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Fabrication and Experimental Investigation of a Solar Flat Plate Domestic Water Heater Performance and Efficiency in Bambili, Cameroon

Jerome Ndam Mungwe[1,2], Derek Ajesam Asoh[1,3*], Njimboh Henry Alombah[4], Fonyuy Diedonne Njodzela[5]

[1]Department of Renewable Energy, Higher Technical Teachers Training College, The University of Bamenda, Bambili, Cameroon
[2]Material Science Innovation and Modelling (MaSIM) Research Focus Area, North West University, Mahikeng Campus, Mmabatho, South Africa
[3]Laboratoire de Génie Electrique, Mécatronique et Traitement du Signal, ENSPY, University of Yaounde I, Yaounde, Cameroon
[4]Department of Electrical Engineering, College of Technology, The University of Bamenda, Bambili, Cameroon
[5]Department of Electrical and Power Engineering, Higher Technical Teachers Training College, The University of Bamenda, Bambili Cameroon
Email: *derekasoh@gmail.com

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Abstract

The main energy source used to heat water in rural Cameroonian households is wood. The use of wood as an energy source (wood fuel) has negative environmental and health impacts, which can be avoided by using alternative energy sources that contribute to eliminating wood use. Harnessing solar energy for water heating can reduce typical households' water heating wood fuel consumption to between 50% and 70%. The objective of this study was to fabricate a Flat Plate Domestic Water Heater (FPDWH) and experimentally investigate its performance and efficiency under local environmental conditions. A passive open loop flat plate serpentine solar flat plate domestic water heater was fabricated from local materials; and its performance in terms of heated water temperatures and thermal efficiency was investigated under local irradiance conditions in Bambili, North West Region of Cameroon; where the average solar irradiance was 484.8 W/m^2 in the rainy season and 498.8 W/m^2 in dry season; with maximum values of 892.0 W/m^2 and 849.0 W/m^2 in the respective seasons. Results showed average heated water outlet temperatures of 32.6˚C and 34.1˚C in the rainy and dry seasons respectively; with maximum values of 47.0˚C and 40.9˚C in the respective seasons. The average thermal efficiency of the FPDWH was 49.8% in the rainy season and 51.8% in the dry season, and the maximum was 92.9% and 92.3% during rainy and dry seasons respectively. A temperature difference of 11.5˚C between the cold inlet and heated outlet water was attained with the highest outlet temperature of 47˚C during the rainy season. These performance measures indicate the viability of the locally fabricated FPDWH as a low-cost technology that can be exploited for domestic water heating services, thereby eliminating the use of wood and corresponding negative health and environmental impacts.

Keywords

Domestic Water Heating, Solar Flat Plate Collector, Experimental Investigation, Low-Cost Technology, Performance Measures, Thermal Efficiency

1. Introduction

Domestic hot water usage accounts for a substantial component of residential energy consumption, with daily per capita hot water consumption varying from 19 to 225.8 liters per person/day [1] [2]. A household may consume about 140 to 300 litres of hot water per day, depending on the household size, type, country, and period of the year [2]. In households, hot water may be used for cooking, laundry, washing dishes, and bathing. Hot water of 40˚C to 43˚C is mostly used for hygienic purposes, *i.e.* bathing, while warm water of 32˚C to 90˚C is use for laundry and washing of dishes [2].

The residential sector accounts for about 20% to 40% of total primary energy consumption in developed countries. Therefore, reducing energy consumption in this sector will contribute in the reduction of greenhouse gas emission and its consequent environmental effects of global warming and climate change [1] [3]. Energy to provide domestic hot water comes from many sources [4]; and heating water accounts for 25% of residential energy use worldwide, achieved mostly by burning fossil fuels. In some developed countries such as the USA, water heating accounts for 20% of house energy cost and is the second largest end-use of energy in households [1] [5] [6].

In Cameroon, energy consumption is dominated by biomass, petroleum, and electricity which respectively contribute about 75%, 18% and 7% share to the national energy mix. The residential sector consumes mostly biomass and account for about 64% of the final energy consumption of Cameroon [7]. Hot water demand profile in the North West Region, in particular, and Cameroon in general, which is projected from international data and from domestic hot water demand in neighbouring country Nigeria, shows that a household will consume about 100 litres per day. The main energy sources that households in Cameroon use to warm water is wood, kerosene, liquefied petroleum gas (LPG), and/or electricity. The use of these forms of energy is very expensive and has many negative environmental impacts. Harnessing solar energy using solar water heaters can reduce household fuel consumption for water heating to between 50% and 70%. The use of solar heating can reduce dependency on traditional energy sources for water heating and also reduce energy cost for the household [4] [8]. Therefore, it is important to increase the use of renewable energy technologies to provide hot water to households [1]. Though a tropical country, households in Cameroon need hot water for several applications including cooking activities, laundry, dishwashing and bathing. Solar water heaters are rare in the local markets and even when available, they are imported and are of very high cost. The objectives of the study are two folds: first, to fabricate, a passive open-loop Flat Plate Domestic Water Heater (FPDWH) using local and low-cost materials and second, to experimentally investigate its thermal performance and efficiency under local environmental conditions in Bambili, Cameroon. Evaluating the performance of solar collectors is important for design improvements [9] and economic considerations. The innovativeness of this study lies in the FPDWH being a passive and open loop water heater fabricated using locally available materials. The use of local materials and a passive system design ensures low-cost compared to imported solar water heaters, making the technology more affordable in Cameroon. Furthermore, the relative low fabrication cost will contribute to technology diffusion and sustainability for Cameroonian household hot water heating needs. To the best knowledge of the authors, few investigations of locally fabricated solar water heating systems have been reported in Sub-Saharan African, and particularly Cameroonian climatic conditions. Finally, a cut-across the seasons investigation of the study ascertains the performance for all-year round use. For this reason, the thermal performance and efficiency of the FPDWH were experimentally evaluated during the two seasons (rainy and dry seasons) of the locality (Bambili, Cameroon).

