

# A microcontroller-based Active Solar Water Heating System for Domestic Applications

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**Abstract-** A potential solution to adequate and sustainable electricity supply problems in most developing countries is dependent on proper harnessing of solar (radiant) energy. Owing to the over dependence on fossil-fuel based energy, there is an exponential rise in carbon dioxide (CO<sub>2</sub>) emissions into the atmosphere, thereby causing severe environmental degradation and ozone layer depletion. This paper seeks to apply the readily available radiant energy source to solar water heating, and establish possible economic benefits to its use in domestic applications for residents of Covenant University campus. The microcontroller-based active solar water heating system (ASWHS) is designed to effectively absorb radiant energy using solar collectors, and store it as hot water in a water tank via a direct current (DC) circulation pump powered by a stand-alone photovoltaic (PV) system. The design also incorporates an auxiliary electric heater which is put to use only when there is insufficient radiant energy. A case study is reported to show the importance of the ASWHS for domestic water heating. The maximum design efficiency and the expected energy output of the solar collector throughout its working life is 79.94% and 498,225kWh respectively. A reduced dependence on grid supply and/or fossil-fuel based generator sets during hot water demand periods is recorded using the ASWHS with a high payback period of 15 years; and a lower unit cost (US\$0.01/kWh) of the ASWHS makes it more economically viable as compared to the unit cost (US\$0.18/kWh) of the grid supply for the same amount of energy consumed.

**Keywords-** ASWHS, CO<sub>2</sub> emissions, microcontroller, solar energy, solar collector, unit cost.

## 1. Introduction

Solar energy is a naturally occurring renewable energy source obtained directly from the sun. There is a growing increase in the demand of sustainable power supply for domestic and industrial applications. Literature review reports have emphasized the reliable contributions of solar energy to sustainable energy production [1-5]. Conventional power generation majorly focuses on burning fossil fuels which have adverse effects on the environment. Hence, there is a desire need to consider renewable energy sources to save our planet from sudden collapse. The application of solar energy to heating water for domestic and industrial purposes will reduce the accumulation of CO<sub>2</sub> compounds that would have been

produced from burning fossil fuels. Most companies are now becoming conscious of the need for cleaner energy sources – they calculate their carbon footprints and are expected to reduce the amount of CO<sub>2</sub> emissions they contribute as environmental pollution [6].

The amount of solar power on a unit surface is measured in W/m<sup>2</sup>. Nigeria receives very high intensity of sunlight during the dry seasons (October to April) with about 7 hours per day of sunshine in the northern regions close to the Sahel and about 6 hours per day of sunshine in the southern regions close to the Atlantic [7]. Several factors have been considered to reduce the intensity of solar radiation reaching our planet such as insolation, transparency and properties of earth's surface, albedo and absorption in atmosphere, cloud cover and aerosol

concentrations, and revolution of the earth around the sun [8]. The method of harnessing solar energy puts into consideration material factors such as durability of materials, conductivity of materials, specific heat capacities of materials, resistivity of insulating materials, heat transfer efficiency (convection in fluids), colour and heat absorption of materials, reflective power of materials, tracking ability of solar trackers and more.

The energy consumed by an electric water heater in kWh/day is the product of the number of hours and its rated power in kW. Therefore, for a domestic electric water heater of 1.5kW, the energy consumed when used for a 2-hour period in a day is 3.0kWh/day. A unit cost of US\$0.18 per kWh of electricity for households in Covenant University campus gives a cost of US\$0.54 for using the electric water heater for that day. In Covenant University (Lat. 6.67°N, Long. 3.15°E), effective solar radiation ranges between 3 – 6 hours during clear weather days. The solar water heater would only be in operation in the hot mornings and afternoons. Therefore, a solar collector can be used in place of an electric water heater during these periods. With world population increasing on a daily basis, there is a subsequent increase in the number of people that will require energy in one form or the other. The result of this is an overall increase in energy demand per capita which when unavailable or inadequate results in power outages, overloading and at times competition for power sources as available natural fuel resources diminish due to their continuous exploitation worldwide.

Several literatures have clearly given a background history of solar water heating systems [9], dating back to the late nineteenth and the early twentieth centuries. Heating water dominates the energy usage of households worldwide. In US households, heating water is second only to space heating and air conditioning in energy consumption. For households in developing nations, heating water is often the most energy intensive process, and therefore the most expensive and time intensive[10]. Water heating is a major energy consumer worldwide. It is required year round, making it a good application of solar energy.

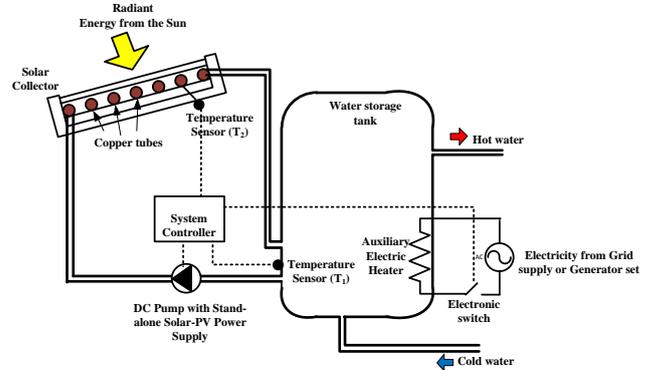
The solar water heating system can be classified into two types: the active and the passive systems. The active system incorporates the use of a pump for forced water circulation as compared to the passive system design which employs the natural rise of hot water as temperature increases. The passive systems are less expensive, affordable, and easy to set up and maintain compared to their active counterparts [11]. However, for larger and faster production of hot water, active systems are more reliable as presented in this study.

