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Investigating Performance of Hybrid Photovoltaic–Thermal Collector for Electricity and Hot Water Production in Nigeria

Kar R. Awai [1], Peter King [1,*], Kumar Patchigolla [2,*] and Sagar M. Jain [1,*]

[1] School of Water, Energy and Environmental, Cranfield University, Cranfield MK43 0AL, UK; richard.awai@cranfield.ac.uk
[2] Net Zero Industry Innovation Centre, Teesside University, Middlesbrough TS2 1DJ, UK
* Correspondence: peter.king@cranfield.ac.uk (P.K.); k.patchigolla@tees.ac.uk (K.P.); sagar.m.jain@cranfield.ac.uk (S.M.J.)

Abstract: The research work explores the impact of temperature on Silicon photovoltaic (PV) panels, considering Nigeria as a case study. It is found that high solar radiation in Nigeria increases the surface temperature of PV panels above 25 °C of the optimal operating temperature. The redundant energy gain from solar irradiance creates heat at the rear of solar panels and reduces their efficiency. Cooling mechanisms are therefore needed to increase efficiency. In this study, we demonstrated a unique hybrid system design employing a heat exchanger at the back of the panel, with water circulated through the back of the PV panel to cool the system. The system was simulated using TRNSYS at three locations in Nigeria—Maiduguri, Makurdi, and Port Harcourt. The results of the peak annual electrical power output in Maiduguri give a power yield of 1907 kWh/kWp, which is the highest, due to a high solar radiation average of 727 W/m^2 across the year. For Makurdi, the peak annual electrical power output is 1542 kWh/kWp, while for Port Harcourt the peak power output is 1355 kWh/kWp. It was observed that the surface temperature of Polycrystalline Si-PV was decreased from 49.25 °C to 38.38 °C. The electrical power was increased from 1526.83 W to 1566.82 W in a day, and efficiency increased from 13.99% to 15.01%.

Keywords: photovoltaic–thermal hybrid; TRNSYS simulation; peak annual electrical yield; peak annual thermal yield; surface temperature

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1. Introduction

The annual solar radiation in Nigeria is 3.7 kW/m^2 per day along the shore and 7.0 kW/m^2 per day in semi-arid zones of the country with an average solar radiation of 5.4 kW/m^2 per day [1]. Solar energy generation through photovoltaic (PV) panels is a technology in which solar radiation directed on PV panels is converted into direct current (DC). The present Si-PV panel has the drawback of absorbing the complete solar spectrum. The incident radiation with higher energy than the bandgap is absorbed to produced one pair of electron holes, while the incident radiation with lower energy than the bandgap hits the back of the PV panel without being absorbed and is reflected. This releases an electron hole pair that undergoes internal recombination and ohmic losses to produce heat [2].

1.1. Temperature Effects on Photovoltaic Panels

Solar irradiances elevate the temperature of Silicon solar panels. The increase in temperature decreases the PV voltage because it is attributed to the temperature-dependent parameter of solar panels. The bandgap of the semiconductor decreases with the increase in temperature, which results in a decrease in the voltage of the solar panels. The current is slightly increased because of the temperature-dependent behaviour of the semiconductor material carrier mobility [3]. High solar irradiance increases PV output power, but an increase in temperature decreases efficiency, and without cooling, the electric efficiency

of the PV panel decreases by 0.03–0.05% at any 1 °C in temperature [4]. Sawadogo et al. (2020) investigated the effects of climate variation on photovoltaic output in West Africa and projected a decrease in photovoltaic power in West Africa in the future. They predicted four global warming levels of 1.5 °C, 2.0 °C, 2.5 °C, and 3.0 °C in West Africa in the future. The maximum power output predicted in different regions was below 3.8% at 3.0 °C [5]. The rooftop photovoltaic systems have surface temperature increases of 3–4% during cold and warm weather and 5% under hot weather with high temperatures of 80 °C [6]. The results obtained through the simulations conducted using PowerSim (PSIM) software (www.iotpe.com, access on 7 December 2023) showed that an increase in temperature decreased the voltage and current in both monocrystalline and polycrystalline PV panels due to the increase in solar irradiation. In the amorphous silicon thin-film PV panel, the current increased proportionally with solar irradiation and the voltage slightly decreased. Likewise, temperature changes affected the monocrystalline PV panel more compared to the polycrystalline PV panel, and in terms of solar irradiation changes, the monocrystalline PV panel was more affected than the amorphous silicon thin-film PV panel [7].

Al-Ghezi et al. carried out PVsyst software (www.ijred.undip.ac.id, access on 7 December 2023) simulations and a practical outdoor experiment, and the maximum values of current and voltage were 7.52 A and 22 V, respectively, at a maximum solar radiation of 1000 W/m^2. The minimum current and voltage were 1.51 A and 20.35 V, respectively, at a minimum radiation value of 200 W/m^2. The experiment showed that an increase in temperature of 1 °C increased the current by 0.07% and decreased the voltage by 0.34%. The power output decreased to 0.49% while efficiency decreased to 0.59% [8]. A polycrystalline panel was examined in a laboratory stand with two 400 W halogen lamps used to illuminate it, and the heating of the panel was carried out with the help of an electric heater. The temperature was varied from 25 °C to 55 °C, and the short-circuit current increased by 5.8%, the open-circuit voltage decreased by 11.76%, power decreased by 15.1%, and there was a 15% decrease in efficiency, which sums up the panel efficiency decrease of 0.5% per kelvin rise in temperature [9]. Another 50 W solar PV panel at standard test conditions of 1000 W/m^2 and 25 °C cell temperature was tested outdoors by Senthil Kumar et al. (2019) [10]. The surface temperature of the PV panel varied from 39.5 °C to 46.2 °C, the rear PV panel temperature varied from 38.2 °C to 46.5 °C, and the average temperature of the panel from top to bottom was varied from 38.55 °C to 44.15 °C. The voltage decreased by 19.7 V–19 V, the current decreased by 1.73 A–1.35 A, and the power output decreased from 27.53 W to 20.69 W, with electrical efficiency decreasing from 12.51% to 11.19%.

The high impact of temperatures on the performance of Si-PV panels is a challenge in the field of solar energy, and it must be managed carefully to ensure optimal efficiency and energy production from PV systems. Different strategies of cooling methods have been deployed to mitigate the high temperatures of Si-PV panels, thereby improving the overall power output and efficiency.

1.2. Cooling Techniques

Heat removal from the rear of photovoltaic panels has the positive effect of increasing their efficiency. Combining the photovoltaic panel with a thermal plate to form a photovoltaic–thermal (PVT) system is an appealing invention. The idea was first reported in the 1970s [11]. The temperature distribution of PVT was investigated by Al Tarabsheh et al. by recording the individual cell temperatures of PV panels. The temperature difference was because of the temperature gradient of the fluid flowing across the tubes in the opposite direction of the heat exchanger. The temperature of each PV cell was used in the calculation of current and voltage characteristics [12]. In another study, Tarabsheh et al. used three different cooling pipe geometries to investigate the cooling effect on a PV panel. The pipe designs were labelled A, B, and C with different geometry. Pipe A was used to circulate water from the inlet to the outlet with an efficiency of 15.5%. Pipe B split the cooling pipe into nine channels, and each channel was used for the cooling of nine cells in series. A constant flowrate was maintained in all cases, and the temperature of the cells

in the PV panel dropped more with the B design compared to A and C, with the efficiency of B being 16.4% and that of C 16.2%, showing B as the most efficient design geometry to adopt in piping [13].

