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Experimental Evaluation of Photovoltaic Water Heater System under Wasit-Iraq Climate Conditions

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ABSTRACT

Over the past ten years, Iraq's population growth has resulted in a significant rise in energy consumption. Households can save money and the environment by utilizing less energy received from the grid and more renewable energy. One of the solar photovoltaic energy applications is solar heating water by converting solar energy to thermal energy by relying only on the heating element with direct current as an electrical load connected directly to the photovoltaic panels. It works without using: other heating elements operating with alternating current, an additional electric heater (dependent on the grid that is used to compensate for the shortage in the event of an additional need for hot water), and control units. That is for easy application, reduced losses in energy conversion and make it cheaper. In this research, a photovoltaic solar energy system with a capacity of (2160) W with (1500) a DC heater element was built. To heat water in a tank with a capacity of 120 liters, the performance of a Direct-coupled Photovoltaic Water Heater (DPVWH) was evaluated on December cold days for solar radiation rates at site coordinates (32°.514 N - 45°.819 E) in Wasit –Iraq. It has been recorded the highest values of the water temperature inside the tank, power solar radiation, and power generated, on 8/Dec./2023 without consuming water were 103 °C, 5989 watts, and 1170 watts, respectively. On 15/Dec./2023 consuming water equaled 202.01 liters at a flow rate of 2 L/m, the highest values of the water temperature inside the tank, power solar radiation, and power generated were 56.25 ˚C, 5135 watts, and 1259 watts. The system has been compared with another similar system and with STWH system, it was found that the photovoltaic system can be adopted as a direct source of water heating for domestic and other applications in the summer season, so the system can be invested all year round, unlike STWH systems that are limited to use only in winter.

Keywords:
Photovoltaic applications; solar water heater; stand alone; experimental assessment; DC heating element; DPVWH

1. Introduction

A solar energy is better than other renewable energy sources in terms of availability, cost-effectiveness, accessibility, capacity, and efficiency, it would unquestionably be the best option for meeting future energy demands [1,2]. The planet receives solar energy in a variety of ways,

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including heat and light. Technologies that transform sunlight into usable types of energy fall into two main categories. First, Solar photovoltaic (PV) modules transform sunlight into electricity directly. Second, solar thermal power systems generate steam by concentrating sun energy [3,4].

Rooftop PV is presently one of the less expensive ways for retail power consumers to generate electricity due to recent improvements in efficiency and equipment cost reductions; installation rates for rooftop PV are expected to rise further. Households can save money and the environment by utilizing less energy received from the grid and more renewable energy [5,6]. Over the past ten years, Iraq's population growth has resulted in a significant rise in energy consumption. Iraq currently relies significantly on burning fossil fuels, which entails burning the nation's most lucrative export goods, to generate electricity. Iraq regularly has power outages, despite having a significant solar energy potential. Because Iraq struggles with electricity and, has a lot of solar energy this energy can be used [7]. One of the applications of renewable energy is the photovoltaic solar water heater system. It is an indirect approach (active system), off-grid, PV-direct, for solar water heating implementation. It directly uses the direct current (DC) power generated by solar photovoltaic modules. 100% powered by solar electricity. Historically, solar thermal water heaters (STWHs) have been the main focus of attempts to lower home energy usage for water heating. However, collector freezing and overheating are common issues for STWHs. Technically speaking, PV water heating is attractive since it resolves these conventional STWH control problems. In addition, PV systems require less solar radiation to provide a usable output than STWHs, which must first overcome the collector heat loss [8]. It is possible to provide a tariff for electrical energy consumption according to the state’s price, which is almost double without the calculated cost of maintenance which is more valuable for a STWHs than the cost of a DPVWH due to the many details of the STWHs, including maintenance of the evacuated tubes for it in addition to the maintenance of the pipes extending from the heater to the source consumption and thermal insulation, as well as maintaining the water circulation pump if necessary. In addition, if the vacuum tubes of the STWH are broken or damaged, it will stop working. Conversely, if the panels of the PVWH are broken, it can continue to work, but with less efficiency than it was before the breakage or damage [9]. In late 1996, Dougherty *et al.,* [10] conducted research on installed in the Great Smoky Mountains National Park (GSMNP) solar photovoltaic water heating system (a two-tank system). In 1997, Dougherty and Fanney [11] published an article on two military housing structures in Okinawa, Japan installed a two-tank PVWH system, and prototype single-tank systems were erected and assessed at both NIST and FSEC. In 2015, Pokorny *et al.,* [12] studied a newly created and built glazed liquid PV-T collector prototype that was built using modern PV cell encapsulation technology. In 2017, Matuska and Sourek [13] studied the direct connection of a photovoltaic array to DC resistance heating elements that are submerged in a hot water tank in a solar photovoltaic water heating system. In 2017, Sarduei *et al.,* [14] examined the operation of a PVT solar water heater in four various Iranian cities by using the TRNSYS program. In 2018, Frid and Tarasenko [15] developed and evaluated the mathematical models for PV and conventional water heaters. Commercial PV water heating systems included maximum power point tracker technology controllers. In 2019, Hamdoon *et al.,* [7] conducted a study by using numerical simulations of the electrical and thermal performance of a hybrid photovoltaic/thermal solar domestic hot water system for a five-person home in Mosul, Iraq. In 2019, Rosli and Jamil [16] analyzed the photovoltaic-thermal collector for domestic water heating applications to determine its feasibility. The theoretical F-chart technique was adopted in estimating the monthly energy generated by the solar water heating system. In 2019, Elnaggar *et al.,* [17] conducted a simulation, using TRNSYS software to investigate the differences in solar energy harvesting efficiency between PV systems and solar thermal collectors in two climatically different areas: the sun-rich Gaza Strip in Palestine and a very cold area in Montreal, Canada, especially in the winter. In 2020, Frid *et al.,* [18] calculated the maximum power of a photovoltaic array required to provide a given amount of hot water for a residential building in Uzbekistan using TRNSYS software. This made it possible to calculate the plate power of photo batteries required for 50% and 70% of the hot water delivery load in Uzbekistan for residential buildings. In 2020, Alayi *et al.,* [19] published an article that studied generating heat and electricity at the same time using a solar micro-CHP system. The solar photovoltaic system provides the building's electrical charge, while the solar collectors supply the thermal charge to provide the building with hot water was likewise provided by the solar water heater. In 2021, Al-Hamadani and Yaseen [20] studied experimentally on solar desalination employing a Multi-Stage Effect Photovoltaic Heater, Solid Still, with paraffin as a phase change material, and DC water heater was cused, to ascertain the increase in freshwater production. In 2021, Yildiz *et al.,* [21] used TRNSYS, a thermal energy modeling tool, and real-world data to examine the effects of various daily hot water demand profiles, PV, and DEWH size on the possibility of excess PV use. The analysis focused on the possibility of storing and utilizing surplus PV generation in DEWH. In 2021, Clift and Suehrcke [22] used TRNSYS, to examine how excess photovoltaic power may be used to heat water, using the hot water storage tank as a low-cost thermal battery. The modeling results are validated by measurements from 13 field installations. In 2021, Solomon *et al.,* [23] examined the design and development of a solar-powered smart water heater to replace conventional electric water heaters. The constructed solar-powered smart heater performed admirably in testing carried out in a variety of environments. In 2021, Cámara-Díaz *et al.,* [24] designed a solar hot water system using an experimental electrical conversion device at a low cost that connected photovoltaic modules to a water tank with electric resistance. The electronic device, although still in an experimental phase, can be considered commercially viable due to its components, which are priced at less than EUR 60 per kW peak capacity. In 2021, Sada *et al.,* [25] examined a solar thermal water heater (STWH) that employed a 120-liter thermally insulated tank and an evacuated tube-type solar collector with 20 tubes. Utilizing ANSYS FLUENT software, numerical tests were carried out to investigate the impact of the porous media on extending the duration of hot water delivery at varying flow rates (2, 4, 6, and 8 L/m). In 2022, Badran and Obeidat [26] investigated the possibility of integrating a hybrid PV/T trickling system with a conventional solar heater. I 2022, Słomczyńska *et al.,* [27] investigated the possibility of using two solar-powered systems to charge the 24000 m^3 water pit thermal energy storage tank. System No. 1 is built upon a photovoltaic panel farm, while System No. 2 is a solar collector. The TRNSYS simulation software is used to estimate the parameters of both systems. In 2023, Hachchadi *et al.,* [28] investigated, under two different climate circumstances, the efficiency with which the direct-coupled PV water heater (DPVWH) system connects the heating element and PV array directly. Simulation models were created using MATLAB/Simulink and TRNSYS software to evaluate the performance of a PV system that was connected directly to the heating element for a year. This simulation model was validated using an experimental setup. In 2024, Al-Zurfi *et al.,* [29] used numerical simulations to study the effects of adding various phase change materials to the design of a flat plate solar collector. The study's main focus was on the variable efficiency of solar water heaters caused by environmental constraints such as sporadic sunshine, heat losses, and times when the sun's radiation is low.

