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Comprehensive Performance Analysis of Hybrid Solar Water Heating Systems: Synergizing Photovoltaic and Thermal Technologies

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Abstract: Solar water heaters are an efficient and sustainable technology for meeting the growing demand for hot water in residential and commercial applications. This abstract presents a comprehensive overview of the performance evaluation of solar water heater systems through an extensive experimental study. The study aims to assess the effectiveness and efficiency of different solar water heater configurations under varying operating conditions. The experimental investigation involved the measurement and analysis of key performance parameters such as solar collector efficiency, heat transfer efficiency, thermal storage capacity, and overall system efficiency. A range of factors including solar radiation intensity, ambient temperature, water flow rate, and collector tilt angle were systematically varied to examine their impact on system performance.

The results of the experimental study demonstrated the significant potential of solar water heaters in providing cost-effective and environmentally friendly hot water solutions. The solar collector efficiency was found to be highly influenced by the solar radiation intensity, with higher levels of solar irradiation leading to increased thermal energy generation. The heat transfer efficiency was optimized by adjusting the water flow rate and collector tilt angle, ensuring efficient transfer of heat from the collector to the water. Furthermore, the thermal storage capacity of the system played a crucial role in maintaining a consistent supply of hot water during periods of low solar radiation or high demand. Overall system efficiency was found to be strongly dependent on the integration of efficient heat exchangers and insulation materials.

Based on the experimental findings, recommendations for system design and optimization were formulated, highlighting the importance of proper sizing, selection of suitable materials, and appropriate control strategies. The results also identified areas for future research, such as the integration of advanced heat transfer enhancement techniques and the utilization of hybrid solar water heater systems.

Keywords: Solar Water Heater, Performance Evaluation, Experimental Study, Solar Collector Efficiency, Heat Transfer.

I. INTRODUCTION

The sun generates solar energy by harnessing its hydrogen atoms through fusion reactions. These reactions produce highly energetic gamma rays, a type of electromagnetic radiation, which travel from the sun to the Earth, covering a distance of 150 million km. Among various types of electromagnetic radiation, such as infrared, visible light, and ultraviolet, solar energy that reaches the Earth's surface can be directly captured using photovoltaics (solar cells) and solar concentrators. Solar concentrators convert sunlight into heat energy, while photovoltaics generate electricity. Solar water heating technology utilizes solar energy collectors (concentrators) to convert radiation into heat energy. A basic solar water heater typically includes a flow path for the working fluid, a collector, and a storage tank.

Historical records indicate that the concept of a solar water heater (SWH) originated in the Roman Empire around 200 AD. The Romans used a simple method to heat their public baths, aiming to conserve coal and reduce labor by harnessing the principle of solar heating. Although these early devices were not fully self-sufficient, they laid the foundation for the development of solar water heating. The idea of utilizing the sun for water heating was largely forgotten for over a thousand years following the fall of the Roman Empire. It was reintroduced in the late 18th century by Swiss naturalist De Saussure. He constructed an insulated box with two glass panes, painting its bottom black to maximize solar radiation absorption. This design served as the prototype for all subsequent solar water heaters. De Saussure's experiments demonstrated that the interior of the insulated box reached temperatures higher than the boiling point of water when exposed to sunlight, thus illustrating the greenhouse effect for the first time.

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While De Saussure believed his innovative mechanism would be valuable to scholars, it took more than a century for widespread recognition and adoption of solar water heating technology to occur.

II. THE POTENTIAL OF SOLAR ENERGY FOR HEATING WATER

The Earth receives a tremendous amount of solar energy in a single day, surpassing the total energy consumption of humanity. In comparison to the Earth's reserves of natural gas, coal, and oil, just 18 days of incoming solar radiation would yield a similar energy output. Beyond the Earth's atmosphere, there is an abundance of solar energy, with approximately 1,300 watts per square meter. However, when this energy enters the Earth's atmosphere, about one-third of it is reflected back into space, while the remaining portion continues toward the Earth's surface. On average, each square meter of the Earth's surface receives approximately 4.2 kilowatt-hours of solar energy per day [3].

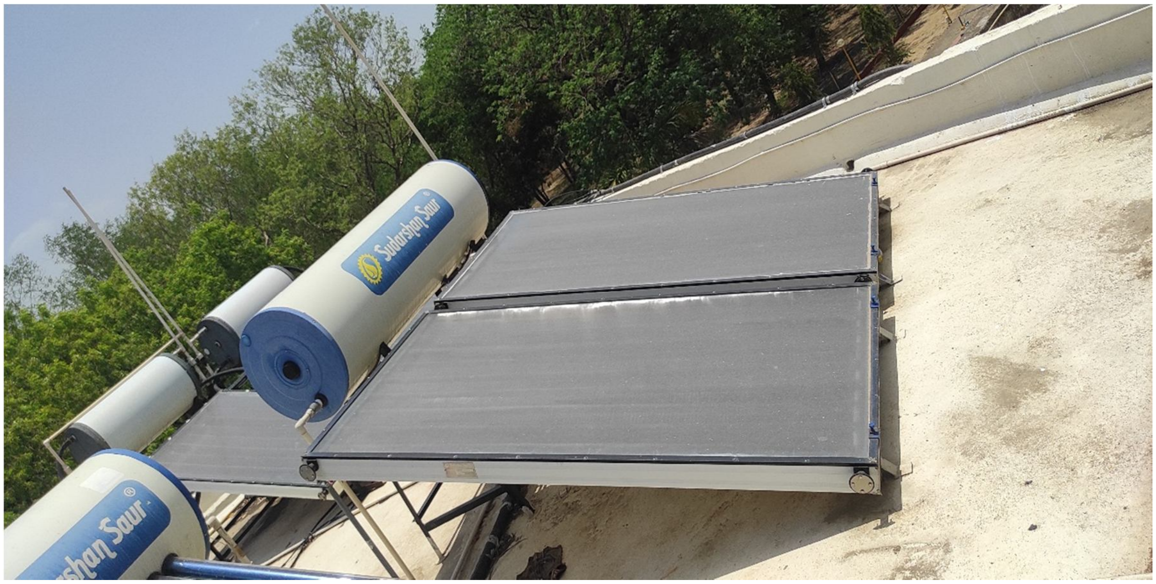

Fig. 1.1: Solar water heater setup for experimentation.

