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Performance Evaluation of a Solar Domestic Hot Water Thermo syphon System for Gembu Taraba State, Nigeria

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ABSTRACT

The performance and economic feasibility of a solar water heating system in Gembu, Taraba state, Nigeria for the provision of hot water demand for domestic application was investigated. The study aimed to determine the effectiveness of the system performance under different weather conditions, and the economic value. Here, the monthly average hot water loads required for domestic use at the location was first estimated as 60 liters per day at 55°C. Based on this demand, the required collector area was calculated using a flat plate collector efficiency of 40%. A TRNSYS model of the thermosyphon system was then developed to simulate thermosyphon system to assess its monthly average performance, considering variations between sunny and cloudy days. The performance of the model was validated through experimental data collected from January to April, with the accuracy measured using the mean average percentage error (MAPE). The findings revealed that 2.04 m² of collector aperture was suitable for most months. The system delivered hot water on the average at 40.15°C in August and 51.91°C in April, falling short of the desired 55°C which necessitated auxiliary heating in some months. The simulation model showed good agreement with the experimental data, with MAPE values ranging from 6.1% to 7.8%, indicating reliability. The system demonstrated a high annual solar fraction of 0.81, reflecting a good savings. The overall annual efficiency of the system was 34%. Economically, the system indicated an annual net saving of approximately 62% after accounting for auxiliary energy costs. The payback period for the system was found to be 7.6 years, with a positive net present value (NPV) of ₦1,439,319 after 20 years. The system offers significant economic benefits and contributes to environmental sustainability by reducing reliance on conventional energy sources. However, its performance varid with seasonal changes in solar radiation, leading to occasional shortfalls in meeting the desired temperature. Future work could focus on optimizing collector area design, improving auxiliary heating solutions, exploring energy storage options, conducting extended field test, and assessing the impact of technological advancements and fluctuating energy costs on the system's economic and environmental benefits. These steps could potentially enhance the system's reliability, efficiency, and overall feasibility, promoting wider adoption in different regions.

Keywords: Efficiency, Performance, Thermo syphon, Simulation, Solar Energy.

1.0 INTRODUCTION

The conventional sources of energy are finite in nature and pose severe threats to man's environment. The industrial and economic development which have been made possible through the harnessing of conventional energy technologies have brought about significant degradation and climate change with severe impact on human and aquatic life. The efficiency of energy end-use services has gradually improved due to technological advancement and energy efficiency legislation. Nevertheless, this improvement has not always been adequate to offset the increase in demand for energy services, such as the production and consumption of commodities. In addition, the ongoing conflict between Russia and Ukraine has caused an energy crisis that has directly affected the heating, cooling, and transportation energy costs of households. In 2021, the European Union imported over 45% of its gas and nearly 40% of its total gas consumption (IEA 2022a).

A solar water heating system is the device that uses solar energy for hot water production. Solar water heating system is renewable energy technology and has been used in many countries of the world. This natural energy is absolutely free and the supply is unlimited in the day whenever there is sunlight. The usage of this energy does not produce any pollutant and therefore is most environment friendly. In private nations, energy utilization in the structure needs of a high energy budget. Most energy is needed for production of hot water and space heating. Hot water is important for bathing and for washing, utensils and other domestic purpose in urban as well as in country areas. Heating water is usually by burning fuel wood in the country areas and by fossil fuel energy such as kerosene oil, petroleum gas (LPG), coal and electricity in metropolitan areas.

Solar water heating systems are available in different forms and can be used in different application. Domestic hot water usually uses small system applications while larger systems are used in industrial applications (Sirajo *et al.*, 2019)

A Thermosyphon Water Heater (TSWH) essentially comprises a solar collector, a storage tank, and a network of several connecting pipes. Its working principle is simple. Naturally, water is heated in the solar collector, and the heated water flows to the top of the storage tank where the outlet is situated (Jamar, 2016). Again, the generation of the thermosyphon head that drives the water occurs due to variation in the temperature and density of water in the solar collector. The advantages of the TSWH include easy operation and maintenance, complete dependence on buoyancy as the driving force, simplicity in construction, strong reliability, and durability compared to the forced convective systems (Kalogirou, (2009). Moreover, the TSWH does not require a pumping component because it can achieve a natural rise of hot water through the thermosiphonic flow into the tank (Fang, 2010).

Water heating for domestic purposes is a simple and effective way of utilizing solar energy. The initial cost of solar water heating system is very high without any operating cost. It is a natural solar thermal technology. In this system, incident solar radiation is converted to heat and transmitted to a transfer medium such as water. Solar energym is one of the renewable energy resources that hold a great potential for developed and underdeveloped countries in the future. Nowadays it is being widely used for heating and electricity generation (Kuhe *et al.,* 2019). Solar water heating (SWH) is the conversion of sunlight into renewable energy for water heating using a solar thermal collector. The collectors capture and retain heat from the sun and transfer this heat to water. Solar thermal heat is trapped using the “greenhouse effect,” in this case, is the ability of a reflective surface to transmit short wave radiation and reflect long wave radiation. Heat and infrared radiation (IR) are produced when short wave radiation light hits a collector’s absorber, which is then trapped inside the collector. Fluid, usually water and other heat transfer fluids in contact with the absorber collectors’ trapped heat to transfer it to storage tank. Solar water heating systems comprises various technologies that are used worldwide increasingly. Water heated by the sun is used in various ways, for space heating, taking baths, washing clothes and utensils, and other domestic purposes in both the urban and rural areas. Solar hot water also has industrial applications e.g., to generate electricity. Moreover, solar energy is the largest energy source available to mankind for consumption on earth and is essentially infinite. For example, the projected depletion of available fossil reserves such as oil, natural gas, and coal will occur in the next 46, 58, and 150 years, respectively. Whereas, if entirely captured and stored, the energy received by the Earth in one single year would provide enough energy that could be consumed for more than 9000 years (IEA 2011, IEA 2010). Thus, solar energy appears to be a promising alternative and/or renewable energy source for mankind (Prasad et al., 2017) because it is abundantly available at the earth’s surface, and essentially, a potential component of future sustainable energy (Herbert, 2010). Hot water is fundamental both in industries and homes. It is required for cleaning up, washing garments and utensils, and other residential purposes in both the urban and rural areas. Hot water is likewise required in extensive amounts in hotels, hospitals, and industries, for example, material, paper, and nourishment preparing of dairy and palatable oil (Sirajo *et al.,* 2019). Thermosyphon solar water heater is one of the most economic devices to meet both domestic and industrial hot water needs. These systems are widely used domestically in many parts of the world, such as Australia, India, Middle East, and Japan. However, the case is still different in Nigeria where installation of solar water heaters

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has not become fashionable although the near equatorial geographical location positions her for all year- round insolation (Agbo *et al.,* 2005).

Nigeria is an energy-deficient country that relies primarily on conventional energy sources such as fossil fuels, coal, and firewood to meet its energy needs (Dioha and Kumar, 2020). Gas-fired power generation currently accounts for 87.5% of total power generation in Nigeria (Dioha and Kumar, 2018) . As a result, the country is now at the forefront of greenhouse gas (GHG) emissions (Balta, 2012). With about 200 million people, the country's energy demand is increasing, and the power holding company of Nigeria (PHCN), Nigeria's main electricity provider, is now experiencing a greater energy deficit. Nigeria had 12 GW of installed on-grid power capacity in 2018, but only 40% of the country's energy was supplied. Energy demand in residential buildings has increased significantly to the point where it exceeds supply as a result of developments in building technology, population growth, and the pursuit of modern civilization.

Solar water heaters are designed to deliver hot water, especially during the summer period, sometimes in winter there may not be sufficient solar heat gain to deliver sufficient hot water, in this case a gas, electric booster or any other alternative resource is used to heat the water. In view of the importance of the solar energy this project is design to enhance heating of water for domestic use using locally available materials.

