Design of a Solar Water Heating System for Kuti Hall, University of Ibadan, Ibadan

ODESOLA, I.F. & T.G. OMOLAJA

Department of Mechanical Engineering, University of Ibadan, Ibadan, Nigeria
Email: if.odesola@mail1.ui.edu.ng; ifodesola@yahoo.com

Abstract

This work presents an energy audit to determine daily heating load and energy eliminated by Solar Water Heating (SWH) system. Monthly average daily irradiance in plane of solar collector and Cold water temperature calculated from weather data collated to determine heating load. Mathematical model was developed based on heat transfer, thermal and optical and energy performance of collector. The absorber plate area, dimensions of solar collector, pipes' diameter, mass flow rate, fluid inlet, outlet temperature, the overall loss coefficient are considered as variables. Optimization procedures formulated and models developed were transposed into a MATLAB computational program. Components selection was also carried out. Data was generated by increasing the absorber plate area from 1 to 20m^2 and the mass flow rate of fluid from 0.001 to 0.009 kg/s. The optimum values recorded for the area and mass flow rate are 18.33m^2 and 0:0087 kg/s respectively. Increasing the mass flow rate above the optimum determines the non change of Exergy efficiency. Heat load per day in KUTI Hall is 636.7MJ and the collector area obtained is 91.64m^2. 6.95MJ of heat is needed per meter square. The SWH system can cater for heating load of 115MJ/day which will sufficiently heat up 600 litres of water from 24^{0}C to 70^{0}C.

Keywords: Water Heater, Collector, Energy Audit, Absorber, Plate

Introduction

The utilization of renewable energy sources has remained one of the major areas of research, especially in the energy sector; due largely to different environmental challenges thrown up as a result of the utilization of fossil fuel in energy generation. Some examples of renewable energy sources are: biofuel, biomass, geothermal, hydroelectricity, solar energy, tidal power, wave power, wind power etc. These renewable energies come from natural sources such as sunlight, wind, rain, tides, and geothermal heat, which are naturally replenished. These energies are used for heating, either for domestic purposes or for industrial purposes (Mark et al, 2010). This paper discusses the design of a solar water heating system for domestic use in Kuti hall of residence, University of Ibadan.

The Solar Water Heater (SWH)

Solar water heaters also called solar domestic hot water system utilize the energy from the sun to heat water for domestic uses. It is a cost effective way of generating hot water for domestic use. It can be applied in any climate, while the fuel use (sunshine) is free. Solar water heating systems include storage tanks and solar collectors. There are two types of solar water heating systems: active and passive water heating systems (Fagbenle, 1991a).

The active water heating systems have circulating pumps and controls for circulating water or heat transfer fluid (HTF) between the collector and the storage tank. There are two types of active solar water heating systems: direct circulation systems and indirect circulation systems. In the former, pumps are used to circulate house hold water through the collectors and into the home. They work well in climates where it rarely freezes. In the later, pumps circulate a non-freezing, heat-transfer fluid through the collectors and a heat exchanger. This heats the water that then flows into the home. They are popular in climates prone to freezing temperatures (Smyth et al, 2006).

Passive solar water heating systems are typically less expensive than active systems, but they are usually not as efficient. In the passive system, the tank acts as both storage and solar collector. However, passive systems can be more reliable and may last longer than the active systems.

There are two basic types of passive systems: integral collector storage passive systems and thermo-siphon systems. The integral collector storage passive system work best in areas where temperatures rarely fall below freezing. They also work well in households with significant daytime and evening hot-water needs. In the thermo-siphon system, water flows through the system when warm water rises as cooler water sinks. The collector is installed below the storage tank so that warm water will rise into the tank. These systems are reliable, but designers must pay careful attention to the roof design because of the heavy storage tank. They are usually more expensive than integral collector-storage passive systems (Schmidt and Goetzberger, 1990).

Types of solar collectors

There are three types of solar collectors used for domestic applications:

Flat plate collector

Glazed flat plate collectors are insulated, weatherproof boxes that contain a dark absorber plate under one or more glass or plastic covers. Unglazed flat plate collectors, typically used for solar pool heating, have a dark absorber plate, made of metal or polymer, without a cover or enclosure.

Integral collector storage systems

Also known as ICS or batch systems, they feature one or more black tanks or tubes in an insulated, glazed box. Cold water first passes through the solar collector which preheats the water. The water then continues on to the conventional backup water heater, providing a reliable source of hot water. They should be installed only in mild-freeze climates because the outdoor pipes could freeze in severe cold weather.