2. Literature Review

According to Oliy and Ramayya [4], domestic hot water service is provided from energy sources such as, firewood, liquefied petroleum gas (LPG), and electricity. It is reported that solar water heating can reduce domestic water heating by 70% and therefore should be employed where possible in order to contribute to achieving a sustainable future [10]-[12]. Solar thermal collectors have been investigated for several applications, including domestic water heating [12]-[15]. Amongst the existing solar water heating technologies, the flat plate collector is the most common type used for residential hot water applications. This contrasts with the parallel tube type (conventional flat plate collector) which has been in service for a much longer time and has more or less the same design, shape, but high operation cost [4] [16]. The high operation cost of the conventional type flat plate collector is inherently due to its characteristic high flow rate. The serpentine type solar collector (of the flat plate family) is characterized by turbulent flow and low flow rate; and consequently has the potential to outperform the conventional type parallel tube flat plate collector; yet it is not common in the market [4]. The fabrication from local materials and experimental investigation of the performance of a serpentine flat plate solar water heater is therefore important and necessary for the introduction of this technology in the local market.

Previous research on the experimental investigation of the performance of domestic solar hot water systems has been reported by Oliy and Ramayya [4]. These authors carried out an experimental study to determine the performance of an improved passive serpentine flat plate collector. At a mass flow rate of 0.00285 kg/s, the outlet temperature of the collector reached 63.9˚C and the efficiency ranged from 55% to 78%. Ayombe and Duffy [13] analysed the thermal performance of a commercially forced circulation domestic scale solar water heating system with a 4 m^2 flat plate collector fitted with an automated sub-system which controlled hot water draw-offs and the operation of an auxiliary immersion heater. The maximum recorded collector outlet temperature was 70.4˚C and the collector efficiency was 45.6% [9]. Zukowski studied the energy efficiency of a solar domestic hot water system made up of 32 flat plate collectors and 21 evacuated tubes collectors with a total collector surface area of 146.29 m^2. The energy [thermal] efficiency of the system ranged from 10% to about 35%. The highest efficiency was recorded during the warmer months and the lowest during the colder months [17]. Nshimyumuremyi and Junqi [18], carried a study to determine the thermal efficiency and conducted a cost analysis of a parallel tube solar water heater fabricated locally in Rwanda. The study was done in three different locations where ambient temperatures ranged from 11˚C to 29˚C. The efficiency of the collectors in the three localities were 78%, 81.34%, 81.7% [18]. Hossain *et al.*, [10], carried out a comparative performance analysis of a serpentine-flow solar water heater and a photovoltaic thermal collector under Malaysians climatic conditions, through modelling and simulation with the TRaNsient SYstem Simulation (TRNSYS) tool; followed by an experimental investigation. The thermal efficiency of the serpentine-flow solar water heater ranged between 87% and 93%. The outlet temperature of the water from the serpentine-flow solar water system varied from 28˚C to a maximum of 40.5˚C [10]. Khan *et al.*, [5] design, fabricated, and studied the efficiency of a novel solar thermal water heating system for small scale hot water production for household purposes. The collector consisted of a flat plate serpentine copper tube fused to the absorber. The water from the outlet reach a temperature of 77.5˚C [5]. Other types of solar thermal collectors and their performances have been studied and analyzed by other authors, including [19]-[21].

From the review of the available relevant literature, there is little or nothing in the literature on the investigation of the thermal performance of a passive open-loop serpentine flat plate solar water heater fabricated from locally available materials and investigated under the environmental conditions in the locality of this study [Bambili, Cameroon]. This study therefore makes a significant contribution, first in the fabrication, and second in an understanding of the performance of a locally fabricated passive open-loop serpentine flat plate solar water heater within the context of Cameroon. This study contributes important knowledge on the practical and economical application of solar water heating technology tailored for the Cameroonian context, where conventional solar water heaters are rare and expensive. This implies that, sooner rather than later, local population will not depend on expensive imported variants of solar water heaters.

3. Materials and Methods

3.1. Materials

3.1.1. Design of the Flat Plate Domestic Water Heater (FPDWH)

The FPDWH consists of a collector casing containing the flow tubes and the absorber. The collector casing, was made out of hardwood with dimensions 1.65 × 0.7 × 0.15 m. These dimensions were adopted from [other types of] commercial solar water heaters available in the local market. The collector absorber plate was made out of aluminium foil (0.3 mm thick) with the same dimensions as the casing. The absorber was painted black with acrylic paint in order to maximise its performance. The flow tube made of copper pipe of length of 15 m was fixed in the collector casing. The flow tube has an inner diameter of 6 mm and outer diameter of 8 mm. The flow tube was transformed into a serpentine structure with a 0.1 m spacing of the tubes with length of 0.6 m. The serpentine structure had a provision for an inlet and an outlet, each with valves to control the water flow as needed. The inlet was connected to a cold-water supply tank and the outlet connected to a hot-water storage tank. The inlet was secured with a valve which was used in regulating the volume of water entering the FPDWH during the experimental step of determining the optimal water flow. A transparent glass-glazing of dimensions 1.65 × 0.7 × 0.003 m was used in the FPDWH. The design of the serpentine flow tube and the collector casing are shown in **Figure 1** and **Figure 2** respectively.

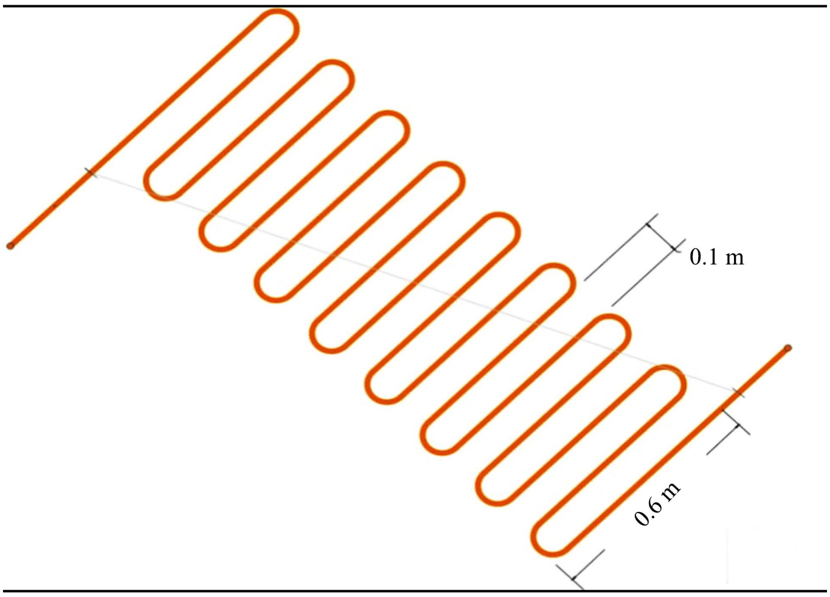

Figure 1. Design of the flow tube.

