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Review Article

A review of water heating systems: A Focus on hybrid technologies prospect in Nigeria

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ABSTRACT

The rising energy demand necessitates a rapid transition to renewable energy and efficient technologies. The Nigerian household sector consumes enormous energy to meet domestic needs such as water heating. Furthermore, rising electricity costs hinders the commercial use of electric water heaters. As a result, energy users rely on conventional methods of heating water. In general, over-reliance on traditional water-heating systems have resulted in environmental degradation and public health crises. Adopting energy-efficient technologies may improve energy security, mitigate energy crises, reduce costs, and further optimize household energy consumption. This paper provides a comprehensive review of existing and emerging water-heating systems with a summary of recent innovations in water- heating systems. Various types of hybrid and renewable water heating systems, as well as their configurations, are examined. In addition, relevant studies on different water-heating technologies are reviewed and classified according to their contribution, study type, and technology. The review findings are well articulated, and policy recommendations for solar water heating systems are made. This review's findings identify research gaps in the hybrid water-heating technology in Nigeria. This survey provides insight into solar and hybrid solar systems as an alternative solution to fossil-fuel-based water heating systems.

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INTRODUCTION

Water is an inevitable domestic necessity. It is required for personal hygiene and household needs such as drinking, bathing, showering and washing. Unfortunately, in most developing countries, water heating is one of the most energy-intensive thermal applications, with high-energy costs.

Studies have shown that building energy consumption accounts for 42% of global energy demand, with water heating being one of the most common energy demands

Highlights

- The use of renewable energy sources in conjunction with electric and heat pump water heaters are identified and discussed
- The techno-economic evaluation of several water heating technologies is investigated.
- Solar and electric water heating systems' limitations and difficulties are addressed.
- The utilization of hybrid technology in water heating in Nigeria is highlighted.

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in residential buildings [1]. Nigeria is an energy-deficient country that relies primarily on conventional energy sources such as fossil fuels, coal, and firewood to meet its energy needs [2]. Gas-fired power generation currently accounts for 87.5% of total power generation in Nigeria [3]. As a result, the country is now at the forefront of greenhouse gas (GHG) emissions [4]. With 196 million people, the country's energy demand is increasing, and the power holding company of Nigeria (PHCN), Nigeria's main electricity provider, is now experiencing a greater energy deficit. Nigeria had 12.GW of installed on-grid power capacity in 2018, but only 40% of the country's energy was supplied. Energy demand in residential buildings has increased significantly to the point where it exceeds supply as a result of developments in building technology, population growth, and the pursuit of modern civilization. As a result, the country suffers from frequent power outages; thus, the costly fossil- fuel-based generators compensated for the power outages. [5]. Back-up generators are the second-largest electricity generation sources in the Nigerian energy market, accounting for approximately 8 TWh in 2010 and increasing to 19TWh by the end of 2020, with a further projected increase to about 21TWh in 2030 , as shown in Figure 1. Water heating equipment is one of the leading energy consumers by households in Nigeria, alongside cooking, cooling, and lighting. Generally, Various studies show that domestic water heating consumption varies by region with 19% in the USA [6], 29% in the UK [7], 25% in Australia, 29% in China [8], 40% in South Africa [9] etc. Although, no comprehensive data on domestic water heating consumption in Nigeria. The rapid increase in countries per capita indicates an improvement in citizens' well-being and consequently the largest energy demand. Furthermore, 70% of households depend on electric water heaters for domestic hot water, which adds unsustainable pressure on Nigeria's energy sector.

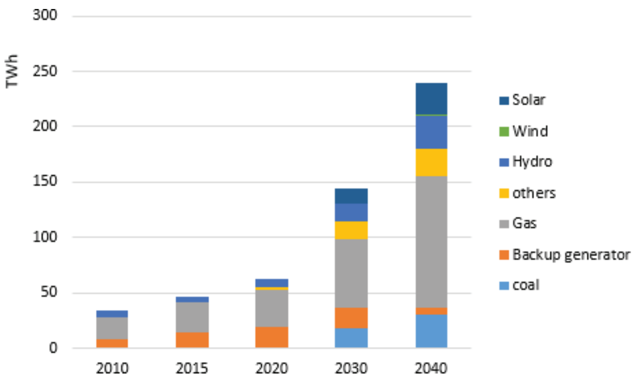

Figure 1. Nigeria electricity generation by technology 2010–2040 [10].