A three-dimensional computational fluid dynamics (CFD) simulation of PVT was carried out, showing a surface temperature reduction of 6%, and the outlet temperature of the liquid of PVT was reduced by 18% with a flowrate of 30 L/h–90 L/h [14]. Asim et al. investigated the electrical efficiency and output power of a monocrystalline PV panel under real weather conditions. A PV panel of 35 W capacity at standard test conditions, with an absorber and heat sink with 17 microchannels, all made with Aluminium, was used. The water temperatures were 49.9 °C and 48.7 °C at Reynolds numbers of 224 and 560, respectively. The surface temperature of the PV panel decreased with increasing Reynolds number, and a maximum temperature of 32.4 °C at 6710 Reynolds number was achieved. A power output of 28.3 W–33.65 W and an electrical efficiency of 15.7–18.7% were also realized at a Reynolds number of 6710 [15]. Ahmadinejad et al. investigated a Fined-Based Photovoltaic Thermal System (FPVTS) with a PV panel without a heat exchanger and a Simple Photovoltaic Thermal (SPVT) system. It was found that FPVTS performed highly in energy production, exergy, and efficiency compared to the PV panel without cooling and the SPVT system. At every 0.001 kg/s increase in mass flowrate (0.002 to 0.02 kg/s), electrical efficiency increased by 0.09% and thermal efficiency increased by 0.92%. In conclusion, it was found that a high flowrate favours high energy, while a low flowrate increases efficiency [16]. Bhat and Qayoum [17] examined a hybrid tube design featuring a straight tube with the passage of nano fluid to cool a PV panel. The new hybrid tube design outperformed the conventional tube by uniformly reducing the PV panel temperature by an average of 324.11 K. The nano fluid reduced the PV panel average temperature to 315.14 K, and with the hybrid tube and nano fluid, an electrical efficiency of 11.41% and a thermal efficiency of 63.39%, with an overall efficiency of 84.51%, were seen [17].

An investigation of a photovoltaic–thermal system was carried out by Adun et al. to determine the potential of the PVT system in electrical power and hot water production for a four-person household in Nigeria. It was noted that Maiduguri in the northeast of the country had the highest electricity yield of 159 kWh/kW at peak, while Port-Harcourt in the southwest of the country had the least output of 75.8 kWh/kW at peak. Maiduguri recorded an annual power output of 1735 kWh/kW at peak. An electrical efficiency of 11.66% was achieved in Maiduguri while 11.99% was achieved in Onitsha [18]. Also, a comparative study was carried out by Maoulida et al. to check the potential of PVT systems in the Comoros and in France. In the Comoros, a 40% performance was shown to be achievable throughout the year while in France, the 40% performance was only attained in the summer. A total of 70% of the domestic hot water needs of Koua in the Comoros was covered, unlike in France, where the system covered 10% to 40% of the needs. About 80% of the electrical power demand in the Comoros was also covered throughout the year, while 20% to 30% of the demand was covered in France. This show the superiority of the PVT system in the sub-Saharan region compared to the continental climate in France [19].

The literature has demonstrated the impact of fluid flowrate on the surface and outlet temperatures, and on power production. A high flowrate is encouraged when the priority is on energy, while a low flowrate increases the efficiency of the system. The heat exchanger design with different geometries like fins and extruded surfaces have also been highlighted and shown to improve the efficiency of the PVT system.

Similar studies exist in the literature but there is a geographical gap on the topic that needs to be addressed. Research has been carried out on the topic in different parts of the world but there is little or no research in Nigeria and Africa as a whole. Africa leads the world in solar power potential (Global Solar Atlas/The World Bank). This research is important to Nigeria in particular because to implement this technology in Nigeria, there is a need to study the weather conditions and the viability of PVT systems in the country. Studies from other countries or continents cannot be used to implement the system or technology in Nigeria. This work shows the outputs during both the raining and dry

seasons, which are peculiar weather conditions in Nigeria and are different from other countries or continents in the world. This research is unique because it provides researchers with a comprehensive report on the potential of the PVT technology in Nigeria and Africa as a whole.

2. Methodology

2.1. Numerical Model of Photovoltaic–Thermal System

The PVT system is made up of different layers which heat transfer processes such as radiative, convection and conduction take place. The layers and the equivalent electrical circuit of the PVT system are shown in Figure 1.

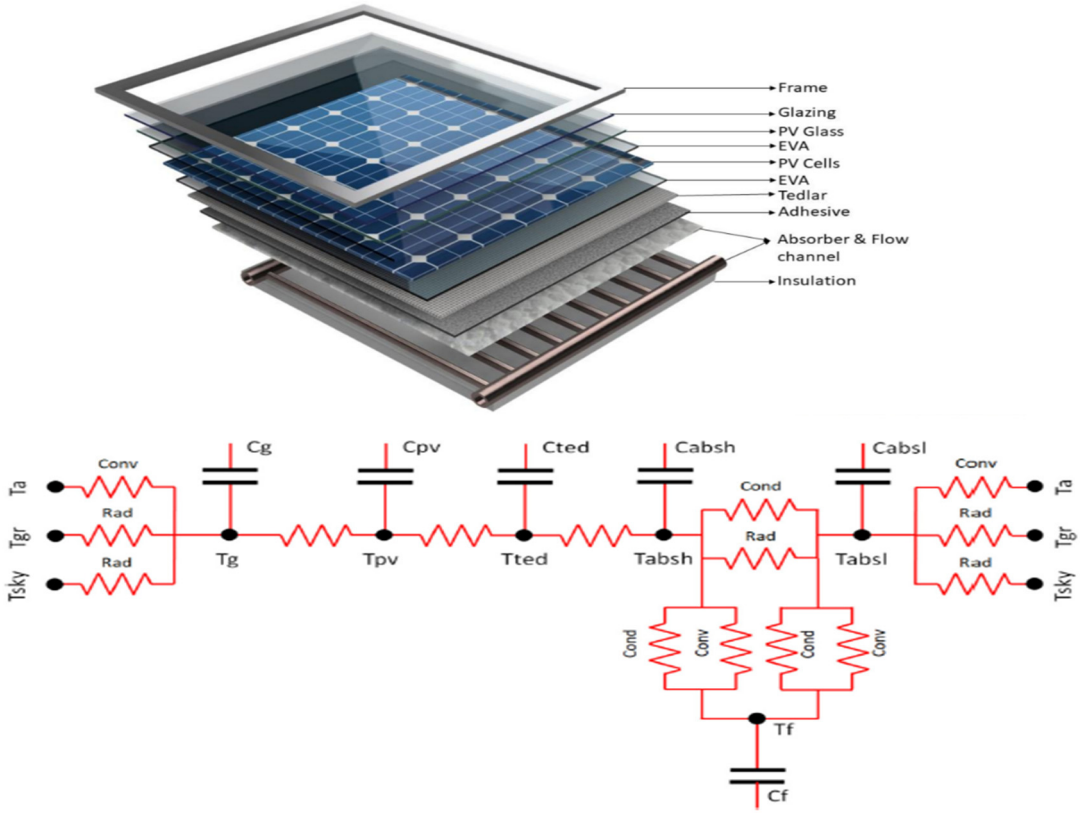


Figure 1. Detailed parts of water-based and equivalent electrical circuit of PVT system [20].

