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Modelling and Simulation of an Embedded Active Solar Flat Plate Collector Water Heater

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ABSTRACT:

The study used TRNSYS 16 software to predict the weekly performance of an active solar water heating system in Yola, Nigeria, latitude 9.2° N, longitude 12.5 °E and altitude 599 m during the months of June to October. The system comprised of a flat plate solar collector with a surface area of 2.10 m2 tilted at 9.2 degrees, a 100-litre thermally insulated vertical storage tank, a 20 Watt solar panel, and 4.8 Watt brushless solar DC pumps. Using typical meteorological year (TMY) weather data for the location, the monthly average hourly performance of the system was simulated. The simulation involved selecting TRNSYS components (TYPE 109) to represent each physical component of the real system, modifying the parameters describing each component according to its characteristics, and linking the components to represent how the system works. The simulation results showed that the system was capable of meeting the daily hot water requirement of 69°C, 68.4°C, 55.2°C, 65.3°C, and 68.9°C for June, July, August, September, and October, respectively, for an average of 15 hours per day. However, in August, the tank temperature dropped to 54.6°C, indicating that auxiliary energy might be required to supplement the hot water requirements for industries, hospitals, and community-based organizations. Overall, the active solar flat plate water heater with an area of 2.10 m2 tilted at an angle of 9.2 degrees to the horizontal would be capable of producing daily domestic hot water of 100 litres for most of the months, except for August.

IndexTerms: Solar water heater, Flat plate collector, Simulation, Collector efficiency, Solar Fraction

Introduction :

Over the past few years, various national and international organizations, private companies, and Non-Governmental Organizations (NGOs) have been implementing renewable energy systems in rural communities of developing nations, where healthcare is of utmost importance (Zaffran, 2014; Zaffran, 2015; World Bank, 2017). The World Health Organization's Expanded Programme on Immunization (WHO/EPI) has been instrumental in examining the viability of different energy sources for cold chain vaccines, electricity, and hot water demand. It was quickly realized that solar energy would play a crucial role in ensuring that remote health centers have access to quality electricity, safe vaccines, and hot water (World Health Organization, 2018).

The adoption of solar water heating is even more critical in developing countries like Nigeria. This is not only because these countries lack natural reserves of conventional fuel, but also because most of their population resides in rural areas where conventional electricity grids have not yet been extended. In such cases, solar water heaters can be used to meet hot water requirements in rural health centers and cottage industries (Sambo, 1997; Agbo and Okparaku, 2016). Currently, water heating in Nigeria is primarily done using conventional electric supply, gas, and fuel wood, which have adverse health, economic, and environmental impacts. Despite the benefits of solar water heating systems, they have not been widely adopted in Nigeria, mainly due to factors such as purchasing power, technology of installation and fabrications, awareness, culture, governmental policy, and politics.

A flat plate collector is a crucial component of solar water heaters. Flat-plate collectors are the most straightforward and commonly used collectors for converting the sun's radiation into useful heat. They are designed for applications that require energy delivery at moderate temperatures (less than 100 degrees), such as water space heating (Duffie and Beckman,2006). Flat-plate collectors have several advantages, such as using both beam and diffuse solar radiation, not requiring sun tracking, and requiring minimal maintenance (Agbo and Okoroigwe, 2017; Fabio, 2014). Scandinavian countries have achieved significant developments in solar water heaters, despite receiving little sunlight. Their large solar water heating plants are known even to be replacing conventional energy sources in some cases and supplementing them in others (Karakezi and Ranja, 2014; Gregory, 2014).

The production of energy from fossil fuels has significant environmental impacts, such as the emission of carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxide (SO_2), and other harmful gases and products. The primary concern is the impact of CO_2 on global climate and human health (MacDonald, 2015).