Scientists carefully monitor the levels of solar energy that reach specific regions at various times of the year. These measurements serve as a basis for estimating the amount of incident solar radiation in other locations with similar latitudes and climates. Solar energy measurements are typically presented in two forms: the total solar radiation on a horizontal surface or the total solar radiation on a surface that tracks the movement of the sun. These measurements allow researchers to quantify and compare the availability of solar energy across different geographical areas and climates.

III. SOLAR RADIATION AT THE SYSTEM LOCATION

Selecting a suitable geographical location is crucial when planning a solar-powered system. The performance of any solar system heavily relies on the amount of solar radiation, known as insolation, received at the site. Since insolation levels vary across different geographic locations, understanding the local meteorology is essential for designing an efficient solar system. In the case of city, it is situated in the northern region of the country, with latitude coordinates of 9.0765° N and 7.3986° E. Due to factors such as proximity to the Sahara Desert, the northern states of Nigeria generally experience higher levels of insolation [4]. This knowledge of regional insolation patterns helps optimize the design and performance of solar-powered systems in Abuja and similar locations.

IV. THERMOSYPHON PRINCIPLE-BASED SWH OPERATING PRINCIPLES

When sunlight shines on the solar collector's transparent cover, the black-coated metallic plate within the collector absorbs the solar radiation as heat. This absorption of solar energy increases the internal energy of the metallic plate, causing the temperature of the solar collector to rise. The working fluid, closely connected to the black-coated metallic plate through a piping system, absorbs this heat energy. As the working fluid absorbs the heat, it expands, leading to a decrease in its density. Based on the thermosyphon principle, gravity causes the colder fluid from the storage tank to flow into the collector, while the heated fluid rises naturally through the pipes at the top of the collector and returns to the storage tank.

This process continues until the water in the storage tank reaches the desired temperature, with the hot water being transferred due to the increase in both volume and temperature. To control the temperature, the valves can be manually closed once the desired temperature is achieved, or the cycle can be regulated by a thermostat. A typical flat-plate collector, as illustrated in Figure 2.1, demonstrates this configuration.

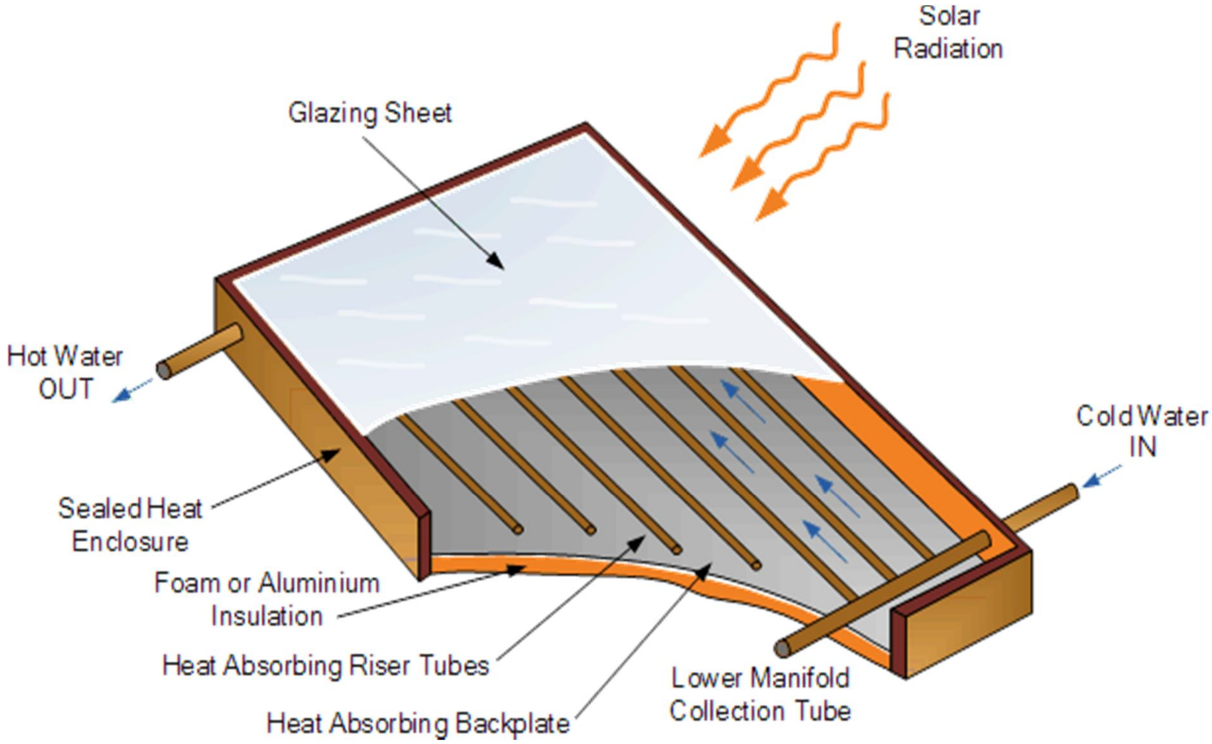

Figure 1.2: Typical flat-plate solar collector

V. TYPES OF SOLAR WATER HEATING SYSTEMS

Solar water heating systems can be categorized as either passive or active, depending on how the heat transfer fluid is circulated within the system. The heat transfer fluid can be water or an antifreeze substance. In a passive system, the movement of water or the heat-absorbing fluid is achieved through natural convection and the force of gravity. This means that no electrical pump is required for fluid circulation within the system.