In this paper, to overcome some techno-economic obstacles and maybe promote this concept in Iraq, the system of producing hot water during the cold winter days in Wasit at (32°.514 N - 45°.819 E) will be investigated using DPVWH. According to the city's winter weather, the water is too cold to use without a heater. The current study aims to conduct an experimental assessment of the DPVWH system that relies entirely on solar energy for home use during the solar noon. It relies only on the heating element (fixed resistance element) with direct current as an electrical load connected directly to the photovoltaic panels. The study aims to simplify the entire solar system and make it cheaper. The feasibility of this system is being verified under the city's weather conditions to find an alternative to thermal solar heaters.

2. System Overview

The system is built in several steps

(i) PV Solar Panel System

PV panels with a capacity of 2160 W were used, consisting of 4 solar panels. The capacity of one solar panel is 540 W. It works with a 48-volt system installed at a tilt angle of 25° from the horizon, which is an optimal angle for the city throughout the year due to its proximity to the latitudes of the city's location because the system will be used in the summer for cooling purposes. And heading to the geographical south of the city of Waist to obtain the greatest capacity of solar radiation falling on it. The area of the panels is estimated at 10.54 m^2, as demonstrated in Figure 1. Table 1 displays the PV module's detailed parameters.

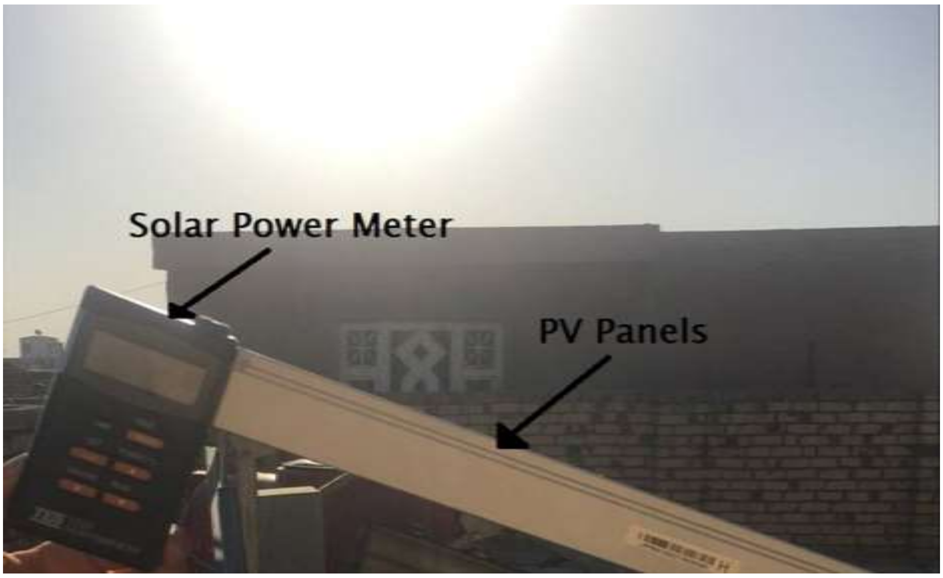

Fig. 1. PV panels

Table 1
The PV module's parameters

Value	Parameter
W540	Maximum power P_{max}
V41.65	Maximum power voltage V_{pm}
Amp12.97	Maximum power current I_{pm}
V49.50	Open circuit voltage V_{oc}
Amp11.14	Short circuit current I_{sc}
-0.284%/˚C	Temperature coefficient of voltage β_{Voc}
0.050%/˚C	Temperature coefficient of current β_{Isc}
˚C45	Nominal operating cell temperature NOCT
21.1	Module Efficiency %

(ii) The load

It is the heating element, consisting of a resistance wire made of nickel-chrome alloy. The heating element shall be covered with a tightly fixed tube on ceramic insulators, and it carrying capacity 1500 W to carry out the heating process. A load of (1500) W operating on continuous voltage was selected in a system (48) volts and the purpose of the use of electric heaters that operate with direct voltage to overcome electrical conversion losses from a direct voltage system to an alternating voltage system as shown in Figure 2.