The recent increase in electricity prices by the national electricity regulatory commission (NERC) forced many energy consumers to rely on solid fuels for domestic needs. Consequently, Co_2 emissions and other high concentrations of pollutants have increased, negatively contributing to the global warming and climate change. Therefore, the federal government has encouraged the use of renewable energy sources and efficient water heating technologies in residential buildings in order to reduce reliance on fossil fuels and the resulting global climate crisis [11]. Buildings such as offices, hotels, hostels, and hospitals rely on solar water heaters (SWHs) to meet their thermal comfort and domestic needs. Furthermore, the federal government has launched a solar power project through the economic sustainability plan (ESP), with the goal of providing off-grid access to more than 6 million households. This means that,

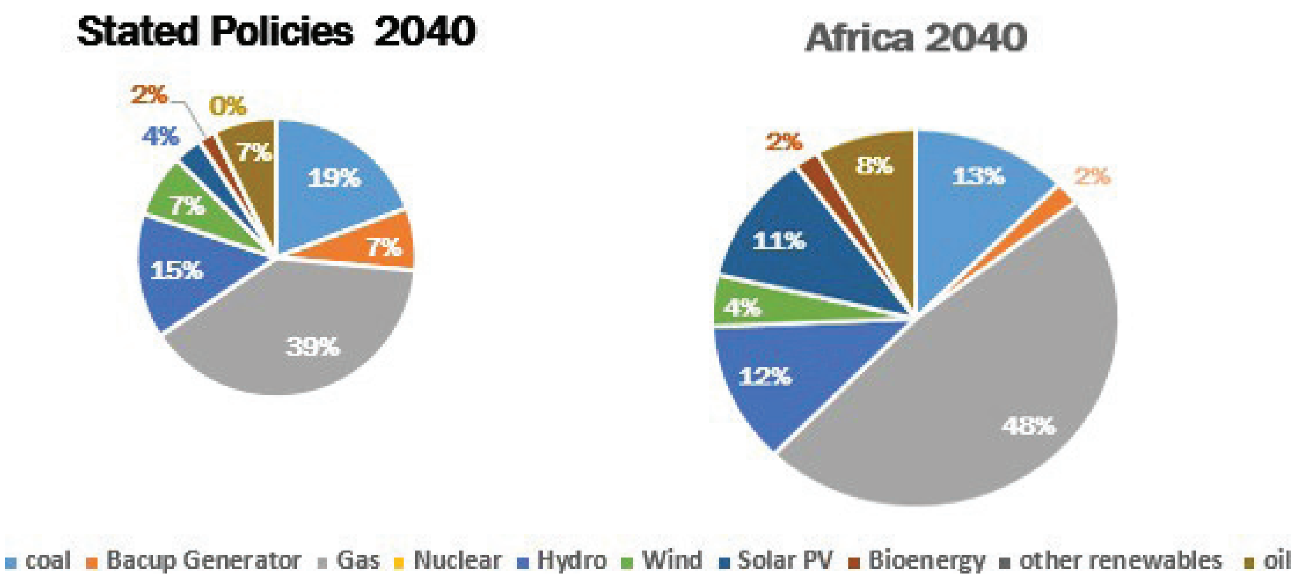

Figure 2. Electricity supply by type, source and scenario in sub-Saharan Africa 2040 [12].

Table 1. A Summary of Recent Literature review on Water Heating Systems in Nigeria

Author/year	Ref.	Collector type	Location	Highlights/Contribution
Agbo and Oparaku (2006)	[13]	[-]	[-]	The review identifies and recommends key policies, incentives and programmes to encourage large-scale deployment of the SWH.
Orovwode et al. (2014)	[14]	Flat plate collector (FPC)	Ogun	The Modified model shows an increase in inlet and outlet temperatures.
Fisayo et al. (2020)	[15]	[-]	[-]	The significance of a sustainable energy transition in Nigeria is highlighted. .
Ijemaru et al. (2014)	[16]	FPC	Akure	Experimental evaluation of SWH efficiency in terms of collector area and volumetric flow rate
Duvuna et al. (2019)	[17]	FPC	Bauchi	Presented a feasibility study of active flat solar collector.
Ogueke et al. (2009)	[18]	[-]	[-]	Survey of solar water heaters in terms of performance, uses, and applications.
Ikpakwu et al. (2017)	[19]	Parabolic trough collector (PTC)	Owerri	Experimental testing of concentrating parabolic trough collector SWH with tubular absorber for optimum solar irradiation.
Raji et al. (2020)	[20]	FPC	Maiduguri	Thermal performance analysis of active SWH

in addition to the stated policy scenario of a solar energy injection of approximately 22 TWh in 2040, the country may increase Africa's electricity supply capacity by 28 TWh through solar energy by 2040, as shown in Figure 2. As a result, households can reduce their electricity consumption and promote net-zero energy building.