Gembu is, the headquarter of Sardauna local government of Taraba state is not connected to the national grid and considering the cold weather of the area, people depend solely on firewood and kerosene for their domestic energy needs. These options have their attendant unfavorable environmental and economic effects. Therefore, the need to introduce cost effective and sustainable alternative energy becomes necessary. The depleting nature of Eucalyptus forests, which is a major source of fuel in the area, is fast increasing causing deforestation and degradation of the environment. Also, the global warming caused by the use of firewood, kerosene etc. and the toxic nature of emissions that go along with these system calls for a need to utilize alternative more environmentally friendly options like the much available solar radiation for use in heating water as a good sustainable replacement for the conventional method. Gembu town has summer period from January to mid- March and rainy season lasts from mid- March until the end of December, with a mean minimum temperature of 21.39 ℃ and maximum temperature of 34.22 ℃ (Oruonye, 2014).

2.0 MATERIALS AND METHOD

2.1 MATERIALS

The tools or materials used for the design, construction, simulation and evaluation of the energetic and economic performance of a thermosyphon water heater for domestic application under the weather data of Gembu, Nigeria are stated here. The energy demand characteristics of a typical family in Nigeria is used to evaluate the actual performance of the system under real load and weather influence. The choice of TRNSYS as the modelling tool to predict the annual performance of the system and the detailed steps in the modelling of the thermosyphon is presented. The viability of the studied system is also presented using an economic analysis based on the current economic indices during the period of the study. The thermosyphon water heater is typically made of the collector, the hot water storage tank, and the connecting pipes. Other materials include the absorber plate, painted black to maximize absorption, the Transparent cover which allows sunlight to pass through while minimizing heat loss from the absorber plate. We have the Case box which is a frame that houses the flat plate solar collector and provides structural support and protection. Fluid passages and headers are made of several cupper tubes of 12.7mm diameter attached to absorber plate, these allow the heat transfer fluid to circulate through the collector. Saw dust is used for Insulation of the set-up to help improve the overall efficiency of the collector by reducing heat loss to the surroundings. A 60litres cylindrical storage tank was made using a 3mm galvanized mild steel sheet. Provision was allowed for cold water inlet 20cm and outlet 10 cm from the bottom of the tank. Table 1 shows the design specifications.

Table 1: Design Specification of the Solar Collector

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Parameter	Dimensions
Length of glass	2040 mm
Width of glass	1040 mm
Glass cover area	2000 x100 mm
Thickness of glass	5 mm
Length of aluminum sheet	2000 mm
Width of aluminum sheet	1000 mm
Area of aluminum sheet	2 m^2
Diameter of tube	12.7mm
Tube spacing	100 mm
Collector casing	2040 x1040 mm
Height of casing	50 mm

2.2 Method

Gembu is situated in Sardauna Local Government of Taraba State, Nigeria. It is in the northeastern region of Nigeria, in the close proximity to the border with Cameroon as shown in Figure 10 Gembu is distinguished by its hilly topography and rolling scenery. The city is in the Centre of the magnificent Mambilla Plateau, renowned for its visual beauty and pleasant environment. The plateau reaches an altitude over 1,800 metre above sea level, establishing it as one of Nigeria's most elevated plateaus. Gembu is on a latitude 6° 30' 00" N to 8° 48' 46" N of the Equator, and longitude 10° 01' 00" E to 11° 50' 18" E of the Meridian, the temperature typically varies from 12 ^{0}C to 29 ^{0}C and is rarely below 11 ^{0}C or 31 ^{0}C.

Figure 1. location of Gembu Community on the Map

The period of the highest amount of solar energy lasts for 2.2 months starting from January 2 and ending on March 9. During this time, the average daily amount of energy from the sun is above 5.9kWh/m^2/day. In Gembu, the month of February is characterized by the highest level of solar energy with an average of 6.2 kilowatt-hours (kWh/m^2. July and August are characterized by lowers solar energy of 4.2 kWh/m^2/day and 4.3kWh/m^2/day of sunlight during this month (Stackhouse, P. (n.d.). *POWER | DAVe*. https://power.larc.nasa.gov/data-access-viewer/) The logical flow and summary of the methodology is illustrated in the Figure 1.

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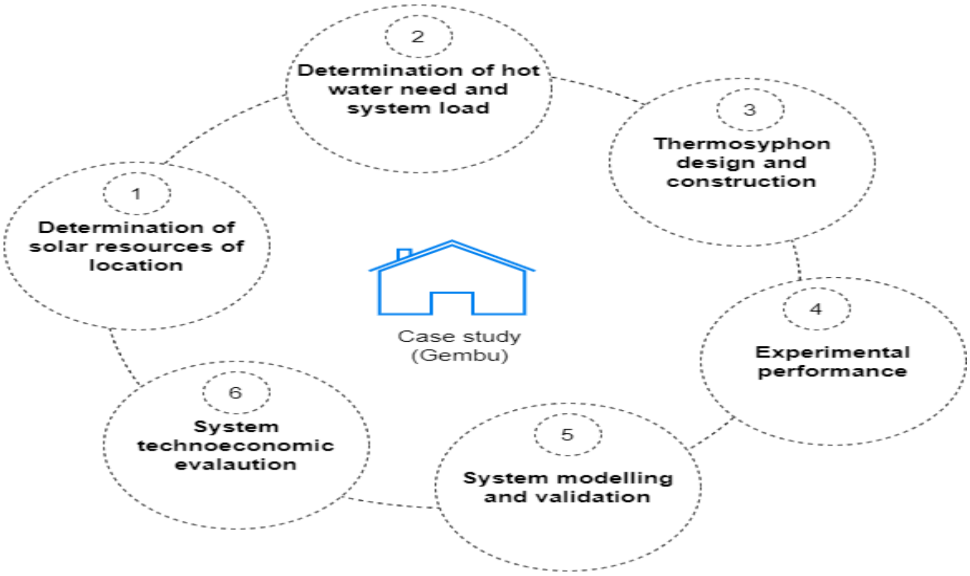

Figure 2. Flow Chart of the Research Methodology

2.2.1 System Description

The thermosyphon solar water heater comprises of a single glazed flat plate collector installed at a tilt angle 7° 20'N tilting to the south as recommended for solar system design, the cold-water storage tank, and a thermal insulated vertical hot water storage tank, interconnected with supply and return pipes. (Ayodeji *et al*,. 2023). The flat plate solar collector casing was made of plywood to minimize heat loss. The flat plate collector has eleven (11) evenly spaced parallel copper pipes (riser) of inner diameter 12.7 mm and two horizontal copper pipes (headers) with inner diameter 12.7 mm. The casing was covered at the top with a 5 mm thick plain window glass secured on top of the casing using Silicone sealant, to prevent heat loss from the plate by radiation. The absorber was made using 1.5 mm thick aluminum sheet, the absorber plate together with the fluid passage pipe were coated with black paint to enhance absorption of heat. The underside of the absorber is insulated with saw dust to reduce conduction heat losses. The hot water storage tank made of galvanized mild steel sheet of 3 mm thickness, properly lagged with saw dust to minimize heat loss to the surroundings. The hot water storage tank was linked to a source of water from the mains water supply through the cold-water inlet. Valves to control the inflow of water into the storage tank from the main supply were incorporated along the length of the pipe linking the mains water supply to the storage tank to prevent draining back of water into the collector when the temperature in the collector is lower than that in the tank, especially in the night when there is no solar radiation, another control value was installed between the pipe connecting the collector hot water outlet and storage tank hot water inlet. The hot water to meet the domestic load is collected through the hot water outlet. The figure 3 below shows the schematic of the system described.