**2. Methodology**

**2.1. System Operation**

A solar collector consisting of copper tubes placed underneath black-painted aluminium fins and covered in

glass for solar absorption and containment, is strategically placed in a position where there is adequate sunlight. Short wave radiation from the sun hits the flat-plate collector to heat up circulating water that finally gets stored in a thermally insulated hot water tank. Figure 1 shows a schematic diagram describing the operation of the microcontroller-based ASWHS.



**Fig. 1.** The microcontroller-based ASWHS schematic diagram

It can be seen that cold water is supplied into the base of the water tank, and then, with the aid of a DC circulation pump, water undergoes forced circulation from the tank to the flat-plate collector and back to the tank as stored hot water after been heated up to the desired temperature set by the system controller. Temperature sensors are strategically placed in the flat-plate collector and the storage tank, and are used in setting the desired temperature of water by the system controller comprising a microcontroller as it monitors and records the difference in real-time between the temperature of water in the storage tank and the temperature of the flat-plate collector.

The in-flow and out-flow of water through the solar collector is controlled by a control loop. The controller used is a microcontroller with the two temperature sensors connected to it. To start the heating process, the temperature of water in the storage tank must be less than that of the solar collector, else the DC pump remains “OFF” until the temperature difference is above the minimum set value required to start the water-heating process (4°C in this case). Here, the microcontroller acts as a differential temperature control device which sends a signal to excite or turn “OFF” the DC pump if the temperature difference ( $\Delta T$ ) between the collector and tank is above or below 4°C respectively. The temperature sensors are placed: one at the solar collector’s fluid exit and the other placed close to the bottom of the tank where the water is coolest. This will help the system controller know when the DC pump should be excited to pump water from the tank to the collector, and when the auxiliary electric heater should go “OFF” at the specified temperature change.

The auxiliary electric heater is included for situations where solar radiation is low. The initial operation of the electric heater is initiated manually, but automatically, when the system controller disconnects it from the mains supply via an electronic switch. The conventional electric water heater usually incorporates a thermostat to

intermittently stop the electric heating process when the water is heated to the required temperature (i.e. in the Electric Mode). As water is taken from the storage tank, there is need to refill it through the public supply. This is done using the floatation method adopted by conventional water closet systems and bathroom water heaters, which would allow in-flow of water from the public supply and stops it when the tank is filled up.