Researchers and scholars in Nigeria have focused on the use of renewable energy in domestic heating applications over the years. Extensive experimental, numerical analysis, and review work in the areas of energy efficiency and solar applications in buildings, particularly for water heating, has been conducted. The studies on solar water heating systems in Nigeria are summarized in Table 1. The review, however, revealed the following research gaps: there has been little research into the use of concentrating collectors in water heating applications, the use of hybrid technology for water heating is rarely reported, the comparison of various water heating systems in terms of types, technology and cost has not been addressed, the use of renewable energy sources with other traditional fossil fuels for water heating is rarely reported, and the review of various water heating technologies has gone unnoticed. The main objective of this study is to provide a comprehensive review of various water heating technology in Nigeria with a focus on the types, principle, state-of the-art, use of collectors, hybrid technologies, and the future prospects of solar energy. Furthermore, to condense the content of the paper and clearly illustrate the main findings of various studies, summary tables of results for pertinent studies on the state-of-the-art on various water heating systems are highlighted in some cases. These studies are classified according to study type, technology, and contribution.

The novelties of this work are summarized as follows:

1. The current state of the art, hybrid technology prospects, progress on hybrid water heating technologies, barriers, and policy recommendations were highlighted.
2. Various hybrid water heating technologies were identified and discussed. The use of renewable energy sources such as photovoltaics, solar thermal collectors, wind energy, and fuel cells in conjunction with electric and heat pump water heaters was extensively discussed. Previous works on the application of water heating technologies, as well as their contributions and limitations, were highlighted.
3. An elaborate of solar water heater (SWH) technologies such as flat plate, evacuated tubes, and concentrating solar collectors was presented. Furthermore, the techno-economic assessment of various water heating technologies was explored.
4. The limitations and issues with solar and electric water heating technologies in domestic water heating applications were identified and discussed. The potential of hybrid technologies to address these issues and limitations was also highlighted.

This study aims to lay a solid foundation for future readers to find relevant information, specifically on the various types, hybrid prospects, and financial cost of water heating systems, as well as the issues, and limitations of solar water heating technologies in domestic applications. To the best of the author's knowledge, research on hybrid water heating technologies is rarely published, particularly in developing countries. Many existing studies and reviews focus on

SWH technology and its future prospect. The information presented in this paper will be a valuable resource for those interested in conducting research involving hybrid technology for water heating applications. Furthermore, this review paper summarizes several significant findings and proposes potential solutions that could significantly advance Africa's sustainable development goals, particularly in Nigeria, while also addressing the country's high energy consumption.

MATERIAL AND METHOD

Selection and Screening of Publications

The review strategy is structured in accordance with the PRISMA framework [21]. This entails conducting an electronic database search for recent and related publications on the keywords, with a focus on high impact factor and index citations. The initial data source is a collection of academic e-databases from Science Direct, Scopus, Web of Science, and PubMed. To identify key scientific literature, the search algorithms used the keywords "Water heating," "Energy," "Hybrid technology," "Heat pump," "Household," "Energy transition," "Hot water," and "Renewable." The document types are limited to journal articles, conference proceedings, conference papers and review papers. The search excluded all articles, conference papers, and review papers published in languages other than English. Further, the inclusion criteria is formulated based on the concept presented in Table 2. On the electronic databases Science Direct, Scopus, Web of Science, and PubMed, a total of 1,286 publications were sought, including 1,070 peer-reviewed journal articles and 214 conference papers. During the screening process, duplicate scientific articles, conference papers, and all papers published prior to 2000 were subsequently excluded. 530 journal articles and 180 conference papers were chosen further based on publication date and duplicate entry. In addition, 540 journal articles and 34 conference papers were reviewed based on title, keywords, and abstracts, and articles and conference papers that did not meet the inclusion criteria shown in Table 2 were excluded. A selection of 120 papers for review.

