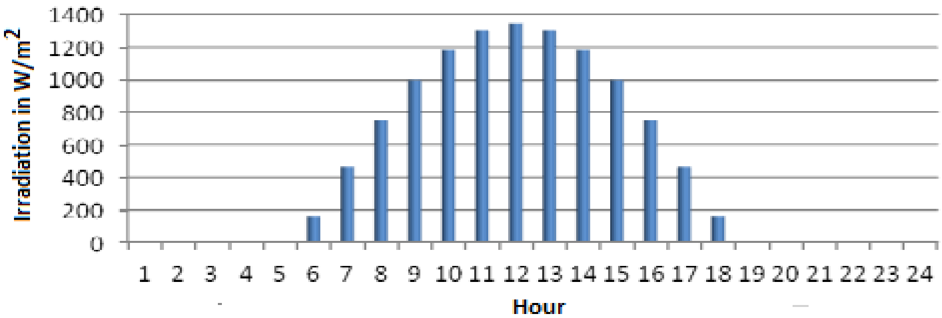

Figure 3: Irradiation Level (W/m^2) on Jan 12th, 2011

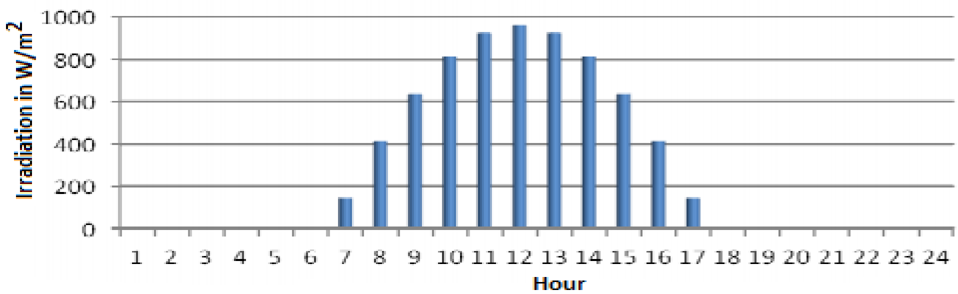

Figure 4: Irradiation Level (W/m^2) on July 12th, 2011

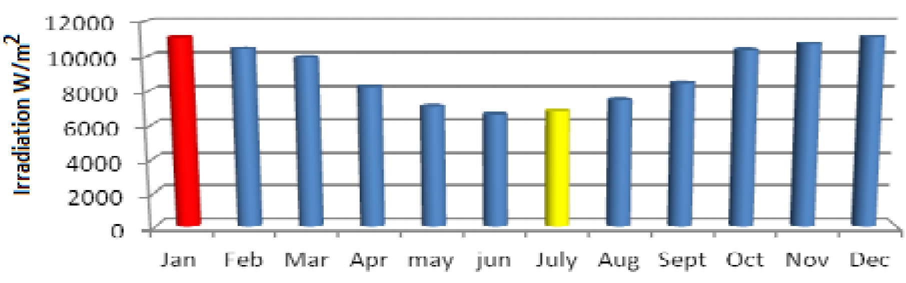

Figure 5: Estimated average monthly radiation in Bayelsa state

The solar radiation throughout the year of 2011 in Bayelsa State is also shown in fig. 5. For the analysis of the solar thermal system, January and July months were used to represent the two different seasons (dry and rainy). The dry and rainy season estimated monthly radiation are therefore marked with red and yellow respectively.

4. LOAD EVALUATION AND TANK SIZE DESIGN

A hot water load requirement for a family of five was estimated for rainy and dry season in Yenagoa and the hot water requirement per person was estimated at 30 litres in rainy seasons and 20 litres in dry season. Due to the high solar intensity of radiation, the load was increased to 50 litres. The main temperature of return water supply (T_{RM}) was assumed to be constant at 22°C in the dry seasons and 18°C in the rainy seasons and the hot water inlet temperature (T_I) was taken as 65°C and these factors were used to estimate the building Load using equation 3.