The energy balance equations for the PVT layers are solved under the following conditions:

i. A steady state condition is considered.
ii. The sky acts as a black body for longer wavelength radiation.
iii. All the thermal and fluid properties are taken as constant.
iv. No heat transfer takes place from the edges and bottom of the PVT system.
v. The fluid flow is uniform and laminar.
vi. There is perfect contact between PVT components.

2.1.1. Energy Equations at the Glass Layer

Convection, radiation, and conduction are energy loses that take place at the glass layer, as demonstrated below.

$$\left(\rho_g \delta_g C_g\right)\frac{dT_g}{dt} = \alpha_g G + hr_{g.sky}\left(T_{sky} - T_g\right) + hr_{g.gr}\left(T_{gr} - T_g\right) + hv_{g,a}\left(T_a - T_g\right) + hc_{pv,g}PF\left(T_{pv} - T_g\right) + hc_{Ted,g}(1 - PF)\left(T_{Ted} - T_g\right) \quad (1)$$

where $\alpha_g G$ is the absorbed solar irradiance by the glass in [W/m^2], while hr, hv, and hc are the heat transfer of radiation, convection, and conduction in [W/m^2.K] respectively. Packing factor (PF) is the surface covered by the PV cells to the total surface of the PV panel considered.

The radiative exchange coefficient depends on T_{sky}, T_{gr} and view factors $F_{g,sky}$ and $F_{g,gr}$, as follows:

$$hr_{g,sky} = \sigma \varepsilon_g F_{g,sky} A\left(T_{sky} - T_g\right) \cdot \left(T_{sky}^2 + T_g^2\right) \tag{2}$$

$$hr_{g,gr} = \sigma \varepsilon_g F_{g,gr} A\left(T_{gr} + T_g\right) \cdot \left(T_{gr}^2 + T_g^2\right) \tag{3}$$

$$F_{g,sky} = \frac{1 - cos\theta}{2} \tag{4}$$

$$F_{g,gr} = \frac{1 + cos\theta}{2} \tag{5}$$

$$hv_{forced} = 5.7w + 11.4 \tag{6}$$

where w is the wind speed in [m/s].

2.1.2. PV Cell Energy Equations

The energy equations at the PV cell are the radiation through the glass and the conduction heat transfer, as follows:

$$PF(\rho_{PV}\delta_{PV}C_{PV})\frac{dT_{PV}}{dt} = \left[\left(\tau_g \alpha_{PV} - \eta_e\right)G + hc_{PV,g}\left(T_g - T_{PV}\right) + hc_{Ted,PV}(T_{Ted} - T_{PV})\right]PF \tag{7}$$

2.1.3. Tedlar Energy Equations

Tedlar is a material that protects the PV cells at the upper and lower layers. The Tedlar energy equations are the radiation that passes through the glass to the PV cells, and the heat of conduction in the upper and lower PV cells.

$$(\rho_{Ted}\delta_{Ted}C_{Ted})\frac{dT_{Ted}}{dt} = (1 - PF)\tau_g \alpha_{Ted} G + (1 - PF)hc_{Ted,g}\left(T_g - T_{Ted}\right) + PF \cdot hc_{Ted,PV}(T_{PV} - T_{Ted}) + hc_{absh,Ted}(T_{absh} - T_{Ted}) \tag{8}$$

2.1.4. Absorber Energy Equations

Absorber energy involves the upper and lower plate surfaces, the energy balance at the upper surface transmitting heat through conduction from the Tedlar layer, and the energy exchange between the absorber plate and the fluid in the tube. Radiative heat transfer takes place between the absorber plate and the tubes housing the working fluid, and heat of conduction also takes place between the absorber plate and the tubes.

$$(\rho_{absh}\delta_{absh}C_{absh})\frac{dT_{absh}}{dt} = hc_{absh,Ted}(T_{Ted} - T_{absh}) + (1 - PC)hc_{absl,absh}(T_{absl} - T_{absh}) + PC \cdot hc_{absl,absh}(T_{absl} - T_{absh}) + hc_{f,absh}\left(T_f - T_{absh}\right) \tag{9}$$

where PC is the percentage of the channel and is a surface of flow to the rest of the absorber.

The upper and lower absorber plate radiative heat transfer coefficient is given by [20]:

$$hr_{absl,absh} = \frac{4\sigma T^3}{\left(\frac{1}{\varepsilon_{abs}} + \frac{1}{\varepsilon_{abs}} - 1\right)} \tag{10}$$

where σ is the Stefan-Boltzman constant; T is the mean temperature of the plate and ε_{abs} is the plate emissivity.

The energy transfer from the lower absorber is transfer from the upper absorber to the fluid and is given as:

$$(\rho_{absl}\delta_{absl}C_{absl})\frac{dT_{absl}}{dt} = hc_{absl,f}\left(T_f - T_{absl}\right) + (1 - PC)hc_{absl,absh}(T_{absh} - T_{absl}) + PC{\cdot}hr_{absl,absh}(T_{absh} - T_{absl}) \quad (11)$$

In force convection:

$$hv_{a,absl} = 5.7w_{bc} \quad (12)$$

2.1.5. Fluid Energy Equations

The heat exchange between the absorber and the fluid is given as:

$$\left(\rho_f\delta_f C_f\right)\frac{dT_f}{dt} = hc_{f.absh}\left(T_{absh} - T_f\right) + hc_{absl.f}\left(T_{absl} - T_f\right) + \dot{m}C_f(T_{out} - T_{in}) \quad (13)$$

where $\dot{m}$ is the mass flow rate in [kg/s]; C_f is the heat capacity of the fluid in [J/kg.K]; T_{in} is the fluid inlet temperature in K; and T_{out} is the fluid outlet temperature in K.

The mean temperature of the fluid is given as:

$$T_f = \frac{T_{out} + T_{in}}{2} \quad (14)$$

The inlet water temperature T_{in} is taken as 20 °C in this work.

The quantity of heat supplied from the PVT system to hot water for household use is given as:

$$\dot{Q} = \dot{m}C_f(T_{in} - T_{out}) \quad (15)$$

The outlet water temperature from the tank T_t is calculated using the effectiveness (ε_H) of the heat exchanger [20].

$$T_{t,out} = T_{t,in} - \varepsilon_H(T_{t,in} - T_t) \quad (16)$$

The energy equation of the water is given as:

$$\left(M_t C_f\right)\frac{dT_t}{dt} = \varepsilon_H\dot{m}C_f(T_{t,out} - T_t) - \dot{m}_l C_w\left(T_t - T_{sup}\right) - U_t S_t(T_t - T_a) \quad (17)$$

where $\dot{m}_l$ is the mass flowrate of the load in [kg/s]; C_w is the specific heat of water in [J/kg.K]; U_t is the heat loss coefficient of the tank to the environment in [W/K m^2]; and S_t is the external surface of the tank.