Table 2. Criteria for selection and exclusion

S/N	Search Scheme	Inclusion Criteria
1	Document type	Journal articles, Conference proceedings and papers and review papers
2	Language type	Publications in English language only
3	Text coverage	Online full text
4	Year of publication	Document published from 2000 to2022
5	Area of study	Energy and Buildings
6	Application	Paper addresses water heating systems, solar energy, heat pumps, hybrid technology, optimal control, energy efficiency, and solar applications
7	Research discipline	Energy and Environmental science
8	Standards	Emphasize on the impact factor

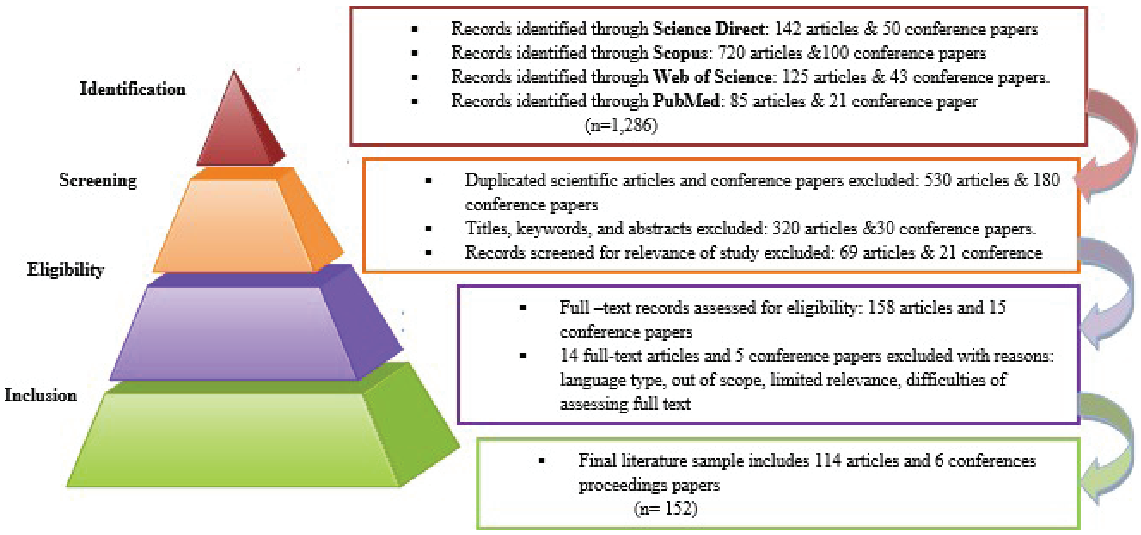

Figure 3. PRISMA review process schematic diagram (source: Authors, 2022).

This process resulted in the rejection of 330 papers (320 articles and 10 conference papers). 94 articles and 14 conference papers were removed after critical reading and assessing their relevance to the study. Furthermore, 158 full-text articles and 20 conference papers were evaluated for eligibility in accordance with the inclusion criteria shown in Table 2, and 16 full-text articles and 5 conference papers were eliminated for reasons such as document not reported in English, limited relevance, and difficulties in assessing full texts. This resulted in the final inclusion of 152 papers, including 142 articles and 10 conference papers. Figure 2 depicts the PRISMA review process schematic diagram.

Households Energy Consumption Pattern

One of the primary drivers of energy consumption in Nigeria is the household sector. Energy consumption in this sector has increased over the last two decades. It accounts for 78% of total energy consumption in 2018 [22]. Nigerian households' consumption is four times that of South African and her per capita electricity consumption is much lower when compared to neighboring countries [23]. Urban areas with electricity access rate of 44.9% in 2016 [24], are more energy- intensive than rural areas. Water heating is one of the most prevalent energy services in large cities, consuming a significant amount of energy. Hot water demand in such cities meet domestic needs such as bathing, drinking, showering, washing, and cooking. However, rural dwellers depend on hot water for cooking. Domestic hot water demand varies by household in Nigeria and it is affected by household income, occupant lifestyles, household size, weather, and thermal comfort desire. Urban dwellers have a high demand for water heating because of their income and desire for a comfortable standard of living. Most urban dwellers are middle-class households with a per capita income of 2790 USD and have an average household size of about 4.7 people. They make up about 32% of the population [25]. Based on the electrification rate, urban dwellers enjoy access to electricity than their counterparts in the rural areas. The electric resistance-based water heaters, such as electric kettles, electric stoves and electric boiling rings, are the most common technologies in middle-class households. However, hot water demand in this household category occurs at peak hours. More so, about 55% of electricity consumers are unmetered energy users [26] with high estimated bills. Some of these households engage in energy theft, while others who cannot afford electricity bills use solid fuel as alternatives. Rural dwellers are low-income households that account 51.9% of the population, with an average household size of five members. They practice energy-efficient farming, with the majority of their energy requirements directed toward cooking and crop preservation. Consequently, high hot water demand for cooking prompt residents to seek for firewood. Furthermore, domestic hot water consumption has increased significantly in the last 5 to 15 years. In local provinces, many residents boil water with kettles or pots to save cost. In addition, an unknown portion of the households uses sawdust, firewood, and biomass to heat water. Few opt for solar water heaters (SWHs) to meet their hot water demand.