Fig. 2. DC heating element

(iii) Water Tank

A water tank was used as an electric heater with a capacity of 120 liters and a thermal insulation insulator that ensures the retention of the water temperature for as long as possible, and a direct voltage heating element was installed inside this tank for direct heating of water and direct use of it without any conversions and electrical conversion losses.

(iv) Data record and storage system

A system was used to read and store data on voltage, current, flow rate, ambient temperature, the water temperature coming to the tank, hot water temperature inside the tank, and the water temperature coming out of the water faucet that was produced from the solar panel system, through voltage (SEN32 REV1.1 AC/DC), flow rate (Flow meter YF-S201), current (ACS758) and temperature (MAX6675) sensors respectively. It is done by using Arduino uno, where data is recorded from the start of the operation at sunrise to sunset, with intervals of 30 minutes for each reading.

(v) The solar radiation data system

The solar radiation data were adopted by using a solar power meter (TES 1333), and recorded every 30 minutes as demonstrated in Figure 1.

Figure 3, shows a schematic diagram for the photovoltaic water heater system.

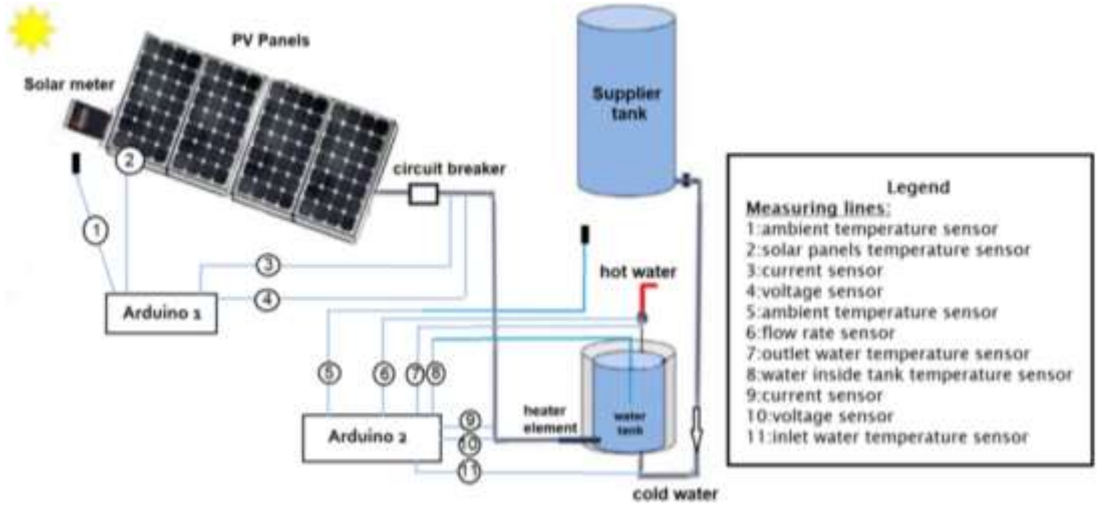

Fig. 3. A schematic diagram for the photovoltaic water heater system

Table 2 provides the accuracy and error percentages for the measurement instruments utilized in this investigation.

Table 2
Accuracies and uncertainty errors for the measurement equipment

Measure Instrument	Model	Accuracy	Range
Solar meter type	TES1333	±5%	Up to 2000 W/m^2
thermocouples	Type K	±0.75%	0 -800 ˚C
Flow meter	YF-S201	±1%	Up to 30 L/m
Voltage sensor	SEN32 REV1.1 AC/DC	±2%	Up to 50 V
Current sensor	ACS758	± 1.5%	Up to 100 Amp

Power of the photovoltaic solar heater:

The power solar radiation (W) coming to the surface of the inclined photovoltaic panels is equal to [17]

$$P = SR * n * A_c \quad (1)$$

Where, SR is the solar radiation (W/m^2), n is the number of PV cells in the module, and Ac is the area of the PV panel (m^2).

While the power generated by photovoltaic panels (W) is equal to [30,31]

$$P_{PV} = I_{DC} * V_{DC} \quad (2)$$

Where, I_{DC} is DC current (Amp), V_{DC} is DC voltage (V).

3. Results and Discussion

The performance of the photovoltaic solar heater was examined and evaluated experimentally by recording the solar radiation values, as well as the voltage, current, and temperatures, and calculating the power of the system.

3.1 DPVWH without Consuming Water

The data was recorded on a sunny day without using water to test the thermal insulation of the water heater tank while monitoring the temperature recording continued until the next day.

3.1.1 Solar radiation

From the data recorded for solar radiation activity for the day 8 Dec. through the solar power meter, shown in Figure 4, it has been observed since the beginning of the morning that there are good solar radiation rates that meet the requirements of work on solar energy applications, including solar heater applications of all kinds, and they rise at midday to record their highest rates. It is noted from the Figure 4, that there is no significant attenuation of these values due to clouds and dust storms. The highest value of solar radiation was 568.2 W/m^2 at 12:35 p.m.