2.2. Electrical and Thermal Performance

2.2.1. Electrical Power Outputs

The electrical power output (P_e) of the PVT system is calculated from the irradiance (G) impinging on the surface area of the PV cell (A_{PV}) and is calculated as:

$$p_e = \eta_e A_{PV} G \quad (18)$$

The electrical efficiency is given as:

$$\eta_e = \eta_{ref}\left[1 - \beta\left(T_{PV} - T_{ref}\right)\right] \quad (19)$$

where η_{ref} is the reference efficiency at STCs; β is the temperature coefficient of the PV panel; T_{PV} is the PV panel surface temperature in [°C]; and T_{ref} is the reference temperature in [°C].

2.2.2. Thermal Power Outputs

The thermal power output (P_{th}) is calculated through thermal equations of the fluid flowing in the heat exchanger at the rear of *PV* panel.

$$P_{th} = \dot{m} C_f (T_{out} - T_{in}) \tag{20}$$

The thermal efficiency is given as:

$$\eta_{th} = \frac{P_{th}}{A_{abs} G} \tag{21}$$

2.2.3. The Total Output and the Total Efficiency of PVT System

The overall outputs of PVT system are given in terms of power and efficiency as:

$$P_t = P_e + P_{th} \tag{22}$$

$$\eta_t = \eta_e + \eta_{th} \tag{23}$$

2.3. PVT System Design and Description

The system components include a PVT panel with a 1.64 m^2 area, a water tank capacity of 200 L, a pump, a charge controller, and a battery. The Si-PV panel is coupled with a heat exchanger at its rear, and water is circulated through the heat exchanger to remove the heat at the back of the PV panel. The water is circulated at the back of the PV panel as soon as the surface temperature of the PV is above 35 °C with the help of thermocouples installed on the surface and the back of the PV panel to remove the excess heat. This decreases the surface temperature of the PV panel and increases both the power output and electrical efficiency of the PV panel. The electrical power produced is delivered to the controller to supply the load demand and, at the same time, to charge the battery. Figure 2 shows the block diagram of PVT system design in TRNSYS.

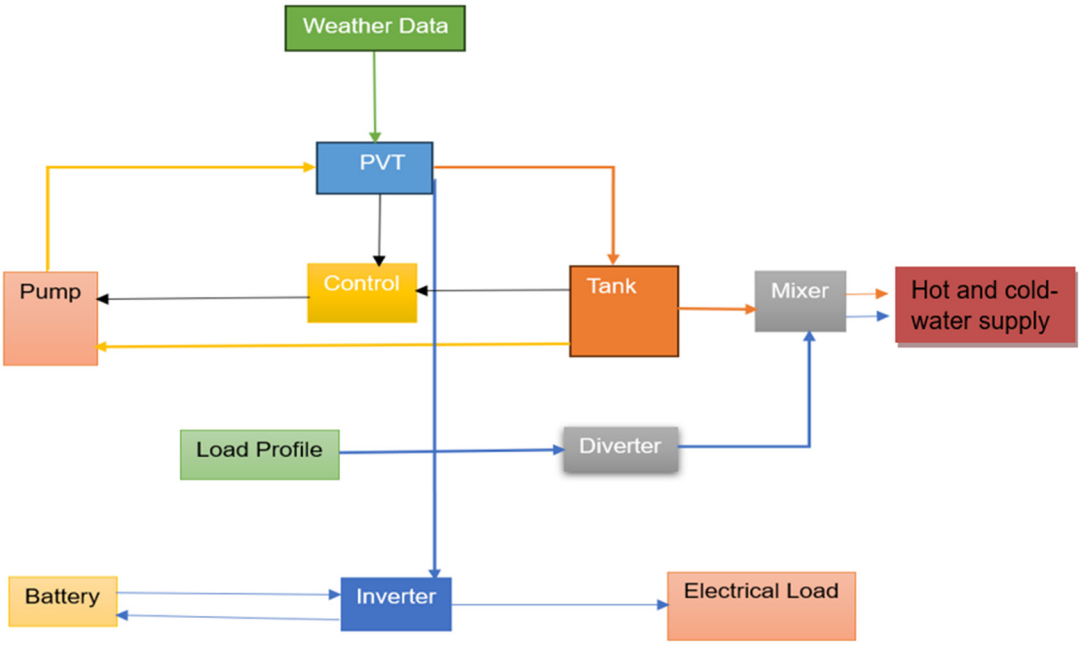


Figure 2. Block diagram of PVT system design.

TRNSYS Simulation Model

TRNSYS is a transient simulation software program that simulates the energy behaviour of the PVT system. Meteorological weather data from the Energy Plus Weather

Format (EPW) with solar irradiance, ambient temperature, and wind speed were simulated to obtain the desired outputs. TRNSYS 18 version software was used for the simulation of the PVT system. The model components in TRNSYS connected in the PVT system were formulated as equations using FORTRAN code to make up its physical behaviour. The inlet water temperature was 20 °C. The simulation time was set from 6:00 a.m. to 6:00 p.m. daily for all twelve months of the year. Figure 3 shows the TRNSYS model for this study.

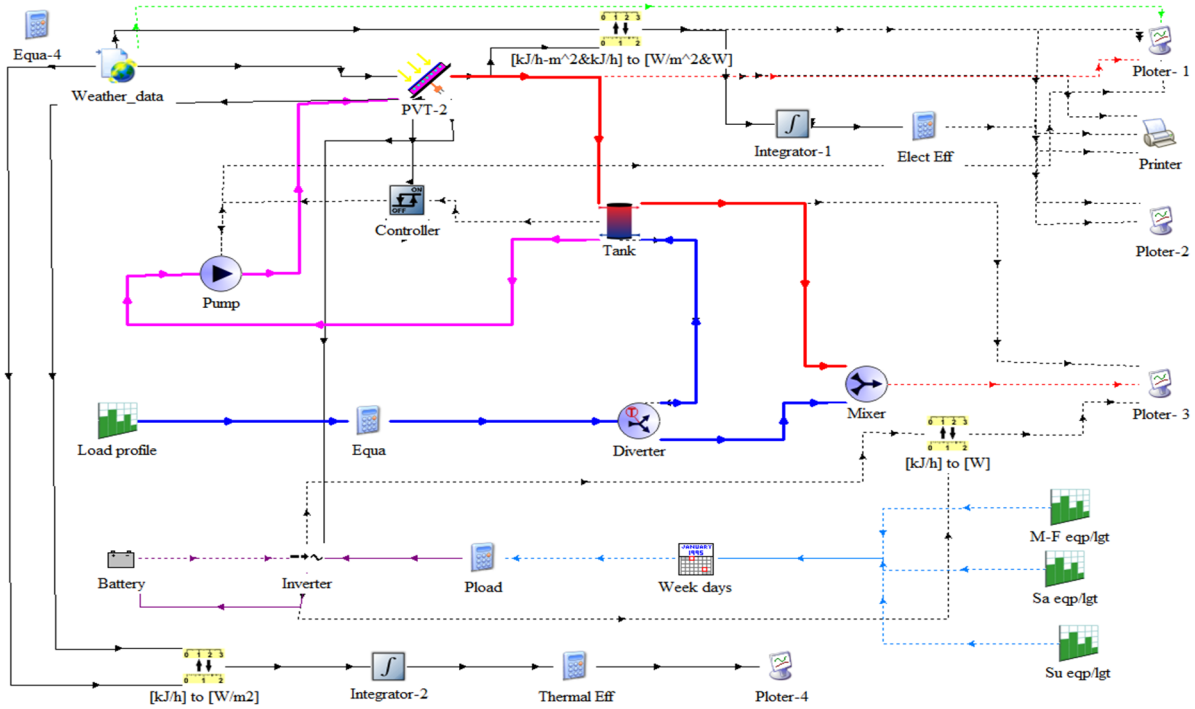


Figure 3. The TRNSYS simulation model of the PVT system design.