The decision to forego a new installation was made due to the lower cost of heating domestic water with natural gas. The oil shock sparked renewed global interest in solar energy technologies. The most commonly known method of converting solar energy into heat is through the use of flat plate collectors for heating water, air, or other fluids. Over the past seventy years, independent investigators have built and tested many different types of collectors, with tests conducted in specific locations and varying test procedures and solar radiation availability. The main goal of these tests has been to convert as much solar radiation as possible into heat at the highest attainable temperature. Abdunnabi and Loveday, (2012) conducted the main British research in this field, beginning with experimental work in 1947 on the characteristics of flat plate collectors. Heywood's early experiments were conducted on small square collectors with an area of $0.093m^2$, using water as the heat transfer fluid. The somewhat simplified theoretical treatment that he established at that time is still used as the basis for some of the current design work on domestic flat plate collectors. After the 1950s, water heater designs using flat plate collectors were greatly improved in Israel, Australia, and Japan through better thermal contact between the black metal plate and the tubing through which water circulates, as well as the development of black surfaces that provided greater net energy recovery from the sun. Commercial firms in Israel began manufacturing and selling solar water heaters for local and foreign use, with sales ranging from 10,000 to 15000 units per year. Currently, about 20% of households in Israel have solar water heaters (Abbasi and Naseema, 2018; Delfin, Carlos and Valentine, 2000). In Australia, solar water heaters were further improved by development studies in the 1950s, and by the early 1960s, several manufacturers went into production. The Commonwealth Scientific and Industrial Research Organization (CSIRO) subsequently published a guide to the principles of the design, construction, and installation of solar water heaters (CSIRO, 2016).

As previously mentioned, the need for hot water in education, healthcare, domestic, and other sectors of the Nigerian economy is high and met through the use of electricity, kerosene, and wood as the primary energy sources. Electricity generation in the country depends on stations powered by natural gas and water-driven turbines. Factors such as irregular natural gas supply, fluctuation in water levels in hydropower sites, and obsolete equipment in the electric utility network contribute to the epileptic supply of electricity in the country (Kasimu, 2014). As a result, electricity is not readily available, particularly in rural communities, which make up approximately 70% of the country's population (FOS, 2017). Therefore, rural dwellers resort to fuel wood for water heating and other energy requirements (ECN, 2016). The associated higher production costs are another factor that hampers the successful utilization of these systems, which is why the increased attention given to this area of study is justifiable. Proving the need to embrace a cost-effective and sustainable alternative to our depleting conventional energy sources is imperative and should not be taken for granted. Preliminary research work must be undertaken to prove this beyond any reasonable doubt. This study proposes a novel solar water heating configuration that uses three in-line fluid passages for hot water demand.

2. Materials and Methods :

The following methodology was adopted for the modelling and simulation of the system

2.1 Determination of the Design Month

The design month is defined as the month with the lowest value of the energy ratio (ER). The energy ratio (ER) is the ratio of the monthly average daily solar radiation on the collector surface to the monthly daily solar system load expressed as:

$$E_R = \frac{H_T}{Q_S/D_{load}} \quad (1)$$

Where; HT is the monthly average daily solar radiation on the tilted collector surface (kJ/m2) and QS/Dload is the monthly average daily load (kJ/day)
Methodology for collector sizing

The sensible heat consideration in system design was calculated as the heat required for increasing the temperature to meet the desired load temperature. For instance, if the rate of hot water demand is $\dot{m}_L$, in kg/hr then the heat Q_s required per day to increase the mains water temperature (Tmains) to the desired load temperature (TL) is expressed in Equation 2 (Hoseinzadeh, *et al.*, 2017).

$$Q_s = \int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) dt \quad (2)$$

Losses from the storage tanks may be significant and should be considered part of the total system load. The rate of tank losses (Q_{stL}) is estimated using the tank loss coefficient-area product $(UA)_{st}$ (mostly specified in the manufactures datasheet and the temperature difference between the tank water temperature Tst and the ambient temperature T_a surrounding the tank. Similarly, the total loss per day is calculated using Equation 3 (Govind and Shireesh, 2006).

$$Q_{stL} = \int_1^{24} (UA)_{st} (T_{st} - T_a) dt \quad (3)$$

For good performance, the solar collector must be sized to meet both the sensible heat requirement and the tank loss which is expressed by Equation 4;

$$Q_L = Q_s + Q_{stL} \quad (4)$$

The heat needed to raise the temperature of water required at a flow rate ($\dot{m}$) in kg/hr of the supply mains temperature (T_{mains}) was calculated using Equations 5 to 7 respectively.