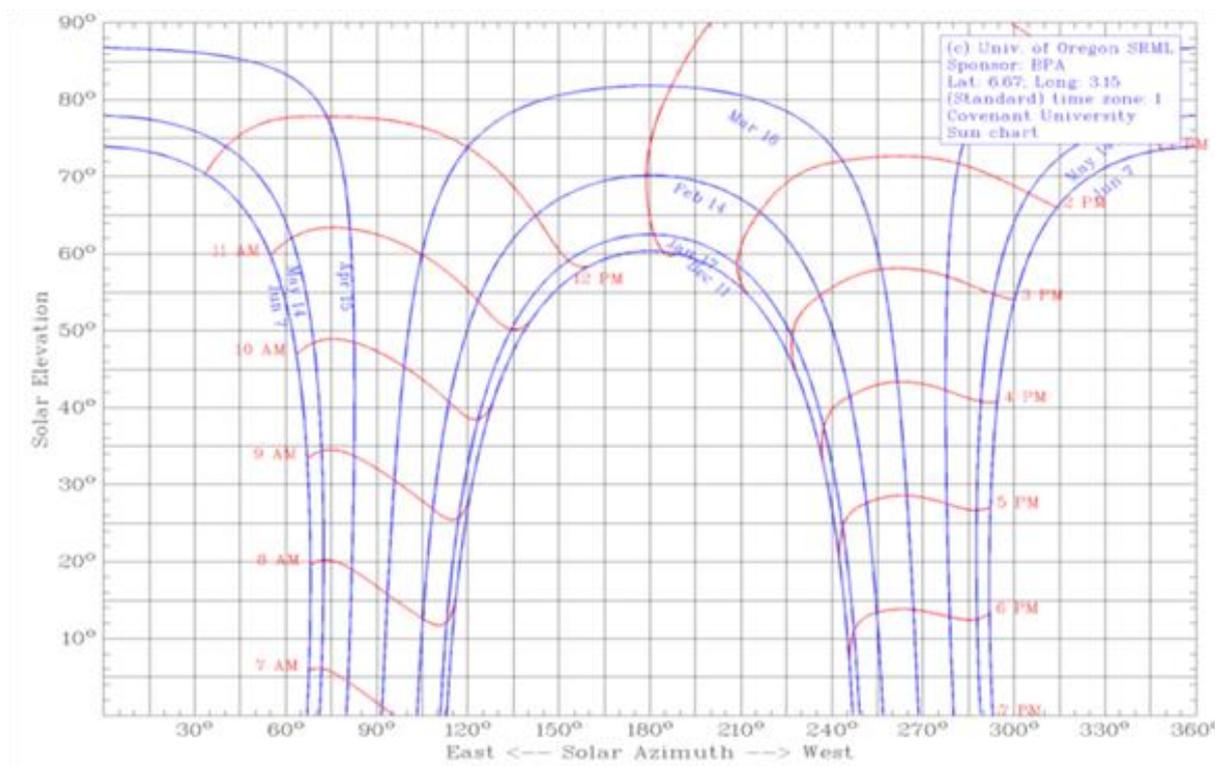
2.2. Collector Location

Solar radiation is one major factor to be considered in the location, installation, and use of the solar option in energy production. Locations with no adequate or good sunlight will be bad investment for the installation of solar collectors. Therefore, before any system planning, adequate and effective survey of the proposed location in question needs to be carried out to measure and ascertain how much sunlight is received by the location at specific periods of time, usually at peak periods. From meteorological data of Table 1, Covenant University has been found to have a high annual average solar radiation intensity of 414.89W/m<sup>2</sup>, making it a desirable location for

the installation of solar water heaters for domestic use. The study location which is in the southern part of the country have lower solar irradiance compared to their northern counterparts which can have solar irradiance values of over 1000W/m<sup>2</sup>.

**Table 1.** Monthly average solar radiation intensity for Covenant University (Lat. 6.67°N, Long. 3.15°E) for year 2011 [4]

Month	Solar Radiation Intensity, I (W/m <sup>2</sup> )
Jan	388.82
Feb	413.64
Mar	433.21
Apr	435.98
May	425.41
Jun	416.18
Jul	418.40
Aug	427.67
Sep	430.12
Oct	416.88
Nov	393.48
Dec	378.93



**Fig. 2.** Sun chart for Covenant University

In every location, the sun moves from the east to the west (i.e. it rises at the east and sets at the west). The position and elevation of the sun for a particular place at different points in time in a day can be obtained using the sun chart; a program designed by Oregon University for the purpose of graphically evaluating the amount of solar obstruction on a particular location [12]. Figure 2 is the sun chart generated for the location under study, and it is

required to get an optimum position and angle of elevation of solar collectors for areas of least shading. Shading is the potential angular obstruction from the sun caused by various high rise buildings or tall structures which will reduce the amount of solar radiation reaching the collectors [13]. The challenge of shading can be solved by either tilting the collector more towards the east, changing the position of the collector so that the angle of elevation

of the shading is reduced, or by increasing the angle of inclination of the collector. Figure 2 is the sun chart for Covenant University for the months of December 2010 to June 2011 the following year.

Using the sun chart, the solar collector of the automated solar water heating system can be installed at locations where there is least shading in order to have the best output from the solar collector for the chosen location.

### 3. Systems Design

#### 3.1. Collector Design

To start the collector design process, the amount of solar radiation available at the test location has to be obtained by measuring the radiation over a period using a pyranometer and recording the data in a computer, and then calculating monthly or yearly average values. Ref. [7] is the National Aeronautics and Space Administration (NASA) website that provides meteorological data as shown in Table 1 for the study location from archives according to longitude and latitude obtained from Google Maps.

##### 3.1.1. Collector Area

In the design of solar water heating systems, the collector area is a very important design consideration. The collector area is calculated by using the following equations (1) to (7) [14,15]. The amount of solar radiation received by the collector is:

$$Q_{in} = I \times A_c \quad (1)$$

where  $Q_{in}$  is the collector heat input, W;  $I$  is intensity of solar radiation,  $W/m^2$ ; and  $A_c$  is the collector area,  $m^2$ .

However, due to the rate of transmission of the glazing and the absorption rate of the absorber which accounts for part of solar radiation reflected back to the sky and some absorbed by the glazing, and the remaining gets transmitted through the glazing and reaches the absorber plate as short wave radiation, equation (1) becomes:

$$Q_{in} = I(\tau\alpha) \times A_c \quad (2)$$

where  $\tau$  is the transmission coefficient of glazing, and  $\alpha$  is the absorption coefficient of collector plate.

As a result of convection and radiation, heat is lost to the atmosphere as the collector temperature gets higher than the surrounding temperature. The rate of heat loss ( $Q_{loss}$ ) is dependent on the collector overall heat loss coefficient ( $U_L$ ) and the collector temperature, and is given as:

$$Q_{loss} = U_L A_c (T_c - T_a) \quad (3)$$

where  $T_c$  is the collector temperature, °C; and  $T_a$  is the ambient temperature, °C.