The parameters of the polycrystalline (FT250Cs) PV module at standard test conditions (STCs) are shown in Table 1.

Table 1. Photovoltaic module parameters [18].

Parameters	Quantity
Peak power (P_m)	250 W_p
Maximum voltage (V_m)	30.1 V
Maximum current (I_m)	8.3 A
Open circuit voltage (V_{oc})	37.2 V
Short circuit current (I_{sc})	8.87 A
Module efficiency	15%
Module dimensions	1638 mm × 982 mm
Panel type	Polycrystalline; FT250Cs
Radiation at reference	1000 W/m^2
Ambient Temperature	25 °C
Weight	27.6 Kg

This paper investigates the potential of PVT systems in sub-Saharan Nigeria in the West African region. Three sites were chosen for the comparative study in the country, which are Maiduguri town, situated in the northeast, Makurdi town located in the north-

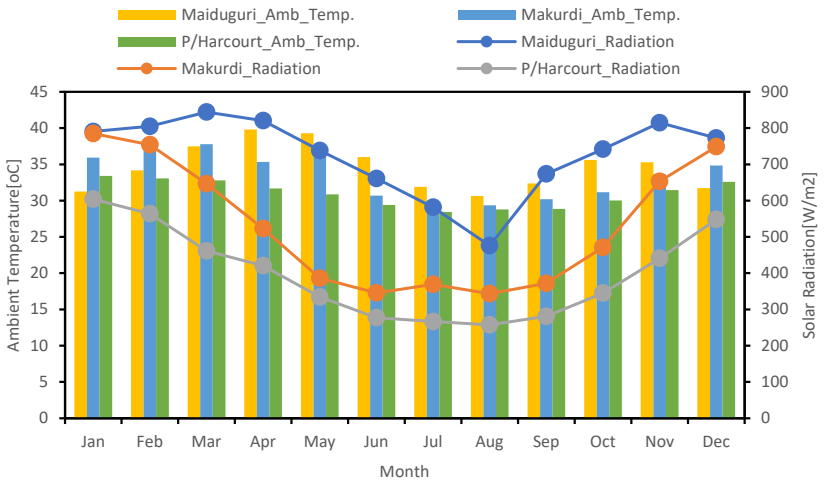
central part, and Port Harcourt town, which is in the south of the country. The simulation was carried out in terms of electricity and hot water production in the selected locations in the country.

A typical household in a developing country like Nigeria consumes on average 5.6 L of hot water per person a day, which is about 28 L per day for a household of four persons [21]. A 200 L tank to produce hot water for a family of four, estimated at 50 L per person at a flowrate of 100 L/h, was selected by experimenting with different flowrates from 10 L/h to 200 L/h.

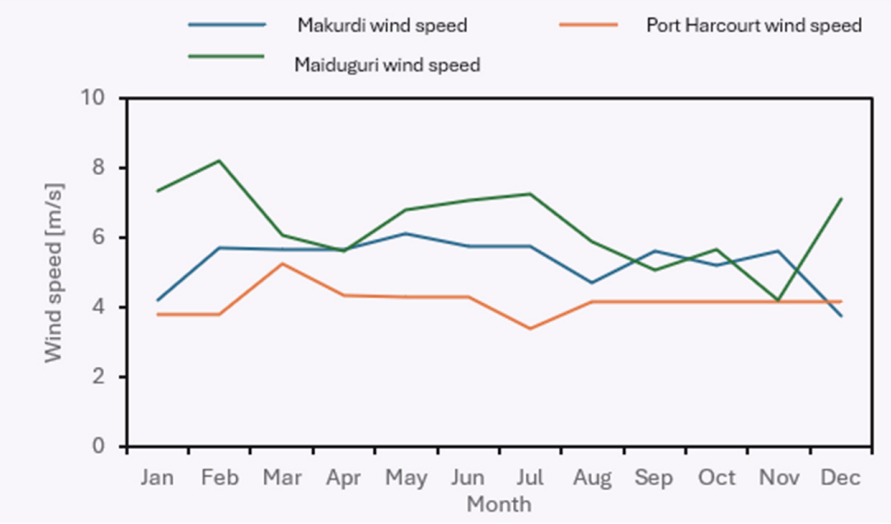
3. Simulation Results and Analysis

3.1. Solar Radiation, Ambient Temperature, and Wind Speed of the Three Locations in Nigeria

The PV panel output was directly proportional to the rate of irradiation presence at a particular area. The surface temperature of the PV panel and the ambient temperature of a place are radiation parameters. The higher the solar radiation of a place, the higher the electrical power output of the PV panel. A higher solar radiation increases the surface temperature of the PV panel as well as the ambient temperature. High ambient temperatures lower the efficiency of the PV panel. Figure 4a,b show the ambient temperature, solar radiation, and wind speed in the three locations in Nigeria.



(**a**)



(**b**)

Figure 4. (**a**) Solar radiation and ambient temperature monthly average of the three locations in Nigeria. (**b**) Wind speed monthly average of the three locations in Nigeria.

3.2. Electrical Power Outputs of the System

Of the three locations in Nigeria, it can be seen that Maiduguri had the highest peak power and total annual electrical power output at 184.02 kWh/kWp and 1906.87 kWh/kWp, respectively. The high-power output produced in Maiduguri signifies high solar irradiation in the region. Makurdi produced the second highest peak power and total annual electrical power at 160.5 kWh/kWp and 1541.82 kWh/kWp, respectively. And at Port Harcourt, the lowest peak power and total annual electrical power yield at 147.53 kWh/kWp and 1355.16 kWh/kWp, respectively, were produced, which signify low solar irradiation in the region. This difference in total annual electrical power output by the PVT system in the country was confirmed by the study of Adun et al. [18]. Figure 5 presents the monthly peak electrical power outputs of the three locations.

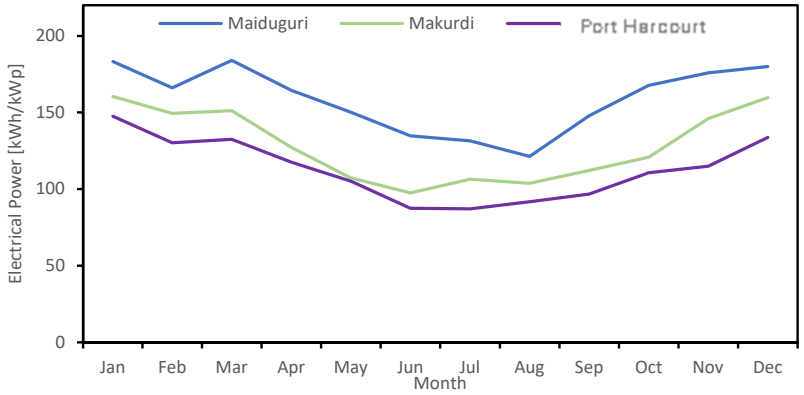


Figure 5. Monthly average peak electrical power outputs in the three locations in Nigeria.