REVIEW OF WATER HEATING SYSTEMS

Kerosene Water Heater (KWH)

In Nigerian households, the most common heat source is a kerosene heater primarily used for cooking and heating. In countries such as the United States, Japan, and Australia, they serve as a backup heat source for power outage. Kerosene water heater (KWH) serves two purposes: it burns fuel through a combustion process and provides thermal energy (heat) for household services such as cooking and water heating. A kerosene heater combines a wick, kerosene, and a burner housed on a fuel tank. The wick operates on the capillary action principle to ensure a continuous inflow of kerosene fuel. The passaging air and kerosene vapour through the burner burns, which generates heat. The knob functions as a thermal regulator, maintaining the thermal level by either increasing or decreasing the temperature. Kerosene heater demand rapidly increased because of rising electricity prices. However, the associated health risk with kerosene heating warrants global concern, particularly its contribution to the climate and health crises. Lam [27] used gas and kerosene heaters to study the effects of toxic pollutants like PM, Co, NOx, and So2 on the environment. Their findings proved that kerosene exposure to household users indoors causes respiratory ailments as well as chronic illnesses like cancer, asthma, and chronic obstructive pulmonary disease. [28], investigated the impact of wick-type kerosene heater emissions on the levels of Co, Co_2, NOx, and particle matter (PM.) in indoor air concentrations, which ranged from

0.02 to 10 micrometers. The study's findings show that using a kerosene heater in an uncontrolled kitchen environment can be hazardous, and they further recommend that the use be limited to lessen the users' health effects. [29], used porous media combustion (PMC) to conduct an energy and efficiency assessment of a kerosene stove. The use of four different fuel flow rates and air flow rates ranging from 60 to 80 lpm is the study's main focus. According to their experimental findings, conical burners have the highest energy efficiency at air flow rates between 120 and 130 lpm. Kimemia[30], investigated the impact of burns and fires on kerosene stoves. The study places a strong emphasis on the consequences of using defective stoves, and their findings demonstrate that users are more at risk for burns and fires when using defective kerosene stoves. [31], examined the impact of household air pollutants (HAP) on pregnant women in Nigeria. The emissions from the bio-ethanol-based stoves and those using kerosene were compared. Their study comes to the conclusion that use of bio-ethanol stoves has a tendency to reduce health-related risk compared to conventional kerosene stoves/heaters in

Nigerian pregnant women during the trimesters and exposure to HAP increases the health-risk of cardiovascular and prothromotic in those trimesters. [32], investigated the performance assessment of conventional cooking stove in Nigeria. It was noted that the three stoves' fuel usage, fuel cost, and cooking rate varied. Although the 3-stove uses less fuel than a kerosene stove, it has a much lower thermal efficiency.[33], compared the emissions from kerosene and bioethanol stoves. According to their research, bioethanol stoves exhibit greater thermal efficiency and fuel savings than kerosene. Figure 4 shows the different solar water heating systems.

Wood-Fueled Water Heater (WFHW)

Wood fuel is the source of energy for water heating and domestic cooking in Nigeria. It is a form of biomass that derives its energy source from firewood. Nigeria, a tropical country surrounded by large tracts of forests, gifted with diverse wood plantations. The rising cost of energy has prompted the widespread use of wood fuel as a primary heat source. Over 80 million tonnes of fuelwood, consumed annually in the country [34]. About 70% of the urban dwellers rely on this heating technology. Wood fueled water heaters (WFWHs) as shown in Figure 5a, are primitive and conventional heaters available as open-fire cook stoves/heaters for heating water. The major drawbacks of WFWH/stoves are their environmental and health effects and high heat loss. Therefore, as shown in Figure 5b, WFWHs have been improved to mitigate their limitations. Wood fueled water heater performance depends on the thermal properties of the wood material, the intensity of heat exposure, the moisture content of the wood, and the thermal thickness. In this system, wood is heated to 1100°F, converting chemical energy from the wood logs to thermal energy via a complex chemical reaction between the wood fuel and oxygen. The thermal decomposition of wood fuel increases as the temperature rises. The heater serves as a heat exchanger, transferring heat via conduction to a metal plate or pot placed on top of the heater while retaining the smoke.