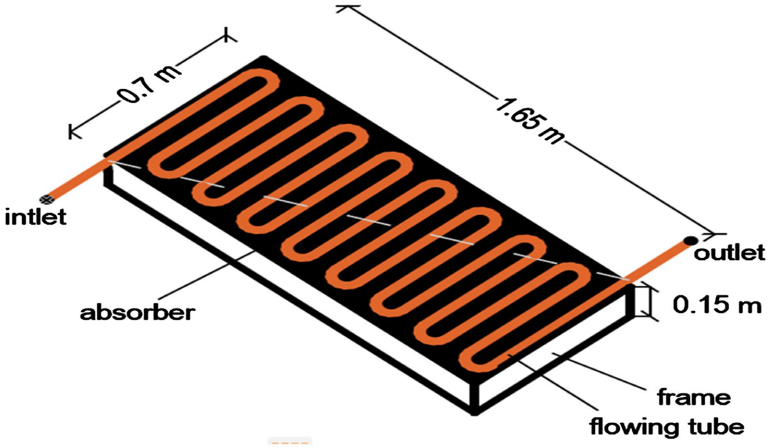

Figure 2. Design of the FPDWH.

3.1.2. Selection and Description of Materials for the Fabrication of the FPDWH

Locally available materials were carefully selected for the fabrication of the FPDWH components: Casing, absorber plate, flow tubes, glazing, and insulation of the absorber.

***Casing*:** The casing, which protects the other components of the heater, was made of hard wood. Hard wood was used not only because of its low-cost and high resistance to environmental deterioration but also because of its low coefficient of thermal conductivity [~0.090 to 0.197 W/mK] which ensures good insulation of the collector.

Absorber plate absorbs the incident solar radiation and converts it to heat which heats the water as it flows through the serpentine tube. The absorber plate was made of 3 mm- thick aluminium metal. Aluminium was selected because it does not rust like iron; it has a high thermal conductivity, and is low cost. To ensure maximum optical absorptivity, the surface of the absorber plate was painted with black acrylic paint. In order to support and provide insulation of the absorber plate from underneath, a 3 mm-thick plywood was used.

Flow tube carries the water through the collector allowing it to absorb heat from the absorber. The tube is made of copper pipe of inner and outer diameters of 6 mm and 8 mm respectively. Copper was selected over aluminium because of its better thermal conductivity, heat tolerance, tensile strength, and ductility. The copper pipe was folded into a serpentine heat exchanger. The serpentine design (Figure 1) was chosen for the heat exchanger because the winding path provides fluid dynamics and practical advantages over straight-tube designs, including enhanced heat transfer through induced turbulence and secondary flows. The design also has a compact and space-saving configuration and was easy and cheap to fabricate with local tools.

Glazing is a transparent white glass cover placed on the open side of the absorber casing; and is used to limit radiation and convection heat losses as well as to protect the absorber plate from extraneous environmental influences.

Insulation of the absorber plate serves to improve the insulation of the underneath of the absorber plate; and is a 5 cm-thick layer of sawdust, uniformly spread on the supporting plywood beneath the absorber plate. Sawdust was selected for its low thermal conductivity, low cost, and high availability in the local environment. The thermal conductivity of the sawdust was assumed to be 0.048 W/mK at a density of 124 kg/m^3 [22].

TES 132 Data Logging Solar Power Meter (Pyranometer) serves to measure the intensity of solar radiation at the experimental site. The device is fully cosine corrected for the angular incidence of solar radiation; and has a spectral response from 400 nm to 1000 nm. Its range of solar irradiance measurement is from 200 W/m^2 to 2000 W/m^2 with a resolution of 0.1 W/m^2, an accuracy of ±10 W/m^2, and a sampling rate of 1 times/second.

3.2. Methods

3.2.1. Description of the Experimental Site

The investigation of the thermal performance and efficiency of the FPDWH was carried out on the campus of The University of Bamenda in Bambili, Cameroon. Bambili is a large village that is rapidly transforming into a semi-urban area in Tubah Sub Division, North West Region (NWR) Cameroon. Bambili serves as the major educational and residential suburb, located 14.5 km East of Bamenda (capital city of the NWR), on latitude 5˚59'0'' North and Longitude 10˚15'0'' East. The climate of Bambili is characterised by two seasons: rainy and dry season. The rainy season covers the period from mid-March to mid-October while the dry season covers the period from mid-October to mid-March. The annual precipitation is about 2000 mm with a maximum between July and September. During the rainy season the rains are intense and above 200 mm; and mist is frequent. At an altitude of about 1500 m above sea level, the average monthly temperature of Bambili is about 18˚C. From April to June the temperature ranges from 24˚C to 27˚C during the day; and from 15˚C to 18˚C during the night. Humidity varies between 76% and 90% during the same period. The average daily hours of sunshine in Bambili ranges from 163.9 to 292.1 hours while the monthly average daily hour ranges from 5.28 to 9.42 hours. The monthly average global solar radiation on a horizontal surface ranges from 15.012 MJ/m^2-day (4.2 kWh/m^2-day) to 23.616 MJ/m^2-day (6.6 kWh/m^2-day) [23] [24]. From the foregoing, it can be noted that the climatic conditions of Bambili make it a suitable site for the experimental investigation of the thermal performance and efficiency of a locally fabricated FPDWH.

3.2.2. Experimental Set-Up

The amount of solar irradiance absorbed by a solar collector depends on its tilt angle and orientation [4]. Several studies present methods to determine the optimal tilt angle as well as recommended values for solar energy technologies [25]-[27]. Soulayman [25], for example, notes that the tilt angle of the FPDWH could be 5 degrees facing South, on the corresponding latitude of the experimental site. The FPDWH investigated in this study was tilted a bit higher at 10 degrees to allow for easy cleaning of dust deposit on the collector, especially during the dry season, when the environment is very dusty. The dimensions of the FPDWH reported above were measured using a tile rite 5 m-long Nylon coated steel measuring tape; with accuracy of 0.0005 m. A batch type 100-litre bucket which served as a reservoir to supply cold water to the FPDWH was connected to the inlet of the FPDWH via a plastic pipe, and elevated to a height of 0.5 m in order to create pressure for the cold water to flow through the FPDWH.

