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# A Review on Solar Water Heating System in Nigeria

Abdulyakin USMAN[1*], Ibrahim A. RUFAI[2], Dalhatu B. YAHAYA[3]

[1*]Department of Mechanical Engineering, Faculty of Engineering, Federal University Dutsin-Ma, Katsina State, Nigeria
[2,3]Department of Mechanical Engineering, Faculty of Engineering, Bayero University, Kano, Nigeria

[1*]ausman8@fudutsinma.edu.ng, [2]iarufai.mec@buk.edu.ng, [3]dbyahaya.mec@buk.edu.ng

***Abstract***
*The most widely used solar thermal technologies in West Africa are solar water heating systems; nevertheless, the adoption of these systems has been slower than expected. This review introduced the three technical methods upon which solar energy can be harnessed, and the solar water heating process falls under the thermal method. The working principle of the solar water heating system was explained to involve gathering heat in a solar collector; transfer the heat to the water supply; and store the heated water until it is used. Solar water heaters were then classified based on method of flow circulation and the type of solar collector. The components of the system for heat collection, heat storage, heat delivery and freeze protection were also introduced. Concept of Modelling and Simulation of solar Water Heating System as well as prospect of the system in family homes, clinics, and other settings reported from literature were included in the review. The review after highlighting the prospects of system however identified some areas that were not resolved in the existing literature to include: hybridizing solar water heater with incinerator water heater, optimizing the performance of the hybrid system using computational fluid dynamics techniques, as well as the sustainability evaluation for the deployment of the system in Clinics and other settings.*

***Keywords:*** *Active, Passive, Prospects, Solar Energy, Solar Water Heater, Water Heating System.*

## 1.0 Introduction

A Currently, domestic hot water demand in Nigeria for households, agriculture, healthcare, education, and office use is primarily met using electricity, kerosene, and fuel-wood. The national electricity grid relies largely on natural gas-fired and hydropower generating stations. However, irregular gas supply, fluctuating water levels at hydropower sites, and obsolete transmission and distribution equipment contribute to the unstable power supply in the country [1]. Consequently, electricity remains largely inaccessible, especially in rural areas which account for approximately 70% of Nigeria's population. As a result, most rural dwellers depend on fuel-wood to meet their water heating and other energy needs. Given Nigeria's abundant solar energy resources, vast landmass, and large population, coupled with the low adoption rate of solar water heating systems and the need to conserve depleting conventional energy sources such as fossil fuels and wood, the potential for widespread deployment of solar water heating systems is substantial [2].

## 2.0 Theoretical Fundamentals

### 2.1 Solar Photovoltaic and Solar Thermal System

The sun provides the earth with light and heat, and its role in sustaining life within the solar system is fundamental. However, the technical exploitation of solar energy only began in the 17th century. Solar radiation undergoes attenuation as it passes through the atmosphere. As a result, only a fraction of the solar constant, approximately 1367 W/m$^2$, reaches the earth's surface [3]. Solar energy is widely regarded as the energy source of the future due to its clean and inexhaustible nature. It can be harnessed through three primary technical approaches: helio-chemical, helio-electrical, and helio-thermal. The helio-chemical pathway occurs through photosynthesis, which sustains life by converting $CO_2$ to $O_2$ and producing biomass. The helio-electrical approach utilizes photovoltaic converters to generate electricity. The helio-thermal approach converts solar radiation into thermal energy for applications such as solar water heating and space heating [4]. Photovoltaic systems generate electricity through the interaction of sunlight with semiconductor materials. Solar radiation reaches the earth in the form of photons. When these photons strike a solar cell, they dislodge electrons from the atoms of the semiconductor material. Electrical contacts on the positive and negative terminals capture these electrons as direct current, which can then be used to power loads such as water heaters and pumps [5]. In contrast, solar thermal systems utilize the heat from sunlight to directly warm air or water. As shown in Figure 1, solar thermal technology has been applied since the 1920s, although its deployment has remained limited [6].

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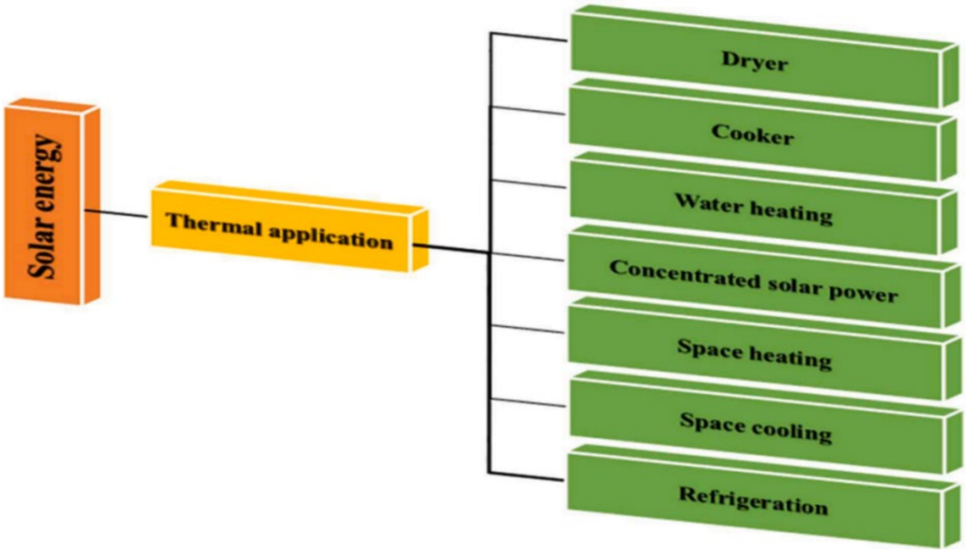


Fig. 1: Solar thermal energy applications Source: [6]

### 2.2 Types of Solar Water Heating System (SWHS)

Solar water heating systems are available in various configurations that differ in design, cost, performance, and level of complexity. Most systems incorporate an auxiliary energy source, such as electricity or gas, to ensure continuous hot water supply during periods of low solar irradiance.A typical solar water heating system consists of an insulated storage tank, a solar collector, a backup heating unit, a circulation pump, and a control system. Based on the mode of heat transfer fluid circulation, these systems are broadly classified into two main categories, as illustrated in Figure 2 [7].