Evacuated tube solar collectors

They feature parallel rows of transparent glass tubes. Each tube contains a glass outer tube and metal absorber tube attached to a fin. The fin's coating absorbs solar energy but inhibits radiative heat loss. These collectors are used more frequently for commercial applications (Marken, 2009).

The first solar water heaters were bare metal tanks painted black containing water and tilted to face the sun. The shortcoming of the bare tank solar water heaters was noticed by Clarence Kemp of Baltimore, Maryland, who used to sell the latest home heating equipment. In 1891, Kemp combine the old practice of exposing metal tanks to the sun with the scientific principle of the hot box where glass-covered box system is used, thereby increasing the tanks' capability to collect and retain solar heat. He called his new solar water heater the Climax. A gradual shift occurred with technological development, from the Climax tanks to a solar panel for solar water heater. Designs suitable for hot climates can be much simpler and cheaper, and can be considered appropriate technology for these places. The global solar thermal market is dominated by China, USA, Europe, Japan, Israel and India (REN21).

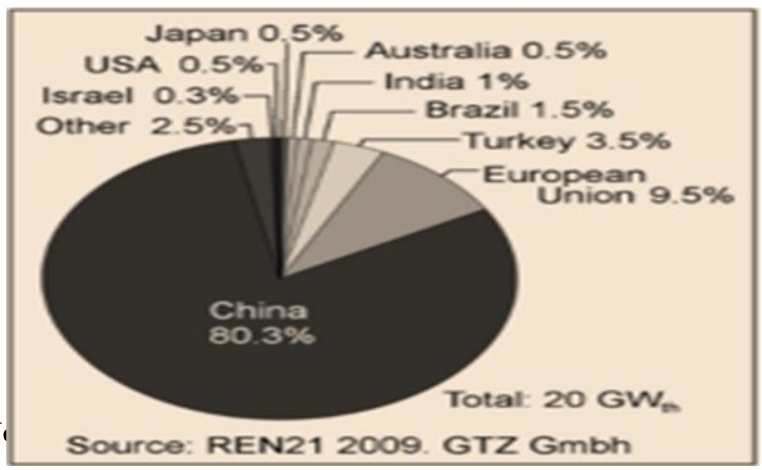

Fig. 1: N

In order to heat water using solar energy, a collector, often fastened to a roof or a wall facing the sun, heats the working fluid that is either pumped (active system) or driven by natural convection (passive system) through it. The collector can be made of a simple glass topped insulated box with a flat solar absorber made of sheet metal attached to a copper pipes and painted black, or a set of metal tubes surrounded by an evacuated glass cylinder. In industrial cases, a parabolic mirror can concentrate sunlight on the tube. Heat is stored in a hot water storage tank. The volume of this tank needs to be larger than the solar heating system in order to allow for bad weather, and because of the optimum final temperature for the solar collector is lower than a typical immersion or combustion heater. The heat transfer fluid for the absorber may be the hot water from the tank, but more commonly is a separate loop of fluid containing anti-freeze and a corrosion inhibitor which delivers heat to the tank through a heat exchanger. Another lower maintenance concept is the 'drain-back'; no anti-freeze is required, instead all the piping is slopped to cause water to drain back to the tank. The tank is not pressurized and is open to atmospheric pressure. As soon as the pump shuts off, flow reverses and the pipes are empty before freezing can occur (Fagbenle, 1991b).

Methodology

First, an energy survey is carried out, followed by risk evaluation and solar site survey. This will help to decide where the system will be built. The project when completed will provide hot water for more than 600 resident students for domestic use such as bathing.

Energy audit of Kuti Hall

A walk-through energy audit was carried out so as to ascertain sources of major energy utilization. This includes recording of the electrical rating parameters of all equipment, electrical bill analysis, fuel consumption and bills (Odesola, 2009 & Odesola, 2010). Kuti hall has five blocks (A – E) with 207 rooms. The major electrical appliances available in most rooms include: hot plate, electric kettle/jug, boiling ring, electric iron, laptop, television, electric fan, electric bulb, rechargeable lamps, refrigerator, and bread toaster. Table I below shows the energy consumption per block in kWh.