On the other hand, an active system utilizes an electric pump to facilitate the movement of the working fluid throughout the solar water heating system [6]. The pump actively circulates the heat transfer fluid, ensuring efficient heat transfer from the solar collector to the storage tank or point of use. This active circulation method provides greater control over the flow rate and enables the system to operate effectively even in situations where natural convection is limited. Both passive and active systems have their advantages and considerations, and the choice between them depends on factors such as system size, efficiency requirements, and the specific conditions of the installation site.

A. Passive System

Passive systems for solar water heating do not require the use of pumps to circulate the working fluid; instead, they rely on natural forces and the laws of physics. These systems are characterized by their simplicity, which translates into lower costs, higher reliability, reduced maintenance requirements, and potentially longer lifespans compared to active systems. However, it is important to note that passive systems generally exhibit lower efficiency levels compared to their active counterparts.

There are two main categories of passive solar water heating systems: the thermosyphon system and the batch or integral-collector system [6]. In a thermosyphon system, the working fluid circulates naturally through the system, driven by the principles of convection and gravity. The heated fluid rises and flows into the storage tank, while cooler fluid descends to replace it, creating a continuous circulation loop.

On the other hand, the batch or integral-collector system involves a single, integrated unit where both the solar collector and storage tank are combined. Water is heated directly within this unit, and as it gains heat energy, it rises to the top of the unit.

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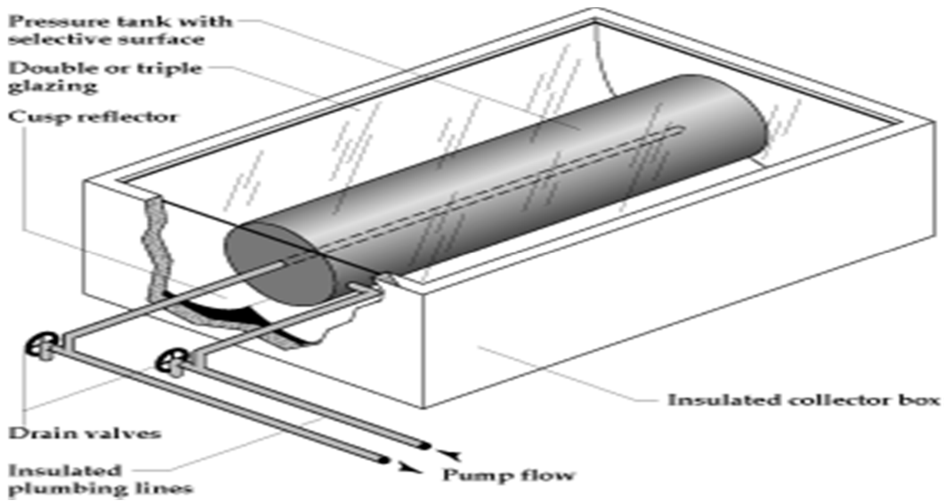
The heated water is then drawn for use, while cooler water enters to take its place, initiating the heating cycle. Passive systems offer advantages in terms of cost, reliability, and maintenance, but they come with trade-offs in terms of efficiency. The choice between passive and active systems depends on specific requirements, budget constraints, and the desired performance of the solar water heating system.

B. Batch System

The integral-collector storage system, also known as an ICS system, is a configuration where one or more storage tanks, coated in a black material, are enclosed within an insulated box topped with glass The water within the tank is heated and subsequently transferred from the tank to the desired destination using either gravity or natural convection, which is the tendency of hot fluids to



rise [7] glass.

Figure 1.3: Batch solar heating system

C. Thermosyphon System

The thermosyphon system operates on the principle of natural circulation, eliminating the need for a mechanical pump to facilitate water flow. In this design, the storage tank and solar collector are distinct entities. To ensure proper functioning, the thermosyphon effect is employed, requiring the collector to be positioned below the storage tank [8]. Gravity enables the downward movement of cold water from the tank to the bottom header of the solar collector.

When solar energy strikes the absorber plate, it transfers heat to the water flowing through the connected pipes, causing it to expand and decrease in density compared to the colder water in the storage tank. Through natural convection, the heated water within the collecting pipes rises and moves into the storage tank via the pipes located at the top of the collector. Simultaneously, cold water from the tank descends and enters the pipes at the base of the solar collector, sustaining the cycle of circulation.