It can be concluded thus, that the rate of useful energy extracted by the collector ( $Q_{out}$ ) under steady state conditions, is proportional to the rate of useful energy absorbed by the collector, less the rate of heat loss to the surroundings. This is expressed as follows:

$$Q_{out} = Q_{in} - Q_{loss} = I(\tau\alpha) \times A_c - U_L A_c (T_c - T_a) \quad (4)$$

The rate of useful energy extracted from the collector can also be expressed as a measure of the amount of heat transferred to the fluid passing through it.

$$Q_{out} = mc_p (T_{out} - T_{in}) \quad (5)$$

where  $m$  is mass flow rate of fluid through the collector, kg/s;  $c_p$  is specific heat capacity of water, kJ/kg-K;  $T_{out}$  is outlet fluid temperature, °C; and  $T_{in}$  is inlet fluid temperature, °C.

Equating equations (4) and (5), the collector area ( $A_c$ ) is expressed as:

$$A_c = \frac{mc_p (T_{out} - T_{in})}{I(\tau\alpha) - U_L (T_c - T_a)} \quad (6)$$

Equation (6) is modified because of the difficulty in defining the collector average temperature. Therefore, it is assumed that the whole collector surface were at the fluid inlet temperature (i.e.  $T_c = T_{in}$ ). The equation now becomes:

$$A_c = \frac{mc_p (T_{out} - T_{in})}{I(\tau\alpha) - U_L (T_{in} - T_a)} \quad (7)$$

##### 3.1.2. Collector Tubing

For larger capture area of solar radiation onto the collector surface so as to get more heating per surface area, copper tubes of ½ inch diameter are bent into coil shapes. Absorber fins made of aluminium sheets are placed over the copper tubes and then fastened to the collector casing. The aluminium sheets are then painted black to increase the collector absorption coefficient.

##### 3.1.3. Collector Casing

A wooden frame made of plywood is constructed to hold the collector and the glass that will be used for glazing. The surrounding edges, bottom and sides of the casing are properly insulated to reduced heat loss by convection and conduction. Caulking using silicon on open edges is done to prevent heat loss by convection while polystyrene insulation is done at the bottom and sides to prevent heat loss by conduction.

##### 3.1.4. Collector Angle of Inclination

For a collector to function optimally, it should be inclined at a specific angle, and large deviations from the optimum angle will result in significant losses in energy produced [16]. In tropical regions, where latitude is less than 36 degrees, the duration of effective collector

irradiation is constant the whole year and the optimal collector angle is given as:

$$\theta_{\max} = \phi_{\text{Lat.}} \quad (8)$$

where  $\theta_{\max}$  is the maximum tilt angle, and  $\phi_{\text{Lat.}}$  is the latitude of the location.

So the optimal angle is equal to the latitude of the region where the collector is to be installed. Covenant University is at a latitude equivalent to  $6.67^\circ$  (this is the optimal angle).

### 3.2. Electrical Hardware

#### 3.2.1. System Controller

A microcontroller is required for the overall system control of the automated solar water heating system. An algorithm of the design considerations of the system controller and its surrounding circuitry is as shown in the flow chart of Fig. 3. An electronic switching circuit is required for the operation of the DC circulation pump and the auxiliary electric heater.

#### 3.2.2. Display Unit - the liquid crystal display (LCD)

It is relevant to display the atmospheric, water, and collector temperature values, with either of the two heating operating modes (Solar Mode or Electric Mode) for the ASWHS also displayed. A digital display would make a microcontroller much more user-friendly and also allow data to be outputted in a more versatile manner. The LCD used are alphanumeric (or graphic) displays which are frequently used in microcontroller-based applications. These display devices come in different shapes and sizes. A LCD can display units for large text. Availability and ease of the set up makes the parallel LCD the preferred choice for the systems display unit.

#### 3.2.3. Analog-to-Digital Converter (A/D) Module and Representation

The A/D module is required to accurately determine the temperature of the water and also the collector. An analog-to-digital converter (A/D) is an important peripheral component of a microcontroller. The A/D converts an analog input voltage into a digital number so it can be processed by a microcontroller or any other digital system.

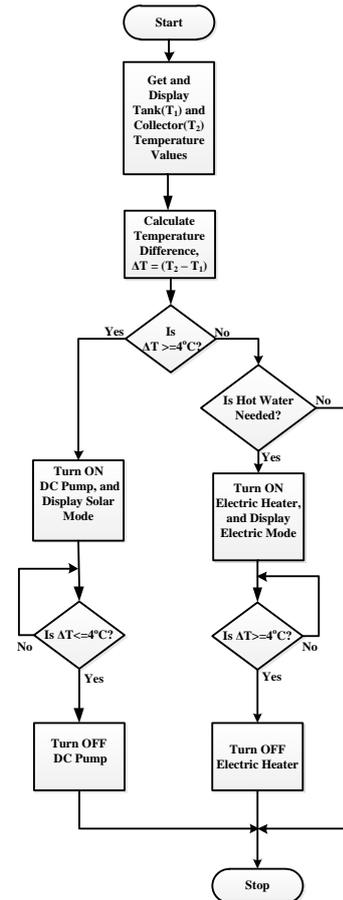


Fig. 3. Flow chart showing control logic of the system controller

Most members of the PIC16F87x family contain a 10-bit A/D converter. If the chosen voltage reference is +5V, the voltage step value is calculated using equation (9).

$$V_{\text{step}} = \frac{V_{\text{ref}}}{2^n} \quad (9)$$

where n is the number of bits, and  $V_{\text{ref}}$  is the reference voltage.