Table I: Energy audit of all blocks in Kuti Hall

S/NO	Block	No of Rooms	Energy Consumption (kWh)
1	A	27	191.11
2.	B	75	517.62
3.	C	42	372.24
4.	D	36	252.34
5.	E	27	187.16
Total		**207**	**1520.47kWh**

Some of the equipment listed above are not used in producing hot water, as such cannot be eliminated by solar water heating system. Table II below is a summary table of energy to be eliminated by the Solar Water Heating System.

Table 2: Energy consumption (KWh) by equipment used majorly for hot water

S/No	Block	No of Rooms	Energy Consumption (kWh) by Equipment used majorly for hot water
1	A	27	114
2.	B	75	317
3.	C	42	181
4.	D	36	150
5.	E	27	115
Total		**207**	**877kWh ≈0.87MWh**

Table 3 below gives a comparison of the total energy consumption in all the blocks for equipments used majorly for hot water production and total energy consumption in kWh.

Table 3: Summaries of total energy

S/No	Block	No of Rooms	Energy consumption by equipment used majorly for hot water (kWh)	Total Energy Consumption for Kuti Hall (kWh)
1	A	27	114	191.11
2.	B	75	317	517.62
3.	C	42	181	372.24
4.	D	36	150	252.34
5.	E	27	115	187.16
Total		**207**	**877kWh ≈0.87MWh**	**1520.47kWh**

The percentage consumption by hot water heating equipment is given as

$$\frac{877.0}{1520.47} \times 100 = 57.67\% \approx 60\%$$

Converting the energy consumption into joule which is the unit for heat, we have $1kWh\ (kilowatt - hour) = 3.6MJ \therefore$ $877kWh = 3.6 \times 877 = 3157.2MJ$

The purpose of the energy audit is to determine the load (in Mega-Joule) performance of the Solar Water heater for the hall. Total Energy Consumption (kWh) by appliances used majorly for hot water production is about 877kWh which is equivalent to 3157.2MJ of heat. We will now design a solar system with an average daily load pattern of 3157.2MJ.

Calculation of solar energy variables

The following equations are used in calculating the variables used in the design of the model. *The declination* (δ) is the angular position of the sun at solar noon, with respect to the plane of the equator. Its value in degrees is given by Cooper's equation.

$$\delta = 23.45\sin(2\pi\frac{284+n}{365}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where n is the day of the year (i.e. n =1 for January 1)

Solar hour angle (ω_s) is the angular displacement of the sun east or west of the local meridian; morning negative while afternoon positive.

$$\cos\omega_s = -\tan\varphi\tan\delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where $\delta = declination$,

$\varphi = latitude\ of\ the\ site\ (the\ latitude\ of\ Ibadan\ is\ 7.43°N)$

Extraterrestrial radiation (H_0) for the day of the year n is given as:

$$H_0 = \frac{864G_{sc}}{\pi}\left(1+0.033\cos 2\pi\frac{n}{365}\right)(\cos\varphi\cos\delta\sin\omega_s + \omega_s\sin\varphi\sin\delta) \quad \ldots\ldots (3)$$

Tilted Irradiance (H_T)

$$H_T = H_bR_b + H_d\left(\frac{1+\cos\beta}{2}\right) + H_{\rho g}\left(\frac{1-\cos\beta}{2}\right) \quad \ldots\ldots\ldots\ldots (4)$$

Where β = slope of the collector; H_d = monthly average diffuse radiation; ρg = reflection of radiation on ground in front of the collector.

Cold water temperature (T_s)

$$T_s = \frac{T_{min}+T_{max}}{2} - \frac{T_{max}-T_{min}}{2}h\cos(2\pi\frac{n-2}{12}) \quad \ldots\ldots\ldots\ldots (5)$$

Estimated load calculation

Energy Required (Q_{load})

$$Q_{load} = C_p\rho V_l(T_h - T_c) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

T_c = Cold water temperature

T_h = Required hot water temperature

Optical Analysis (S)

$$S = (\tau\alpha)I_T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

Where I_T is the effective product transmittance-absorbance equal with the optical efficiency.

Exergy analysis

The general form of the Exergy balance equation is

$$E_{in} + E_s + E_{out} + E_l + E_d = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where E_{in}, E_s, E_{out}, E_l and E_d are the inlet, stored, outlet, leakage and destroyed Exergy rate.