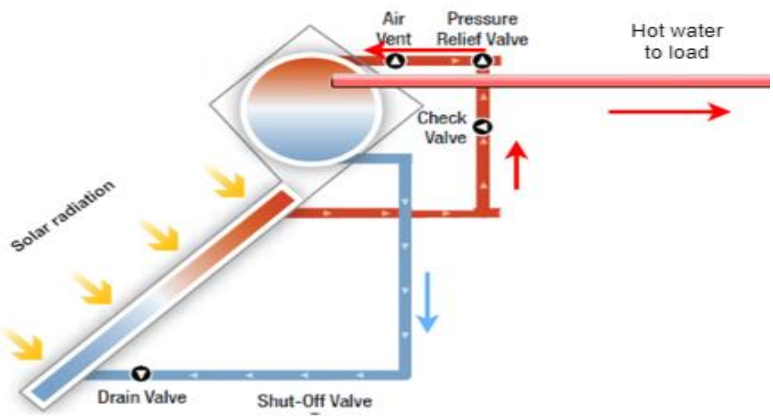

Figure 3. Schematic of the Described Thermosyphon

In this study, the free solar and weather data site was accessed using the link https://power.larc.nasa.gov/data-access-viewer/ to download the one year (01/01/18 to 31/12/18) solar and weather data of Gembu. The parameters needed to

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access the data as required by website are as shown in Figure 4. After the monthly averaged daily solar insolation is downloaded, it was then processed using excel to obtain the annual averaged daily solar insolation of the location. This parameter is an important design parameter in sizing the collector needed to heat the water to the desired load temperature. Figure 4 shown the monthly solar radiation of Gembu.

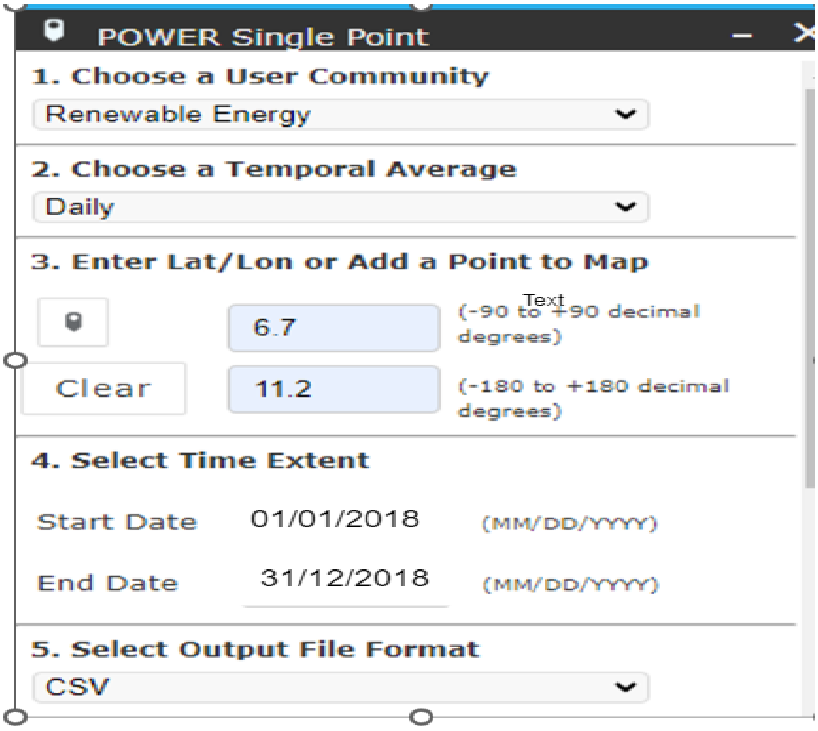

Figure 4. Parameter Table Required for Downloading the Solar Data of any Location from the website

Various factors, such as the number and size of units, tenants' lifestyle, and the kind of heating system, might affect the hot water demand profile in a typical residential structure. This study adopts the recommendation of ASHRAE (Li and Kao, 2017; Hoseinzadeh and Azadi, 2017)) both suggest a daily hot water consumption of 240 liters per day for a family of 4 with typical daily profile as shown in Figure 4.

To design the system, the hot water demand is first evaluated since it is the load that the system is required to meet. In this study, the load demand temperature T_L is selected as 55°C because it is the required temperature for laundry. Therefore, the quantity of energy needed to be supplied by the solar system to meet this load temperature is estimated using equation below.

$$\dot{Q}_{DHWL} = \dot{m}_L C_p (T_L - T_{mains}) \qquad (1)$$

where $\dot{Q}_{DHWL}$ is the rate of thermal energy required to meet the load. $\dot{m}_L$, *is* the demand flow rate as shown in Figure 14 resulting to a total 60Litres/day. C_p is the specific heat capacity of water, T_L, *is* the load desired temperature for hot water application, and T_{mains} is the temperature of water from the mains. The total hot water requirement for a day is found by integrating the rate for (1) hours as expressed in equation below.

$$Q_{DHWL} = \int_1^{24} \dot{m}_L C_p \Delta T dx \qquad (2)$$

Where $\Delta T = (T_L - T_{mains})$ is the desired temperature difference between the desired temperature and the mains water temperature. In this case, since the desired temperature T_L is 55°C and the mains water temperature is approximately 26 °C ΔT in this study is 29°C.

After the total hot water load is estimated, the required collector area is found using equation below

$$A_c = \frac{mC_p \Delta T}{\eta_c H_T T_{sh}} \qquad (3)$$

$$m = \rho V \qquad (4)$$

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Where V is the volume of hot water and ρ is the density of water. η_c is the collector efficiency of the selected flat plate collector (typically 40%), H_T is the average hourly solar insolation of Gembu and T_{sh} is the average sun shine hours for Gembu.

The whole setup was supported on a framework fabricated with Eucalyptus wood, such that the collector was oriented in north- south direction, inclined at 7.2° to the horizontal (latitude of Gembu) in order to receive maximum solar radiation (Bukola, 2006). The hot water storage tank was placed 50 cm above the collector and was linked to the source of cold-water tank placed 3000 mm above the ground level to enable the cold-water flow by gravity into the storage tank using polyvinyl chloride (PVC) pipes. Valves to control the inflow of water into the hot water storage tank were incorporated along the length of the pipe linking the cold-water tank and the storage tank, to prevent draining back of water into the collector when the temperature in the collector is lower than that in the hot water tank, especially in the night period when there is no solar radiation.

System modelling and simulation

In this study, the transient system simulation tool, TRNSYS 16 is selected for the system modelling, performance simulation and evaluation. TRNSYS 16 is a modular software package with a comprehensive library of validated components of different solar energy models that can be customized to any conceived energy solution and with great flexibility for adaptation for different applications. After the system components have been selected and linked, as illustrated in Figure 3.9, the design specifications for each component as specified in Table 4 are provided.

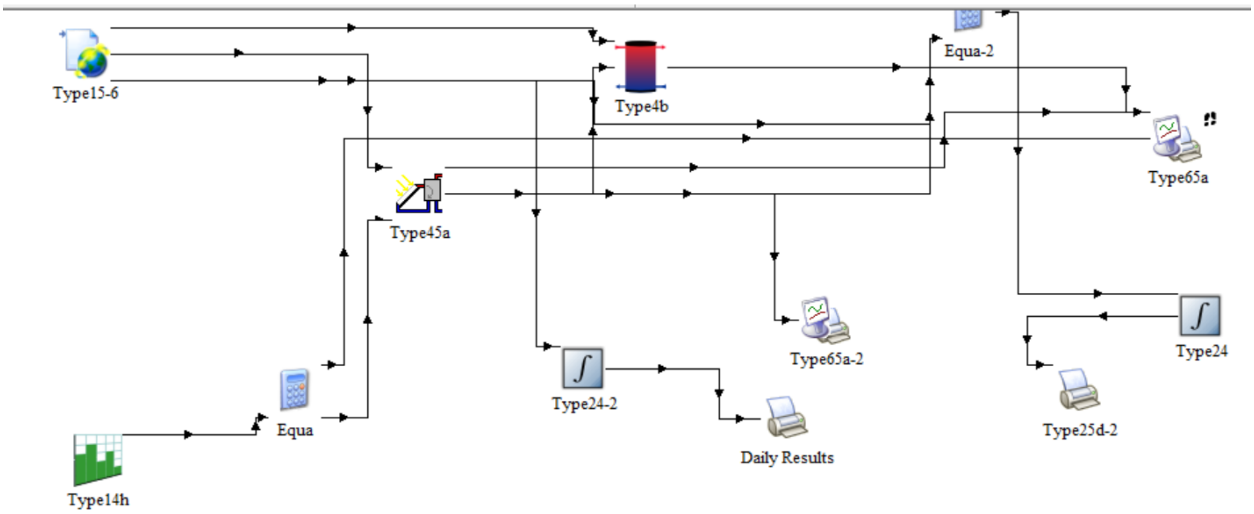

Figure 5. TRNSYS Model to Predict the Annual Performance of the Thermosyphon

Table 2: System Components and their Function in the Model Created

SN	Model name	Real name	Function
1	Type 15	Weather data processor	This component serves the purpose of reading data at regular time intervals from an external weather data file, interpolating the data (including solar radiation for tilted surfaces) at timesteps of less than one hour, and making it available to other TRNSYS components. The model also calculates several useful terms including the mains water temperature, the effective sky temperature, and the heating and cooling season forcing functions.
2	Type 45	Thermosyphon water heater	This component models the thermosyphon solar collector system. The system consists of a flat-plate