The daily load QL was calculated as

$$QL = MC_P (T_I - T_{RM}) \quad (3)$$

Where M is in kg and C_P is specific heat capacity (4.19KJ/Kg/°C)

T_I = water inlet temp.

T_{RM} = Temperature of return water supply

The load of the building was estimated per hour across 24 hours of a day and was measured in Mega Joules. The load profile is shown in fig. 6 and 7 for the two seasons and were used to calculate the tank temperature as shown in Table 3 and table 4.

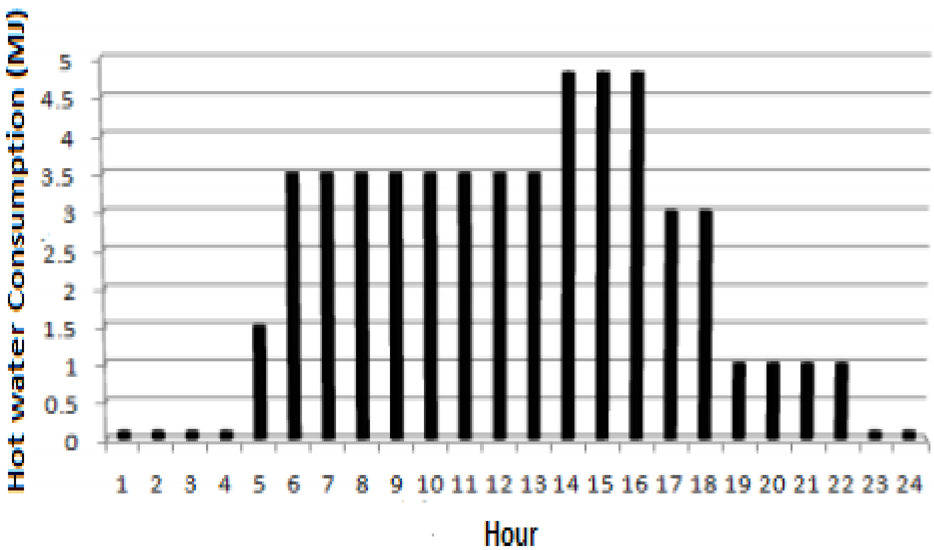

Figure 6: Dry season load distribution

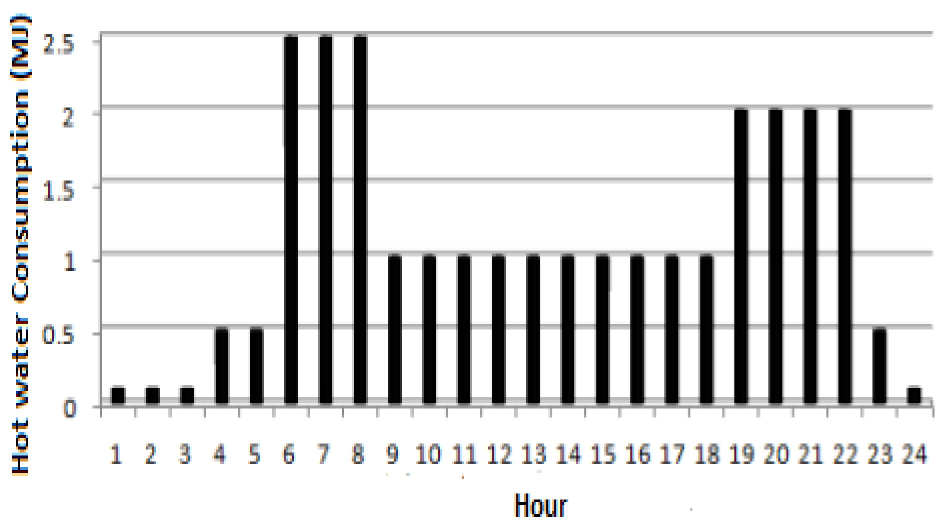

Figure 7: Rainy season load distribution

In order to actualize the design some specifications of a typical solar thermal collector such as;