Therefore, for an input voltage of 1.0V, the converter will generate a digital output using equation (10).

$$D_{\text{out}} = \frac{V_{\text{in}}}{V_{\text{step}}} \quad (10)$$

where  $V_{\text{in}}$  is the input voltage, and  $D_{\text{out}}$  is the converter digital output.

The microcontroller used has an in-built ADC in which each preset temperatures must be converted to decimals for proper comparison.

#### 3.2.4. Temperature Sensing

To acquire the temperature of the water and also the collector, a temperature sensor is required. A sensor is a device that normally operates along with other circuitry that is used to measure or monitor a process so as to record the concerned variables (temperature values in this case). A typical temperature sensor component is the LM335 IC

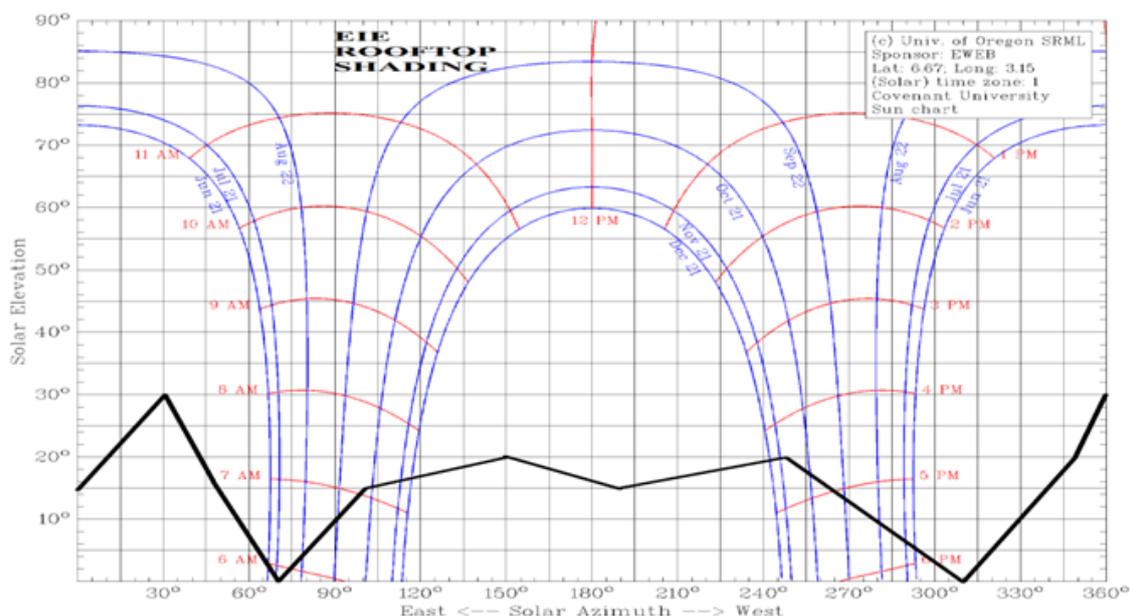
which converts ambient temperature into an equivalent output voltage. The circuit is a resistive temperature device type of temperature sensor. The voltage output of the LM335 increases by about 10mV by every increase in 1 Kelvin. In the circuit, the output of the LM335 is fed into a 741 op-amp (any standard op-amp may be used) which is configured as a voltage follower. As such, the output of the 741 is the same as the voltage output of the LM335. The main function of the op-amp, therefore, is just to buffer the LM335 output so that it is not affected by whatever load is connected to the temperature sensor circuit. Most sensor choices overlap in temperature range and accuracy, selection of the sensor will depend on how it will be integrated into a system.

#### 4. A Case Study of the AWSHS Design

A case study is here presented for one project to meet hot water demands for some families resident in Covenant University campus. This project is to supply the required hot water needs at 45°C using the ASWHS. Considering the demands and to ensure a continuous hot water supply for some days, a 2,500-litre hot-water storage capacity is chosen for the system. The specifications of the active solar water heating system are listed in Table 2.

**Table 2.** Specifications of the Active Solar Water Heating System Design

Component	Specification
Collector array area	25m <sup>2</sup>
Number of collectors	17
<b>One Collector Dimensions</b>	
Length	1 meter
Width	0.5 meter
Area	1.5m <sup>2</sup>
Collector tube	Copper
Diameter	0.5 inches
Length	160 meters
Collector casing	Black-painted & Polished wooden frames (plywood)
Storage tank	2,500 litres (thermally insulated)
DC pump	12 Volts, 0.5 Amps, 6.5 litres/min, Max. 3 meters Water Head
PV module	15 Watts
Inclination of flat-plate collector	6.67°
Absorber plate	Black-painted Aluminum sheets (emissivity = 0.875)
Number of glass covers	One (4-mm thickness)