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			solar collector, a stratified storage tank (either vertical or horizontal cylinder) located physically above the collector plate, a check valve to prevent reverse flow, and water.
3	Type 4	Simple hot water storage tank	This subroutine models a vertical cylindrical dual-element electric water heater with integrated controls.
4	Type 65	Online plotter	The online graphics component is used to display selected system variables while the simulation is progressing
5	Type 25	Printer	The printer component is used to output (or print) selected system variables at specified (even) intervals of time.
6	Type 14	Forcing function	Use to model a time dependent operation which has a behavior characterized by a repeated pattern.
7	Equation model	Equation model	Employed to create control function to control the operation of the system to certain conditions. It is also used for evaluating the performance of the system through some sets of equation modelled in it.
8	Type 24	Quality integrator	The quality integrator component is used in conjunction with equation. It integrates result and ensure that the accuracy and stability requirement are met.

Validation therefore is the process of determining that the model on which the simulation is based It is an acceptably accurate representation of reality (Sargent, 2011). In order to validate the predicted system performance obtained from the model, the tank outlet temperature, (temperature load) measured during the experiment was used as the validation parameter. The daily records were compared with the system simulated results. In this study, the mean absolute percentage error (MAPE), which is a statistical tool that measures the accuracy of the developed model was employed. MAPE quantifies the magnitude of error in percentage terms, offering insight into the predictive performance of the developed model. It is calculated using the following formula, which shows that it is the average of the negative percentage error.

$$MAPE=100 \text{ x} \frac{1}{n} x \sum_{i=1}^{n} \frac{Obs_i - Model_i}{Obs_i} \quad (5)$$

Where Obs_i represents the observed value and $Model_i$ denotes the predicted value for each data point. The MAPE provides a standardized measure of prediction accuracy, allowing for comparisons across different techniques.

Table 3: Simulation Start and Stop Time for Typical Particular Days in Month

Month	Time of simulation	Duration (Days)	Simulation start time (hours)	Simulation Stop time (hours)

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Jan	17/01/2018 to 18/01/2018	1	384	408
Jan	17/01/2018 to 24/01/2018	7	384	552
March	1/03/208 to 31/03/2018	31	1416	2160
Jan to Dec	1/01/2018 to 31/12/2018	365	0	8760

The formulated and experimentally validated model of the thermosyphon water heater is useful for the analysis of the hourly, daily, monthly, and annual performance of the energy system. The hourly performance of the solar collector is essential in estimating the performance of the entire thermosyphon water heating system in meeting the hot water demand in the building. The rate of useful energy from the collector can be estimated from equation (6).

$$\dot{Q}_{coll} = \dot{m}c_p(T_{co} - T_{ci}) \qquad (6)$$

where $\dot{Q}_{coll}$ is the rate of useful energy from the collector, $\dot{m}$ is the water mass flow rate T_{co} and T_{ci} are the collector outlet and inlet temperature, respectively. The quantity of thermal energy delivered by the system to meet building hot water demand is estimated as:

$$\dot{Q}_d = \dot{m}_L C_p(T_d - T_{mains}) \qquad (7)$$

where T_d is the temperature of the hot water delivered by the system from the preheated water tank to the auxiliary heat tank. Since the extra energy to heat water to the desired hot water temperature is only required when the water temperature in the heater tank falls below the designed temperature, the required auxiliary thermal energy is calculated as:

$$\dot{Q}_{aux} = \max((\dot{Q}_{DHW} - \dot{Q}_d), 0) \qquad (8)$$

Where $\dot{Q}_{DHW}$ is the hot water load. The max before the equation means that only positive value of the difference between $\dot{Q}_{DHW} - \dot{Q}_d$ are considered. The excess thermal energy dumped with no application is found in the expression.

$$\dot{Q}_{dumped} = \max((\dot{Q}_d - \dot{Q}_{DHW}), 0) \qquad (9)$$

The thermal energy $\dot{Q}_{useful}$ that is used in meeting the load of the system generated by the collectors is estimated as

$$\dot{Q}_{useful} = \dot{Q}_d - \dot{Q}_{dumped} \qquad (10)$$

The overall thermal efficiency is found using equation (11) Al-Waeli *et al.*, *(*2017)

$$\eta_{th} = \frac{Q_u}{I_T A_C} \qquad (11)$$

A lower value of the efficiency indicates that most solar energy falling on the collector is lost. The Hottel–Whillier equation defines Qu as the difference between thermal heat losses and the absorbed solar irradiance expressed as in equation 12 (Al-Shamani *et al.*, 2016).

$$Q_u = A_c F_R(S - U_L(T_i - T_a) \qquad (12)$$

Another technical performance indicator is the solar fraction (SF). SF is the fraction of energy demand met from the solar system to the total demand expressed in Eq (13), The SF value demonstrates the contribution of the solar system in meeting the total energy demand (Al-Shamani *et al.*, 2016).

$$SF = \frac{load\ met\ by\ system}{Total\ energy\ demand} \qquad (13)$$

Where the *load met by system* is equal to the energy of the system that is used in meeting the load, a higher value indicates the energy savings and the amount of emission displaced. (Alturki *et al.*,*(*2020). To assess the mitigation

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impact of the proposed energy system, environmental impact of system is estimated from the avoided emission displaced by the system calculated as shown in eq. (14).

$$ACO_2 = Amout\ of\ fuel\ displaced\ \times Emission\ factor\ of\ fuel \quad (14)$$

Recommended emission factors of 0.439kgCO_2/kWh for grid power and 2.6kg CO_2/L for diesel generators in the case of Nigeria (Sam-Amobi *et al.*, 2019).

3.0 RESULTS AND DISCUSSIONS

3.1 Estimation of Hot Water Load and Required Collector Area

Table 4 presents the monthly average hot water load and the estimated collector area, which was calculated based on the solar potential of Gembu using a typical flat plate collector efficiency of 40%. The hot water demand, estimated at 60 litres per day at 55°C for laundry, remains constant throughout the year. However, as indicated in Table 4, the monthly average load fluctuates, despite the daily volume being consistent. This variation in the hot water load can be attributed to the differing initial temperatures of water, which are influenced by the fluctuating ground temperature, as shown in Figure 6, from which the mains water is supplied to the hot water tank. It is evident from Table 4 and Figure 6 that January has the highest hot water load due to the highest monthly average mains water temperature. In contrast, June exhibits the lowest load, coinciding with the lowest mains water temperature, as observed in Table 4. The data also reveal that during months with higher solar energy availability, the required collector area is less than 2.0 m², while months with poorer solar conditions demand a collector area larger than 2.0 m². Since the collector area varies from month to month, it is essential to determine the optimal collector size that meets the system's thermal demand while maintaining economic efficiency.