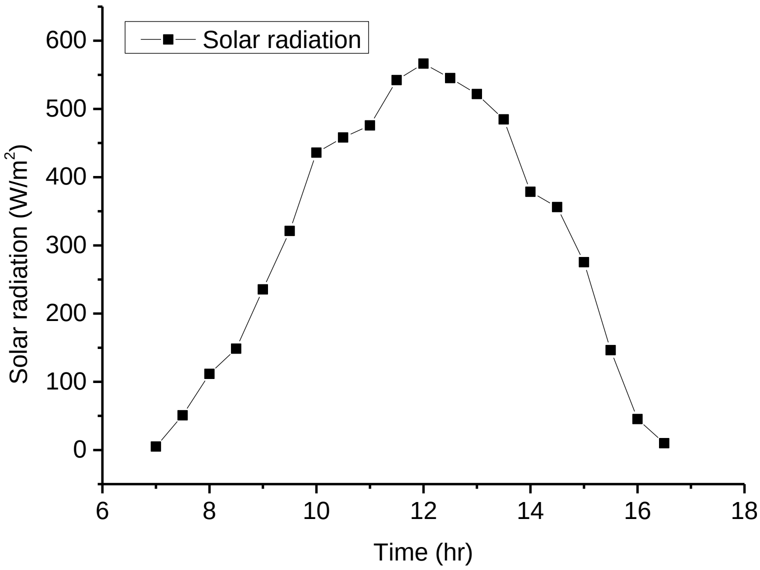

Fig. 4. Solar radiation rates for day 8 Dec

3.1.2 Power of the photovoltaic solar heater

Figure 5 represents the relation between the power of solar radiation and the power generated by photovoltaic panels over time. The highest value of the power of solar radiation was 5989 W at 12:35 p.m., and the highest value of the power generated was 1170 W at 11:35 a.m. It was almost stable from 9:30 a.m. to 1:00 p.m.

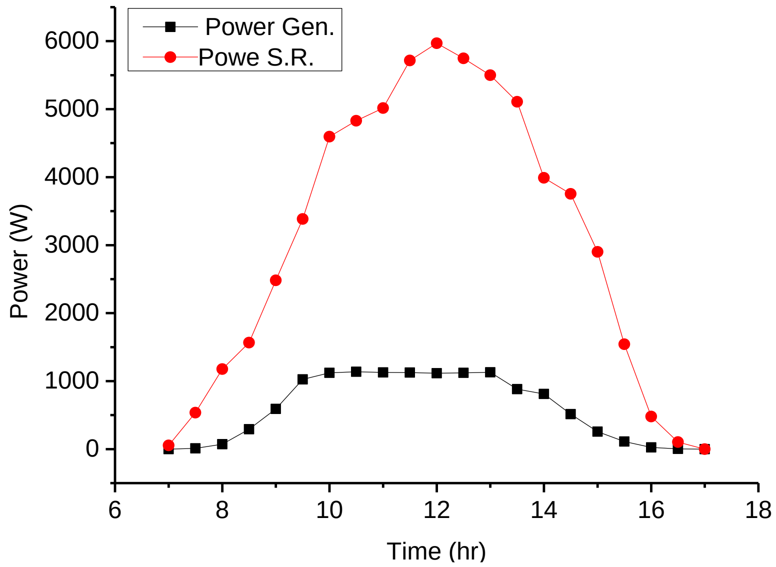

Fig. 5. Power generated and power of solar radiation with time for day 8 Dec

3.1.3 Ambient and panels temperature

The temperature sensors recorded ambient temperatures for the day at two points, first beside the PV panels and second beside the heater to know the difference between the two temperatures in these two locations and their relationship with the temperature of the PV panel's surface. As shown in Figure 6, the figure shows normal temperatures that increase as the day increases, but these climates require the presence of hot water for some household uses, such as bathing and kitchen uses. A gradual rise in temperatures is observed at midday due to the clarity of the atmosphere and the availability of relatively good solar radiation rates. The ambient temperature near the photovoltaic panels was significantly higher than the ambient temperature near the heater because the panels were in a place directly exposed to the sun, while the heater was located in the shade. While, the surface temperature of photovoltaic panels was slightly higher due to their influence by the ambient temperature, as the highest temperature was recorded at 36.50 °C.

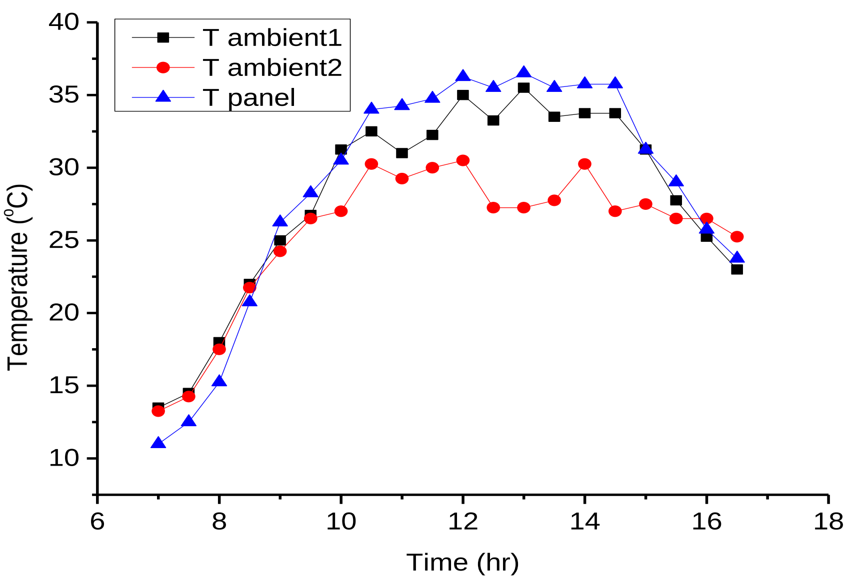

Fig. 6. Ambient and PV system temperature for day 8 Dec

3.1.4 Water temperature of the photovoltaic solar heater

Figure 7 shows the water temperature values of the solar heater that began to be recorded at the beginning of sunrise on December 8, the heater was left unused to observe the time required for the water temperature to rise, as well as monitor the thermal insulation of the heater from the difference between the temperature of the water inside the heater and the ambient temperature near it. It is noted from the curve that the water temperature reached 50 ˚C after less than four hours from the sunrise, this long time for the water temperature to rise is due to the slow gradual increase in solar radiation values at the beginning of the morning. which is a suitable temperature for home use such as showering or kitchen uses, etc. After approximately five hours, the water temperature reached approximately 80 ˚C, which is a high temperature, while the temperature of the water entering the heater and the temperature of the water leaving the heater did not change due to leaving the heater unused. Approximately at 1 p.m., the water temperature reached 100 ˚C. Through this curve, the temperature of the water heater can be controlled at a certain temperature by an electronic control circuit and converting the results of the PV panels system into other uses.