3.3. Thermal Output

Figure 6 shows that Maiduguri produced the highest peak thermal output and total annual thermal output at 26.99 kWp and 287.09 kWp, respectively. Makurdi had a peak thermal output and annual thermal output of 25.03 kWp and 249.47 kWp, respectively, while Port Harcourt again had the lowest peak thermal output and total annual thermal output at 23.13 kWp and 224.44 kWp, respectively. High solar radiation in Maiduguri contributed to the high thermal results recorded in the location, followed by Makurdi and Port Harcourt with the lowest thermal output because of low solar radiation in the region.

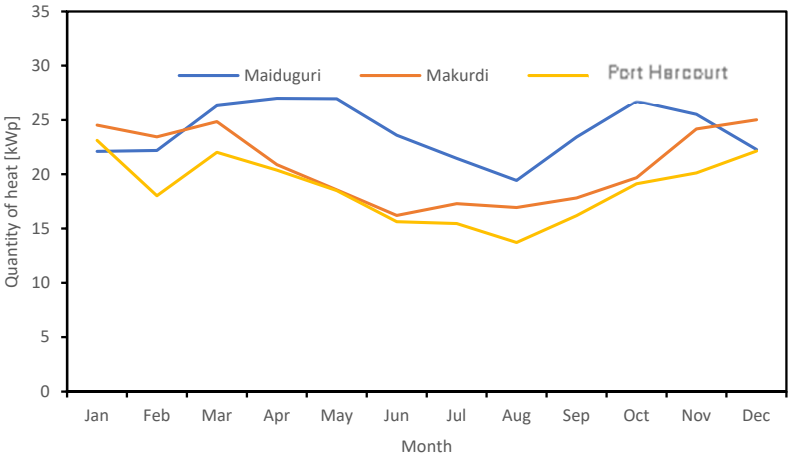


Figure 6. Monthly average peak thermal outputs generated in the three locations in Nigeria.

3.4. Electrical Efficiency

Figure 7 shows that Port Harcourt had the highest monthly average electrical efficiency peak at 14.89% because of the low radiation and low ambient temperature, which contribute

to a lower PV panel surface temperature. Makurdi had the second-highest monthly average electrical efficiency at 14.87%, and last was Maiduguri with a monthly average electrical efficiency of 14.84% because of the high solar radiation and high ambient temperature in that region that produce a high PV panel surface temperature.

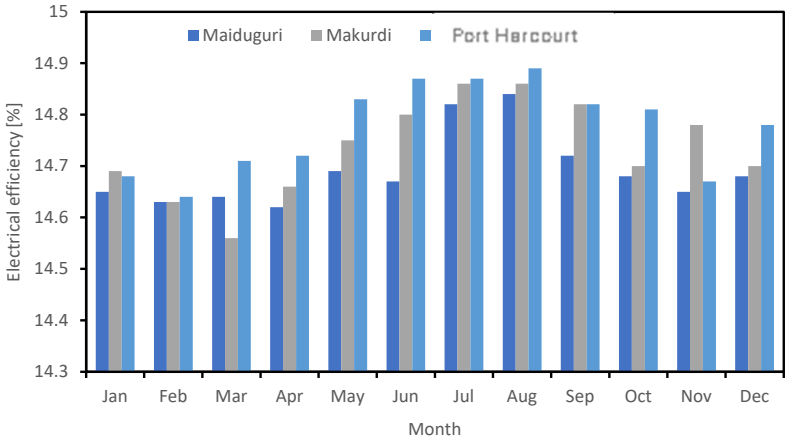


Figure 7. Monthly average electrical efficiencies of the three locations in Nigeria.

3.5. Thermal Efficiency

Figure 8 shows the monthly average thermal efficiency of the three locations. Port Harcourt produces the highest thermal efficiency at 67.23%. Makurdi has the second highest thermal efficiency at 60.26 and Maiduguri produced the lowest thermal efficiency at 58.65%. These results continue to show that lower solar radiation and ambient temperatures in a location produce high efficiency, as displayed by Port Harcourt.

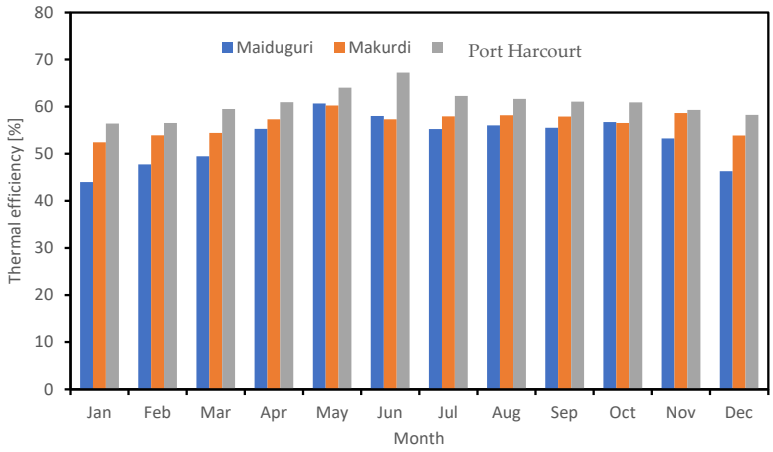


Figure 8. Monthly average thermal efficiencies of the three locations in Nigeria.

3.6. Outlet Fluid Temperature from PVT System

Maiduguri recorded a monthly average fluid outlet temperature of 29.79 °C as the highest outlet temperature because of high solar radiation and ambient temperature. Makurdi recorded 29.04 °C (second highest) and Port Harcourt recorded 27.38 °C as the lowest outlet temperature because of the low solar radiation and ambient temperature in that region. The outlet fluid temperature of PVT system in the three locations in Nigeria is shown in Figure 9.

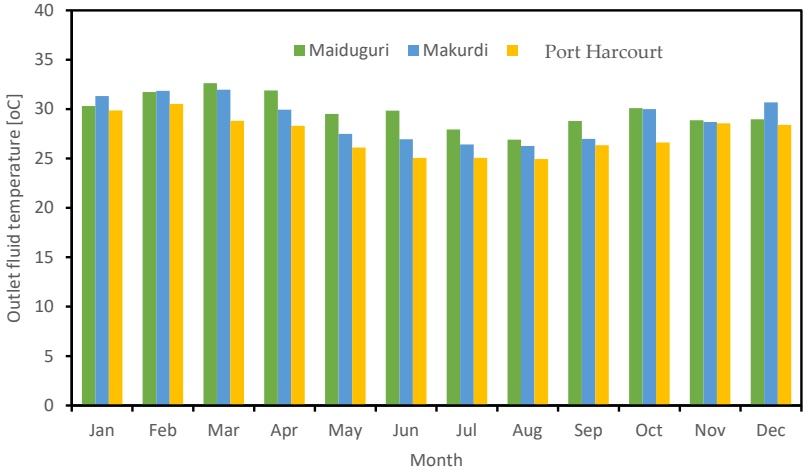


Figure 9. Monthly average outlet fluid temperatures of the three locations in Nigeria.