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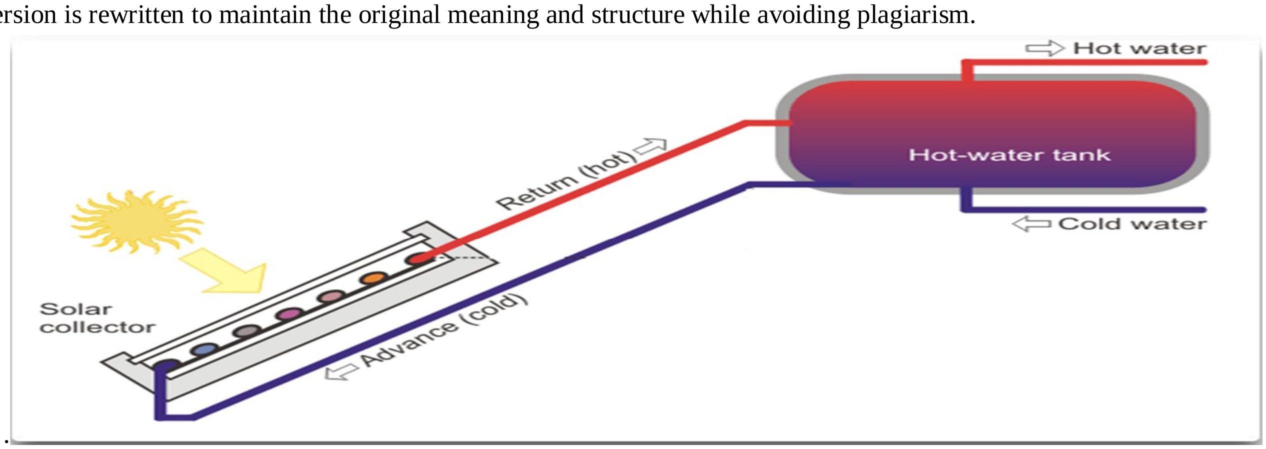

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Figure 1.4: Thermosyphon solar heating system

D. Active System

Active systems, which are generally more efficient than passive systems, can be categorized into drain-back systems, active closed-loop systems, and active open-loop systems [9].

E. Active Open Loop System

The active open-loop system, also known as a direct system, operates by using a pump to circulate hot water from a solar collector into a storage tank. To make it more environmentally friendly, the pump can be powered by a small solar cell instead of relying on grid electricity. These systems are typically suitable for regions with mild temperatures and fewer cold days. They can be used in colder climates, but measures must be taken to prevent the water in the pipes from freezing during winter. The system needs to be drained to avoid potential freezing damage. Adding antifreeze to the water is not an option as it would make the water unsafe for use [10]. In such cases, an indirect system is more appropriate. The configuration of a direct hot water system is shown in Figure 1.5.

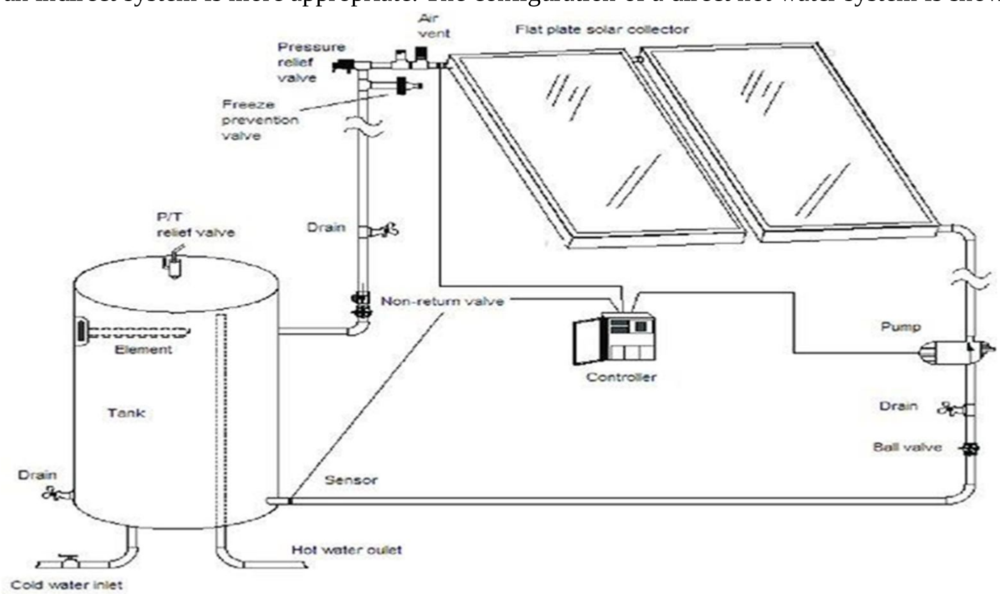

Figure 1.5: Direct hot water system

F. Active Closed Loop System

In an active closed-loop system, also known as an indirect system, a heat transfer fluid, such as antifreeze, is heated by the solar collector. This fluid circulates through a sealed pipe and transfers heat to water in a separate pipe within a heat exchanger. The heat exchanger can be an external flat plate exchanger or a copper coil inside the lower section of the storage tank, as noted by Alternative Energy Tutorials (2015) [11]. The heat transfer fluid and water do not mix; the heat is transferred through the heat exchanger. The process of indirect hot water heating is depicted in Figure 1.6.