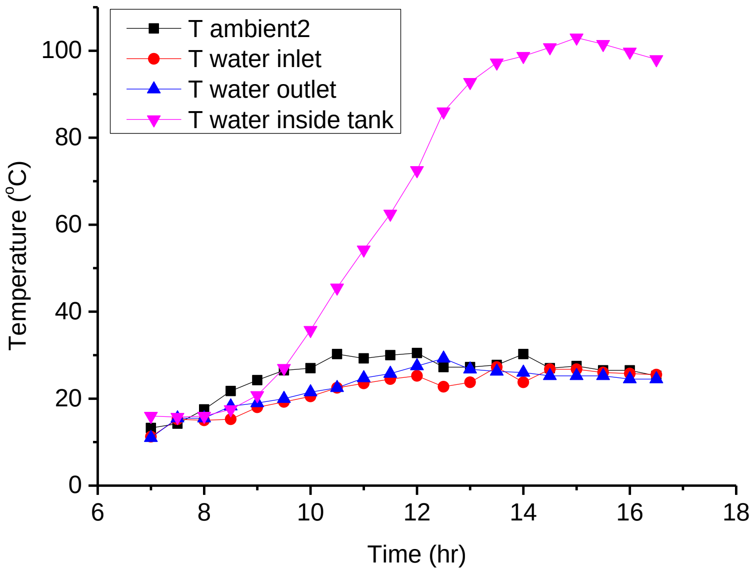

Fig. 7. Ambient temperature and water temperature for day 8 Dec

The temperature gradient continued to be monitored when water was not used until the second day to estimate the thermal insulation of the heater as shown in Figure 8.

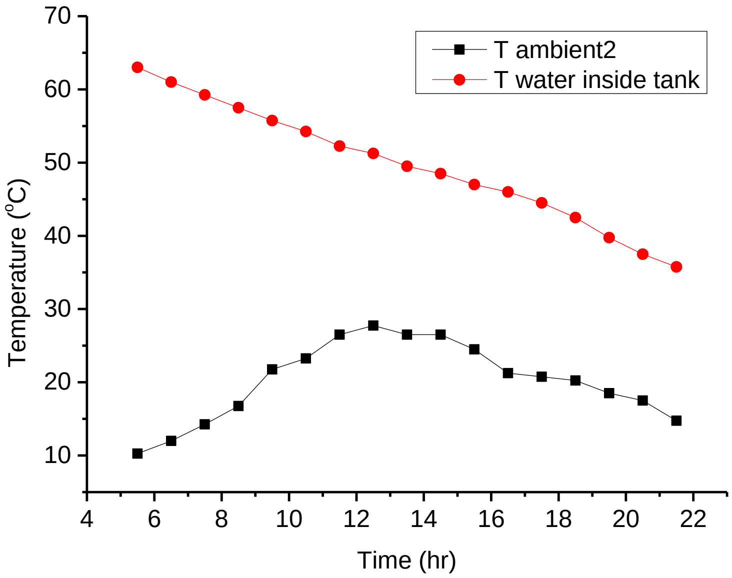

Fig. 8. Ambient temperature and water temperature for day 9 Dec

3.2 DPVWH with Consuming Water

The data were recorded on a very foggy and cloudy day with continuous water use at a rate of 2 L/m to check the thermal load on the heater until the temperature of the water entering the heater equaled the temperature of the water leaving the heater to determine the rate of breakdown of the heating element.

3.2.1 Solar radiation

On 15 Dec., solar radiation data was recorded on a very foggy and cloudy day, it begins to rise with time, and the change in solar radiation continues until after midday when the highest values are recorded due to the rising angle of the sun's perpendicularity to the horizontal surface. With the appearance of some low values due to the presence of some scattered clouds, the weather became variable between cloudy and sunny, but it did not generally affect the natural rates of solar radiation. The highest value of solar radiation was 487.2 W/m^2 at 1:00 p.m., as illustrated in Figure 9.

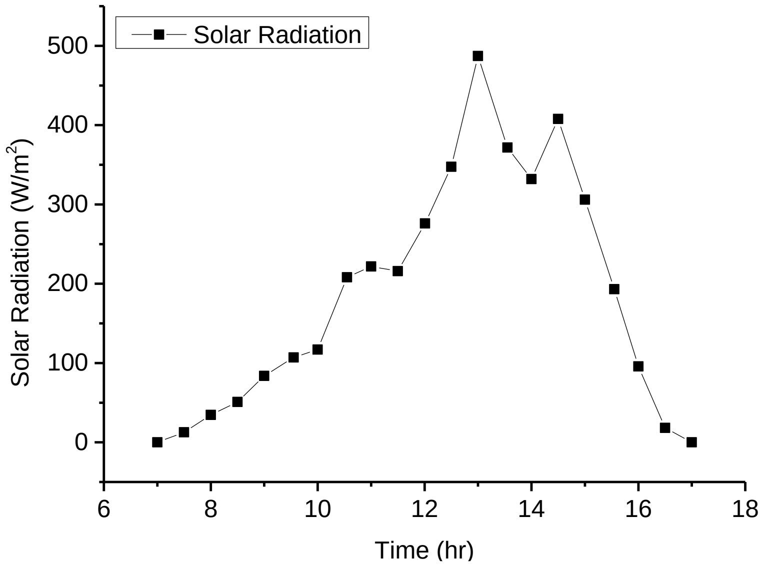

Fig. 9. Solar radiation rates for day 15 Dec

3.2.2 Power of the photovoltaic solar heater

The relationship between the power of solar radiation and the power produced by photovoltaic panels over time is depicted in Figure 10. The highest value of the power of solar radiation was 5135 W at 1:00 p.m., and the highest value of the power generated was 1259 W at 1:00 p.m.