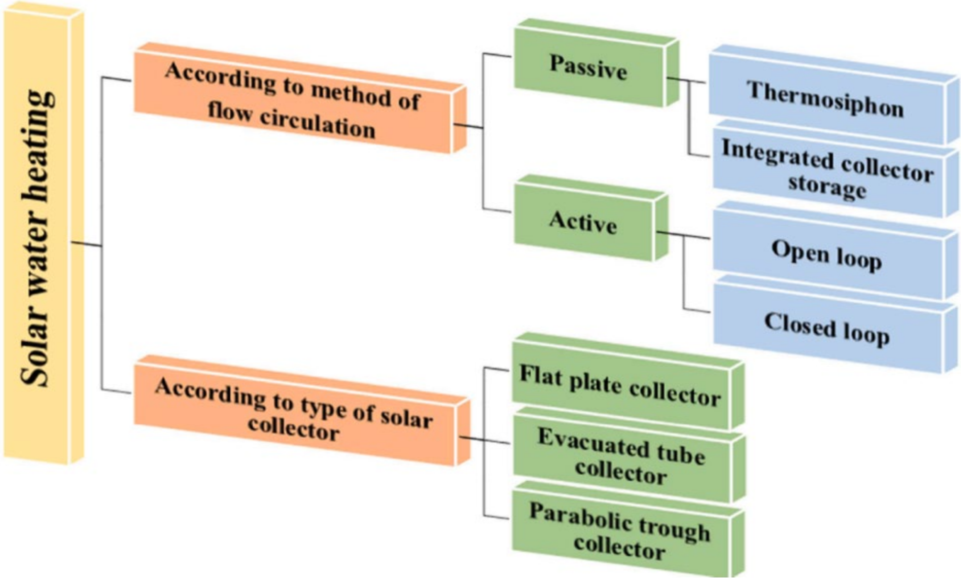


Fig. 2: Type of solar water heating system Source: [6]

#### 2.2.1 Classification of SWHS According to Method of Flow Circulation

I. **Active Solar Water Heating System:** Active systems generally exhibit efficiencies that are 35%–80% higher than those of passive systems. However, they are more complex and costly. As a result, they are best suited for industrial applications with high thermal loads, for installations where the solar collector and storage tank must be located far apart, or for systems requiring multiple collectors [8]. Water-based active systems utilize pumps to circulate the heat transfer fluid between the solar collector and the thermal storage tank. This forced circulation provides greater flexibility in the placement of storage tanks and heat exchangers, and allows easier integration with other energy systems. Furthermore, pumped systems permit optimal collector positioning, typically on building rooftops. The electrical energy consumed by the pumps is relatively low and can often be supplied by a dedicated photovoltaic system [9]. All active solar water heating systems, as shown in Figure 3, incorporate an electronic controller. In its basic configuration, the controller compares the temperature of the fluid in the collector with that in the storage tank and activates the pump when the collector temperature

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exceeds the tank temperature by a preset value [10]. Although active systems have higher initial and operational costs, this disadvantage is offset by their significantly higher thermal efficiency [8].

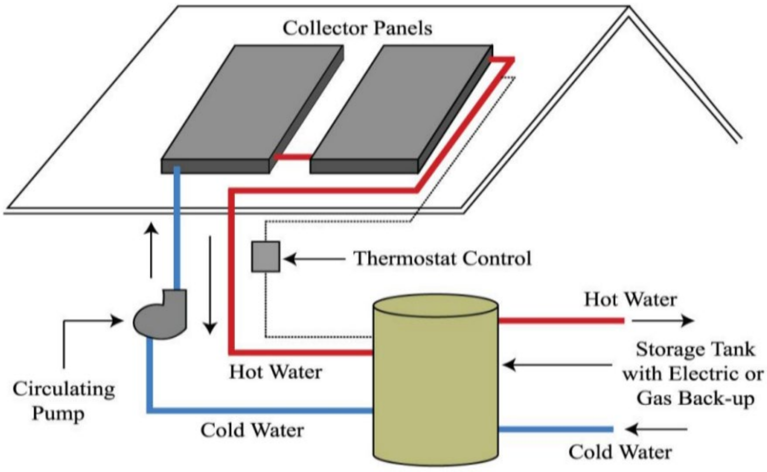


Fig. 3: Schematic diagram of active SWHS Source: [6]

Active systems are further divided into two categories: Open-loop (Direct) and Closed-loop (Indirect) Active System.

i. **Open-Loop Active Systems:** In this system, pumps circulate pressurized potable water directly through the collectors, as illustrated in Figure 4. The design offers high thermal efficiency and reduced operating costs. However, it is unsuitable for areas with hard or acidic water, as scaling and corrosion can rapidly impair system performance and lead to failure [6].

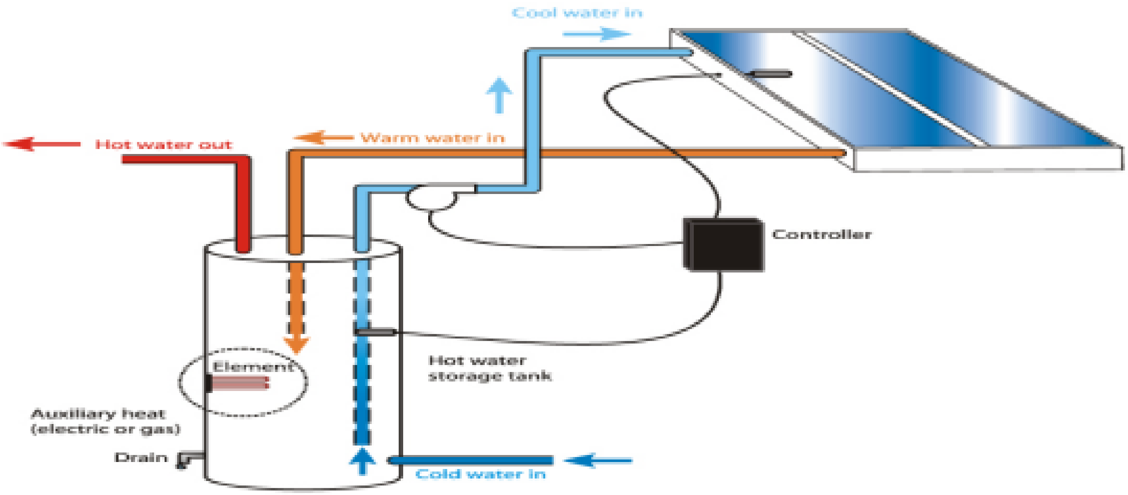


Fig. 4: Active open loop system Source: [8]

ii. **Closed-Loop Active Systems:** As shown in Figure 5, closed-loop systems circulate a heat-transfer fluid, typically a glycol-water antifreeze mixture, through the collectors instead of potable water. Heat exchangers are then used to transfer thermal energy from this fluid to the service water stored in the tank. The heat exchanger may be located either internally within the storage tank or externally as a separate unit. Due to their freeze protection capability, closed-loop glycol systems are widely adopted in regions that experience prolonged periods of sub-zero temperatures [11].