Kuhe et al. [35], performed an economic analysis of a clay-based wood stove using cost and fuel savings as economic comparative metrics. It compares the clay stove to a three-stone stove as a baseline. Their findings show a significant improvement in terms of thermal efficiency, evaporation time, fuel consumption rate, and cost. Using emission factors, [36] investigated the impact of solid waste on wood

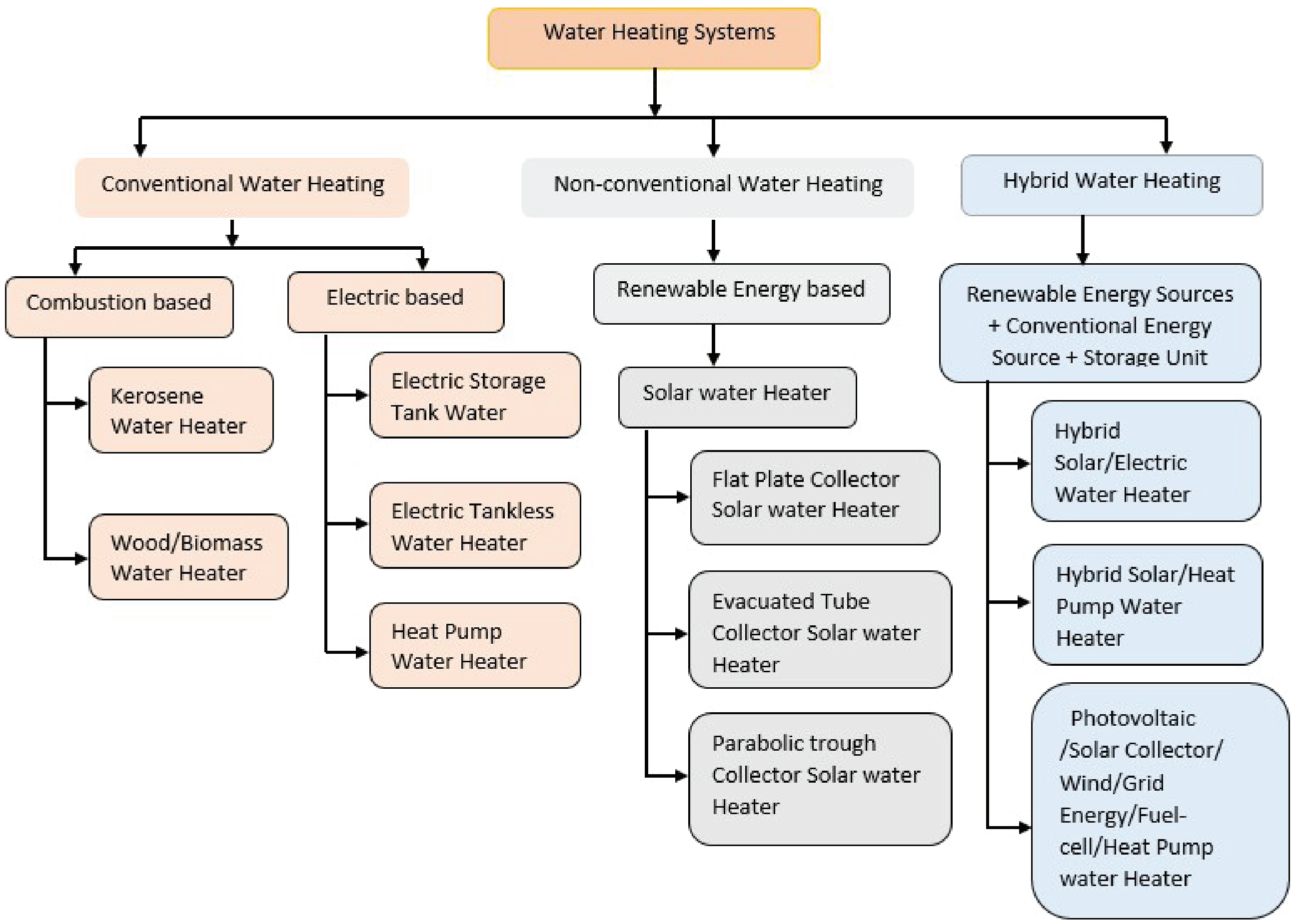

Figure 4. Summary of the different types of water heating systems.