Average absorptivity, $\alpha = 0.9$
Average transmitivity, $\tau = 0.91$
Over all heat loss co-efficient, $U_L = 2.15\ W/M^2/°C$ per Collector Area
Heat removal factor $F_R = 0.9$ Heat loss coefficient for storage tank, $U_i = 1.5\ W/M^2/°C$
Ambient Temperature $T_A = 30°C$
$H_A = HT\ (\tau\ \alpha)$ = Solar energy absorbed by collector

Were used in equation (4 -10) to actualize our design.

The Area of Collector, A_C;

$$A_C = Q_L / \eta + H_T \qquad (4)$$

Where η = efficiency HT = total solar radiation, the total collector area was calculated to be $2.1m^2$

The efficiency η was calculated from;

$$\eta = F_R\ (\alpha\ \tau) - F_R\ U_L\ ((T_I - T_A) / H_T) \qquad (5)$$

The useful energy Qu was calculated as;

$$Q_U = F_R\ [H_T\ (\alpha\ \tau) - U_L\ (T_I - T_A)\ A_C] \qquad (6)$$

The useful energy gain per unit of collector area is given;

$$q_U = Q_U / A_C \qquad (7)$$

$$q_U = FR\ [H_T\ (\alpha\ \tau) - U_L\ (T_I - T_A)] \qquad (8)$$

Tank loss, $Q_{LOSS} = U_L\ A_C\ (T_S - T_{RM})$ (9) where, T_S = Storage tank temperature

The tank size was calculated from the number of the litres per meter square collector area. This range from 40 -70 litre/m^2 collector area. For our design, 70 litres/m^2 collector area was used and the surface area of the tank was then calculated to be $1.3926m^2$.

$$T_S^* = T_S + [dt / (MC_P)s]\ [Q_U - Q_L - Q_{LOSSES}] \qquad (10)$$

Where:

T_S is the initial storage temperature of 65°C
T_S^* = Final storage tank temperature
$(MC_P)s$ = 70 litres/m^2x total Surface Area

The final tank size and tank temperature for the building were calculated from equation (1 – 10) for both seasons (that is, Jan and July). The calculated values are shown in table 3 for dry seasons and table 4 for the rainy (wet) seasons. The daily tank hourly temperature for 12th of January is shown in fig. 8 and daily tank hourly temperature for July 12 is shown in fig. 9.

Table 3: Result for solar thermal application in dry season (12th Jan 2011)

Time(Hour)	Room Tempt	HT (MJ)	Ha	UL(Ti -Trt)	qu	η	Qu	QL	QLOSSES	Ts °C	Ts* °C
1	30		0	0.27	0	0	0	0.1	0.25	52.31	51.41
2	30		0	0.27	0	0	0	0.1	0.25	51.41	50.51
3	30		0	0.27	0	0	0	0.1	0.25	50.51	50.03
4	30		0	0.27	0	0	0	0.1	0.25	50.03	49.54
5	30		0	0.27	0	0	0	1.5	0.25	49.54	47.13
6	30	0.57	0.47	0.27	0.18	0.31	0.35	3.5	0.25	65	56.39
7	30	1.58	1.38	0.27	0.99	0.59	1.99	3.5	0.25	56.39	51.93
8	30	2.71	2.22	0.27	1.75	0.65	3.51	3.5	0.25	51.93	51.3
9	30	3.59	2.94	0.27	2.4	0.67	4.8	3.5	0.25	51.3	53.96
10	30	4.27	3.49	0.27	2.9	0.68	5.81	3.5	0.25	53.96	59.15
11	30	4.69	3.84	0.27	3.21	0.69	6.43	3.5	0.25	59.15	65.91
12	30	4.84	3.96	0.27	3.32	0.69	6.65	3.5	0.25	65.91	73.22
13	30	4.69	3.84	0.27	3.21	0.68	6.43	3.5	0.25	73.22	79.98
14	30	4.27	3.49	0.27	2.9	0.68	5.81	4.8	0.25	79.98	81.88
15	30	3.59	2.94	0.27	2.4	0.67	4.8	4.8	0.25	81.88	81.25
16	30	2.71	2.22	0.27	1.75	0.65	3.51	4.8	0.25	81.25	77.34
17	30	1.58	1.38	0.27	0.99	0.59	1.99	3	0.25	77.34	74.14
18	30	0.57	0.47	0.27	0.18	0.31	0.35	3	0.25	74.14	66.78
19	30		0	0.27	0	0	0	1	0.25	66.78	63.62
20	30		0	0.27	0	0	0	1	0.25	63.62	60.45
21	30		0	0.27	0	0	0	1	0.25	60.45	57.28
22	30		0	0.27	0	0	0	1	0.25	57.28	54.1
23	30		0	0.27	0	0	0	0.1	0.25	54.1	53.21
24	30		0	0.27	0	0	0	0.1	0.25	53.21	52.31
		39.66			26.18		52.43	54.5			