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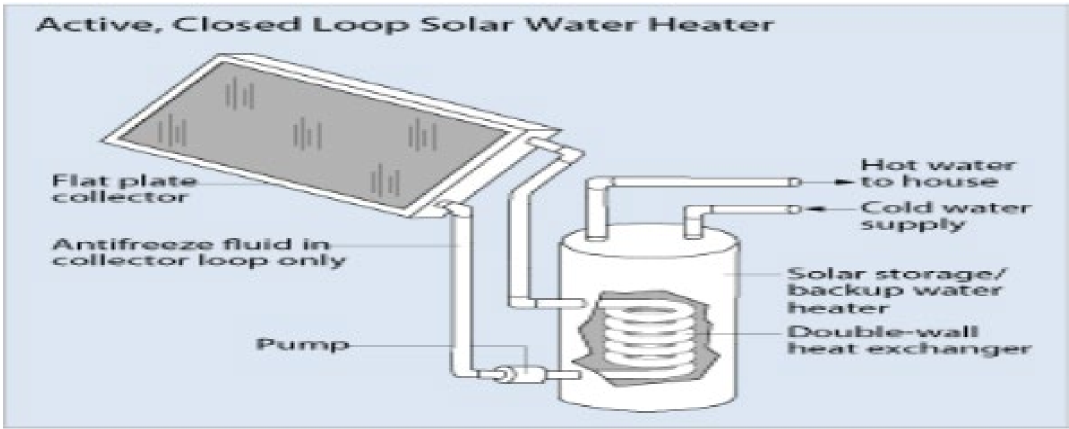


Fig. 5: Active closed loop system Source: [8]

II. **Passive Solar Water Heating System:** Passive systems are characterized by their simplicity and high reliability. However, these advantages come with certain limitations. The systems are inflexible because they require the hot water storage tank or heat exchanger to be located above the solar collectors. They are also difficult to integrate with other alternative energy technologies [12]. Passive systems depend on natural circulation driven by gravity and the density difference that occurs when water is heated. They are generally less expensive and easier to construct and install than active systems, but their thermal efficiency is often lower. As a result, they are best suited for domestic applications and for load demands that are low to medium [6] and [13]. Passive systems can operate as either open-loop direct or closed-loop indirect configurations. In open-loop systems, potable water circulates directly through the collector. In closed-loop systems, a heat-transfer fluid absorbs solar energy in the collector and transfers it to the service water in the storage tank via a heat exchanger. The natural circulation flow rate is primarily governed by the level of solar insolation. The two most common types of passive systems are integral-collector storage systems and thermosyphon systems. The open-loop and closed-loop classifications, however, apply only to thermosyphon systems [8].

i. **The Integrated Collector Storage System:** As illustrated in Figure 6, batch systems, also known as integral collector storage systems, are simple passive systems. They consist of one or more storage tanks housed in an insulated enclosure with a glazed surface facing the sun. In this design, solar collection and thermal storage are combined into a single compact unit [12]. These systems were the first type of solar water heater to be commercially produced and are available in various shapes and configurations. They typically comprise one or more black-painted tanks or tubes placed within an insulated, glazed box. Cold water enters the collector-storage unit where it is preheated by solar radiation before flowing to a conventional backup water heater. Due to the lack of inherent protection against freezing and overheating, integral collector storage systems are best suited for moderate climates where ambient temperatures rarely fall to 0 $^{o}$C [14].

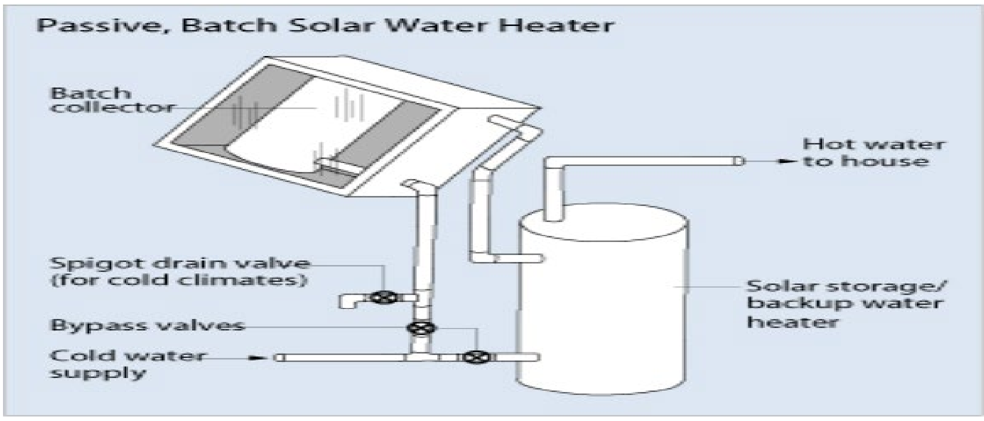


Fig. 6: Passive batch solar water system Source: [8]

ii. **The Thermosyphon Solar Hot Water Systems:** In 1909, William Bailey patented the first thermosyphon-type solar water heating system, a design that significantly advanced SWHS technology. The system positions the storage tank above the solar collector to enable natural circulation. As solar radiation heats the water in the collector, its density decreases and it rises into the top of the tank. At the same time, cooler, denser water flows from the bottom of the tank into the collector to replace it, thereby establishing a continuous thermosyphon loop. Since its introduction, SWHS technology has gained widespread adoption globally and

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now accounts for approximately 80% of the worldwide solar thermal market [7]. A schematic diagram of a thermosyphon system is presented in Figure 7. Thermosyphon systems are broadly classified into two types: single-phase systems, which operate without phase change materials, and two-phase systems, which utilize phase change materials [7].