**Fig. 4.** Shading plots for a test location at the rooftop of the EIE office building

#### 5. Results and Discussion

##### 5.1. Shading Test

Shading is the obstruction of the solar radiation from reaching the collector. A Shading test was carried out on the study location in order to determine the level of solar obstruction on the flat-plate collector. This was simply

performed by making plots on a sun chart for the location as shown in Fig. 4. The Electrical and Information Engineering (EIE) Department building rooftop was the design and test location for this study. The above plot for the location shows the very low shading levels indicated by the range of solar elevation curves crossing the blue and red contours (i.e. between 60°-120°, and 240°-300° Solar Azimuth) on the sun chart. This test result hence indicates a very suitable location for flat-plate collector installations

since no-shading periods (i.e. between 0°-60°, 120°-240°, and 300°-360° Solar Azimuth) occur within a wider range on the sun chart.

5.2. Collector and Storage Capacity Sizing

An estimated collector area for the automated solar water heating system for the desired pre-heated temperature (T<sub>out</sub>) of 45°C for the annual average solar radiation intensity of Table 1, is calculated using equation (6). For large hot water storage during peak periods of sunshine, a 2,500-litre hot water storage tank is used to secure adequate supply for some days using a 12 Volts DC circulation pump of 6.5 litres/min for approximately 6 hours of sunshine daily during the dry seasons. Therefore, an estimated collector array area of 25m<sup>2</sup> is calculated using equation (6) if an initial inlet fluid temperature of 27°C is assumed.

5.3. Collector Performance Characteristics

Equation (11) shows instantaneous thermal efficiency (η<sub>c</sub>) equation for flat-plate collectors [15,17,18]. The collector efficiency which is a value set by the materials used for construction and some constants is expressed as follows:

$$\eta_c = F_R \tau \alpha - F_R U_L \left( \frac{T_{in} - T_a}{I} \right) \quad (11)$$

where F<sub>R</sub> is the collector heat removal factor, and U<sub>L</sub> is the collector overall heat loss coefficient, W/m<sup>2</sup>-K.

Equation (11) shows that the efficiency of a flat-plate collector is dependent on the transmission coefficient of glazing (τ), the absorption coefficient of collector plate (α), collector heat removal factor (F<sub>R</sub>), intensity of solar radiation (I), ambient temperature (T<sub>a</sub>), inlet fluid temperature (T<sub>in</sub>) and the collector overall heat loss coefficient (U<sub>L</sub>). These parameters are enumerated as follows:

- The transmission coefficient of glazing (τ) is 0.85 because a single layer glazing of 4-mm thickness is used [19].
- The absorption coefficient (α) of plate is 0.95 because the collector fin plates are painted black [20].
- The collector heat removal factor (F<sub>R</sub>) is 0.99. This is a quantity that relates the actual useful energy gain of the collector to the useful gain if the whole collector surface were at the fluid inlet temperature.
- The ambient temperature (T<sub>a</sub>) is estimated at 25.7°C by metrological data from NASA and the inlet fluid temperature (T<sub>in</sub>) can vary at any point along the inlet copper tubing [7].
- The collector overall heat loss coefficient (U<sub>L</sub>) is 5.5W/m<sup>2</sup>-K because only one layer of glazing is used [21].

The amount of radiation striking an object is absorbed if the energy is retained by the material. The percentage of incoming radiation that is absorbed by a material is

referred to as its absorptance and is a measure of the ease with which a material or surface collects energy. Table 3 presents absorptance for various materials in sunlight [20]. The best materials are those with high absorptance and very low emittance. The high absorptance and low cost of black paint makes it a good choice for the collector design.

Flat plate collector performance is a measure of the collector efficiency (η<sub>c</sub>), and is defined as the ratio of the useful energy gain (i.e. the collector heat input, less the heat loss) to the incident solar energy over a particular time period. Ref. [15] shows the derivation for the instantaneous thermal efficiency of the collector as given in equation (11), and the collector heat removal factor (F<sub>R</sub>). The efficiency is a linear function of the three parameters (I, T<sub>in</sub>, and T<sub>a</sub>) defining the operating condition if F<sub>R</sub>, τ, α, and U<sub>L</sub> are assumed constant for a given collector. This gives a straight line plot as shown in Fig. 5 of the collector efficiency η<sub>c</sub> versus (T<sub>in</sub> - T<sub>a</sub>)/I curve, with a slope of (-F<sub>R</sub>U<sub>L</sub>). The slope represents the rate of heat loss from the collector. The maximum collector efficiency occurs when the fluid inlet temperature equals the ambient temperature (i.e. T<sub>in</sub> = T<sub>a</sub>).

The ratio of equation (5) to equation (4) gives a collector heat removal factor (F<sub>R</sub>) of 0.99, and hence the maximum possible collector efficiency of 79.94%. The useful energy extracted from the collector using equation (5) is calculated to give 9.1kW, and for a 6-hour period of sunshine in a day we get 54.6kWh of expected useful energy from the collector array. If a 25-year life span is assumed for the ASWHS, a maximum total of 498,225kWh of useful energy throughout its working life is expected.