The solar irradiance incident on the area of the FPDWH was recoded using a TES 132 data logging Solar Power meter. A mercury thermometer was inserted in the inlet to record the temperature of the cold water entering the FPDWH. This thermometer has a range of −10˚C to 50˚C and an accuracy of 0.25˚C. Heated water from the FPDWH was collected in a graduated 20 litres container. A second mercury thermometer was inserted in the outlet to record the temperature of the heated water from the FPDWH. This thermometer has a range of −10˚C to 100˚C with an accuracy of 0.5˚C. The experimental set-up is shown in **Figure 3**. The specification of the measurement devices is presented in **Table 1**.

Table 1. Specification of measurement devices used in the study.

Device	Made	Parameter measured	unit	Accuracy
Solar Power meter	TES132	Incident solar irradiance	W/m^2	±10
Thermometer 1	Mercury-in-glass	Inlet temperature of water flowing into solar collector	˚C	±0.5
Thermometer 2	Mercury-in-glass	outlet temperature of water flowing into solar collector	˚C	±0.25
Measuring tape	Tile rite 5 m-long Nylon coated steel	Length and width of the aperture of the FPDWH	m	±0.0005

Figure 3. Experimental set up of the fabricated FPDWH.

3.2.3. Experimental Procedure

The water flow rate through the FPDWH was determined by noting the time it took for water from the outlet to fill a 1 litre container and subsequently dividing this volume by the noted time. Based on the results obtained, the cold water inlet flow was adjusted accordingly via the valve at the inlet until an optimal rate of 0.016 kg/s (1 litre/minute) was obtained as recommended by Sanaka *et al.*, [28]. This flow rate was adjusted regularly to ensure that it was constant throughout the experiment. Also, the hydraulic head in the reservoir of cold water was kept constant by constant refilling. Data was collected during a period in the rainy and another period in the dry season to allow for a comparison of the thermal performance and efficiency of the FPDWH during the two seasons.

After calibration (establishing the optimal flow rate), subsequent measurements were taken for a duration of 15 minutes between 9:00 am to 15:00 pm on select days of the rainy and dry seasons. Specifically, data was collected for three days (6th, 7th, and 9th June 2024) during the rainy season and another three days in the dry season (27th February, and 13th and 16th March 2025). The chosen days were representative of the prevailing weather outlook (clear sky, intermittent cloud, and heavy overcast sky) climatic conditions of the experimental site, as described above; in line with previous studies [9].

The thermal efficiency (η) of the FPDHW, was calculated as the ratio of solar energy incident on the collector (Q_{in}) and the energy carried away by the heated water (Q_{out}). Numerically, Q_{in}, Q_{out}, and η are computed using Equations (1) and (2) [9] [10], and Equation (3) [18].

$$Q_{in} = I * A \tag{1}$$

$$Q_{out} = \dot{m} c_p \left(T_{out} - T_{in} \right) \tag{2}$$

$$\eta = \frac{Q_{out}}{Q_{in}} \tag{3}$$

where:

η is the thermal efficiency (%).

Q_{in} = *is the solar energy incident on the collector* (W/m^2).

I = *solar irradiance on the collector area* (W/m^2).

A = *collector area exposed to solar irradiance* (m^2).

Q_{out} = *the energy carried away by the heated water.*

$\dot{m}$ = *mass flow rate of water through the collector* (*kg/s*).

C_p = *heat capacity of water* (4200 *J/Kg K*).

T_{out} = *temperature of water at the outlet of the collector* (˚C).

T_{in} = *temperature of water at the inlet of the collector* (˚C).

3.3. Uncertainty and Experimental Errors

When measurements to collect data are carried out as in this experimental study, there is the challenge of errors and uncertainties in the measurements. While an error is the difference between the actual value and what is measured, uncertainty quantifies the range within which the true (actual) value is found. Uncertainties and errors are inevitable, given that that they are linked to the measuring instrument and its calibration, the measuring process, and the measured parameters [29].

From Equations (1), (2) and (3), the efficiency of the FPDWH depends of the area of the collector (A), the water flow rate ($\dot{m}$), solar irradiance (I) and the difference between the inlet and outlet temperatures of water flowing through the collector. Therefore, anticipated data errors in this study could come from the measurements of collector area, inlet and outlet water temperatures, collector solar incident irradiance, and water flow rates.

The uncertainty in measuring the foregoing parameters was calculated using the Root Sum Square Method (RSSM) as described in Equations (4) and (5) [13] [14].

$$s = \sqrt[2]{\left(\frac{\Delta u_1}{u_1}\right)^2 + \left(\frac{\Delta u_2}{u_2}\right)^2 + \left(\frac{\Delta u_3}{u_3}\right)^2 + \cdots} \tag{4}$$

where $u_i, i = 1, 2, 3, \cdots$ is a measured parameter.

For this study and from Equations (1), (2) and (3), the uncertainty in the thermal efficiency of the FPDWH, S_η , is given by

$$S_\eta = \sqrt[2]{\left(\frac{\Delta DA}{DA}\right)^2 + \left(\frac{\Delta DT}{DT}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2} \tag{5}$$

where:

$\frac{\Delta DA}{DA}, \frac{\Delta DT}{DT}, \frac{\Delta I}{I}$ and $\frac{\Delta \dot{m}}{\dot{m}}$ is the error in determining the area of the collector, temperature difference between the inlet and outl let average irradiance and water flow rate throug the collector respectivey.

From Equation (5), the uncertainty in the thermal efficiency of the FPSDWH was obtained as 7.2%.

The uncertainty value of temperature difference is noted to be higher than that of irradiance because irradiance values are larger and measured with the high precision pyranometer at one source; whereas temperature values are relatively smaller, and are measured with the less precise thermometer from two different sensors, and subjected to compounding of measurement errors from two sensors. (**Table 2**)

Table 2. Standard uncertainty of the measured parameters.

Parameter	Average calculated	Standard deviation (s)	Number of measurements (n)	Standard uncertainty (u)	Uncertainty (%)
Area of aperture of FPDWH (A)	1.17 m^2	-	-		0.1%
Solar irradiance (I)	491.7 W/m^2	190.8 W/m^2	123	17.204	3.5%

Continued

Difference between inlet and outlet temperatures T	4.6˚C	3.2˚C	123	0.2851	6.1%
Water flow rate through the FPDWH	0.016 kg/min	0.003	123	0.00028	1.6%

4. Results and Discussions

The daily performance of the FPDWH was evaluated during three days within the rainy season and three days within the dry season. The days were representative of prevalent weather outlook conditions in Bambili (clear sky, intermittent cloud, and heavy overcast sky). The aperture area of the experimental FPDWH was 1.1690 ± 0.0009 m^2. The daily performance of the collector was evaluated in terms of the inlet and outlet temperatures of the water flow through the collector, solar irradiance, and the thermal efficiency of the collector.