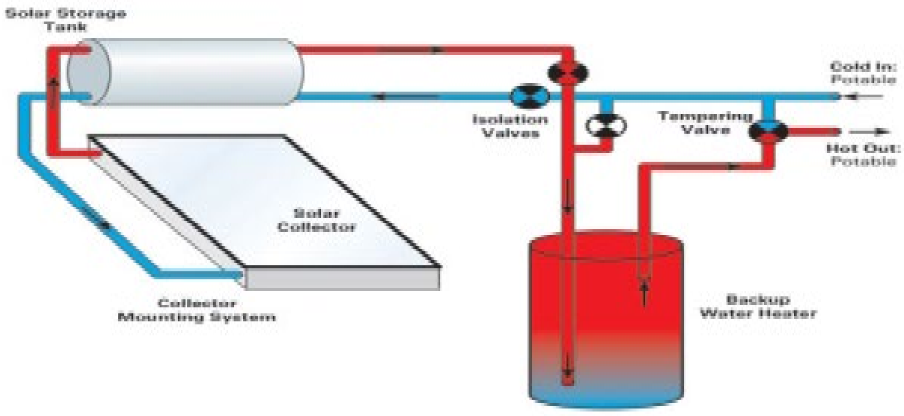



Fig. 7: Thermosyphon SWHS Source: [7]

a. **Two Phase Thermosyphon System:** This type of solar water heating system belongs to the indirect-loop category. It employs a phase-change material, typically a refrigerant, to transfer heat between the solar collector and the service water. Heat transfer relies on the latent heat of vaporization during condensation. Within the collector, the heat-transfer fluid absorbs solar energy and vaporizes. The vapor rises by buoyancy to the heat exchanger in the storage tank, where it condenses and releases its latent heat to the service water. The condensed liquid then returns to the collector by gravity to repeat the cycle [15]. Because these systems use refrigerants as the working fluid, they require a sealed circuit that must remain free of moisture and non-condensable gases such as atmospheric air to maintain performance and prevent corrosion.

**b. Single Phase Thermosyphon System:** In single-phase thermosyphon systems, the service water itself circulates directly between the solar collector and a storage tank positioned above the collector. These systems therefore operate as direct-loop configurations. Heat transfer occurs through natural convection. As water in the collector is heated, its density decreases and buoyancy forces drive it upward into the storage tank. Cooler water from the tank simultaneously flows downward into the collector, establishing a continuous circulation loop. Due to their simplicity and reliance on direct water circulation, single-phase thermosyphon systems are most suitable for applications with low hot water demand and in regions with mild climates where freezing is not a concern [13].

### 2.2.2 Classification of SWHS According to Type of Solar Collector

Solar collectors are the primary component of solar heating systems. Their function is to absorb solar radiation, convert it into thermal energy, and transfer that heat to a working fluid such as water, air, or a solar heat-transfer fluid. The three most widely used types of solar collectors are flat-plate collectors, evacuated-tube collectors, and parabolic trough collectors [6]. The thermal performance of a collector is influenced by several factors, including ambient weather conditions, collector design, and installation orientation. Collectors operate by capturing the sun's electromagnetic radiation and converting it into usable heat energy [16].

I. **Flat Plate Collector:** Flat-plate collectors are the most widely used type for residential water heating and space heating applications. Their popularity is due to low cost, simple design, and ease of construction. They are primarily used for low- and medium-temperature applications, but higher temperature or load requirements can be met by connecting multiple collectors in series [9]. As shown in Figure 8, a typical flat-plate collector consists of an absorber plate, one or more transparent cover sheets, and an insulated housing. The absorber is usually made of a high-thermal-conductivity metal such as copper, aluminum, or steel, and incorporates integral tubes or attached ducts for the working fluid. The absorber surface is coated to maximize solar absorptance and, in some cases, to minimize thermal emittance. The insulated box provides structural support, sealing, and reduces heat loss from the back and sides. The transparent cover, or glazing, transmits solar radiation to the absorber while reducing convective heat loss from the absorber surface [17]. Heat losses still occur due to temperature differences between the absorber and ambient air. Convective losses depend on the collector tilt angle and the spacing between the glazing and absorber plate, while radiative losses result from heat exchange between the absorber and the surroundings [18]. The absorber plate spans the full aperture area and must perform three functions: absorb the maximum solar irradiance, transfer the captured heat to the working fluid with minimal temperature difference, and minimize heat loss to the environment. To achieve high absorptance of short-wavelength solar radiation, the plate is coated with selective surfaces such as black paint or plating. Such coatings can absorb over 95% of incident solar radiation. To reduce re-radiation in the long-wavelength infrared, selective coatings are also designed to have low emittance [19]. Tube spacing is critical to performance. If tubes are spaced too far apart, the plate temperature midway between them drops significantly, reducing efficiency. One or more glazing layers are used to suppress convection above the absorber and protect the collector interior from dirt, moisture, and insects. Collector housings may be constructed from metal, plastic, or wood and must be well sealed to prevent heat loss [20].

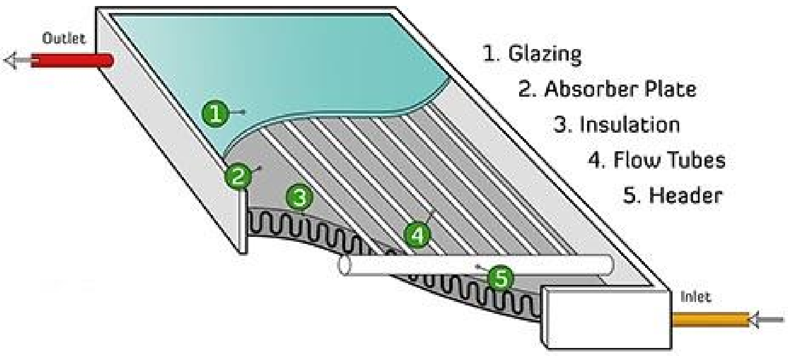



Fig. 8: Schematic diagram of flate plate collector Source: [7]

II. **Evacuated Tube Solar Collectors:** While most direct and indirect active systems utilize flat-plate collectors, some applications employ evacuated-tube collectors. These collectors are primarily used in industrial and commercial systems where delivery temperatures up to 100°C are required. As illustrated in Figure 9, an evacuated-tube collector consists of parallel rows of modular transparent glass tubes. The number of tubes can be increased or decreased to match hot water demand. Each tube contains an outer glass tube and an inner metal absorber tube with an attached fin. The fin is coated with a selective surface that maximizes solar absorption while minimizing thermal emission. The annular space between the two glass tubes is evacuated to form a vacuum, which virtually eliminates conductive and convective heat losses [16]. Due to these low heat losses, evacuated-tube systems perform better than flat-plate collectors at low ambient temperatures and are slightly more efficient overall. However, they are also more expensive. The unit area cost is approximately twice that of flat-plate collectors [13]. Although conductive and convective losses are essentially eliminated in a vacuum, some radiative heat loss still occurs as heat is transferred from the warmer absorber to the cooler outer tube. This loss is relatively small compared to the useful heat gained by the heat-transfer fluid [21].