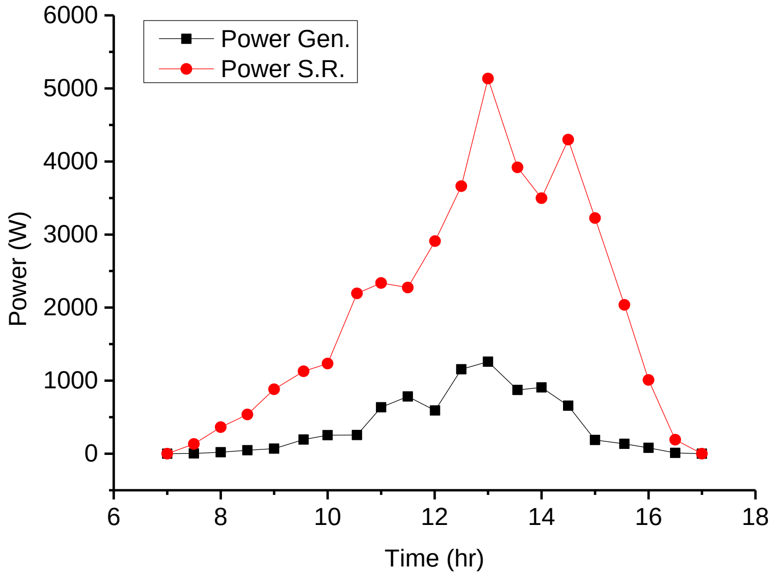

Fig. 10. Power generated and power of solar radiation with time for day 15 Dec

3.2.3 Ambient and panels temperature

The ambient temperatures for this day were recorded next to both the PV panels and the heater and were within the range (9.50–24.25 ˚C), as demonstrated in Figure 11. The highest temperature recorded for the surface of PV panels is 24.50 °C.

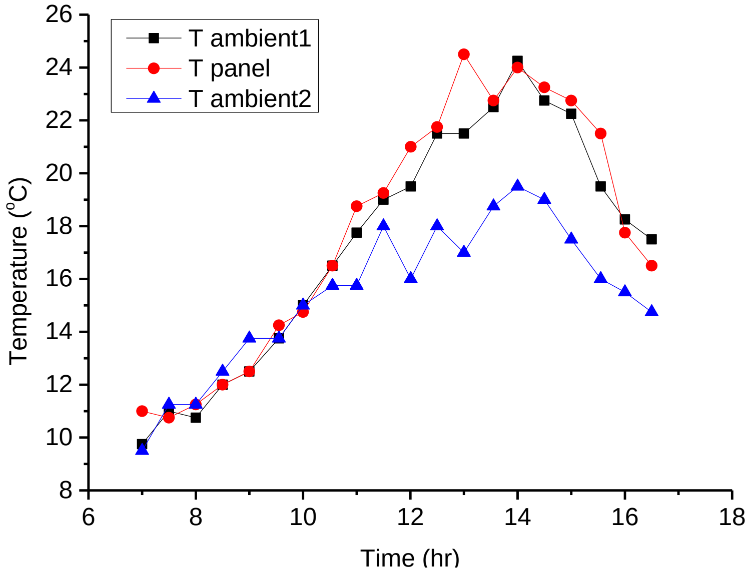

Fig. 11. Ambient and PV panels temperature for day 15 Dec

3.2.4 Water temperature of the photovoltaic solar heater

The photovoltaic solar heater was operated from the beginning of sunrise at 7:00 a.m., as shown in Figure 12, until the water temperature inside the photovoltaic solar heater tank reached 56.25 ˚C at 12:45 p.m., which is a suitable temperature for home uses. It can be noted that from the curve, it was clear that the water temperature has reached 40 ˚C about 12:00 p.m., and this temperature may be suitable for some household applications. The hot water was used at 12:45 p.m. to test the speed of the water temperature falling in the DPVWH when used continuously.

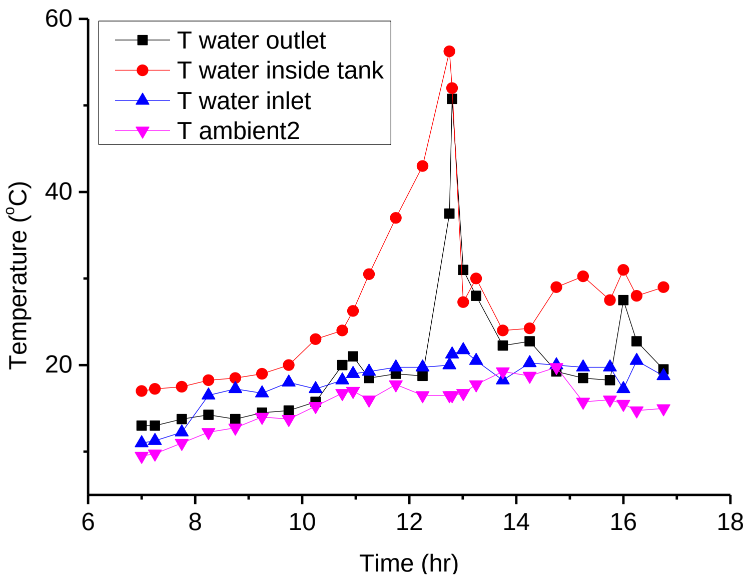

Fig. 12. Ambient temperature and water temperature for day 15 Dec

Figure 13 shows the process of decreasing the water temperature of the solar heater with continuous use and a flow rate of 2 L/m. It is observed that during the period during which the water temperature dropped from 56.25 ˚C to 24.75 ˚C inside the heater tank, the temperature of the water entering the heater was almost equal to the temperature leaving the heater. It had an amount of used water of approximately 202.01 liters and took about 95 minutes. That was a test of the thermal load on the heating element until the temperature of the water entering the heater equaled the temperature of the water leaving the heater.