3.7. PV Cell Temperature

The PV cell temperature of the three locations at a monthly average is 38.39 °C for Maiduguri, 36.43 °C for Makurdi, and 34.36 °C for Port Harcourt. Again, Maiduguri, with high solar radiation and ambient temperature, recorded the highest PV cell temperature. Figure 10 shows the results of the PV surface temperature of all three locations. Port Harcourt record the lowest PV cell temperature because of the low solar radiation and ambient temperature in that region.

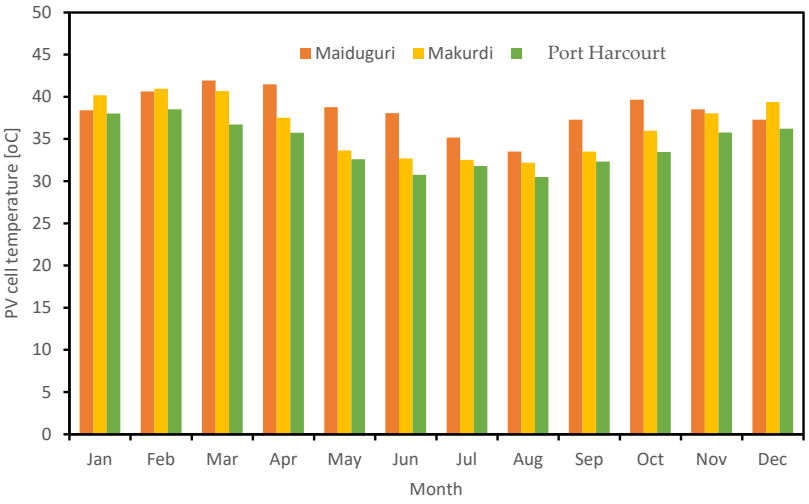
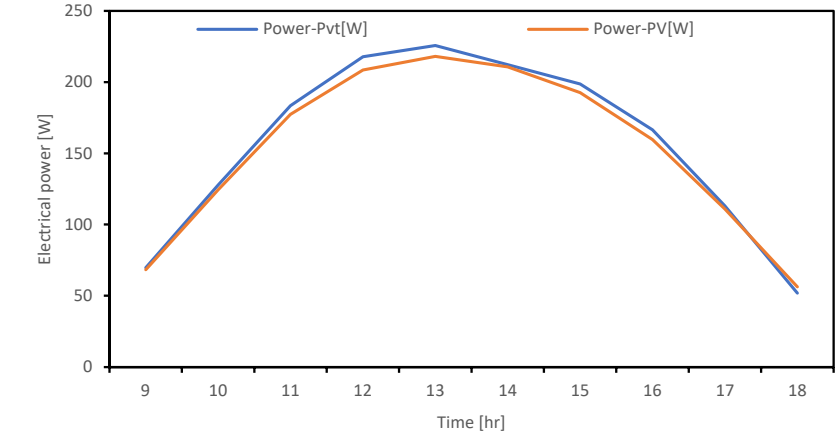


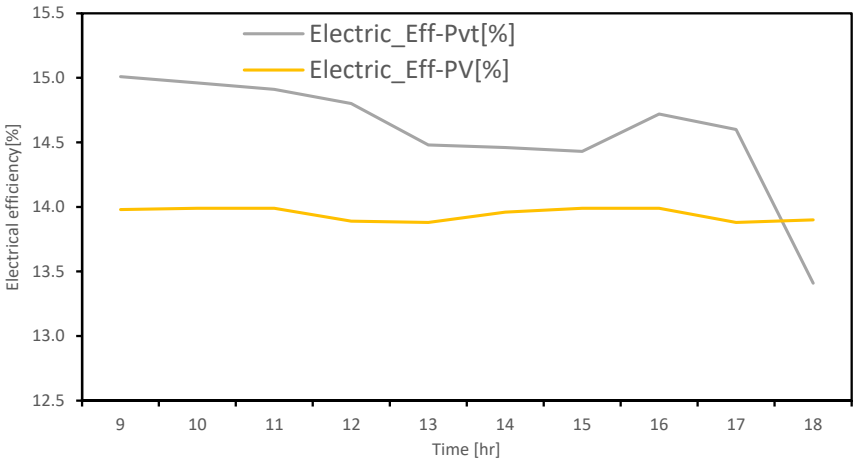
Figure 10. Monthly average PV surface temperature of the three locations in Nigeria.

3.8. The Comparative Performance Evaluation of a Conventional PV Panel and the PVT Design

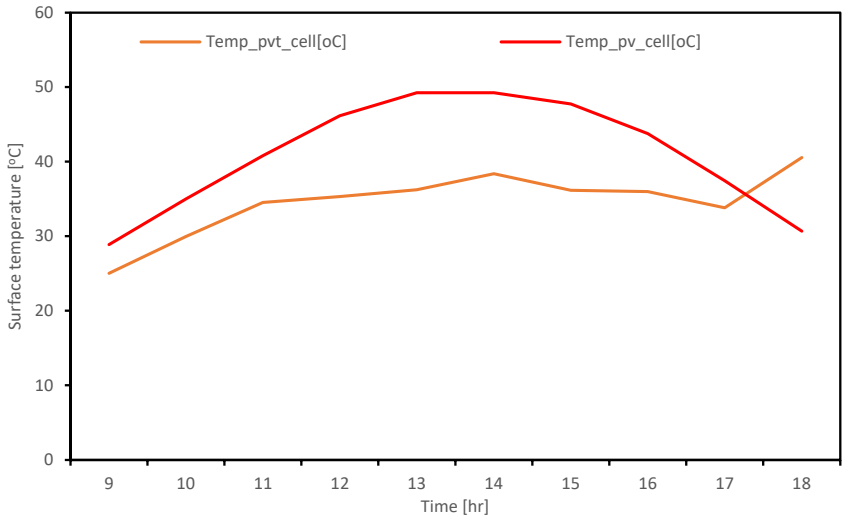
The performance evaluation of a conventional PV panel and the PVT system was carried out on 7th April in Maiduguri town using meteorological weather data. The conventional PV system produced a total electrical power output of 1526.83 W in a day while the PVT system generated a total power output of 1566.82 W on the same day. An electrical efficiency of 13.99% was recorded at maximum for the conventional PV system, while the PVT system recorded an electrical efficiency of 15.01% at maximum value. The conventional PV system recorded a cell surface temperature of 49.25 °C at the peak sunny time of the day while the cooled PVT system recorded a surface temperature of 38.38 °C at the peak sunny time of the day. The cooling process in the PVT system helps in improving the power output, electrical efficiency, and surface temperature reduction that is absent in the conventional PV panel. Figure 11a–c show the comparison results of the PV panel and the PVT system in terms of power output, efficiency, and cell surface temperature, respectively.



(**a**)



(**b**)



(**c**)

Figure 11. (**a**) Hourly power outputs of PV panel and PVT system in a day. (**b**) Hourly electrical efficiency of PV panel and PVT system in a day. (**c**) Hourly surface temperature of PV panel and PVT system in a day.