Table 4: Estimation of required collector area based on the monthly average hot water load and solar radiation of Gembu

Time	Monthly average load (kWh/month)	Monthly average solar energy (kWh/month)	Required collector area (m^2)
Jan	153.27	190.04	1.92
Feb	138.13	159.04	2.07
Mar	150.55	180.70	1.98
Apr	141.89	200.63	1.68
May	142.23	162.54	2.08
Jun	134.10	142.47	2.24
Jul	136.63	138.20	2.35
Aug	136.94	133.14	2.45
Sep	134.92	154.26	2.08
Oct	143.38	166.17	2.05
Nov	142.99	202.82	1.68
Dec	151.38	187.01	1.93
Annual average	**142.20**	**168.08**	**2.04**

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From Table 4, it is evident that the required collector area fluctuates monthly, ranging from a minimum of 1.68 m² in April and November to a maximum of 2.45 m² in August. For months such as January, March, April, November, and December, an average collector area of 2.04 m² provides sufficient coverage, ensuring reliable hot water supply. During February, September, and October, the average collector area is close to the required value, so while the system still functions, there is a risk of minor shortfalls or reduced reliability. Although the average collector area may not precisely meet the requirements every month, it offers a balanced performance across the year. The average collector area ensures adequate capacity during months with high load and low solar radiation, such as December and January. These months benefit from the system's surplus capacity, which helps to maintain reliable demand coverage.
For the purposes of this research, the adopted average collector area is 2.04 m², providing a practical, cost-effective, and reliable solution for a solar hot water system. While it may not be optimal during every month, it ensures balanced performance throughout the year, simplifying both system design and maintenance. The simplicity, cost savings, and overall reliability make this approach a preferable option for many applications.

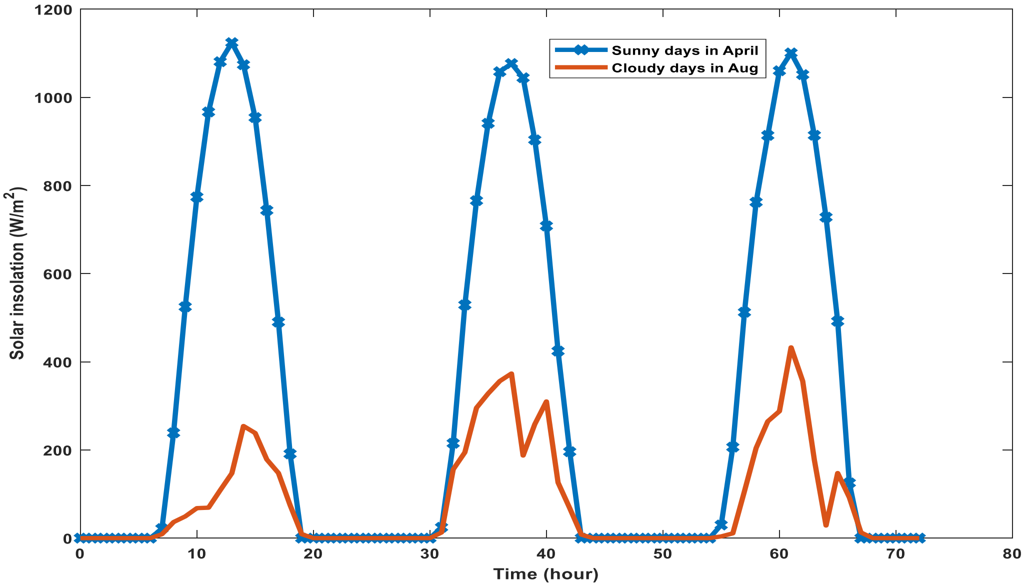

Figure 6. Solar radiation of Gembu on typica sunny day in April (10th to 13th) and cloudy days in August (8th to 11th)

3.2 System Simulation and Variation of Tank Hot Water Temperature

A key objective of this study was to model and simulate the performance of the thermosyphon hot water system. Table 5 presents the simulated monthly average daily hot water temperature delivered by the thermosyphon to meet the load. From the data in Table 4, it is observed that in January, the delivered hot water temperature is 50.87°C, which is close to the desired setpoint of 55°C for laundry but still falls short by 4.13°C. This shortfall indicates a moderate need for auxiliary heating. While the system remains relatively efficient, supplementary energy will be required to compensate for the deficit and ensure the water reaches the target temperature. In February, the temperature drops further to 49.46°C, widening the gap to 5.54°C from the setpoint. This implies a higher auxiliary energy requirement compared to January, leading to increased overall energy consumption. Similarly, in March, the temperature decreases slightly to 49.13°C, with a 5.87°C gap, resulting in a continued need for auxiliary energy.
The simulated hot water temperature ranges from 51.88°C in April (the best performance) to 40.15°C in August (the poorest performance), with shortfalls varying from 3.09°C to 14.85°C, respectively. The months with significant temperature shortfalls (June, July, and August) suggest an increased demand for auxiliary energy to meet the hot water requirements for laundry. Overall, the system’s inability to consistently meet the 55°C target throughout the year leads to varying levels of auxiliary energy demand. During warmer months (May to August), the system performs significantly worse, necessitating greater auxiliary heating and raising energy costs. In contrast, cooler months

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(September to December) see improved system performance, reducing the need for supplementary heating and leading to lower energy consumption.

Table 5. Simulated monthly average hot water temperature delivered to meet load

Time	Monthly average Temperature to load (°C)
Jan	50.87
Feb	49.46
Mar	49.13
Apr	51.91
May	45.05
Jun	42.44
Jul	40.41
Aug	40.15
Sep	43.38
Oct	45.75
Nov	51.88
Dec	51.69

Solar radiation is a crucial factor influencing the performance of a solar water heating system. Figure 6 illustrates the solar radiation in Gembu on typical sunny and cloudy days during April and August. Figure 7 demonstrates the system's performance on these sunny and cloudy days. On typical sunny days, the thermosyphon system delivers hot water at temperatures exceeding the desired 55°C for much of the day, requiring auxiliary energy only during the early hours. This high performance is attributed to the favourable solar radiation levels, which ensure that the 2.04 m² collector area, as calculated in Table 5, is more than sufficient to meet the 55°C target for 60 litres of water.
However, Figure 7 also shows that the 2.04 m² collector area fails to meet the hot water demand during months with poor solar energy. In such cases, the delivered water temperature is below the desired 55°C by approximately 20°C, indicating the need for substantial supplementary energy to compensate for the shortfall. While the system performs excellently on sunny days, it faces significant challenges in meeting temperature requirements during cloudy days. Additional energy sources are necessary to cover the deficit in solar energy on such days.

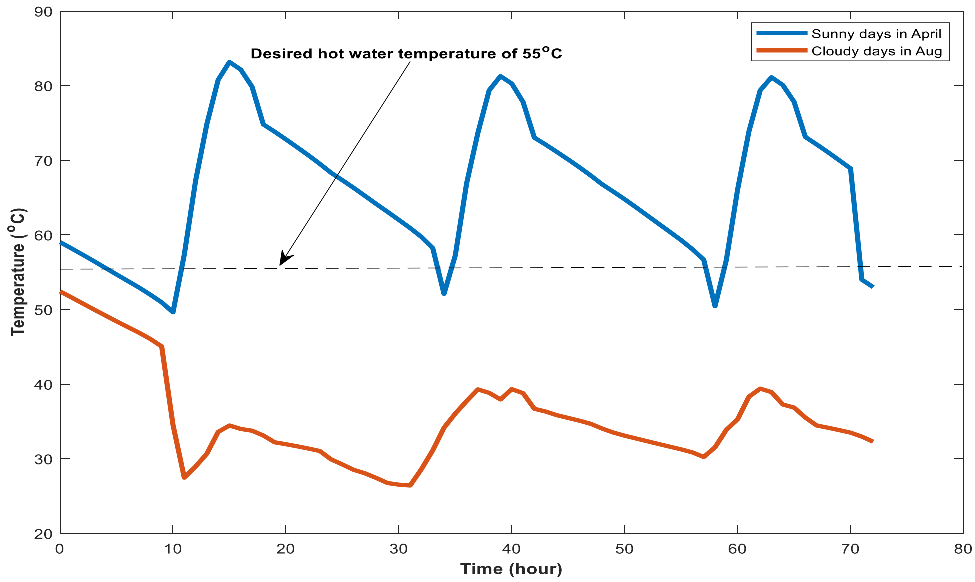

Figure 7. Delivered hot water temperature on typical sunny day in April (10th to 13th) and cloudy days in August (8th to 11th)