$$Q_l = \int_1^{24} \dot{m} C_p (T_l - T_{main}) dt + Q_{stL} \quad (5)$$
$$Q_p = \int_1^{24} \dot{m} C_p (T_p - T_{main}) dt + Q_{stp} \quad (6)$$
$$Q_s = \int_1^{24} \dot{m} C_p (T_s - T_{main}) dt + Q_{sts} \quad (7)$$

Where; C_p is the specific heat capacity of water in kJ/kg.K, Q_l, Q_p, and Q_s are the average daily thermal energy demand obtained by integrating the hourly hot water demands. Tl, Tp and Ts are the desired hot water temperature. The second term in Equations 5 to 7 represents the tank losses of the hot water storage tank.

Furthermore, from each application's daily thermal energy requirement values, the collector area requirement is approximated for each application based on Equations 8 to 10. A_l, A_p and A_s are the desired collector areas

$$A_l = \frac{Q_l}{LF \times \int_1^{24} I_T dt} \quad (8)$$
$$A_p = \frac{Q_p}{LF \times \int_1^{24} I_T dt} \quad (9)$$
$$A_s = \frac{Q_s}{LF \times \int_1^{24} I_T dt} \quad (10)$$

Where; LF (= 0.56) is the hourly utilisability factor of the hourly available irradiance (I_T) obtained from the study location's solar radiation analysis based on formulations, as suggested by Duffie and Beckman (2013). The size of collector area was estimated based on Equations 8 to 10 which determine the length of water passages' tubing.

2.2 System Performance measurement and analysis

The size of a solar system in a particular location is heavily influenced by the weather conditions. However, given the unpredictability of the weather, sizing a solar system can be a difficult and intricate process (Kalogirou, 2009). To evaluate the long-term (annual) performance of a solar system based on preliminary design parameters, numerical simulation using TRNSYS is a commonly used approach (Diez *et al.*, 2019). This approach allows for the visualization of the hourly and even daily performance throughout the year, enabling the adjustment of design parameters until reliable performance is achieved. The Hottel-Whillier-Bliss (HWB) mathematical models and energy balance equations expressed in Equation 11 are used to predict the thermal characteristics of a flat plate collector in a steady-state state. According to Equation 11 (Diez *et al.*, 2019), the rate of useful energy gain of the solar collection (represented by Q sub u) at a given moment is the positive difference between the energy absorbed by the plate and the energy lost by the collector to the environment.

$$\dot{Q}_u = F_R [S - U_L (T_i - T_a)]^+ \quad (11)$$

Where FR, S, UL, Ti and Ta are the energy absorbed by the absorber plate, the collector overall heat loss coefficient, circulating fluid collector inlet temperature and the temperature of the surrounding where the collector is placed respectively. The plus superscript indicates that only positive values of the square bracket terms were used. The Hottel-Whillier equation defines the efficiency of a solar collector (η_{coll}) under a steady radiant energy per unit area (I_T) falling on the collector surface with fluid flowing at a steady fluid flow rate, and constant wind speed and ambient temperature, as expressed in Equation 12 (Braun, 2020).

$$\eta_{coll} = \frac{Q_u}{I_T A_c} \quad (12)$$

The collector efficiency is also calculated as the ratio of the total useful energy from the collector to the total solar radiation ($I_T A_c$) received on the collector surface using Equation 13.

$$\eta_{coll} = \frac{Q_{u1} + Q_{u2} + Q_{u3}}{I_T A_c} \quad (13)$$

Where: Qu1, Qu2 and Qu3 are the useful energy of the proposed collector from outlet 1, 2 and 3 respectively and Ac is the total collector area.