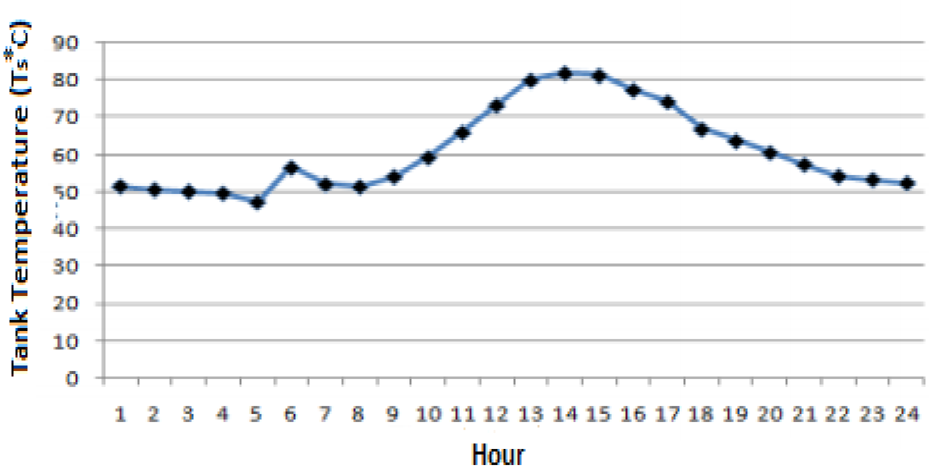

Figure 8: Daily tank temperature for 12th January 2011

Table 4: Result for solar thermal application in rainy season (12th July 2011)