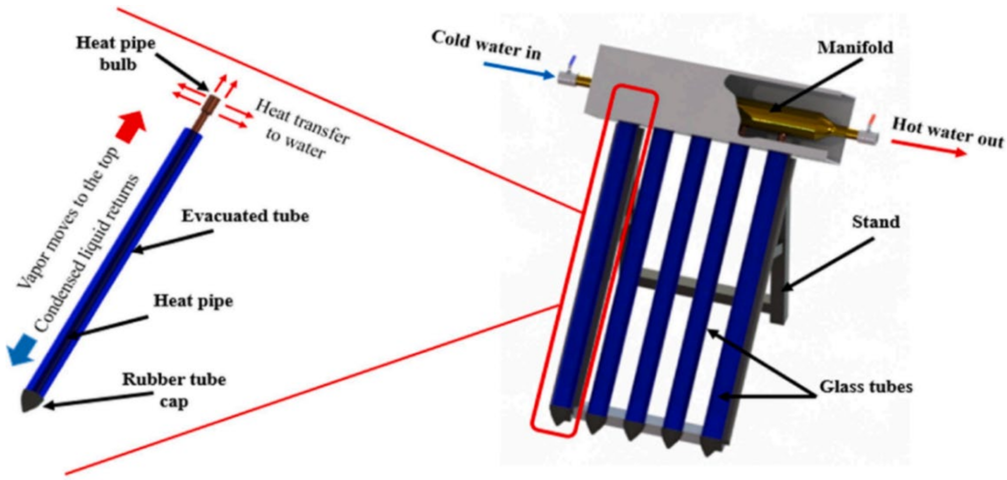



Fig. 9: Evacuated tube solar collector Source: [7]

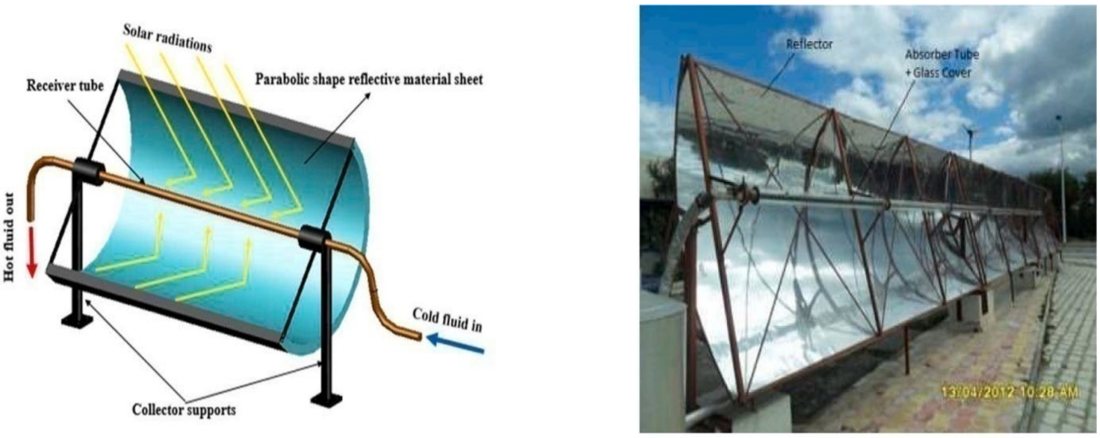
[7] Compared flat plate collectors with evacuated tube solar collectors and makes the following recommendations:

a. Performance: Flat-plate collectors generally deliver better year-round performance.

b. Efficiency: Flat-plate collectors are most effective at providing the temperatures required for typical domestic hot water applications.
c. Cost and Value: Flat-plate collectors are less expensive and provide more energy per unit cost than evacuated tubes.
d. Cold Weather Performance: Contrary to common belief, vacuum tubes hold no clear advantage in snowy conditions because snow accumulation on the tubes reduces performance.
e. Installation: Evacuated-tube collectors require more time to assemble, whereas flat-plate collectors are heavier and require more effort to lift onto the roof.
f. Durability: Evacuated tubes are more fragile and generally require more frequent maintenance.

However, high-quality evacuated-tube collectors can outperform flat-plate collectors in cold climates. Because they rely primarily on incident solar radiation rather than ambient air temperature, they are less affected by wind and can efficiently absorb diffuse radiation under cloudy conditions. Their performance also remains more consistent between summer and winter for the same irradiance levels. In contrast, in extremely hot climates, flat-plate collectors are usually the more cost-effective option [16].

III. **Parabolic Trough Collectors:** As illustrated in Figure 10, a parabolic trough collector employs a linear parabolic reflector to concentrate direct solar radiation onto a receiver tube positioned along the trough's focal line [8]. The collector uses single-axis tracking to follow the sun from east to west throughout the day. Mechanical drives rotate the troughs slowly to maintain continuous focus of reflected sunlight on the receiver. A heat-transfer fluid circulating through the receiver tube is heated to temperatures between 300$^{o}$C and 400$^{o}$C. The heated fluid is then transported to a central power block where it passes through heat exchangers to generate high-pressure superheated steam. This steam drives a conventional steam turbine-generator to produce electricity [22]. To ensure dispatchability, most operating solar trough plants are equipped with gas-fired backup heaters. These allow electricity generation during periods of low irradiance, such as cloudy conditions or at night [23].




(a) (b)

Fig. 10: Parabolic trough collector Source: [7]

**2.3 The Working Principles of Solar Water Heating System**

A solar water heating system is an assembly of components and subsystems designed to capture solar energy and convert it into thermal energy for domestic hot water supply. As a renewable energy technology, it has been deployed in many countries worldwide. Effective system design requires proper sizing of components based on available solar resources and hot water demand [24]. The use of solar energy for water heating dates back to the late 1800s, when simple exposed water tanks were used on farms and ranches in the southwestern United States. Widespread adoption occurred in the mid-20th century, driven by rising conventional energy costs and growing environmental concerns. With continued volatility in fossil fuel prices and the urgent need for environmental protection, solar energy remains a promising source for water heating [1]. The basic operating principle involves solar collectors, typically mounted on rooftops, absorbing solar radiation on a dark surface. Part of the absorbed energy is then transferred to water stored in an insulated tank. During periods of low solar availability, such as winter, auxiliary or "booster" heating using electricity, gas, or a wet-back system is used to maintain the required water temperature. Although solar water heating systems vary in design and configuration, all systems perform three fundamental functions: collect solar heat, transfer it to the water supply, and store the heated water until needed [16].