Design of the collector

The flat plate collector design is based on the Duffie and Beckman, 1991 equation. *Energy collected per unit collector area per unit time* (Q_{coll}) is

$$Q_{coll} = F_R(\tau\alpha)G - F_R U_L \Delta T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

F_R is the collector's heat removal factor, τ is the transmittance of the cover, α is the shortwave absorptivity of the absorber, G is the global incident solar radiation on the collector, U_L is the overall heat loss coefficient of the collector, and ΔT is the temperature differential between the working fluid entering the collectors and outside.

Determination of area of collector (A_c)

$$Q_{load} = A_c F_R(\tau\alpha)H_T\varphi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

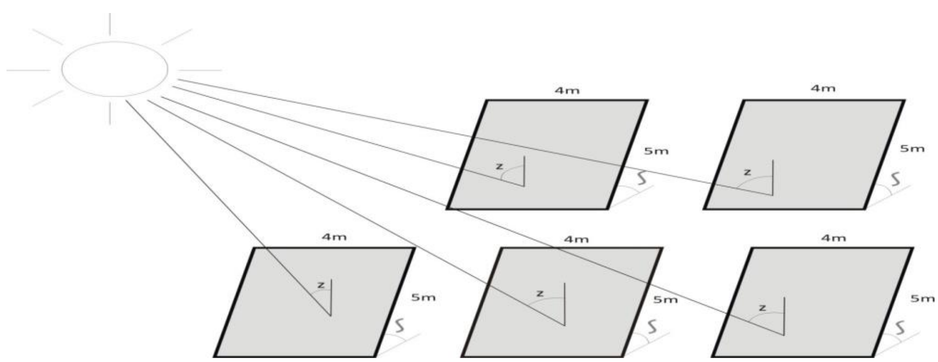

Fig 3: Illustrative diagram of Collector area of 20m² for each building in Kuti

θz = incident angle = 10° for south facing collectors n areas with latitude less than 8.5°N

S = tilt angle = latitude + 10°

Tank design

Number of rooms = 207
Approximate number of students per room = 3
Approximate total number of students = 3 x 207 = 621 students
Average capacity of electric kettle or jug = 4litres
Quantity of hot water needed by all students = 4litres x 621 = 2482

$$4 litres \times 621\ students = 2484\ litres \approx 2500 litres$$

Assumed size of tank = 3000 litres

Results and discussion

Figures 4-7 show the behaviour of the Exergy efficiency as a function of the mass flow rate of fluid and the absorber plate area. The incremented quantities are the absorber plate areas that ranged from 1 to 20.0 m^2 and the mass flow rate of fluid from 0.001 to 0.009 kg/s. The calculated values for the global maximum point are A_p = 20.0 m^2, m = 0:0087 kg/s, η_{ex} = 3.898%. It was observed that the coordinate of the maximum point is equal with the values of optimized parameters. Increasing the mass flow rate above the value of m = 0:0087 kg/s determines the non change of Exergy efficiency for A_p = 20m^2. This allows the designer to optimize the solar collector regarding other conditions such as design limitations and thermal applications. Whereas, decreasing the mass flow rate below the value of m = 0:0087 kg/s determines the sensible decrease of Exergy efficiency for A_p = 20m^2. Since heat required per day in KUTI Hall is 636.7MJ and the A_p calculated is 91.6378m^2, 6.948MJ of heat is needed per m^2 of the absorber plate. The SWH system can cater for heating load of 115MJ/day which will sufficiently heat up 600 litres of water from T_{in} (24^{0}C) to T_{out} (70^{0}C) on the average, hence ΔT = 46^{0}C. This is equivalent to the average T_{out} from the simulation results. It will cost N1, 780,000 to build 5 units of the Solar Hot Water System for the Hall (Table 8).

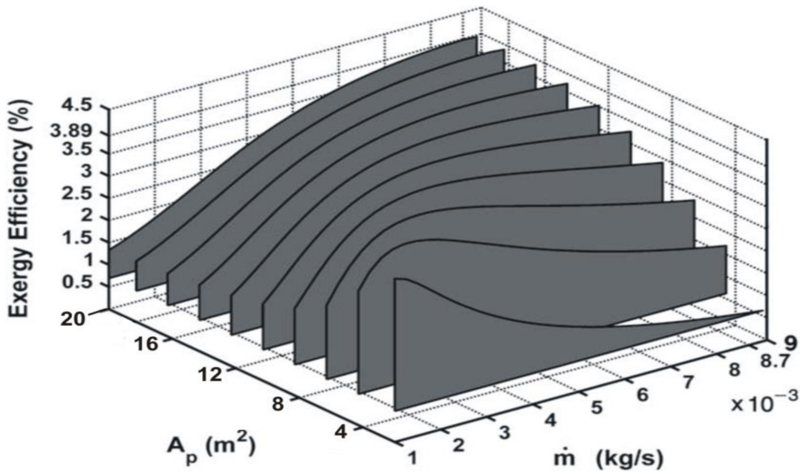

Fig. 4: Shows the variations of the exergy efficiency according to the mass flow rate of fluid efficiency versus the pipes' diameter by increasing the pipes' and absorber plate area