To evaluate the overall system performance, the solar fraction SF is a better performance indicator than the collector efficiency and heat removal factor. It assesses the entire system's overall efficiency rather than a component. Beausoleil-Morrison *et al*., (2019), expressed solar fraction (SF) as the fraction of the actual hot water demand met by the solar system to the total system load.

$$SF = \frac{Actual\ load\ met\ by\ solar\ system}{Total\ system\ load} = 1 - \frac{Q_{Aux}}{Q_L} \quad (14)$$

Where, Q_{Aux} is the energy supplemented by another system component to provide for the shortfall needed to meet design load completely. This energy could include supplementary thermal energy by electric or gas boiler. The average daily auxiliary energy is found from the positive value of Equation

15. When Equation 15 results in negative value during the simulation, the negative values are taken as the system's excess thermal energy.

$$Q_{aux} = \left[\int_1^{24} \dot{m}_L C_p (T_L - T_{mains}) dt - \int_1^{24} \dot{m}_L C_p (T_d - T_{mains}) dt\right]^+ \quad (15)$$

T_d and T_{mains} are the hot water temperatures delivered by the system and the mains water temperature. Another performance indicator that does not consider whether the collector's energy matches demand is system efficiency. Using this evaluator gives an idea of how well the system converts the total incident energy to hot water without concern for its usefulness. The system efficiency is defined as the ratio of the heat that changes the mains water temperature (Tmains) to the temperature at which water is delivered (T_{LDT}) by the system load to the total energy received on the collector surface ($H_T A_c$) as expressed in Equation 16 (Ayompe, 2013).

$$\eta_s = \frac{\dot{m}_L C_p (T_{LDT} - T_{mains})}{H_T A_c} \quad (16)$$

3. Results and Discussion :

Figures 1 to 5 show the weekly average daily system simulated performance of the system for the months of June to October, 2023

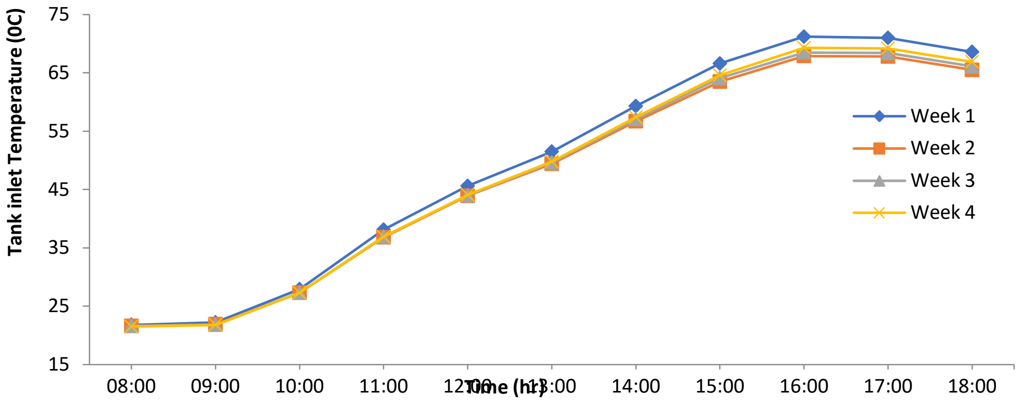

Fig. 1: Weekly average daily simulated system performance for June, 2023

The chart depicted in Figure 1 displays the simulated system performance on a daily basis for an entire week in June 2023, with data for weeks 1, 2, 3, and 4. It is evident from the figure that the system's performance has improved. In week 1, the system showed the best performance, which was then followed by consistent performance in the following three weeks. The system's performance remained similar throughout the four weeks. The figure indicates that the peak temperatures were reached at around 16 to 17 hours of the day in all four weeks. This implies that the system's solar power is adequate to meet the required hot water temperature or energy needs throughout the entire month.