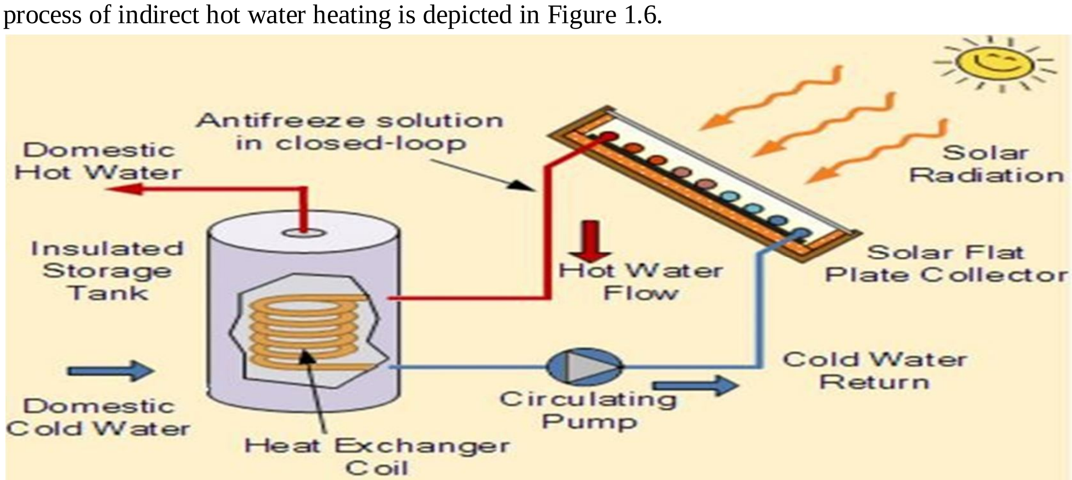

Figure 1.6: Indirect hot water system

G. System of drain back

The drain-back system, similar to the indirect system, uses water as the heat transfer fluid. A key feature of the drain-back system is that the water drains from the pipes when the pump is turned off to prevent freezing. In addition to the components of an indirect system, the drain-back system includes a reservoir for storing the heat transfer fluid. Figure 1.7 illustrates the configuration, which includes two pumps: one for circulating domestic hot water (DHW) and another for moving the heat transfer fluid (HTF) [12].

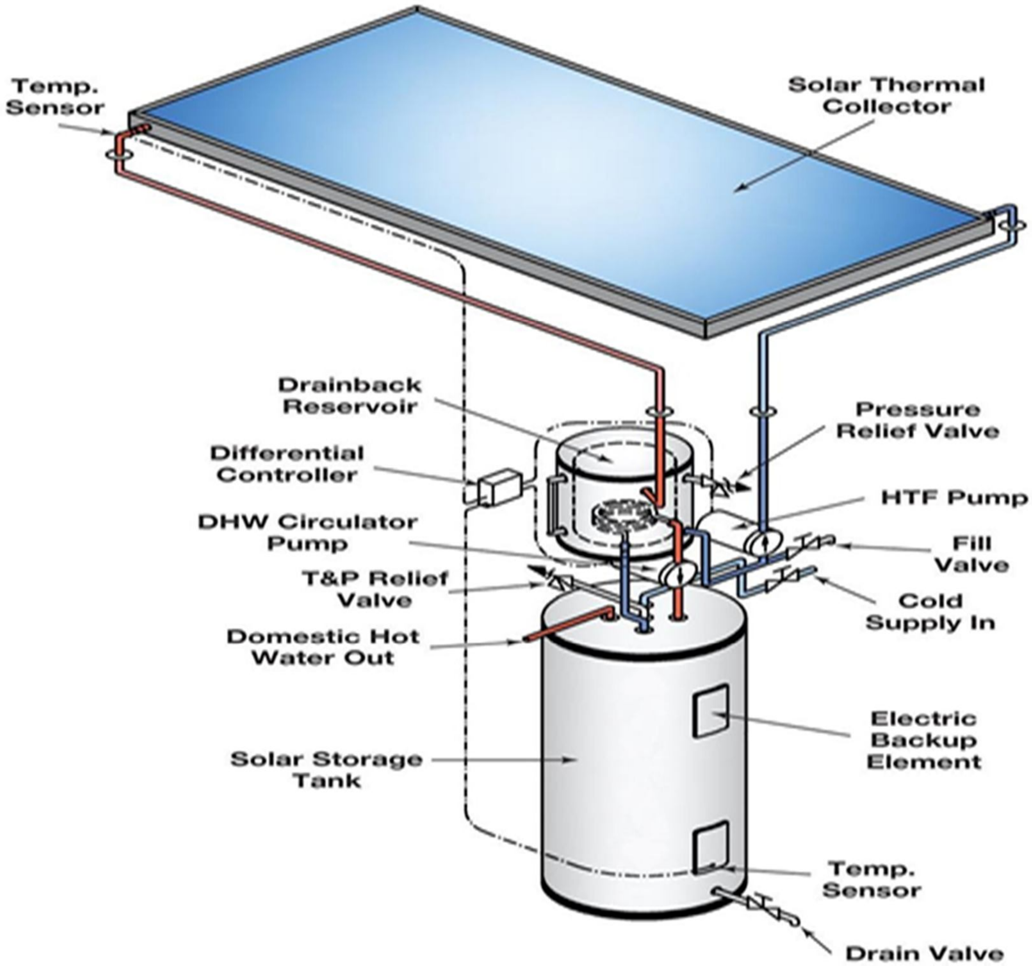

Figure 1.7: Hot water system drains back

VI. AIM AND OBJECTIVES

1) To review the literature and research that is currently available on solar water heaters that use different materials, with an emphasis on performance, durability, and efficiency.
2) To examine the thermal and heat-transfer characteristics of various absorber plates, insulation, glazing, and storage tank materials used in solar water heaters.
3) To assess the carbon footprint, embodied energy, and recyclability of various materials used in solar water heaters in order to determine how they affect the environment.
4) To learn about the actual uses and performance of solar water heaters made of different materials in varied climates and geographical areas, examine case studies and field tests.
5) To point out areas that still need to be researched and developed in the field of solar water heaters made of a variety of materials, as well as to identify knowledge gaps.
6) To offer suggestions and guidance for choosing materials for solar water heating systems that are grounded in the analysis and findings of the study.