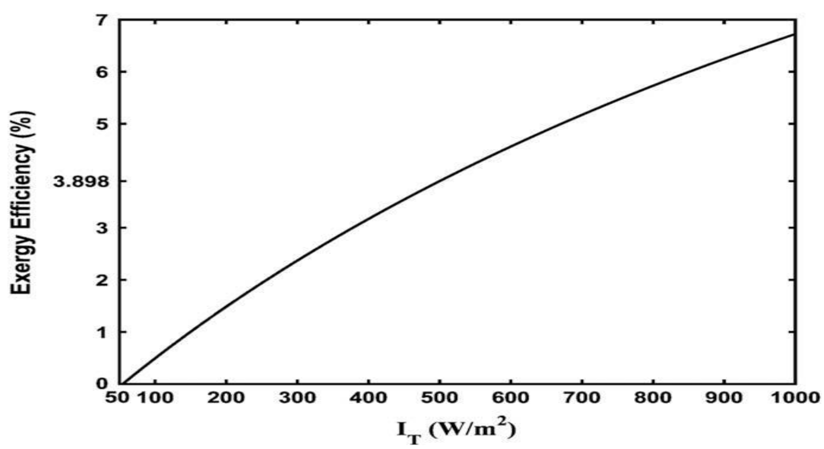

Fig. 5: The variations of the exergy efficiency versus the incident solar energy per unit area of absorber plate

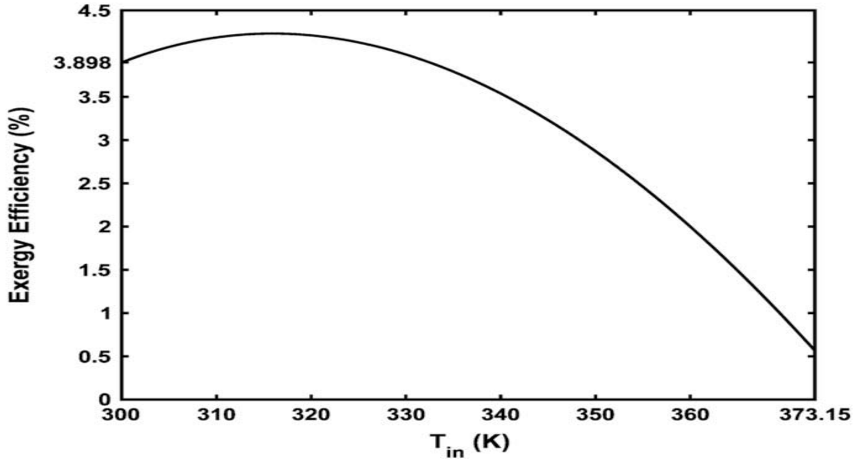

Fig. 6: The variations of the exergy efficiency versus the fluid inlet temperature

Cost savings

The solar water system in Kuti hall of residence is designed such that it will cater for 636.7MJ/day
1kWh = 3.6MJ
636MJ = 636/3.6 = 176.67kWh
University of Ibadan Tariff = N11/kWh
From the above, we have ₦ 176.67 x 11 = ₦ 1943.37 to be saved per day.
Cost savings in a - month = ₦ 1943.37 x30days = ₦58, 301.1
Cost savings in a year = ₦ 58, 301.1 x12months = ₦ 699, 613.2