a. Open Fire Water Heater   b. Improved Water Heater

Figure 5. Schematics of wood-fueled water heaters.

heaters. A total of 18 tests were carried out experimentally using waste materials such as waste firewood, municipal solid waste, and organic PMX, PCDD/F, HC, and PAH-S products. The findings indicate that there is a rising trend in the production of harmful pollutants from burning solid waste, and they also urge strict regulation of wood stove use. The dynamic simulation "TRNSY" was used by [37] to develop a mathematical model of wood pellet boilers and stoves. Although there was a clear correlation with the experimental data, additional model modifications were recommended. [38], reviewed the impact of wood stove emissions, with a focus on the high concentration of particle matter (PM) emissions that occur during the wood heating process. Further, recommends the implementation of strict regulations to reduce PM emission levels and enhance air quality. [39], investigated the effectiveness of wood pellet emissions using potassium chloride (Kcl). In the study, wood logs were compared under various circumstances, both with and without Kcl. The result reveals that wood logs exposed to Kcl emit large particles and emit fewer nano-sized particles than wood logs exposed to potassium chloride. Performance analyses of four stoves—metal-shield, metal-charcoal, clay-charcoal, and three-stone—were presented in [40] their findings indicate that the four wood stoves have various efficiency traits.

Clay charcoal uses less fuel than metal charcoal and has a longer cooking time. Metal shields are preferred for their lower fuel consumption rates.

Electric Storage Water Heater (ESWH*)*

The core dominant functions of an electric storage water heater are (1) to generate thermal energy via electricity for domestic hot water production, and (2) to retain hot water for later use. Its thermal storage potential makes it a preferred option in most residential households, especially in the cold provinces of Nigeria and other parts of the world. Electric storage water heater (ESWH) combines electric heating elements, a storage tank that serves as a hot water buffer, and temperature control thermostats. The ESWH operates on the energy conversion principle. The heating elements convert electrical energy into heat (thermal) energy, which then transfers to the surrounding water via conduction. As the process continues, the thermal level of the entire water mass within the storage tanks rises. A thermostat controls the heating elements by turning them on and off to maintain the user's desired set-point temperature. Figure 6a shows a typical ESWH, has two heating elements, one close to the top third of the tank near the hot water outlet and the other at the bottom near the cold-water inlet. Besides, electric storage water heater has one thermostat per heating element and the two heating elements interlocked, with the upper heating element having priority.

[42], developed an improved electric water heater and evaluated its efficiency in comparison to conventional heaters. In terms of discharge efficiency and energy consumption, the improved system outperforms the conventional ESTWH. [43], presented a fuzzy-based controller for electric heaters to reduce peak electricity consumption. [44], proposed an energy control algorithm to reduce heating resistance and peak energy demand. [45] , experimentally assessed the thermal properties of an ESTWH. Their research demonstrates that the tank pressure and heating energy have a significant impact on the heating time.[46], proposed an energy control scheme that reduces the energy