### 2.4 Components of Solar Water Heating System

Solar water heating systems have components for heat collection, heat storage, heat delivery and freeze protection. Active systems need controls for pump operation and valves for safety and proper operation. Passive systems utilize many of the same components but in some cases for different reasons. Typically, there are three primary components: the solar collector, storage tank, and heat transfer fluid. However, depending on the specific SWHS configuration, additional elements may be included such as piping units, heat exchangers, pumps, Storage Tank Insulation, Heat Transfer Fluid (HTF), Tempering Valve, Isolation Valve, Expansion Tank, Controller, and auxiliary heating units [14].

## 3.0 Advanced Research in Solar Water Heating System

### 3.1 Concept of Modelling and Simulation of Solar Water Heating System

Modeling and simulation is the process of developing a conceptual representation of a system and using it to conduct experiments. The goal is to understand system performance and to evaluate alternative design options, management strategies, and decision-making scenarios based on simulation results [25]. This approach reduces the time, cost, and risk associated with full-scale physical testing. For a model to be credible, it must be both verified and validated. Verification addresses the mathematical correctness of the model, ensuring that the equations are solved accurately. Validation addresses the physical accuracy of the model, ensuring that it correctly represents the real system behavior. Together, they provide evidence of a model's correctness and applicability for a specific scenario [26]. A simplified representation of the modeling and simulation process is shown in Figure 11.

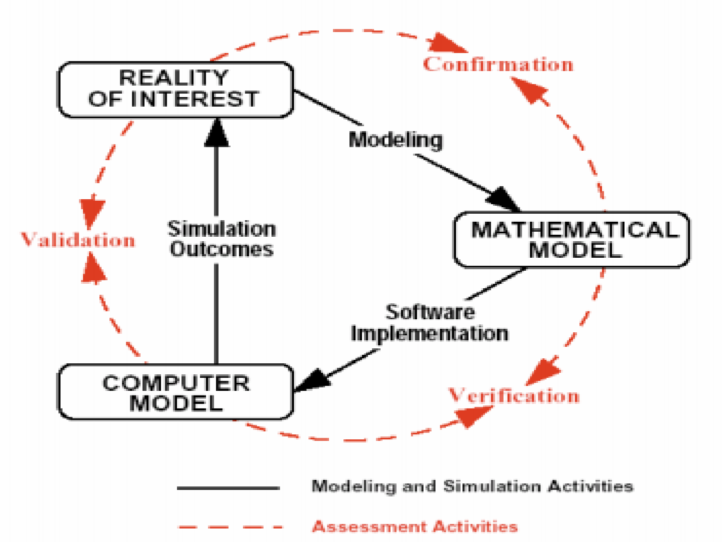



Fig. 11: Model verification and validation process Source: [26]

Before reviewing individual studies, it is useful to distinguish the terminology that underlies model-based engineering analysis. The Reality of Interest denotes the actual physical system or engineering problem under study. To analyze this reality, researchers construct a Mathematical Model, comprising a conceptual framework, governing equations, and the input parameters needed to define the system's behavior. When this mathematical model is translated into a numerical form suitable for computation including discretization schemes, solution algorithms, and other numerical settings the result is termed a Computer Model. Modeling, then, is the exercise of isolating the essential characteristics of the Reality of Interest and choosing suitable mathematical simplifications to capture them. The overall correctness of this process is judged through Confirmation, which is further divided into two complementary checks: Verification, which searches for and removes errors within the computer implementation, and Validation, which tests how closely the simulated output matches experimental measurements [26]. Two statistical indicators are commonly used to quantify this experimental–simulation agreement: The Coefficient of Variation of the Root Mean Square Error, CV (RMSE), and the Mean Bias Error, MBE [27]. Building on this framework, several researchers have used simulation software to model solar water heating performance before physical deployment. [10] carried out a numerical study of an active solar water heater intended to supply 90 °C domestic hot water using Typical Meteorological Year (TMY2) data for Maiduguri. Using TRNSYS 16, the hourly thermal behavior of the system was evaluated; representative days were extracted from the monthly-averaged demand profile, with August adopted as the design month. The results showed that a 2.04 $m^2$ collector, operating at an inlet flow of 120 kg/h and tilted at 12°, could supply 0.1 $m^3$ of hot water daily at the target temperature. Validation, performed through the Nash–Sutcliffe Efficiency and RMSE, produced temperature errors of 1.6 °C (ambient) and 3.6 °C (storage tank), corresponding to prediction accuracies of 82%

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and 96%. The same study found that riser-header collectors outperformed serpentine designs during early-morning hours across the months examined.

A different simulation effort by [28] examined the thermodynamic, environmental, and economic behavior of a hybrid solar–biomass system supplying 60 °C domestic hot water and underfloor space heating for a Hammam facility in Marrakesh. The configuration combined small pellet-fired boilers with three collector types evacuated tube, flat plate, and parabolic trough and the biomass subsystem was validated in TRNSYS against measured data before being compared to the optimized hybrid configurations across energy, exergy, environmental, and cost metrics. Minimizing the Levelized Cost of Heat (LCOH) required collector areas of 300 m² (parabolic trough), 224 m² (flat plate), and 204 m² (evacuated tube), giving LCOH values of $0.0755/kWh, $0.0696/kWh, and $0.0642/kWh respectively. The evacuated-tube configuration was identified as most favorable, reaching a 57% solar fraction, $0.509M in lifetime savings, 40% energy and 3.9% exergy efficiency, and a 4.9-year payback for an annual load of 533 MWh, while avoiding roughly 656 tons of $CO_2$ per year.

Separately, [29] built a simplified mathematical model of a hybrid solar–electric water heater intended for direct implementation on embedded hardware without heavy computational demands, supported by a data-logging setup for performance monitoring. Averaged weekday figures included 225.03 L of hot water drawn, 5.25 kWh of thermal energy delivered, 1.52 kWh of electricity consumed, and a COP of 3.50, alongside 579.67 W/m² of solar radiation, 23.58 °C ambient temperature, a 0.52 solar fraction, and an energy factor of 4.02. A regression model built to predict the energy factor achieved $R^2$ values of 0.952 (training) and 0.935 (validation), indicating strong predictive reliability that could aid homeowners, utilities, and policymakers in assessing hybrid system adoption.