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3.3 Experimental Results and System Model Validation

To validate the accuracy of the developed model for predicting system performance, the system was constructed and tested from January to April. Figure 8 compare the simulated hot water temperatures with the measured temperatures. This figure demonstrates that the simulated results closely match the experimental data, with a difference of less than 3°C for all four months. To quantify the level of agreement, the mean average performance error (MAPE) between the simulated and measured temperatures was calculated and presented in Table 5. The MAPE indicates that the model's predictions are, on average, 6.1% to 7.8% off from the actual measured temperatures. A MAPE of 5% to 10% is typically acceptable for complex systems, as achieving perfect accuracy is challenging (Nunayon and Akanmu 2022). Han et., (2021) notes that a MAPE under 10% is indicative of a good model for solar energy systems, and this is consistent with results from other energy modeling studies (Fu et al., 2019). Therefore, the MAPE obtained in this study, ranging from 6.1% to 7.8%, demonstrates that the model accurately predicts the system's performance based on the weather data for Gembu.

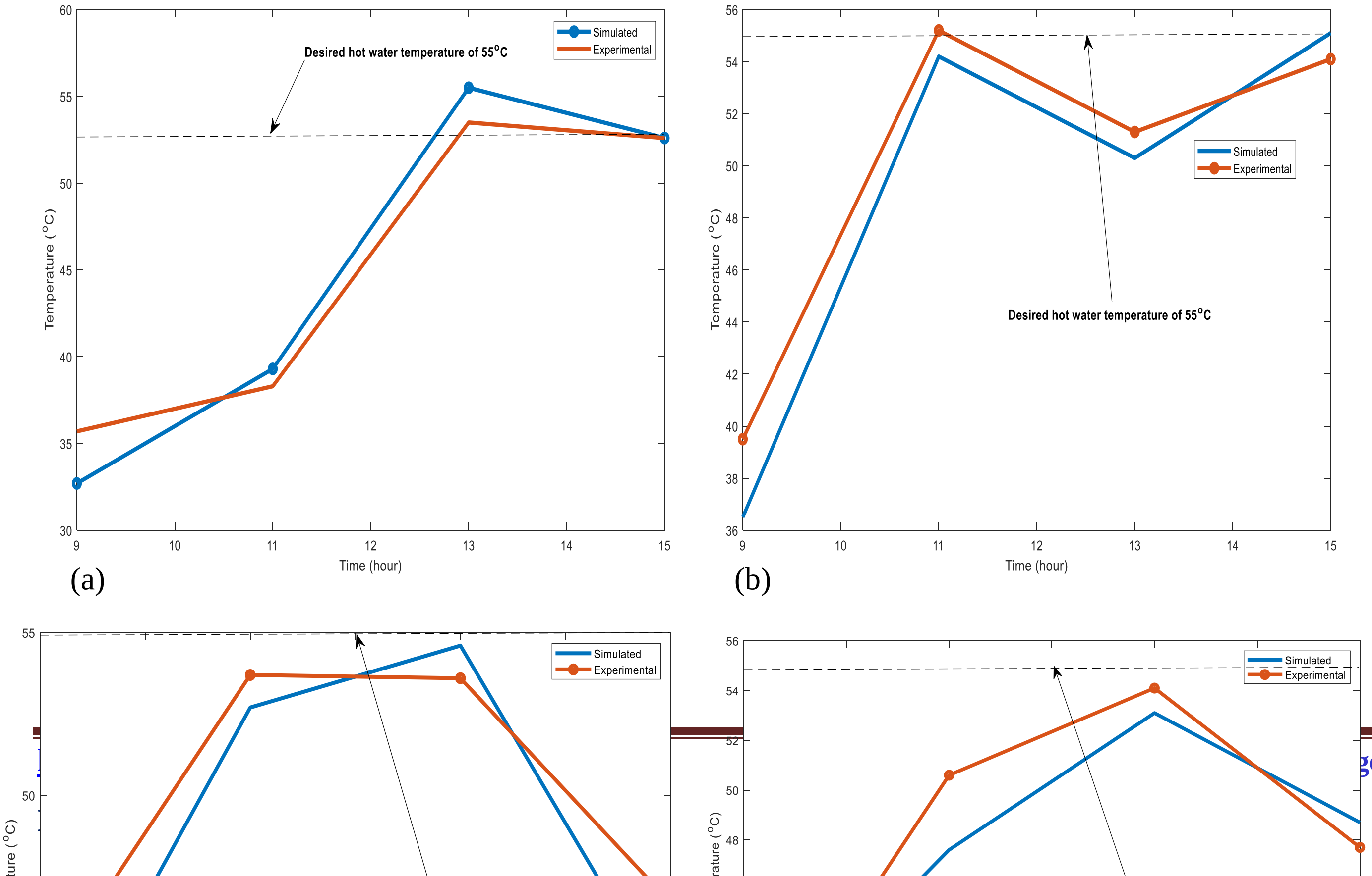

Figure 8. Comparison of simulated and experimental results for (a) January 13, 2018;

(b) February 1, 2018; (c) March 1, 2018; and (d) April 1, 2018.

The monthly average thermal performance of the system provides insights into its overall annual effectiveness. Figure 9 compares the monthly average hot water demand and the hot water produced by the system. From Figure 9, it is evident that the system generates enough hot water to meet or exceed the demand from January to April, suggesting that the system can meet a significant portion of the hot water requirement during these months if the load profile aligns with the energy produced. However, in the months of May through October, the system's performance falls short of meeting the monthly hot water demand. This is primarily due to insufficient solar radiation during these months. In November and December, the system again produces more than enough hot water to meet the demand.

Annually, the system delivers 1,453.05 kWh of energy, while the total hot water load amounts to 1,784.25 kWh, resulting in a shortfall of 330.20 kWh. Nevertheless, the system performs well overall, with an energy saving of approximately 81%, requiring only 19% of the total energy from other sources to meet the annual demand. Figure 10 compares the monthly average hot water demand, the energy delivered by the thermosyphon, and the energy used from the delivered energy to meet the load. It is observed that in months with good performance, such as January, where the system generates more energy than needed, the energy utilization is lower than the total energy generated. For instance, in January, only 87% of the energy generated is used to meet the load.

In months like April and November, where performance is optimal, only 77% of the produced energy is utilized, implying that 23% is dumped. Conversely, during months with poor solar energy, such as June through August, the energy utilization rises slightly above 90%. The energy produced is often mismatched with the demand, especially during peak sunlight hours, leading to wasted energy. Optimizing energy utilization would involve either adjusting the load profile to match peak production times or finding other uses for the excess hot water.