Table 3. Absorptance and emissivity of sample materials

Material	Absorptance	Emissivity
Black Paint	0.95	0.875
White Paint	0.2	0.9
Polished Aluminum	0.1	0.05
Selective Surfaces	0.85-0.95	0.12-0.08

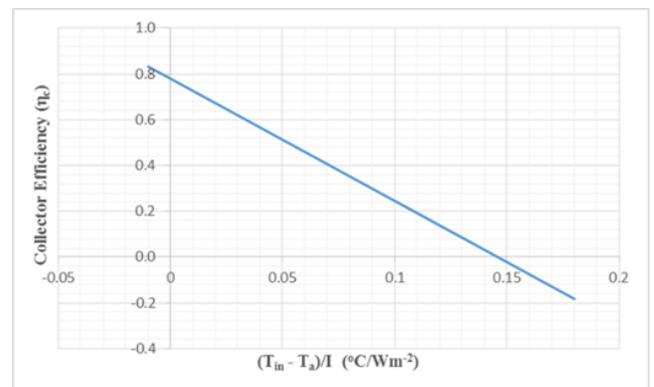


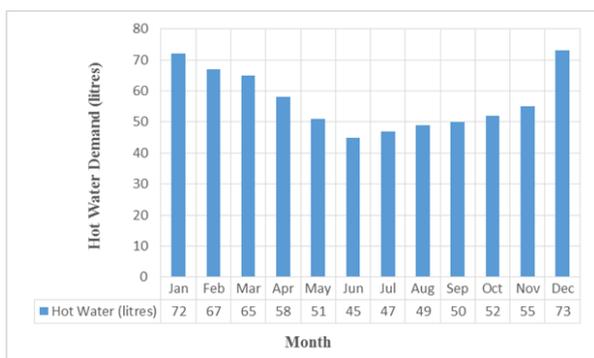
Fig. 5. Performance characteristics curve of a flat-plate collector at T<sub>a</sub> = 25.7°C

5.4. Energy Costs and Savings

Dependence on electric power is reduced through the use of the automated solar water heater. This will in turn affect savings in energy and costs. Table 4 shows an estimated average daily amount of hot water demand for some residence at the study location. Figure 6 shows the daily monthly average hot water demand for a family of four persons, with peak values in the month of December and January during the dry seasons. From Table 4, a family of four persons consumes a daily average of 57 litres of hot water in the year. These hot water demands include household activities on a daily basis such as bathing, cooking, and washing. This will require one solar hot water system with at least 75-litre storage capacity installation in such homes. Table 5 shows the duration and energy consumed by a 1.5kW electric heater for heating different volumes of water to 45°C daily. The possible expected energy to be saved daily on a monthly basis is also as shown.

**Table 4.** Daily yearly average hot water demand for some residence in Covenant University, Nigeria.

Family Size	Morning (litres)	Afternoon (litres)	Evening (litres)	Total (litres/day)
5	36	6	21	63
4	32	5	20	57
2	12	4	10	26



**Fig. 6.** Daily monthly average hot water demand for a family size of 4 for the year 2011

**Table 5.** Daily operation of a 1.5kW electric heater for heating water to 45°C monthly for a family of 4

Month	Volume (litres/day)	Duration (hour)	Energy Consumed (kWh/day)	Cost of Energy (\$/month)
Jan	72	2.1816	3.2724	18.26
Feb	67	2.0301	3.0452	15.35
Mar	65	1.9695	2.9543	16.48
Apr	58	1.7574	2.6361	14.23
May	51	1.5453	2.3180	12.93
Jun	45	1.3635	2.0453	11.04
Jul	47	1.4241	2.1362	11.92
Aug	49	1.4847	2.2271	12.43
Sep	50	1.5150	2.2725	12.27
Oct	52	1.5756	2.3634	13.19
Nov	55	1.6665	2.4998	13.95
Dec	73	2.2119	3.3179	18.51



**Fig. 7.** Expected average cost savings for the design year 2011

If hot water is produced only with the solar water heater in peak sunny periods during the dry seasons, the amount saved on electricity bills in the month of January would be US\$18.26 (₦2,994.64, Nigerian currency). Figure 7 shows the expected average cost savings on a monthly basis for the design year. A total of US\$170.56 (₦27,971.84, Nigerian currency) cost savings is expected for the year. This is a relatively small amount of savings, and the economic benefits for the use of the ASWHS can be more attractive with increase in unit cost per kWh of electricity usage. With an estimated cost of US\$2,500 for the ASWHS, a unit cost for energy consumption of US\$0.01/kWh is expected throughout its working life. This is a lower unit cost of energy than the grid supply counterpart of US\$0.18/kWh. A payback period of 15 years to recover the initial investment on the purchase of the ASWHS is recorded.