[30] took a broader modeling approach, developing four distinct thermal electrical models unglazed PV/T, glazed PV/T, PV-only, and flat-plate thermal collectors to enable long-run simulation and optimization. Running these models across a wide operating envelope revealed that flow rate, temperature, radiation, and wind speed all strongly shaped system performance. Coupling TRNSYS with the NSGA-II optimization algorithm allowed a full-year, multi-objective optimization of a PV/T domestic hot water system, generating a Pareto front balancing life-cycle savings against primary energy-saving efficiency. Along this front, mass flow rates ranged from 0.0085 to 0.011 kg/s, while tank volumes for a 2 m² glazed PV/T collector spanned 99.5–218.6 L with roughly even distribution.

[31], meanwhile, extended a standard electric water heater model to incorporate solar input in a deliberately simplified form, adopting justified assumptions such as constant ambient air temperature to preserve accuracy while limiting complexity. This work targeted load-management and forecasting applications for hybrid solar–electric systems, and the resulting model ran efficiently on CompactRIO hardware with low memory and time overhead. The authors suggested that small-scale experimental datasets could subsequently be used to validate the model further. In a related design-oriented study, [32] examined solar water heating for a detached residence in St. John's, Newfoundland, using the SAM and HOMER platforms to estimate hot water consumption and system cost, concluding that pairing solar water heating with space heating offers an effective way to meet residential energy demand.

Focusing on the Nigerian context, [14] investigated solar-based water heating for Akure, developing a model to identify the main factors governing system efficiency. Thermosyphon systems were highlighted as best suited to Nigeria's climate, and the analysis linked collector efficiency and gross area to volumetric flow, showing that efficiency gains and larger collector areas both raise the volume of water heated per unit time. [33] Took a comparative simulation approach, using TRNSYS to model hybrid PV/T systems — both thermosyphon (passive) and pumped (active) built from polycrystalline and amorphous silicon modules paired with water-extraction units. Testing spanned three latitudes (Nicosia 35°, Athens 38°, Madison 43°) and found that the combined thermal-and-electrical output improved the systems' economic case, particularly where both hot water and electricity are simultaneously required.

### 3.2 Prototype Developed and Field-Tested Solar Water Heating System

Beyond simulation, numerous studies have built and tested physical prototypes toward commercialization. [34] Improved the thermal performance of a solar water heater under Iraqi conditions by integrating heat-storing porous media into the storage tank, testing the design in Tikrit with a circulation flow of 0.016 kg/s and a tank thermal load of 0.0066 kg/s across two configurations with and without solar reflectors. The configuration combining porous media with reflectors reached a peak daily efficiency of 36.40%, versus 32.21% without reflectors, and this outcome compared favorably against earlier published designs. Motivated by similarly demanding conditions, [22] built and tested a thermosyphon-based solar heater in Nsanke village from locally sourced materials, using two 1.68 m² flat-plate collectors each with a copper-tube absorber under 4 mm glass connected in series to a nested double-barrel insulated tank. The trapped radiation raised absorber temperature, and the finished system could raise water from 23 °C to at least 51 °C on clear days, supporting its use as a renewable resource for the village and its surroundings.

On the Covenant University campus, [35] developed a microcontroller-managed active solar water heater that used a PV powered DC pump for circulation, with an auxiliary electric heater engaged only when solar input was insufficient. The collector reached a peak design efficiency of 79.94% and an expected lifetime output of 98,225 kWh. Although the payback period was relatively long at 15 years, the system's unit energy cost of $0.01/kWh compared favorably to the $0.18/kWh grid rate, supporting its economic case despite the slow payback. In Wum, [13] designed a fully automatic active system to supply 500 L of 70 °C hot water daily, drawing solar data from the PVGIS database and building the controller logic in Proteus around an Arduino platform. After determining an optimum collector tilt of 11° (yielding 432 W/m² average irradiance), the analysis found an annual thermal efficiency of 55.49%; simulation further showed the pump and auxiliary heater consuming 4.5 kWh and 2.075 kWh respectively while delivering 26.187 kWh to raise water from 25 °C to 70 °C daily.

Other prototyping work has emphasized affordability using local materials. [12] Fabricated an indirect active solar heater following a broad review of existing designs, prioritizing low-cost, locally available construction methods and considering the resulting social, economic, and environmental implications. In Ogun State, [19] sized a system around the state's average solar radiation (4.775 kWh/m²), comparing lagged and unlagged storage tanks across a range of collector tilts (2.5°–20°): average inlet/outlet temperatures were 27.8 °C/60.1 °C for the unlagged tank and 28.3 °C/63.0 °C for the lagged version, with the system reaching 72.5% efficiency and saving 2.798 kW. [17] Built and tested a prototype with a piping network, storage vessel, and backup heater, recording seasonal thermal conversion efficiencies of 29.24% (summer), 14.75% (winter), and 15.53% (rainy season). [23] designed a combined domestic hot water and space heating system with thermal storage for a single-family home, sizing an 18 m² collector array and 31 m³ tank (area-to-volume ratio 1.72); solar coverage reached 32% for space heating and 59% for hot water, with 51% average collector efficiency, and combined coverage of both loads reached 100% matching earlier reported outcomes and supporting the system's viability as a complete heating solution.

Experimental prototypes have also examined collector geometry directly. [36] tested a 1.83 m × 1.22 m × 0.1 m flat-plate collector with a 0.5 mm black copper absorber and clear glazing, finding that under 700 W/m² radiation it could heat 60 L of water from 15 °C to 45 °C within 70 minutes; the study also linked the collector efficiency factor F' directly to absorber properties and inversely to tube spacing. Using a similarly constructed thermosyphon system with locally sourced materials, [1] recorded peak values of 55 °C outlet temperature, 51 °C collector temperature, and 1,480 W/m² insolation, reinforcing the case for solar heaters in high-irradiance regions. Addressing Nigeria's unreliable grid supply specifically, [37] built a portable thermosyphon heater with a 36 L insulated tank, serpentine flow channel, and single-glazed collector, tested across six days spanning the late rainy and dry seasons at a flow rate of 0.15 L/min. Outlet temperatures reached 65 °C during the rainy-season tests and 79.3 °C during the dry season (alongside a peak irradiance of 940 W/m² and 68.19% efficiency), confirming stronger performance under higher irradiance.