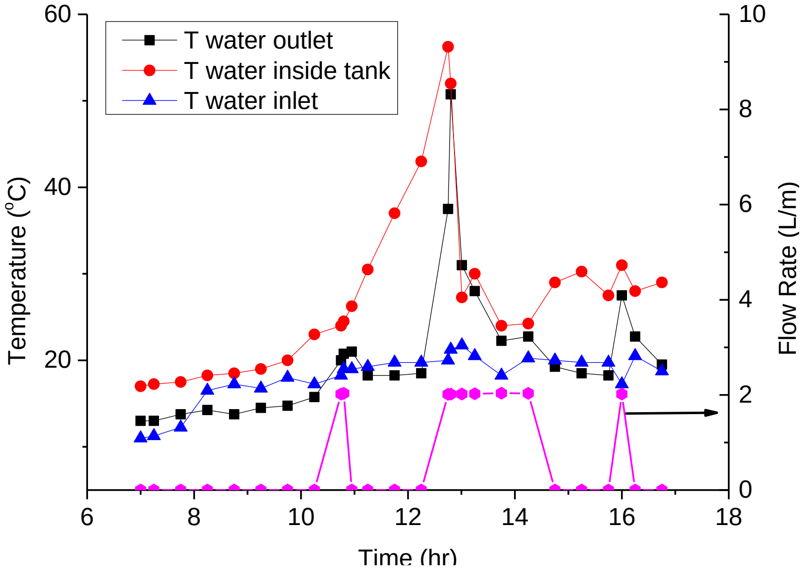

Fig. 13. Water temperature with flow rate for day 15 Dec

4. Comparison

4.1 Comparison with another DPVWH

The results of December 15 were compared with Matuska and Sourek [13] for a typical household (3 to 4 persons), which analyzed the performance of a photovoltaic solar water heating system. The PV arrays were connected directly to DC heating elements in MPPT-off condition in Istanbul city using TRNSYS 18. It conducted an experimental test to verify the theoretical analysis, as shown in Figure 14. The results of the comparison are shown in Table 3. There was substantial agreement between the two studies in the comparison.

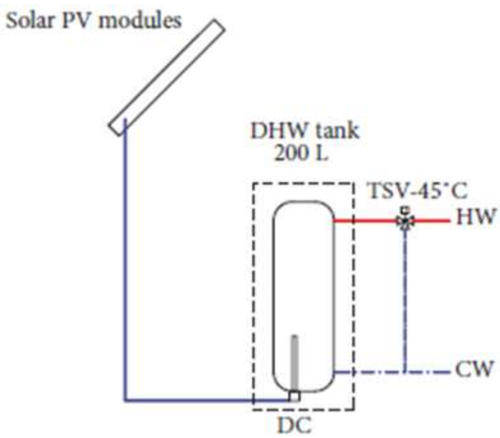

Fig. 14. Scheme of solar hot water systems (PV without MPPT) [13]

Table 3
Comparison results

Parameter	Present Work	Matuska and Sourek [13]
Number of PV modules	4	8
Maximum power of each module	540 W	250 W
Peak power output of PV modules	2160 W	2000 W
Orientation	south	south
Slope	25°	45°
Average ambient temperature	17.38 °C	14.1 °C
Daily hot water load	202.01 L	200 L
Solar water tank volume	120 L	200 L
Maximum water temperature in solar tank	56.25 °C	85 °C
Solar collector area	10.54 m^2	12.8m^2
Maximum power generated	1259 W	1920

4.2 Comparison with STWH

A comparison was made with Sada *et al.,* [25], who studied a thermal solar heater in the same city Wasit-Kut to verify the feasibility of the photovoltaic solar heater. The comparison was made specifically with the temperature of the water inside the tank and solar radiation, as in Figure 15 the increase in the temperature of the water inside the tank was recorded in the case of not using water, on 8/Dec./2023, which the present work is represented by T inside tank 1, with the researcher's data on 12/Feb./2021, which is represented by T inside tank 2. Figure 16 represents the decrease in the temperature of the water inside the tank due to the continuous flow of water at a rate of 2 liters per minute after its temperature increased. In this research, the use of water began at 12:45 p.m. on 15/Dec./2023. While the researcher began using the water at 1:00 p.m. on 2021/Feb./13. As shown in Figure 15, in the PV solar heater, the water temperature continued to rise to very high levels compared to the solar thermal heater. From Figure 16, it can be seen that the water of the photovoltaic system did not decrease smoothly, but rather increased slightly more than once despite the continuous flow of water. This is due to the continuous power generated entering the heating element and its attempts to continue its function and heat the water.

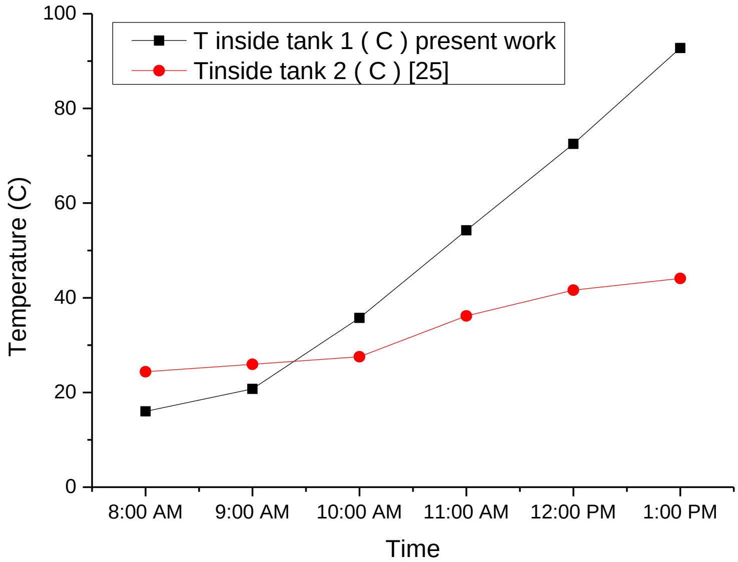

Fig. 15. Temperature of water inside tank without flow rate with time

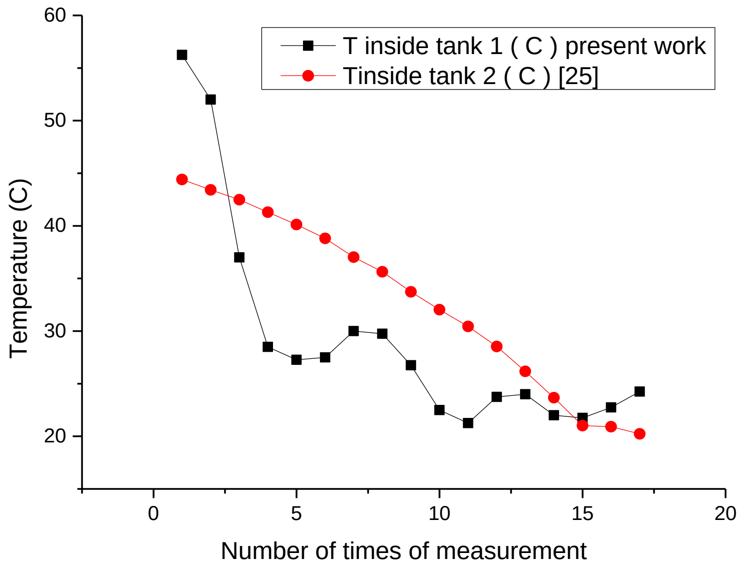

Fig. 16. Temperature of water inside tank with flow rate

Figure 17 shows the comparison between the solar radiation values in the case of not using water for both systems, where the solar radiation values were almost close to each other.