4.1. Cost of the FPDWH

The cost of FPDWH is US$ 133.80. The costs of the individual components (all sourced locally) are presented in Table 3. Imported Solar water heaters in Cameroon can only be found in large cities and through specialised vendors. The cost of these imported Solar Water Heaters range from $1500 to $5000, about FCFA 943,000 to FACFA 3,000,000. From discussions and experience working with the local metal works company that manufactured the single prototype used in this study, it is estimated that if 5000 units or more were produced, the labour cost per unit will drop by about 80%, *i.e.*, 3000 FCFA per unit. Similar drop in material cost is anticipated. On this basis, the economies resulting from producing a large quantity (mass-production) will certainly result in the FPDWH being a low-cost technology, affordable for the local populations.

Table 3. Cost of the FPDWH.

S/N	Item	Units	Quantity	Unit Price (FCFA)	Amount (FCFA)	Amount ($USA)
1	Copper tube	m	15	2150.00	32250.00	51.24
2	4 mm thick aluminium absorber plate	m^2	1.12	6696.43	7500.00	11.92
3	Wooden casing	U	1	10000.00	10000.00	15.89
4	Black paint	U	1	3500.00	3500.00	5.56
5	Transparent glass	m^2	1.27	12570.71	15964.80	25.36

Continued

6	Labour	U	1	15000.00	15000.00	23.83
TOTAL (1 USD = 629.26 FCFA)					**84214.80**	**133.80**

4.2. Inlet and Outlet Temperatures of Water Flow through the Collector

The inlet and outlet temperature of water flow through the solar collector is a key parameter in the analysis of the thermal efficiency of the collector. During the experimentation days in the rainy season, the average inlet and outlet temperatures of the water flow through the collector were 28.3˚C ($\sigma = 3.3$˚C) and 32.6˚C ($\sigma = 5.3$˚C); the maximum inlet and outlet temperatures were 36.0˚C and 47.0˚C respectively; while the minimum inlet and outlet temperatures of the water flow through the collector were 21.0˚C and 23.9˚C respectively. The average and maximum temperature difference between the inlet and outlet temperatures were 4.3˚C ($\sigma = 3.2$˚C), and 11.5˚C ($\sigma = 3.2$˚C).

In the dry season, the average inlet and outlet temperatures of the water flow through the collector were 29.1˚C ($\sigma = 3.2$˚C) and 34.1˚C ($\sigma = 3.7$˚C); the maximum inlet and outlet temperatures were 34.5˚C and 40.9˚C respectively while the minimum inlet and outlet temperatures of the water flow through the collector were 22.5˚C and 24.5˚C respectively. The average and maximum temperature difference between the inlet and outlet temperatures were 4.9˚C ($\sigma = 3.1$˚C) and 11.5˚C ($\sigma = 3.13$˚C) respectively. The evolution of the inlet and outlet temperatures of the water flow through the collector during the rainy season and the dry season respectively are presented in **Figure 4** and **Figure 5** respectively.

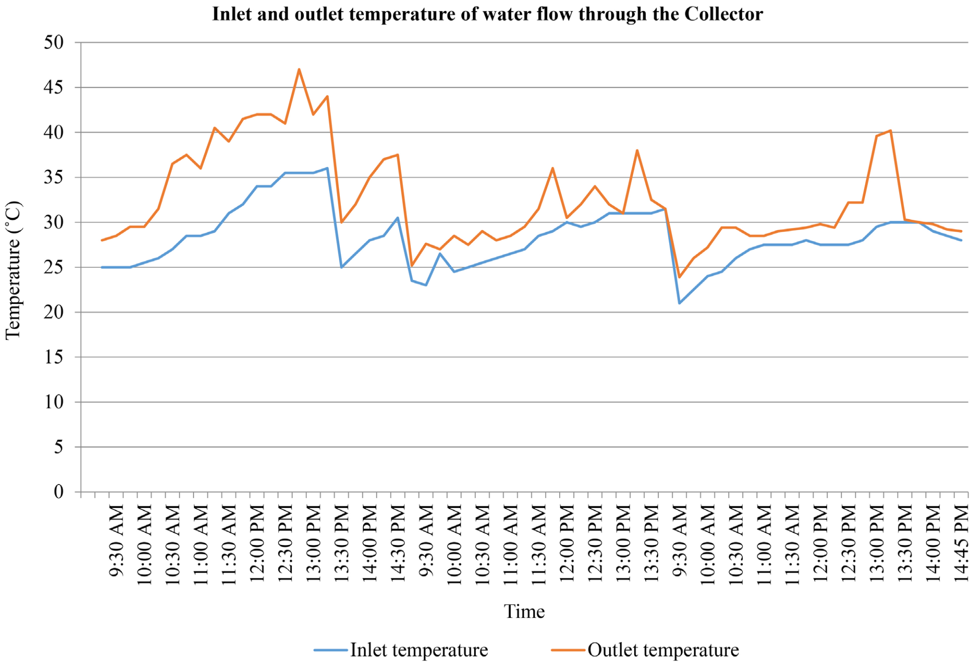

Figure 4. Evolution of inlet and outlet temperatures during the rainy season.