3.9. Power Consumed by the Pump in Pumping Water to Cool PVT System in a Day

The power used in pumping the water to cool the PV panel is of importance. The selection of pump capacity depends on the height of the installation and the viscosity of the cooling fluid. In this work, water was used as the working fluid and its viscosity was low so it did not need a high-power pump. The pump selected in this work had a 16.67 W maximum power capacity. The maximum power consumed by the pump was 8.33 W at a flowrate of 100 kg/h. In a day, the total power consumed by the pump was 66.67 W, and taking this power out of the total power produced by the PVT system in the day, which was 1566.82 W, the final output power was 1500.15 W. This power was 26.68 W less than the conventional PV panel power output, which was 1526.83 W. Figure 12 shows the power output of the PVT system and the power consumed by the pump.

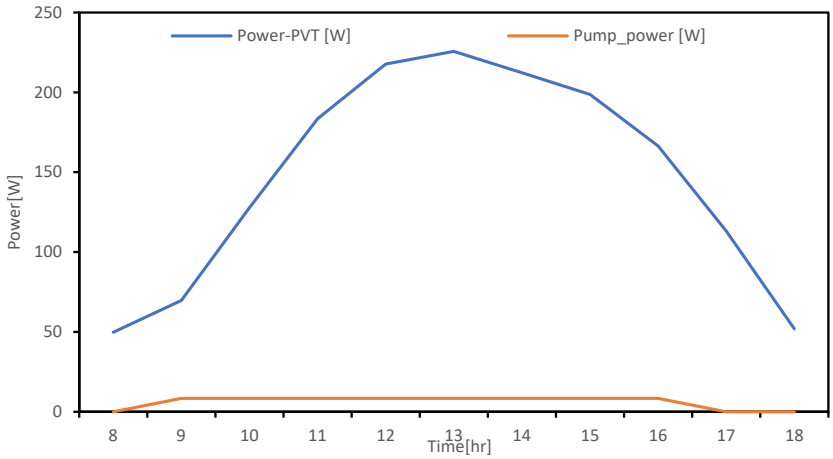


Figure 12. Power output of the PVT system and power consumed by the pump.

This power lost in pumping is compensated from the hot water production or thermal output which is more than the power lost during pumping. The hot water production contributes to reducing fossil fuel and carbon footprints. The power consumption of the pump can be minimized when the PV panel is installed by using a thermocouple to detect a high temperature. The thermocouple regulates the pump to initiate the pumping process when a high temperature is recorded on the PV panel surface, and this makes the pump work only during high temperatures or when cooling is needed.

Another way of minimizing the power consumed by the pump is by using a separate PV panel to supply power to the pump in the PVT system. The pump flowrate is determined by the solar irradiation intensity on the PV panel supplying power to the pump because an increase in solar irradiation increases the flowrate and this enhances heat convection between the water and the collector to provide better thermal performance. For a pump that is powered directly by the PVT system, the flowrate is constant, and this limits the heat convection between the flowing water and the collector [22]. In the case where the working fluid is of high viscosity like in nano fluid, the power consumption of the pump will be higher, and therefore low-viscosity working fluids are recommended for cooling to achieve a low pumping power.

4. Conclusions

This paper investigated the potential of PVT systems in Nigeria. The annual performance of the combined system was established by means of the TRNSYS simulation model. The simulation results showed that for the Maiduguri region of Nigeria, the total annual electrical power output of 1906.87 kWh/kWp was the highest because of high solar radiation presence in the region. This was compared with Makurdi, with a total annual electrical power output of 1541.82 kWh/kWp, and Port Harcourt, with a total annual power output of 1355.16 kWh/kWp. The differences in power output were due to the different solar

radiation intensities and different ambient temperatures of the three locations. The ambient temperature also influenced electrical efficiency, as observed in the results. As the operating temperature increased, efficiency decreased. It is also worth noting that high power and thermal outputs were observed during the months of the dry season (November–March) because of clear skies and high solar radiation as compared with the months in the raining season (April–October) with cloudy skies and low solar radiation. The trend also shows that as one moves from the northern to the southern part of Nigeria, the solar radiation decreases, and the PVT system output also decreases. Other findings of the present study are outlined below:

- The power output increased by 2.62% with the hybrid PVT system.
- The cooling system helped in decreasing the PV panel surface temperature by 22.07%.
- The electrical efficiency of PVT increased by 7.29%.
- The overall efficiency of PVT was 75.46% as against the conventional PV panel that only performed at a maximum efficiency of 20%.

This system can improve the life span of PV panels by reducing the degradation that might occur by overheating due to high temperatures in Nigeria. This work paves the way for an investigation on the capability of PVT integration in enhancing the efficiency of PV panels and generating hot water as an important by-product. The work opens up a plethora of applications and further investigations for the bifunctional use of solar panels, particularly in high-temperature regions or locations.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature and Abbreviations

T	Temperature [°C]
C	Specific heat capacity [KJ/kg.°C]
$hc_{j,k}$	Conductive heat transfer coefficient in layer j and k [W/m^{2}K]
$hr_{j,k}$	Radiative heat transfer coefficient in layer j and k [W/m^{2}K]
$Hv_{j,k}$	Convective heat transfer coefficient in layer j and k [W/m^{2}K]
PF	Packing factor
$F_{j,k}$	View factor in layer j and k
A	Area [m^2]
w	Wind speed [m/s]
G	Solar radiation [W/m^2]
PC	Percentage of collector occupied by tubes
Nu	Nusselt number
$\dot{m}$	Mass flow rate [kg/s]
$\dot{Q}$	Quantity of thermal supply [kJ/s.K]
$\dot{m}_l$	Mass flow rate of load [kg/s]
U_t	Heat loss coefficient of tank [W/m^2 K]

	Scripts
g	Glass
sky	Sky
gr	Ground
a	Ambient
PV	Photovoltaic
Ted	Tedlar
absh	Higher absorber plate
absl	Lower absorber plate
f	Fluid
abs	Absorber plate
free	Natural convection
r	Radiation
v	Convection
c	Conduction
in	Inlet

S_t	External surface of the tank [m^2]
T_t	Average tank temperature [°C]
T_a	Ambient temperature [°C]
T_{sup}	Temperature of supply water from mains [°C]
ε_H	Effectiveness of heat exchanger
STCs	Standard test conditions
p_e	Electrical power [W]
P_{th}	Thermal power [W]
P_t	Overall power output of PVT [W]
T_{in}	Temperature entering the collector [°C]
T_{out}	Temperature leaving the collector [°C]
Pr	Prandtl number
Ra	Rayleigh number
T_f	Average fluid temperature inside PVT panel [°C]
w_{bc}	Wind speed at back of collector [m/s]
out	Outlet
ref	Reference
e	Electrical
th	Thermal
t	Tank
$forced$	Force convection
	Greek symbols
ρ	Density [kg/m^3]
δ	Thickness [m]
α	Absorptivity
σ	Stefan–Boltzmann constant
ε	Emissivity
τ	Transmissivity
η_e	Electrical efficiency
η_{ref}	Reference efficiency
β	Temperature coefficient
η_{th}	Thermal efficiency
η_t	Overall efficiency
θ	Tilt angle

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