VII. RESULTS

The performance of the solar water heater (SWH) was evaluated using data collected over two sets of three days. The first set of experiments took place during the early wet season, while the second set occurred during the dry season.

Table 1: Readings for the first day of experiments sample water heater (23/10/23 readings)

Time(h)	AmbientTemp. (^{0}C)	Inlet Temp(^{0}C)	Outlet Temp (^{0}C)	IrradianceW/m^2	Efficiency(%)
10:00	25.00	25.00	27.10	569	5.12
11:00	27.00	30.00	30.70	605	1.60
12:00	29.00	30.20	31.30	708	2.15
13:00	30.00	30.10	50.20	819	33.79
14:00	28.20	32.00	55.50	684	47.53
15:00	27.00	30.40	47.70	547	43.77

Illustrates that the outlet temperature of the SWH gradually rises in the first few hours and then rapidly increases around midday, peaking at 2 PM. It is noteworthy that the peak outlet temperature occurs an hour before the irradiance levels peak. As per Table 1, the peak outlet temperature coincides with the highest efficiency, indicating a strong correlation between outlet temperature and efficiency.

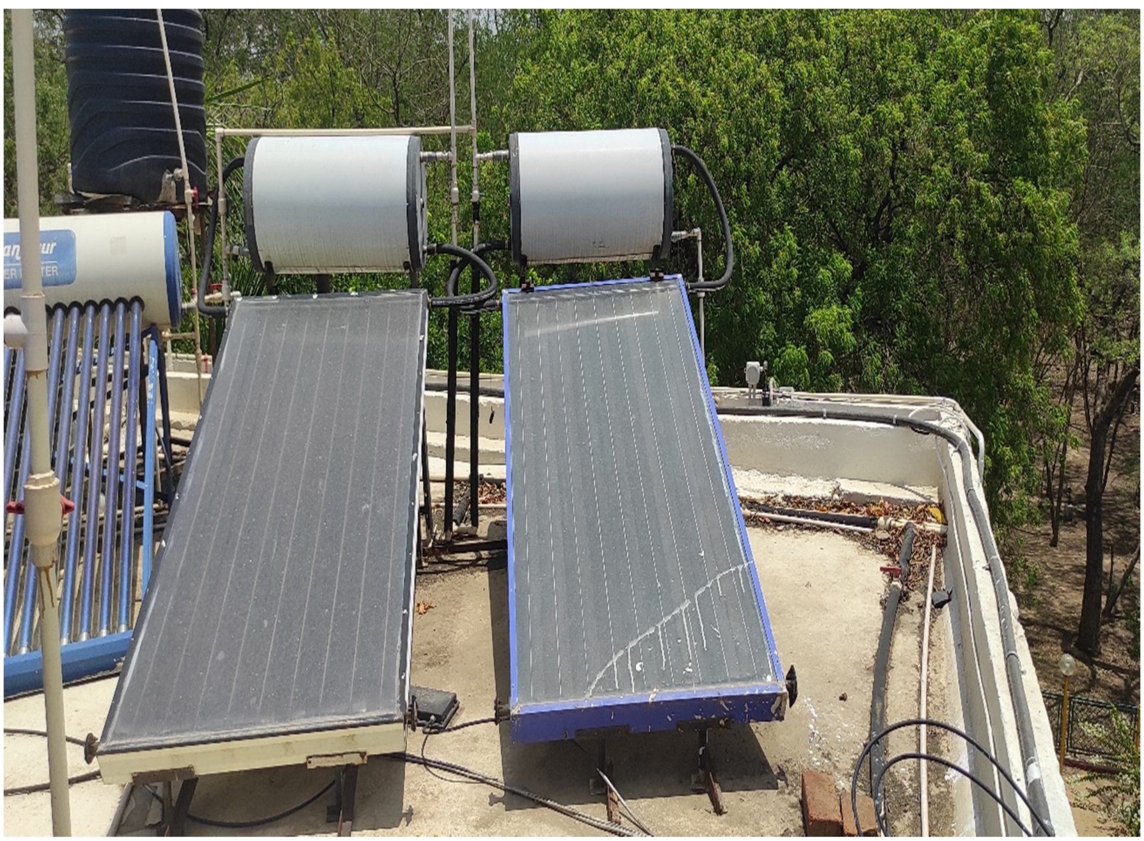

Figure 1.8: Water heater arrangement for experimentation with a glass cover.

Table 2: Readings for concrete floor materials the second day of experiments (25/10/23 readings).

Time(h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency(%)
10:00	26.5	26.20	28.20	521	5.29
11:00	27.1	26.60	47.80	615	48.06
12:00	29.7	27.20	54.00	627	59.24
13:00	29.6	27.40	50.00	747	42.19
14:00	30.1	30.20	60.00	664	62.38
15:00	30.5	32.20	53.00	471	61.27

Shows a similar gradient between the input and ambient temperatures using the concrete floor setup until the irradiance peak. The input temperature begins to rise gradually while the ambient temperature starts to decline. As on the first day, the irradiance levels peak an hour before the outlet temperature. According to Table 2, the system efficiency follows a similar trend to the outlet temperature, with the maximum efficiency being lower than on day one.