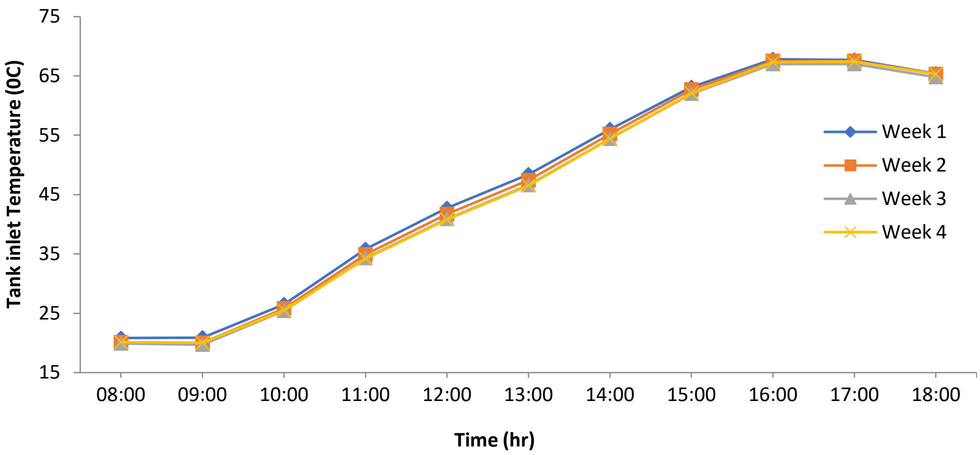

Fig. 2: Weekly average daily simulated system performance for July, 2023

The system's weekly average daily simulated performance during weeks 1, 2, 3, and 4 in July 2023 is illustrated in Figure 2. The system's behavior and performance were quite similar throughout the four weeks, with peak temperatures occurring around 16-17 hours of the day. In week 1, the temperature peaked at 73.2 degrees Celsius, while weeks 2 and 4 had peak temperatures of 72.1 degrees Celsius, and week 3 had a peak temperature of 70.2 degrees Celsius, as shown in the Figure. This indicates that the solar system is capable of meeting the energy requirements throughout the month, as demonstrated in the Figure. Additionally, the slight variations in performance during the weeks can be attributed to differences in the solar and weather conditions experienced during those weeks.

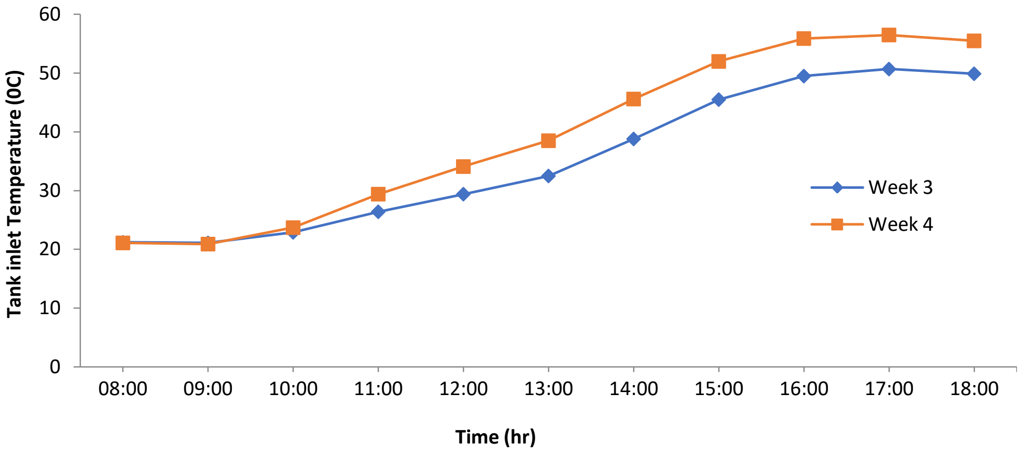

Fig. 3: Weekly average daily simulated system performance for August, 2023

The third figure displays the average daily system performance for weeks three and four in August of 2023. According to the figure, the performance of the system in week four was superior to that of week three. The temperature steadily rose from 8:00 am until it peaked at 55.2 degrees Celsius around 4:00 pm and then fell to 18:00 hours. Week three saw a system performance that also peaked at 50.2 degrees Celsius at approximately 4:00 pm. The figure shows that the system's performance was low in both weeks, indicating a drop in its performance. The low system performance can be attributed to the low amount of solar radiation that the collector received during the month. During the month, the highest values of solar radiation, relative humidity, ambient temperature, and wind velocity were recorded at 2:00 pm, 8:00 am, 1:00 pm, and 10:00 am, respectively, with values of 769.8 W/m^2, 84.1%, 29.5 degrees Celsius, and 2.9 m/s. The solar and weather data recorded in those weeks were lower than the values recorded in other months. Auxiliary energy would be required to meet the hot water or energy needs of the month of August.