6. Conclusion

A microcontroller-based active solar water heating system has been developed in this study using locally sourced materials for its implementation. The performance characteristics, and energy cost analyses of the solar water heating system for domestic applications have also been presented. The main energy source for the production of hot water by this system is solar energy; a free and renewable form of energy that is pollution free. The design and implementation of the ASWHS would help in an effort to curb environmental pollution since the burning of fossil fuels will be greatly reduced by the optimal utilization of the sun's radiant energy. The active heating method is used due to the relatively high demands of hot water daily. Results have shown that implementing the ASWHS on a domestic scale for hot water production is economically viable even with the expected high initial investment for the system and the high payback period obtained. As such, the AWSHS for hot water production is more economically viable than that of the grid supply due to its lower unit cost per kWh of energy produced throughout its working life. A reduced payback period for the use of the solar water heating system will only be realizable if the

present unit cost per kWh of electricity from grid supply is appreciably increased. Further works on conventional domestic electric water heater retrofitting, and the ASWHS to industrial applications can be given consideration in future studies.

## References

- [1] Jayen Veerapen, and Milou Beerepoot, Co-generation and Renewables - Solution to a low-carbon energy future, International Energy Agency, 9 rue de la Fédération 75739 Paris Cedex 15, France, pp. 7-8, 17-20, 2011.
- [2] D. Arvizu, et al, Direct Solar Energy, In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, chp. 3 and 9.
- [3] S. Jaisankar, J. Ananth, S. Thulasi, S. T. Jayasuthakar, and K.N. Sheeba, "A comprehensive review on solar water heaters", Renewable and Sustainable Energy Reviews, Vol. 15, Issue 6, pp. 3045–3050, 2011.
- [4] M.S. Hossain et al., "Review on solar water heater collector and thermal energy performance of circulating pipe", Renewable and Sustainable Energy Reviews, Vol. 15, Issue 8, pp. 3801–3812, 2011.
- [5] G. Faninger, "Solar Hot Water Heating Systems", Comprehensive Renewable Energy", Vol. 3: Solar Thermal Systems: Components and Applications, pp. 419–447, 2012.
- [6] Tim Hirsch, A Case for Climate Neutrality—Case Studies on Moving Towards a Low Carbon Economy, The United Nations Environment Programme (UNEP), and the UNEP Climate Neutral Network, Nairobi, Kenya, pp. 8, November 2009.
- [7] NASA Surface meteorology and Solar Energy Data Set, available at: <http://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?uid=3030>, accessed on March 10, 2010.
- [8] Factors affecting intensity of sunlight radiation, available at: <http://funnel.sfsu.edu/courses/GM310/labs/cmap.SolRad.II.pdf>, accessed on 14 June, 2010.
- [9] Professor Ashok Gadgil, Domestic Solar Water Heater for Developing Countries, Energy and Resources Group ER-291-3, Final Report, Design for Sustainable Communities, pp. 2-22, May 16, 2007.
- [10] D.W. Shepherd, Energy Studies, 2nd edition, Imperial College, London, UK, 2003, chp. 2, 3, and 11.
- [11] David A. Bainbridge, The Integral Passive Solar Water Heater Book, The Passive Solar Institute, pp. 2-79, 1981.
- [12] University of Oregon Solar Radiation Monitoring Laboratory: Sun path chart program, available at: <http://www.solardat.uoregon.edu/SunChartProgram.html>, accessed on 26 November, 2009.
- [13] The Atmospheric Science Data Center (ASDC) at NASA Langley Research Center: Design of solar collector, available at: <http://www.eosweb.larc.nasa.gov>, accessed on 15 April 2010.
- [14] P.I. Cooper, and R.V. Dunkle, "A non-linear flat-plate collector model", Solar Energy, Vol. 26, Issue 2, pp. 133-140, 1981.
- [15] Fabio Struckmann, "Analysis of a Flat-plate Solar Collector", Heat and Mass Transport, Project Report, 2008MVK160, May 08, 2008, Lund, Sweden.
- [16] A. Adell, "Determination of the optimum inclination of a flat solar collector in function of latitude and local climatic data", EDP Sciences, Rev. Phys. Appl. (Paris), Vol. 17, Issue 9, pp. 569-576, September 1982.
- [17] BILD IT SOLAR: The Renewable Energy site for Do-It-Yourselfers, available at: <http://www.builditsolar.com/References/Measurements/CollectorPerformance.htm#Efficiency>, accessed on 24 September, 2013.
- [18] Power from the sun book, chps 5 and 6, available at: <http://www.powerfromthesun.net/>, accessed on 24 September, 2013.
- [19] Y.Raja Sekhar, K. V. Sharma, and M. Basaveswara Rao, "Evaluation of Heat Loss Coefficients in Solar Flat Plate Collectors", ARPN Journal of Engineering and Applied Sciences, Vol. 4, No. 5, pp. 15-19, July 2009.
- [20] A. Manickavasagan et al., "An Experimental Study on Solar Flat Plate Collector Using an Alternative Working Fluid", Putra Universiti, Putra, Malaysia Press, Vol. 13, Issue 2. ISSN: 0128-7680, 2005.
- [21] S. T. Wara and S. E. Abe, "Mitigating Climate Change by the Development and Deployment of Solar Water Heating Systems", Journal of Energy, Hindawi Publishing Corporation, Article ID 679035, pp.1-7, 2013.