### 3.3 Broader Assessments on Solar Water Heating System

Complementing the design and modeling literature, [7] compiled a broad overview of solar water heating components, classifications, and trade-offs, paired with an economic and environmental case study across several building types in Lebanon homes, schools, restaurants, hotels, and gyms to estimate savings relative to electric heating and the associated payback periods and $CO_2$ reductions. At high utilization rates (Pr = 0.9), the estimated payback periods were 14.2 years (homes), 4.6 years (schools), 9.2 years (restaurants), 4.4 years (hotels), and 5.3 years (gyms), with corresponding annual per-unit $CO_2$ reductions of 0.16, 0.016, 0.04, 0.37, and 0.11 tons respectively — demonstrating that heavier reliance on solar water heating shortens payback and cuts emissions in tandem. A separate review, also attributed to [7], compared passive and active configurations for domestic and industrial use: active systems, while costlier and more complex, generally deliver higher efficiency and suit large loads or situations where the collector must sit apart from the storage tank, whereas passive systems remain cheaper, simpler to install, and best suited to low-to-medium domestic loads; the review also discussed field experience and the economic barriers limiting wider adoption.

[38] Reviewed a wider set of configurations flat-plate and concentrating collectors, integrated collector-storage units, PV/T-combined heaters, solar-assisted heat-pump systems, and phase-change-material heaters — assessing them on thermal performance, cost, and energy/exergy efficiency. The review concluded that performance gains typically come from higher flow rates and steeper tilt angles, altered collector geometry or count, textured or electro-deposited reflective coatings, corrugated or specially coated absorbers, turbulence-enhancing features, conductive fluids or nanofluids, and improved tank design and insulation — all of which raise heat-transfer area, thermal conductivity, Reynolds/Nusselt numbers, and overall energy and exergy efficiency. Evacuated-tube designs were found to reach higher temperatures than flat collectors, particularly with active circulation and heat-pipe integration, while concentrating collectors achieved the highest temperatures overall, especially with rotating mirror concentrators; combining any of these with storage, phase-change materials, or heat pumps further improved performance relative to conventional designs.

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Several narrower studies examined how orientation and material choices affect output. [39] Found that increasing a collector's tilt raises outlet temperature but reduces flow rate, concluding that a properly balanced inclination is needed to secure both adequate temperature and flow. [40] Similarly reported that performance depends heavily on orientation toward the sun, system dimensions, active-versus-passive design, absorber material and thickness, and pipe shape and finish, testing a square-section pipe (0.5" × 0.5", 1 m long) fitted with a K-type thermocouple and recording a peak outlet temperature of 49 °C. [41] Diagnosed and corrected a circulation fault that was suppressing efficiency below expectations: after resetting the collector tilt to match local latitude and revising the flow layout, outlet temperature and thermal efficiency rose to 75 °C and 81% respectively.

### 3.4 Solar Water Heating for Healthcare Facilities

Hospitals typically direct about 15% of their water use to non-domestic purposes and 85% to domestic use, depending on facility type and scale [42]. Where site-specific hot water data are unavailable, standard estimates are commonly substituted: the U.S. National Renewable Energy Laboratory places hospital demand at 52.0 gallons per day [37], while [42] cites 18 gallons per person per day, and [3] estimates 55 liters per bed per day at 60 °C. Addressing this demand through waste-heat recovery, [43] designed and analyzed a shell-and-tube heat exchanger to capture flue-gas heat from an incinerator for water heating at Jimma University Referral Hospital in Ethiopia, using the hospital's daily hot water load and heating energy requirement largely sourced from incinerated administrative and clinical waste as design inputs. The resulting design recovered 475.25 kWh per day, equivalent to a saving of 256.63 Ethiopian Birr daily.

A solar-based alternative was proposed by [2] for Sheikh Muhammad Jidda General Hospital in Fagge, Kano, where T*Sol Pro 5.5 (R6) software was used to model thermal and economic performance under the site's annual irradiation of 2,201 kWh/m². For a daily hot water demand of 5.59 m³, the software specified 31 flat-plate collectors (31 m² total area) tilted 12.05° south, three storage tanks totaling 4.35 m³, and an auxiliary heater; the initial investment of ₦5,586,955 was projected to total ₦16,603,675 over a 20-year lifespan while generating ₦98,458,560 in lifecycle savings, at a solar energy cost of ₦43.2/kWh and a 4.4-year payback. With a 50% design efficiency, 32.92 m² collector area, and 4.4 m³ tank volume, the system was expected to reach a 75% annual solar fraction (37,887 kWh solar against 12,551 kWh electricity, at 56% operating efficiency) while avoiding 29,685 kg of $CO_2$ emissions. The study concluded that, paired with auxiliary heating, the design could meet most of the hospital's hot water needs and remained financially sound, citing a net present value of ₦7,982,640, an internal rate of return of 51.55%, and the same 4.4-year payback.

## 4.0 Conclusion

Solar energy has been applied technically since the 17th century, with solar thermal systems in practical use since the 1920s, and the case for expanding solar water heating adoption remains strong. Active configurations whether open- or closed-loop generally outperform passive designs because pumps actively circulate the heat transfer fluid between collector and tank, whereas passive designs favor simplicity and reliability by relying on gravity and natural convection; the two dominant passive layouts are integral-collector-storage and thermosyphon systems, and only thermosyphon designs support both open- and closed-loop variants. The solar collector remains the central component of any such system, with flat-plate, evacuated-tube, and parabolic trough types most common; storage tanks and heat transfer fluid complete the core, while piping, heat exchangers, pumps, insulation, valves, expansion tanks, controllers, and auxiliary heaters may be added depending on configuration. Across the literature, both simulation-based modeling and physical prototyping have been used to anticipate performance and manage risk before full deployment, and separate work has quantified hospital hot water demand and explored incinerator flue-gas recovery as a complementary heating strategy in healthcare settings.

## 5.0 Directions for Further Work

Existing studies confirm solar energy's promise as a clean, effectively inexhaustible heating source and have explored diverse configurations standalone and hybrid, passive and active for homes, clinics, and other facilities. Even so, several gaps remain unaddressed: no study has numerically or experimentally examined hybridizing solar heating with incinerator flue-gas recovery; no work has applied computational fluid dynamics to optimize such a hybrid system's performance; and research on deploying hybrid solar water heating specifically within clinical settings remains limited.

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