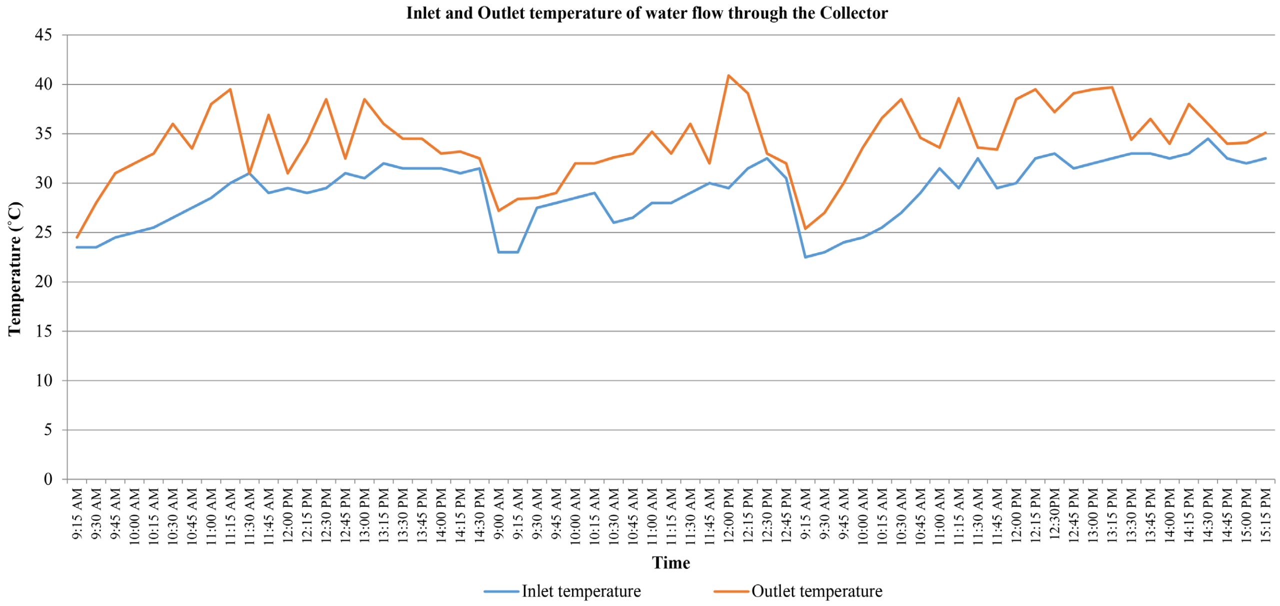

Figure 5. Evolution of inlet and outlet temperatures during the dry season.

In the rainy season, the daily maximum outlet temperature of the water flow through the collector ranged from 38.0˚C to 47.0˚C corresponding to a maximum irradiance range of 769.5 W/m^2 to 892.0 W/m^2; while in the dry season, the daily maximum outlet temperature ranged from 39.7˚C to 40.9˚C corresponding to a maximum irradiance range 692.5 W/m^2 to 849.0 W/m^2. These ranges of outlet temperatures during the rainy and dry season were within the range of hot water used for hygienic purposes, such as bathing, and for laundry and washing of dishes [11]. Table 4 and Table 5 present the average, maximum and minimum temperatures of the inlet and outlet water flow through the collector during the rainy and dry season respectively. From the recorded temperatures of the outlet, the maximum was surprisingly noticed in the rainy season; indicating that in this tropical locality of the study, the solar collector attained a higher temperature on a certain day in the rainy season rather than in the dry season as expected. This could have been due to clear skies days in the rainy season and dust-filled skies days in the dry season. This trend was also noticed with the recorded solar irradiance, where higher values were recorded in some days in the rainy season.

Table 4. Inlet and outlet collector water flow temperatures in the rainy season.

	Inlet temperature (˚C)			Outlet temperature (˚C)			Temperature Difference (˚C)		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Average	29.6	27.9	27.2	36.7	30.5	30.1	7.1	2.6	2.9
Maximum	36.0	31.5	30.0	47.0	38.0	40.2	11.0	6.5	10.2
Minimum	25.0	23.0	21.0	28.0	25.2	23.9	3.0	2.2	2.9

Table 5. Inlet and outlet collector water flow temperatures in the dry season.

	Inlet temperature (˚C)			Outlet temperature (˚C)			Temperature Difference (˚C)		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Average	28.8	27.7	30.1	33.7	32.8	35.2	4.9	5.1	5.1
Maximum	32.0	31.5	34.5	39.5	40.9	39.7	9.5	11.4	11.5
Minimum	23.5	23.0	22.5	24.5	27.2	25.4	0.0	1.0	1.1

4.3. Solar Irradiance

Solar irradiance is another important parameter in the analysis of the performance of a solar collector. An average solar irradiance of 484.8 W/m^2 (σ = 214.2 W/m^2) and 498.8 W/m^2 (σ = 165.1 W/m^2), were recorded during the experimentation period in the rainy and dry seasons respectively. In the rainy season, maximum and minimum irradiances of 892.0 W/m^2 and 92.75 W/m^2 respectively were recorded; while in dry season the maximum and minimum were 849.0 W/m^2 and 132 W/m^2 respectively. Figure 6 and Figure 7 shows the variation of solar irradiance during the experimentation period in the rainy and dry seasons respectively. Table 6 and Table 7 show the average, maximum, and minimum irradiations recorded during the experimentation period in the rainy and dry seasons respectively. It is observed that although a higher maximum irradiance was recorded in the rainy season, the minimum irradiance in the dry season was higher than the minimum in the rainy season. Furthermore, the average irradiance during the dry season was higher than in the rainy seasons as expected. What this tells us is that while we may have some isolated days in the rainy season with unimpeded irradiance resulting in higher maximum of collector outlet water flow temperature as noted earlier, overall irradiance quantities are generally higher in the entire dry season (as reflected by the average) compared to the rainy season.

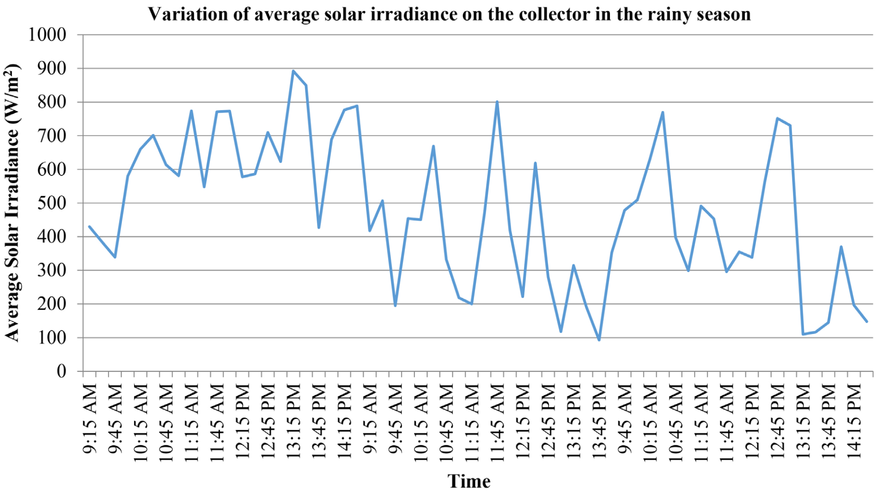

Figure 6. Variation of Solar Irradiance during the experimentation days in the rainy season.