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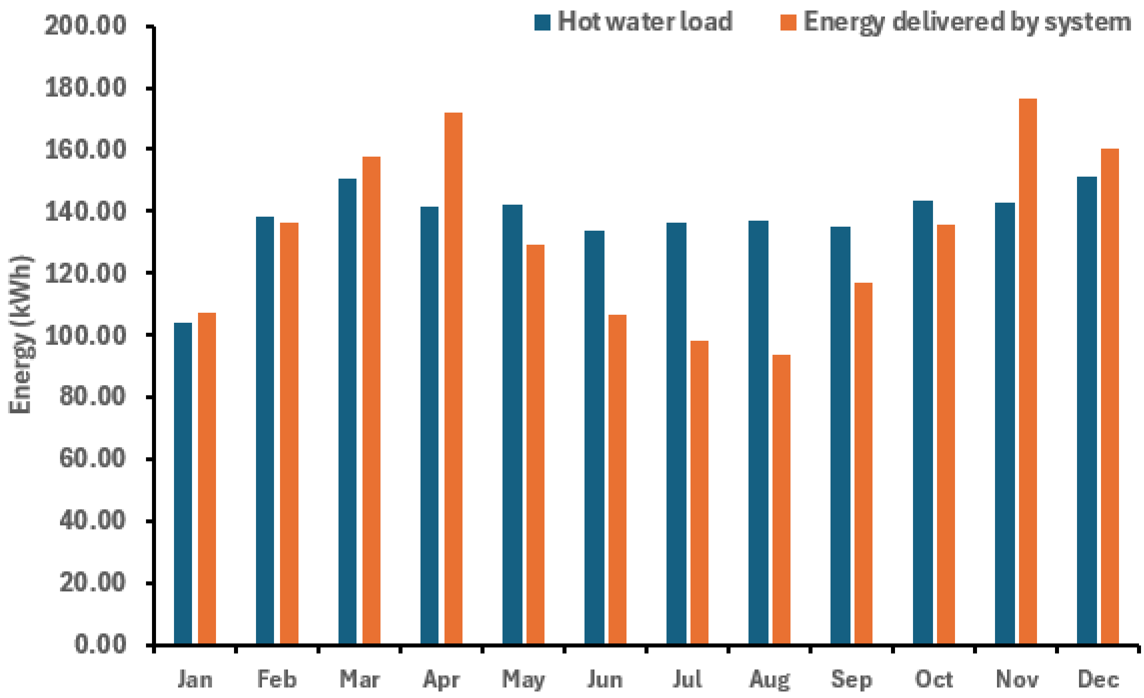

Figure 9. Comparison of hot water monthly average hot water demand with the energy delivered by the thermosyphon solar water system

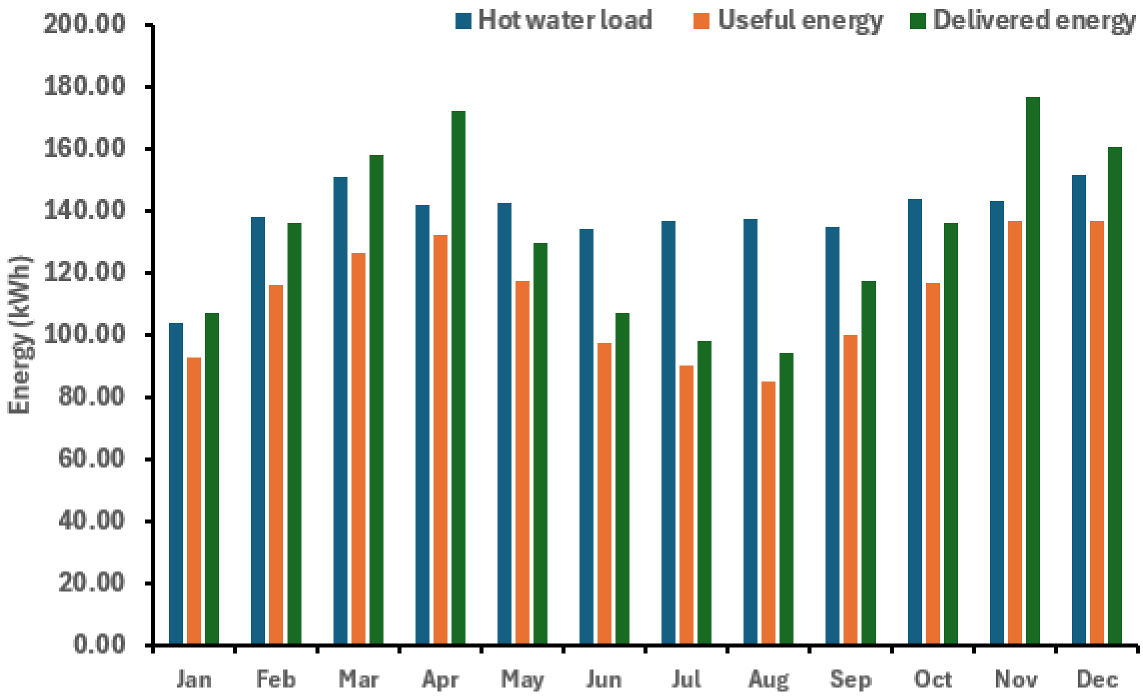

Figure 10. Comparison of monthly average hot water demand, the energy delivered and useful energy by the thermosyphon

3.4 System Solar Fraction and Efficiency

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The solar fraction is a key performance indicator that reflects the system's ability to meet the demand using solar energy, while system efficiency measures how effectively the solar system converts incident solar energy into useful energy. Figures11 and 12 show the monthly variations in solar fraction and system efficiency. The solar fraction ranges from 0.62 in August to 0.96 in November, peaking in the months with good solar radiation (January to April) and dropping during colder months. This variation is typical of solar systems and correlates with changes in solar insolation. July and August exhibit the lowest solar fractions at 0.62 and 0.61, respectively. On an annual basis, the system maintains an average solar fraction of 0.81, ensuring that over 80% of the hot water demand is met by solar energy, which significantly reduces dependency on auxiliary energy sources. A study by (Koua et al., 2020) reported a solar fraction of 0.54. This suggests that the Gembu system is more effective in utilizing solar energy to meet hot water demands, likely due to favourable solar irradiance and system design.

The system's efficiency fluctuates between 31% and 36% throughout the year, with the average efficiency calculated at 34%. This efficiency is in aligns with findings from various studies conducted in similar climates and regions. For instance, a study in Damaturu, Nigeria, (Musa et al., 2024) reported an average efficiency of 28.06% in June, with the system meeting the hot water requirements of the hostel. This is comparable to the 34% efficiency observed in Gembu, indicating consistent performance across different locations in Nigeria.