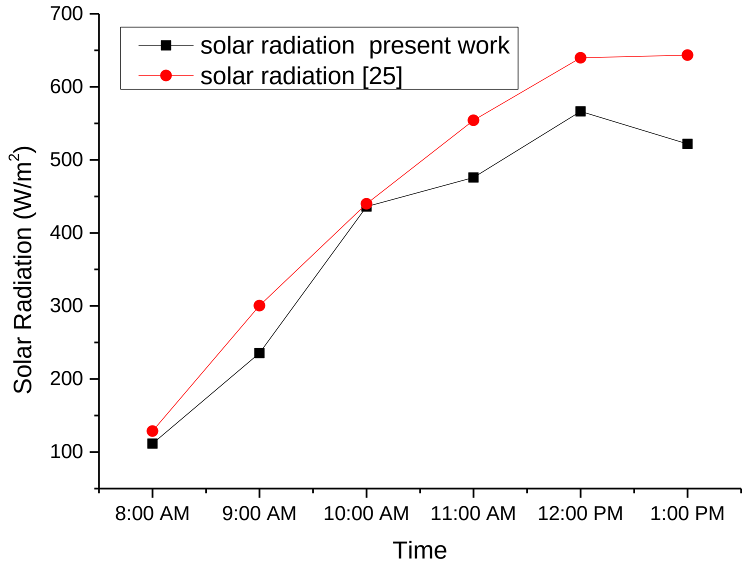

Fig. 17. Comparison of solar radiation values when water is not used

Figure 18 shows the comparison between the solar radiation values in the case of using water for both systems, where the solar radiation values when using the STWHs were higher by about (200-300) W/m^2 than in the case of using the DPVWH, due to climate change between the periods of readings.

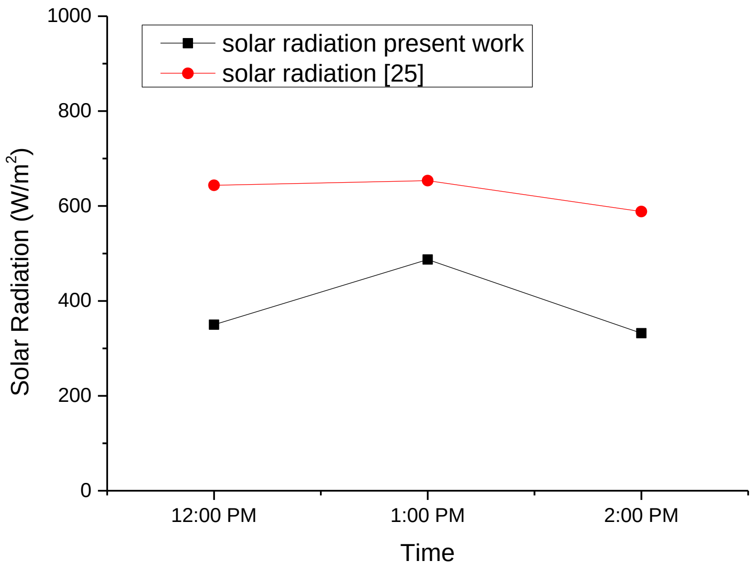

Fig. 18. Comparison of solar radiation values in the case of using water

5. Conclusion

The falling cost of PV panels makes utilizing solar PV a more attractive choice for water heating applications. This study deals with the experimental evaluation of the use of a DPVWH. It offers a thorough grasp of how to test the system by taking into account the PV array's components and characteristics as well as the weather. Selecting a suitable generated power value is a critical step in optimizing the performance of DPVWH. In addition, discussed how well DPVWH performs in Wasit

(Iraq) climate by compared it with another similar system and with STWH system. Its major conclusions are as follows

i. The optimal generated power value for the heating element depends mainly on the DC voltage and DC current generated by the photovoltaic panels, the number of photovoltaic panels connected in parallel or series, and the amount of solar radiation incident in the research region.
ii. The energy generated by photovoltaic panels increases with increasing solar radiation.
iii. The highest values of the water temperature inside the photovoltaic solar heater tank, voltage, current, and power generated, on 8/Dec./2023 without consuming water were 103 °C, 44.8 volts, 26.16 amps, and 1170 watts, respectively, and on 15/Dec./2023 with consuming water, they were 56.25 ˚C, 46.63 volts, 27.60 amps, and 1259 watts.
iv. It is recommended to use a DPVWH in cold areas due to its robustness and efficiency even in foggy and cloudy weather conditions, and its simplicity, given DPVWH that technology depend on the brightness hours of solar radiation.
v. Based on the comparison, it is evident that these outcomes are commendable in terms of power generation, it was found that the photovoltaic system can be adopted as a direct source of water heating for domestic. Heating water with a DPVWH is not much different from heating water with a STWH, given that both technologies depend on the brightness hours of solar radiation. The difference between them is the economic feasibility and ease of implementation and dealing with the DPVWH, and its simplicity compared to the STWH. The electrical energy that can be saved from the DPVWH is double compared to with STWH.
vi. This is considered almost the first PV system in Iraq for heating water that is being evaluated to be an alternative to STWH systems to overcome the problems of impurities in the water used for domestic purposes, which reduce the efficiency of STWH systems, and to overcome heat losses when transporting water through pipes.

6. Future Work

The effect of the Albedo on the system's performance will be tested by increasing the solar radiation on the photovoltaic panels' second (back) side.

The system can be used throughout the year, such that it is used in the winter for heating purposes and in the summer for cooling purposes.

Conducting a simulation model using the TRNSYS program to verify the validity of the experimental results.

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