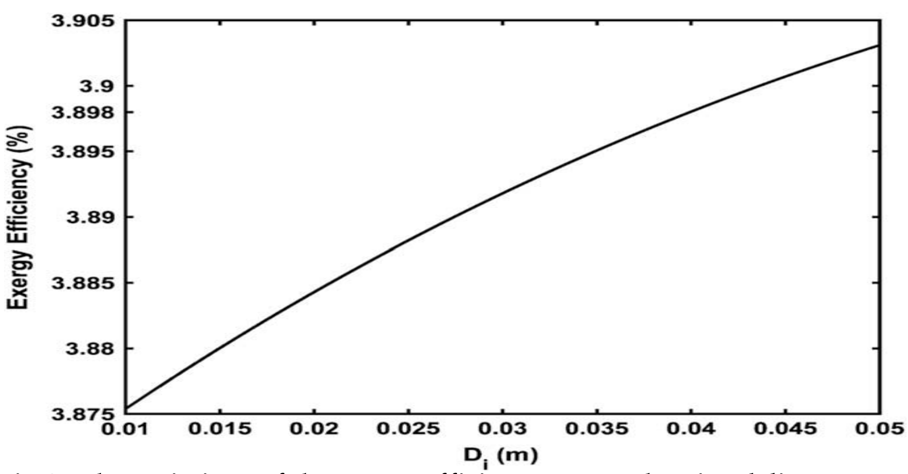

Fig. 7: The variations of the exergy efficiency versus the pipes' diameter

Table 8: Investment calculation

S/N	System comp.	Unit measurement /Size	Qty	Unit price	Amount (N)(costs)
1.	Collector plate	20m²	5	1m² = 15000	1,500,000
2.	Pipes	100yards, thickness-0.04m	-		105,000
	Tank construction	Size -600ltrs	5	18500	92500
	Insulation of pipes	Recommended Insulation thickness- 1 inch,	4 spray cylinders	2500	10000
3.	Supply tank	3000 litres size	1	18500	18500
4.	Pump frm supply tank	1hp	1	24000	24000
5.	Collector structure	-	5	3000	15000
6.	Storage tank stand	-	5	3000	15000
				Total	**1,780,000**

Conclusion

The energy audit for Kuti hall of residence was carried out in order to determine daily heating load and energy eliminated by Solar Water Heating (SWH) system. Energy delivered by hot water systems with storage is estimated. Monthly average daily irradiance in plane of solar collector and Cold water temperature were calculated from weather data collated to determine heating load. The computer simulation result was in good agreement with the widely known experimental data viewed. This further proved that designed solar water heating system will fulfil its purpose. The project has an initial cost of N1, 780,000. The economic analysis showed that the project will save N699, 613.2 per year. Payback time will be in the third year. This is because by the third year (699, 613.2 x 3yrs = 2,098,839.6) would have been saved which is above the initial capital cost of 1,780,000.

References

Duffie, J.A. and W.A. Beckman (1991). *Solar Engineering of Thermal Processes, 2nd Edition*, John Wiley & Sons, New Jersey, USA.

Fagbenle, R.L. (1991a). Monthly average of daily extraterrestrial solar radiation for Nigerian Latitudes. *Nigerian Journal of Renewable Energy*. Vol. 2., pp. 1-8.

Fagbenle, R.L. (1991b). Optimum collector tilt angle and average annual global radiation for Nigerian locations. *Nigerian Journal of Renewable Energy*. Vol. 2., pp. 9-17.

Jacobson, M.Z. and M.A. Delucchi (2009). "A Path to Sustainable Energy by 2030". Scientific American 301(5):58-65. Doi:10.1038/scientific American 110 9-58. PMID 19873905.

Mark, Z.J. and A.D. Mark (2010). "Providing all global energy with wind, water and solar power; Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials" Energy Policy. Elsevier Ltd.

Marken, C. (2009). Solar Collectors – Behind the glass. *Home Power.* Vol. 133, 70-76.

Odesola, I.F. (2009). A survey on the Energy Consumption and Demand in the Post Graduate School, University of Ibadan. A Technical Report Submitted to the Dean, Post Graduate School, University of Ibadan, Ibadan.

Odesola, I.F. (2010). A survey on the energy consumption and demand in a school. International Journal of Sustainable Development, Volume 3, Number 3.68-75.

REN21 – "Renewable Energy and Policy Network for the 21st Century". Retrieved May 20, 2010 from http://www.ren21.net/globalstatusreport/g2009.asp.

Schmidt, C. and A. Goetzberger (1990). Single-tube integrated collector storage systems with transparent insulation and involute reflector. *Solar Energy*. Vol. 45, 93-100.

Smyth, M., P.C. Eames and B. Norton (2006). Integrated collector storage water heaters. Renewable and Sustainable Energy Reviews. Vol. 10, 503-538.