Time(Hour)	Room Tempt	HT (MJ)	Ha	UL(Ti -Trt)	qu	η	Qu	QL	QLOSSES	Ts °C	Ts* °C
1	28		0	0.29	0	0	0	0.1	0.27	63.29	62.93
2	28		0	0.29	0	0	0	0.1	0.27	62.93	61.99
3	28		0	0.29	0	0	0	0.1	0.27	61.99	61.06
4	28		0	0.29	0	0	0	0.5	0.27	61.06	59.11
5	28		0	0.29	0	0	0	0.5	0.27	59.11	57.17
6	28		0	0.29	0	0	0	2.5	0.27	57.17	50.16
7	28	0.53	0.43	0.29	0.13	0.25	0.26	2.5	0.27	65	58.65
8	28	1.48	1.21	0.29	0.83	0.56	1.67	2.5	0.27	58.65	57.55
9	28	2.3	1.88	0.29	1.44	0.63	2.88	1	0.27	57.55	59.16
10	28	2.93	2.4	0.29	1.9	0.65	3.81	1	0.27	59.16	61.69
11	28	3.33	2.72	0.29	2.19	0.66	4.39	1	0.27	61.69	64.81
12	28	3.46	2.83	0.29	2.29	0.66	4.59	1	0.27	64.81	68.13
13	28	3.33	2.72	0.29	2.19	0.66	4.39	1	0.27	68.13	71.25
14	28	2.93	2.39	0.29	1.9	0.65	3.8	1	0.27	71.25	73.78
15	28	2.3	1.88	0.29	1.44	0.63	2.88	1	0.27	73.78	75.39
16	28	1.48	1.21	0.29	0.83	0.56	1.67	1	0.27	75.39	75.79
17	28	0.53	0.43	0.29	0.13	0.25	0.26	1	0.27	75.79	74.78
18	28		0	0.29	0	0	0	1	0.27	74.78	73.51
19	28		0	0.29	0	0	0	2	0.27	73.51	71.24
20	28		0	0.29	0	0	0	2	0.27	71.24	68.97
21	28		0	0.29	0	0	0	2	0.27	68.97	66.7
22	28		0	0.29	0	0	0	2	0.27	66.7	64.43
23	28		0	0.29	0	0	0	0.5	0.27	64.43	63.66
24	28		0	0.29	0	0	0	0.1	0.27	63.66	63.29
		24.6			15.27		30.6	27.4			

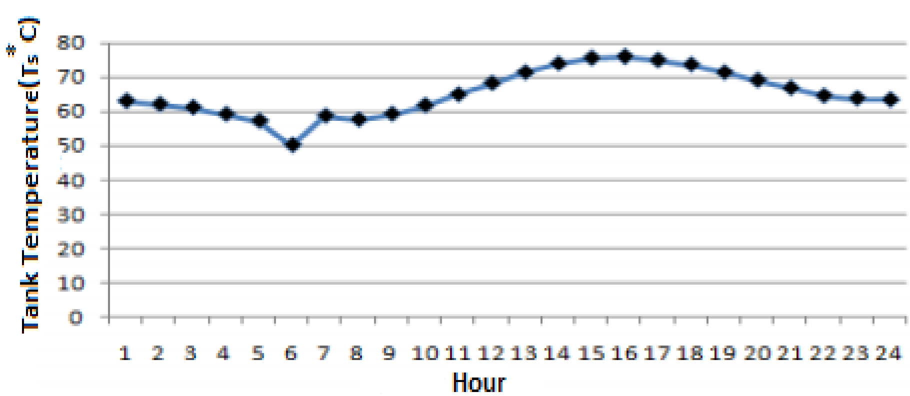

Figure 9: Daily tank temperature for 12th July 2011

DISCUSSION

From fig. 5 it was observed that the sun radiation was greater in the dry season (October – March) than in rainy season (April – September). The highest radiation was January and in the dry season and was used for the calculation of the collector area and the storage tank temperature. This calculated area was used to analyze the solar thermal system in July which gave the lowest radiation as is shown in fig. 4. The load of the building was increased to mitigate tank storage temperature which was above the boiling point temperature. This was due to the high solar intensity as is shown in table 4. From the analysis it was observed that the estimated collector area gave a moderate temperature. The loads and storage tank temperature used for both analyses were estimated for 24 hours period of the day. For both seasons the design results meet the anticipated result of storage tank temperature which is from 45° to 80°C.

CONCLUSION

From the design, the hourly and daily heat energy delivered by the system for both rainy and dry seasons are shown. It is anticipated that solar power hot water can reduce hot water system consumption by 70 percent. Also solar power systems are sustainable and are in line with the Kyoto protocol of December 1997. Due to the fact that the energy comes from the sun, solar hot water is produced at no cost and plays a major role in the reduction of household carbon pollution. Solar hot water system cost more than electric heater but it can pay for itself within 5 – 10 years dependency on the domestic hot water usage. Due to the environmental benefits the government needs to subsidize the cost for the initial installation.

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