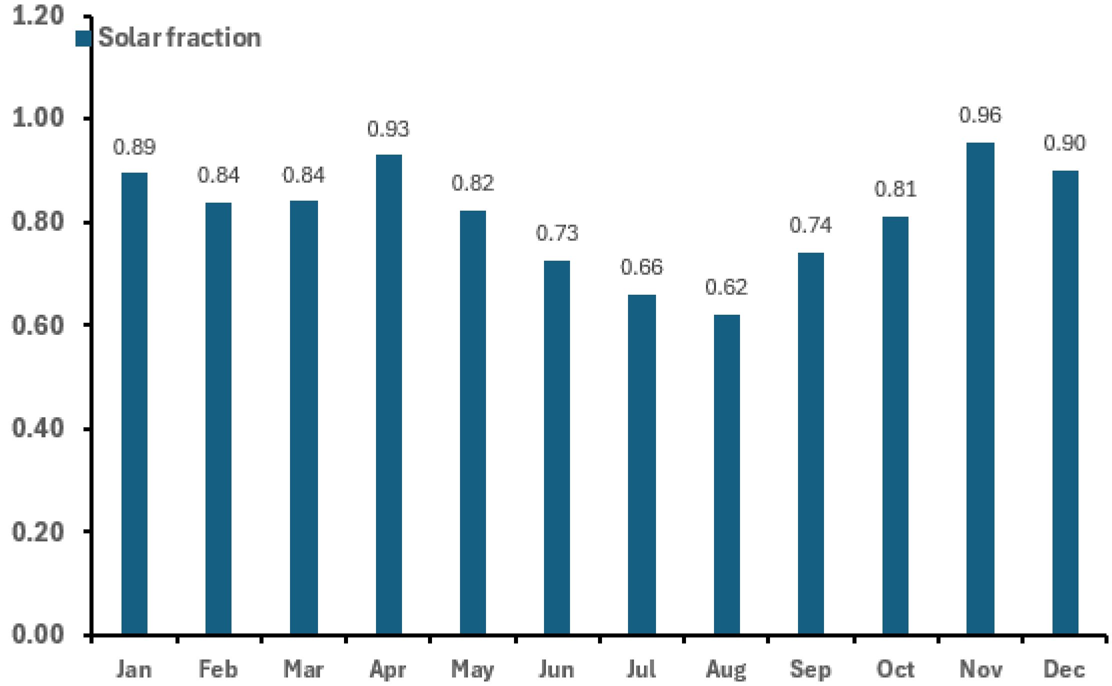

Figure 11. System monthly average solar fraction

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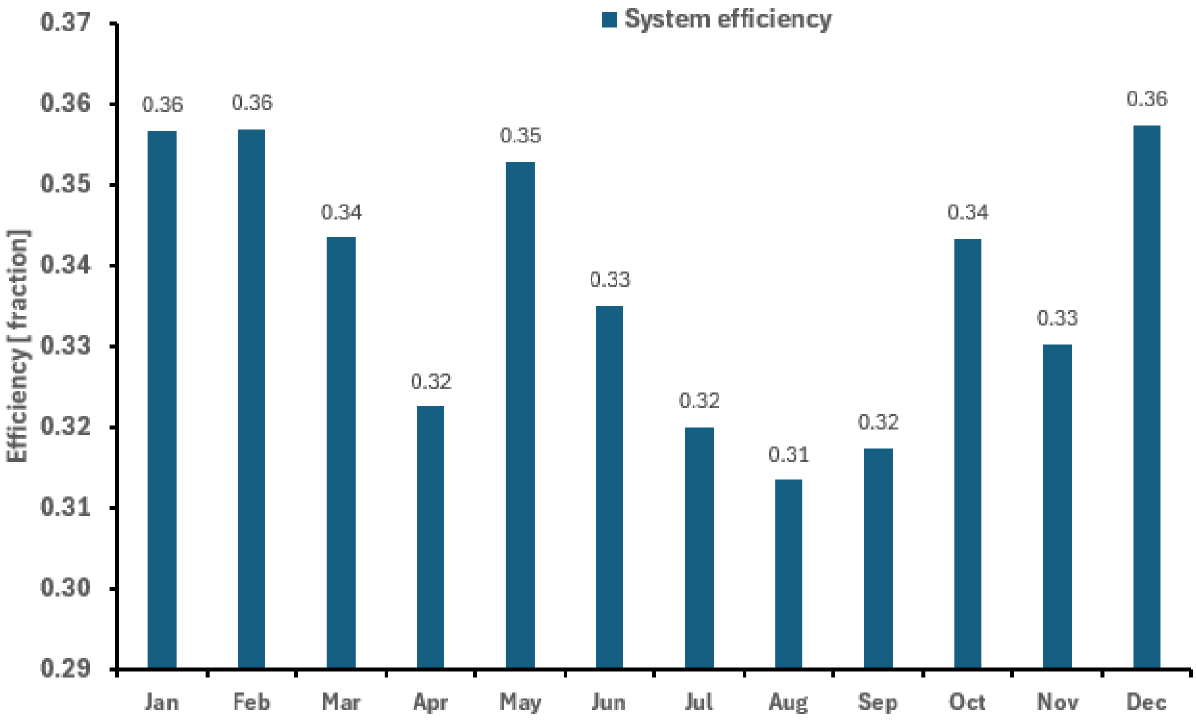

Figure 12. Variation of the monthly average system efficiency

3.5 Monthly Environmental Impact of the System

Figure 13 demonstrates the monthly variation in carbon footprint and CO_2 emissions reduced by the solar water heating system. The system significantly reduces its carbon footprint, providing over 81% of the hot water demand using renewable solar energy, thus minimizing reliance on fossil fuels. The reduction in CO_2 emissions is significant, especially in light of global efforts to combat climate change. By lowering the overall carbon footprint and relying more heavily on solar energy, the system supports goals outlined in the Paris Agreement to limit the increase in global temperature. This reduction in CO_2 emissions is not only a key environmental benefit but also contributes to overall energy sustainability in off-grid communities.

The environmental impact of the Gembu system, with significant reductions in CO_2 emissions, is consistent with findings from other studies that highlight the environmental benefits of solar water heating systems. For example, Agyekum et al., (2023) emphasized the environmental advantages of solar water heating systems, noting their potential to reduce reliance on fossil fuels and lower greenhouse gas emissions.

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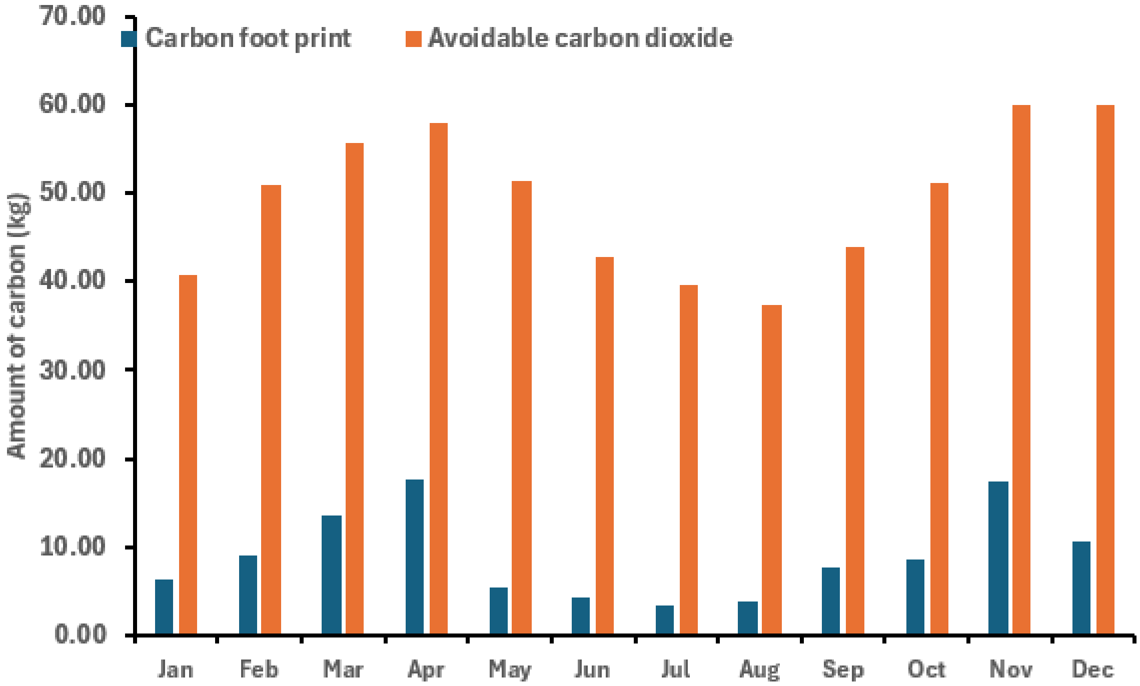

Figure 13. System carbon footprint and avoidable carbon dioxide

4. CONCLUSION

1. This study has evaluated the performance of a solar domestic hot water thermosyphon system tailored for the climatic conditions of Gembu, Taraba State, Nigeria. The key findings are as follows:
2. The analysis revealed that both the monthly hot water demand and the required collector area varied in response to fluctuations in mains water temperature. These variations peaked in January and reached their lowest in June. To ensure consistent year-round performance, a collector area of 2.04 m² was identified as optimal, within a required range of 1.68 m² to 2.45 m².
3. Simulation outcomes showed that the system consistently delivered water temperatures between 40.15°C and 51.91°C throughout the year. Although performance remained high, the system occasionally fell short of the 55°C target during colder months, highlighting the need for auxiliary heating. This reliance, particularly on cloudy days with reduced solar radiation, had implications for both cost-effectiveness and energy efficiency.
4. On days with ample solar radiation, the system frequently exceeded the desired temperature threshold. However, the significance of auxiliary heating increased during low-radiation periods. Experimental validation conducted between January and April confirmed the model's accuracy, with mean absolute percentage errors (MAPE) ranging from 6.1% to 7.8%, thereby affirming the reliability of the simulation.
5. From an environmental perspective, the system's ability to supply approximately 81% of the annual hot water demand using solar energy resulted in a substantial reduction in CO_2 emissions. This contribution supports global sustainability goals and demonstrates the system's potential to reduce dependence on fossil fuels.

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