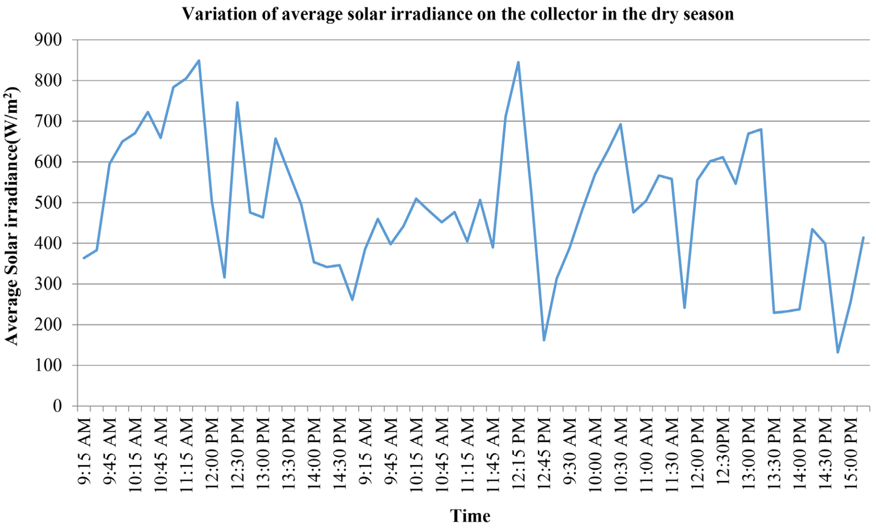

Figure 7. Variation of solar irradiance during the experimentation days in the dry season.

Table 6. Solar irradiance during experimental days of the rainy season.

	Solar irradiance (W/m²)		
	Day 1	**Day 2**	**Day 3**
Average	634.8	366.9	429.3
Maximum	892.0	801.0	769.5
Minimum	339.0	92.8	116.5

Table 7. Solar irradiance during experimentation days if the dry season.

	Average Solar irradiance (W/m²)		
	Day 1	**Day 2**	**Day 3**
Average	558.5	479.9	456.8
Maximum	849.0	845.0	692.5
Minimum	316.0	261.0	132.0

4.4. Thermal Efficiency of the FPDWH

The thermal efficiency was evaluated using Equation (3). The average thermal efficiency of the collector during the experimentation days of the rainy season was 49.8% (σ= 21.3%). During this experimental period the maximum and minimum thermal efficiencies were 92.9% and 8.7% respectively. The minimum thermal efficiency (8.7%) was recorded on a particularly cloudy day, though without rain fall. During the dry season the average thermal efficiency recorded was 51.8% (σ = 23.6%); and the maximum and minimum thermal efficiencies were 92.3% and 10.6% respectively. Table 8 and Table 9 show the analysis of the thermal efficiency of the experimentation days in the rainy and dry season respectively.

Table 8. Thermal efficiency of the collector during the rainy season.

	Thermal Efficiency of collector (%) in the rainy season		
	Day 1	**Day 2**	**Day 3**
Average	58.8	48.4	41.2
Maximum	92.9	85.1	89.9
Minimum	33.8	8.7	15.7

Table 9. Thermal efficiency of the collector during the dry season.

	Thermal Efficiency of collector (%) in the dry season		
	Day 1	**Day 2**	**Day 3**
Average	46.3	52.7	55.9
Maximum	85.8	92.3	87.9
Minimum	14.4	12.5	10.6

It is noted that although the maximum efficiency was recorded in one of the days of the rainy season (corresponding to maximum irradiance) the collector performed better in the dry season than in the rainy as expected, since the overall average irradiance in the dry season was higher than in the rainy season. Figure 8 and Figure 9 show the variation of the thermal efficiency of the collector during the experimentation days of the rainy and dry season.

The average efficiency of the locally fabricated FPDWH over six-day experimental period cutting across the rainy and dry season is 50.7%. This value is comparable to the annual average efficiency of similarly designed flat plate collectors in northern temperate climatic conditions [9] [14].

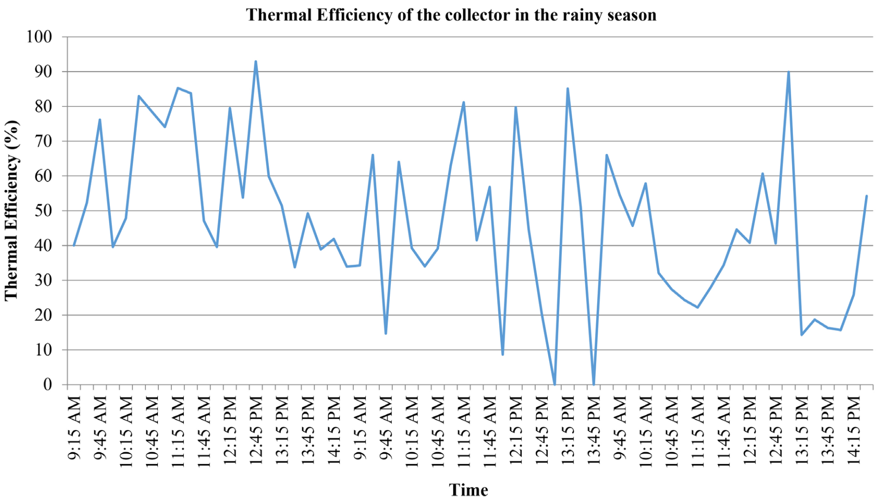

Figure 8. Thermal efficiency of the collector during the rainy season.

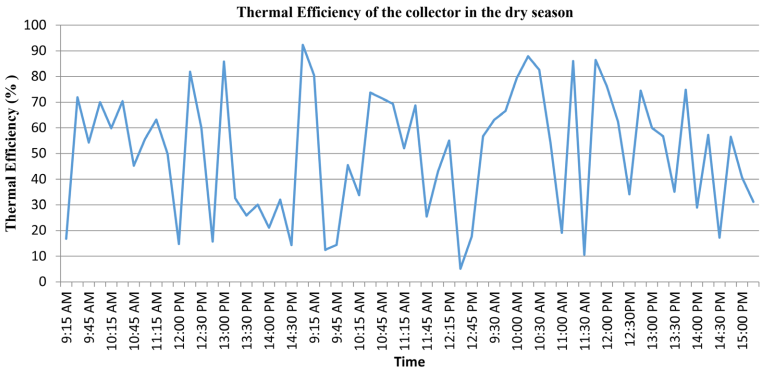

Figure 9. Thermal efficiency of the collector during the dry season.