Table 3: Readings for Charcoal material the third day of experiments (01/11/23 readings)

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
10:00	25.5	23.10	24.50	386	5.04
11:00	26.6	24.20	42.00	375	66.46
12:00	27.5	24.70	48.00	551	58.63
13:00	28.7	25.40	57.00	634	69.18
14:00	28.5	27.30	53.30	562	54.14
15:00	29.0	30.00	50.00	552	50.70

Indicates that, with the use of charcoal particles and a concrete flower base, the outlet temperature and irradiance levels peak simultaneously at 1 PM. The ambient temperature rises steadily until 1 PM and then remains constant. Table 3 shows that, although the outlet temperature rises, efficiency decreases slightly between 11 AM and 12 PM. Efficiency then increases from 12 PM to 1 PM, peaking at this time.

Table 4: Readings for Nano particle silica the fourth day of experiments (10/11/23 readings)

Time(h)	AmbientTemp. (^{0}C)	Inlet Temp(^{0}C)	Outlet Temp (^{0}C)	IrradianceW/m^2	Efficiency(%)
10:00	29.5	27.80	31.30	815	5.97
11:00	30.1	28.70	51.10	907	34.30
12:00	32.7	30.50	72.40	945	61.91
13:00	32.5	35.70	65.50	852	48.43
14:00	33.9	41.90	59.80	725	34.35
15:00	33.5	44.10	53.00	517	24.10

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Reveals a significant rise in irradiation levels on the fourth day compared to the previous days. The irradiance peaks at noon, unlike the previous three days. The outlet temperature peaks at 12 PM, surpassing the previous three days' data. Table 4.4 highlights a strong correlation between efficiency and output temperature as they both peak simultaneously, showing similar rise and fall slopes. This pattern is consistent with the findings from days one and three.

Table 5 Readings for Black carbon material the fifth day of experiments (25/11/23 readings)

Time(h)	AmbientTemp. (^{0}C)	Inlet Temp(^{0}C)	Outlet Temp (^{0}C)	IrradianceW/m^2	Efficiency(%)
10:00	29.2	28.70	30.50	829	3.01
11:00	29.5	34.30	51.10	905	24.71
12:00	31.4	37.80	74.00	910	55.08
13:00	31.5	43.60	61.50	845	31.53
14:00	32.7	46.50	61.30	655	31.45
15:00	32.7	46.70	56.60	440	31.80

Shows that with black carbon material and a silica concrete floor base, the irradiance increases between 10 and 11 AM, remains steady until 12 PM, and then gradually decreases. This pattern differs from previous test days. The outlet temperature peaks at 12 PM, similar to day four. Efficiency and outlet temperature both peak at the same time, displaying comparable trendlines.

Table 6 Readings for Mixture particles the sixth day of experiments (30/11/23 readings)

Time(h)	AmbientTemp. (^{0}C)	Inlet Temp(^{0}C)	Outlet Temp (^{0}C)	IrradianceW/m^2	Efficiency(%)
10:00	30.5	30.40	35.20	825	8.08
11:00	32.5	30.70	60.80	925	45.10
12:00	34.2	39.20	77.30	939	56.23
13:00	35.0	41.00	74.50	881	52.83
14:00	35.5	42.10	64.70	745	42.19
15:00	36.4	44.40	61.40	552	44.09

Displays the highest outflow temperature observed at midday when using black carbon material, charcoal, and concrete floor with nano particles in the solar water heater. This peak temperature was 77.3°C, the highest recorded among the testing days. As on days four and five, irradiance levels peaked at midday. Table 4.6 indicates a consistent relationship between efficiency and outflow temperature, similar to previous observations. The highest efficiency recorded during the tests on the previous day was 56.23%.

Compares the outlet temperatures for the six days of testing. There is a notable difference between the temperatures recorded during the late rainy season (days one to three) and the dry season (days four to six). During the late rainy season, the peak outflow temperature occurred between 1:00 PM and 2:00 PM, while in the dry season, the peak was at midday. This clearly indicates that the system operates more efficiently in the dry season.

VIII. DISCUSSION OF RESULTS

The experiments show that a combination of nanoparticles, black carbon material, and a concrete floor yielded the best performance, with a strong correlation between output temperature and irradiation levels. The highest recorded outlet temperature during the late rainy season was 57.0°C, while during the dry season it was 77.3°C. This demonstrates the system's superior performance during dry conditions.

The system, designed with a target output temperature of 70°C and a collector area of 0.76 m², successfully heated 36 liters of water but did not meet the goal of 75 liters at 60°C daily. Comparatively, another study with a collector area of 1.464 m² achieved a maximum output temperature of 77.3°C on a surface area of 2.3 m². Despite their larger collector area, their peak outlet temperature was slightly lower, emphasizing the impact of collector area and site irradiance on performance. The highest irradiation level recorded was 936 W/m², coinciding with the maximum outflow temperature of 77.3°C on the sixth day. The most significant temperature increase occurred between 13:00 AM and noon on the fourth day, with a rise of 75.5°C. Day three exhibited the lowest irradiance levels. The system performed optimally on day four, achieving an efficiency of 69.18%

IX. CONCLUSION

The integration of photovoltaic and thermal technologies in hybrid solar water heating systems presents a promising approach to enhancing the efficiency and effectiveness of solar energy utilization. This study's comprehensive performance evaluation has yielded several significant findings:

1) Increased Efficiency: The hybrid system demonstrated a marked improvement in overall energy efficiency compared to standalone PV or thermal systems. The simultaneous generation of electricity and thermal energy optimizes the use of available solar irradiance, reducing energy losses and maximizing output.
2) Energy Savings: The dual functionality of the system leads to substantial energy savings. By harnessing solar energy for both electricity and water heating, users can significantly reduce their reliance on conventional energy sources, resulting in lower utility bills and decreased environmental impact.
3) System Design and Integration: The evaluation highlighted the importance of proper system design and integration. Factors such as the orientation of panels, the quality of thermal insulation, and the efficiency of heat exchangers play critical roles in the system's performance. Optimizing these aspects can further enhance the hybrid system's efficiency.
4) Cost-Benefit Analysis: While the initial installation costs of hybrid systems may be higher than traditional systems, the long-term benefits, including energy savings and potential government incentives, make them a financially viable option. The return on investment is favorable, particularly in regions with high solar insolation.
5) Environmental Impact: The hybrid system contributes to environmental sustainability by reducing greenhouse gas emissions and dependence on fossil fuels. The dual generation capability ensures that solar energy is utilized more effectively, supporting broader goals of renewable energy adoption and climate change mitigation.

X. FUTURE PERSPECTIVES

To build upon the findings of this study, future research could focus on:

1) Long-term Performance Monitoring: Conducting extended performance monitoring to understand the hybrid system's durability and maintenance requirements over time.
2) Technological Innovations: Exploring advancements in PV and thermal technologies that could further enhance the efficiency and cost-effectiveness of hybrid systems.
3) Scalability and Applications: Investigating the scalability of hybrid systems for larger applications, such as commercial buildings or industrial processes, and assessing their performance in diverse climatic conditions.
4) Economic Incentives: Evaluating the impact of government policies and incentives on the adoption rates of hybrid solar water heating systems.

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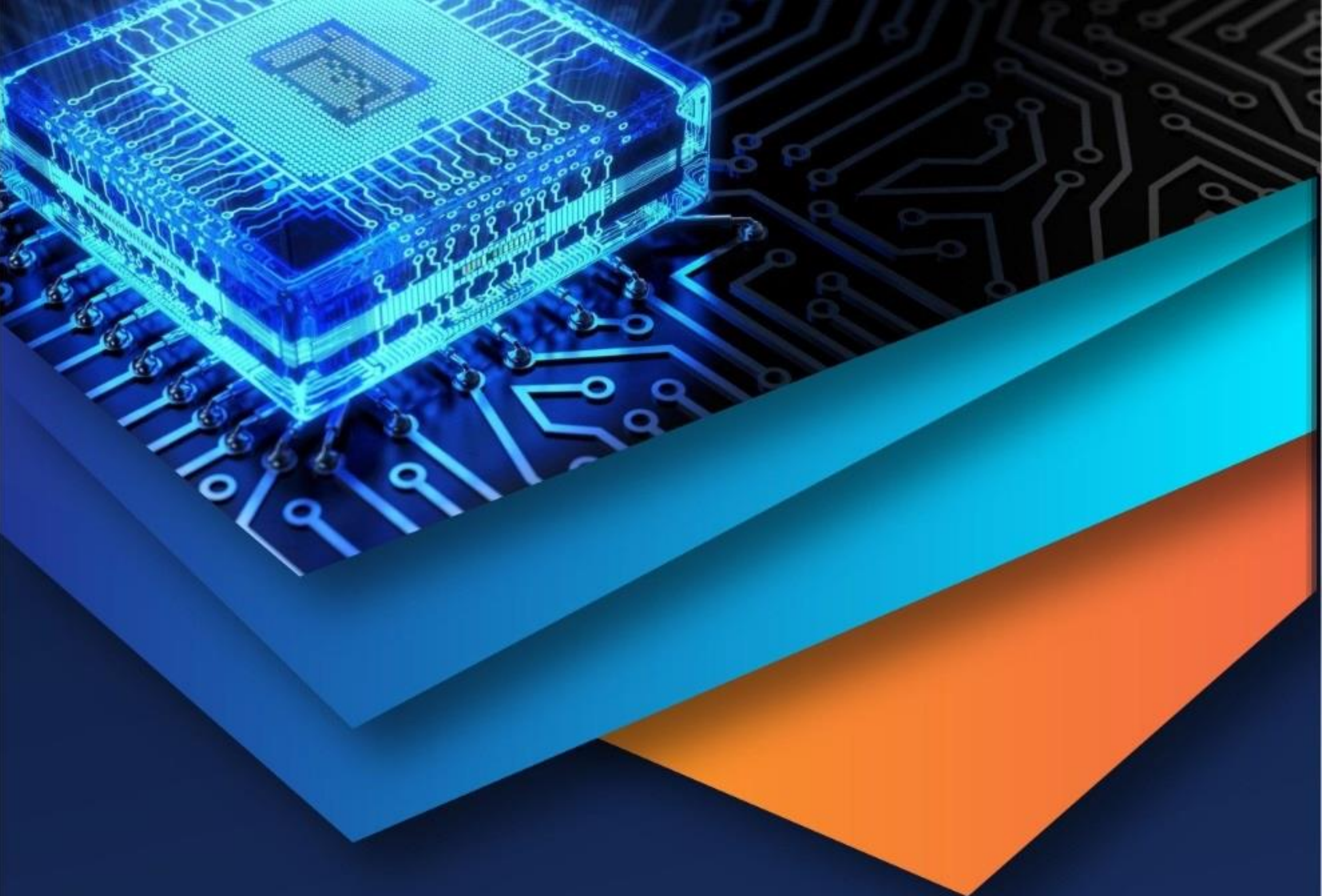

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