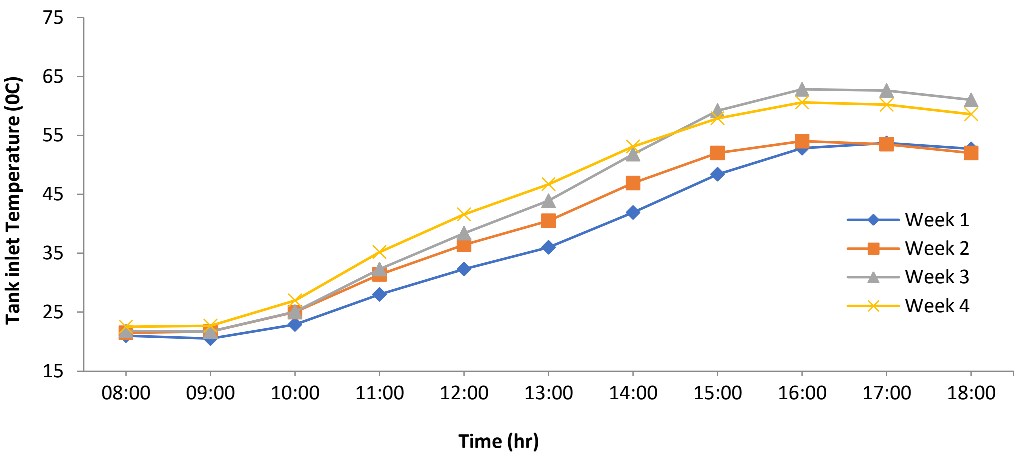

Fig. 4: Weekly average daily simulated system performance for September, 2023

The data presented in Figure 4 indicates the average daily simulated system performance for the weeks 1, 2, 3, and 4 in September 2023. The figure demonstrates that the system performed better in week 4, followed by week 3, then week 2 and finally week 1. During the day, temperatures gradually increase from 8:00 am to 4:00 pm and decrease towards the late hours of the day (6:00 pm). The performance of the system was low in weeks 1 and 2, with highest temperatures reaching 55.8℃ and 56.4℃ respectively, occurring at around 3-4 pm. The variation in the system's performance during those weeks was attributed to differences in solar radiation, ambient temperature, wind velocity, and relative humidity. The highest values of solar radiation, relative humidity, ambient temperature, and wind velocity recorded in September were 860 W/m^2, 84.6%, 32.5℃, and 2.4 m/s respectively, occurring at around 1 pm, 8 am, 1 pm, and 9-10 am. These values were slightly higher than those recorded in August, which were 769.8 W/m^2 and 30.2℃ for solar radiation and ambient temperature respectively. This shows that the solar and weather data in September were better than those obtained in

August, resulting in an improvement in the system's performance. To meet the hot water needs during weeks 1 and 2 of September, auxiliary energy will be required.