4.5. Thermal Efficiency and Solar Irradiance

The relationship between the thermal efficiency and the local solar irradiance showed a weak positive correlation. The correlation was relatively stronger in the rainy season than in the dry season. The correlation coefficients were 0.18 and 0.11 in the rainy and dry seasons respectively. **Figure 10** and **Figure 11** present the variation of thermal efficiency of the FPDWH and solar irradiance during the rainy and dry season respectively.

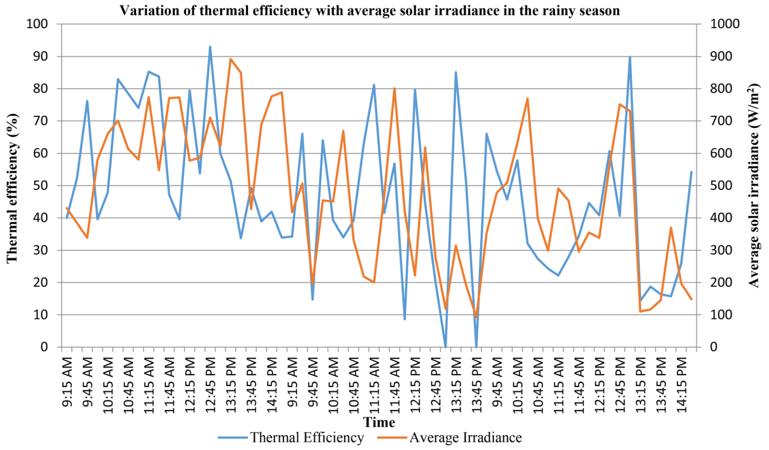

Figure 10. Variation of Thermal efficiency and solar irradiance during the rainy season.

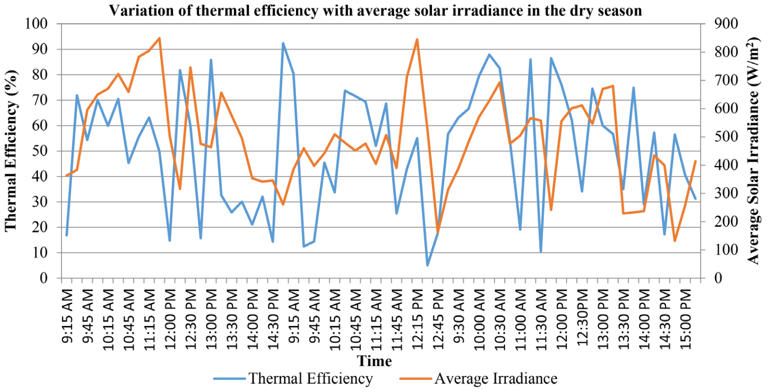

Figure 11. Variation of Thermal efficiency and solar irradiance during the dry season.

5. Conclusions

The residential sector accounts for about 40% of global energy consumption, thus, reducing energy consumption in any area of this sector will contribute in the reduction of greenhouse gas emission and its consequent environmental effects of global warming and climate change. In Cameroon, the residential sector consumes mostly biomass and accounts for about 64% of the total national energy consumption. The main energy sources to warm water in many Cameroonian household is wood, LPG, and/or electricity. The use of these forms of energy is very expensive and has many negative impacts on the environment. Harnessing solar energy using solar water heaters can reduce household water heating fuel consumption to between 50% and 70% and consequently the reduction of total household energy cost; which is highly commended. A full-scale, passive open-loop flat plate serpentine solar domestic water heater was successfully fabricated from carefully selected local materials. The choice and usage of local materials ensured the low-cost of the final product. The thermal performance of the FPDWH in terms of its thermal efficiency was investigated under various local conditions on the campus of The University of Bamenda in Bambili. During the experimentation period in the rainy and dry seasons, the average outlet temperatures of the water flow through the collector were 32.6˚C and 34.1˚C respectively; the maximum temperatures were 47.0˚C and 40.9˚C respectively. Average solar irradiances of 484.8 W/m^2 and 498.8 W/m^2 were recorded during the experimentation days in the rainy and dry seasons respectively. Maximum solar irradiance of 892.0 W/m^2 and 849.0 W/m^2 were recorded during the rainy and dry seasons respectively. The thermal efficiency of the collector varied with solar irradiance. The average thermal efficiencies of the collector during the experimentation days of the rainy and dry seasons were 49.8% and 51.8% respectively. The highest thermal efficiency of the FPDWH was 92.9%. From this experimental study, it is demonstrated that a locally fabricated full-scale, passive open-loop Flat Plate Serpentine Solar Domestic Water Heater (FPDWH) made from low-cost and accessible materials can effectively produce hot water suitable for domestic uses such as bathing, dishwashing, and laundry in tropical climatic conditions as found in the study site, Bambili, Cameroon. The performance of the FPDWH is commendable. An average thermal efficiency of about 50.7% across the rainy and dry seasons is a good indicator that the FPDWH can be effectively used in similar climatic regions of Cameroon and other countries of the world. The collector achieved a maximum outlet water temperature up to 47.0˚C during the rainy season and around 40.9˚C during the dry season, with solar irradiance averaging approximately 480 - 500 W/m^2. This shows that the passive solar water heater can significantly reduce reliance on biomass and fossil fuels, contributing to lower household energy costs and mitigation of negative environmental impacts. The low-cost fabrication method further demonstrates the feasibility; its sustainability and wide adoption as a water heating technology in our local communities will fill a critical gap, where imported systems are expensive and sometimes not available.

6. Further Research

Suggested follow-up research to this study include: 1) Conduct an extended field testing over a complete year and multiple years to assess the durability, maintenance needs, and performance consistency of locally fabricated FPDWH units in different microclimates; 2) Compare the performance of FPDWH to conventional parallel tube flat plate collectors and evaluate flat tube collectors under identical local conditions; and 3) Conduct comprehensive cost-benefit and environmental impact analyses, including life-cycle assessment, to quantify economic savings and carbon footprint reductions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

C_p	Specific heat capacity of water	J/kgK
I_{av}	Average Intensity of solar radiation	W/m^2
k	Thermal conductivity	W/mK
$\dot{m}$	*mass of water collected over a certain time*	kg/s
T_{out}	*The temperature of the water at the outlet of the collector*	˚C
T_{in}	*the temperature of the water at the inlet of the collector*	˚C
I	*the intensity of the solar radiation*	W/m^2
A	*the area of the aperture of the collector*	m^2
Q_{in}	Solar Energy incident on the aperture of the solar collector	W
Q_{out}	Energy carried away water in the solar collector	W
η	Thermal efficiency	%
σ	Standard deviation	