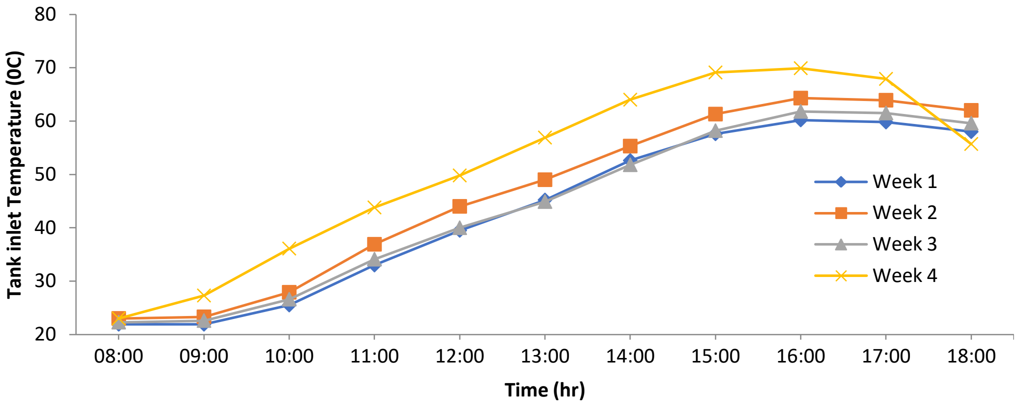

Fig. 5: Weekly average daily simulated system performance for Octorber, 2023

Weekly average daily simulated system performance in weeks 1, 2, 3, and 4 in October 2023 is illustrated in Figure 5. According to the graph, the system performed best in week 4, followed by week 2, and then weeks 1 and 3. The graph also indicates that the system's performance improved, with peak temperatures occurring between 13 to 16 hours of the day. The slight variations in the system's performance during the weeks were due to differences in solar radiation, ambient temperature, wind velocity, and relative humidity. Highest values of solar radiation, relative humidity, ambient temperature, and wind velocity were recorded at around 12 hours, 8 hours, 13 hours, and 9 hours of the day, respectively. This suggests an improvement in solar and weather data during the month, with higher solar radiation and ambient temperature values compared to August and September. This month is approaching the dry season.

The findings in Figures 1 to 5 are consistent with the results of (Kumar and Bhupendra, 2013; Sharma and Joshi, 2013;Rajakrishnamoorthy *et al.,* 2014 and Zwalnan, 2015) which reported water temperatures of up to 72.3℃ in the hot season and 41.8ºC in the wet season in Rajasthan. The studies also reported similar results for solar radiation, relative humidity, ambient temperature, and wind velocity (Rajakrishnamoorthy *et al.,* 2014), obtained water temperatures of 79.7℃ in the hot season and 45.3℃ in the wet season, which were similar to the results of (Kumar and Bhupendra 2013; Julien *et al*., 2013; Sezen *et al*., 2021; Soleymani *et al.*, 2023), simulated a solar flat plate collector for water heating for various applications and obtained similar results. (Raj *et al.*,2017; Singh *et al.,* 2020 and Patel *et al.*, 2021), reported an average maximum temperature of 71.3℃in the hot season and 41.8℃ in the wet season, while the other studies reported comparable findings.

Agbo (2011) and Agbo and Unachukwu, (2007) reported an average water temperature of 81.5℃ with a capacity of 800 litres on a hot summer day under the weather conditions of Sokoto, Nigeria, and lower temperatures in the wet and dusty season. The Nigeria Building and Road Research Institute (MBRRI) maintained a temperature range of 40℃ to 57.1℃ on a clear day in Lagos, Nigeria.
Jouhri and Dhakar (2019) and Anthony *et al.,* (2019) reported temperatures of 70.2℃, 73℃, and 60.4℃ on clear and hot days and lower temperatures during the wet and dusty or cold season in Nsukka, Zaria, and Ibadan, Nigeria, respectively. Zwalnan (2015), also obtained a minimum temperature of 61℃ for most of the year, except in July, where the water temperature dropped below 34℃ at the end of the day, under the weather conditions of Zaria, Nigeria. Mong *et al.*, (2020), Njoku *et al.*, (2020) and Mong *et al.*, (2022) conducted simulations and obtained temperatures ranging from 60℃ to 75℃ in clear and hot weather and lower temperatures during the wet and dusty or cold season in different cities in Nigeria. Zwalnan (2015) reported 34℃ during the cooler season and 61℃ during the hotter season in Zaria, Nigeria, while Njoku *et al.*, (2020) and Mong *et al.*, (2022) evaluated the performance of a flat-plate solar thermal collector for daily utilizability and obtained 60℃ in Owerri, Nigeria.

4. Conclusion :

An active solar water heating system was successfully designed and simulated under the weather condition of Yola, Nigeria latitude 9.2° N, longitude 12.5 °E and altitude 599 m. The annual performance (storage tanks inlet and outlet temperatures) of the system was simulated under weather data of Yola using TRNSYS 16 software. The results of the simulation revealed that, the system was capable of meeting the desired daily hot water requirement of 69 °C , 68.4 °C , 55.2 °C, 65.2 °C and 68.9 °C for the months of June, July, August, September and October respectively at averagely 15 hours of the day. This indicated that the active solar flat plate water heater with area of 2.10 m^2 adopted tilted at an angle of 9.2 ° to the horizontal would be capable of producing daily domestic hot water of 100 litres for most part of the months except the month of August where the tank temperature dropped to 54.6 °C, auxiliary energy might be provided in this month.This indicates that the system would be required to supplement the hot water requirements for industries, hospitals and community – based organization.

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