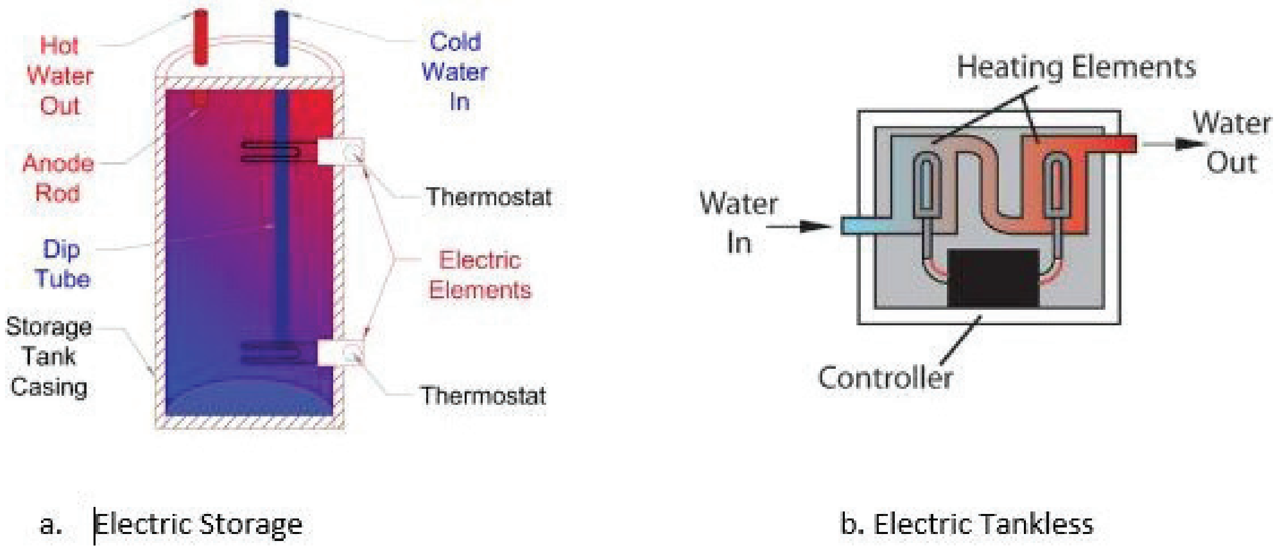

Figure 6. Schematics of e (a) electric storage tank water heater and (b) electric tankless water heater [41].

costs of electric-powered water heaters while also ensuring the users' comfort.

Electric Tankless Water Heater (ETWH)

Electric tankless water heater (ETWH) as shown in Figure 6b, is a tankless based water heater that provides instant access to hot water. ETWHs are increasing in popularity because of their high energy saving capability and instant water delivery on demand. It is more energy efficient than tank-based water heaters [47]. Electric tankless water heater, a demand-type water heater, only heated water on demand. Therefore, it eliminates the hot water storage tank and further minimizes standby loss [48]. Although it is suitable for any climates [49] but as a resistive based heating element, it consumes an enormous amount of electrical energy to meet the required hot water demand. The principal components of electric tankless water heaters are (1) electric heating elements that heat the inlet water via electricity, (2) the cold inlet valve controls the flow of cold water; (3) the hot water outlet valve controls the flow of hot water. (4) Thermistors serve as flow temperature measurement and feedback mechanisms and (5) a controller regulates hot water temperature by the user-defined temperature set point. Using energy consumption data, [50] investigated the energy assessment of three electric heaters. It was discovered that the efficiency of each heater differs depending on its insulation, resistance, and thermostat type and discussed the water sustainability and energy efficiency of electric tankless water heaters. [51], compared the effectiveness of ETWHs using different various control algorithms. The result shows that the hybrid control scheme performs better than model predictive control. Using LabVIEW [52], developed a simulation model of hybrid heating systems. The proposed model was compared to a conventional system, and the results show a significant reduction in energy consumption at low water demand.

Solar Water Heater (SWH)

Nigeria, among other African countries, receives abundant solar irradiation throughout the year. Approximately 5.5kWh/m^2 per day of solar irradiation is available year-round. Figure 6, shows the annual average daily global horizontal from 1994–2018 in Nigeria, indicated in kWh/m^2. Figure 7 reveals that Kano receives the highest average daily global irradiation. Other cities such as Onitsha and Lagos receive 4.43 kWh/m^2 and 4.42kWh/m^2, far below the total daily average of 5.5kWh/m^2 per day [53]. Annually, the daily total solar irradiation varies from 3.5kWh/m^2 per day to 7.0kWh/m^2 per day. The solar irradiation is evenly distributed across the country. The country has vast solar energy potential for water heating applications. Thus, there is a promising prospect for large-scale deployment of solar technology, such as solar water heaters, solar power plants, and stand-alone solar home systems for domestic and residential uses.

The solar water heater (SWH) is a green technology that harnesses solar thermal energy via a solar thermal collector to generate hot water. This type of water heating is on an increasing trend since they are economically and environmentally beneficial. The system uses clean, inexhaustible, and eco-friendly renewable energy source, which aids in carbon footprint reduction[54]. SWH systems are a trending solar technology used in several countries for solar hot water production. China has the highest global solar water heater installed capacity among other countries [55], as illustrated in Figure 8. Along with China, the US, Germany, Brazil and India dominate the solar thermal market. SHW systems are steadily gaining market share in many African

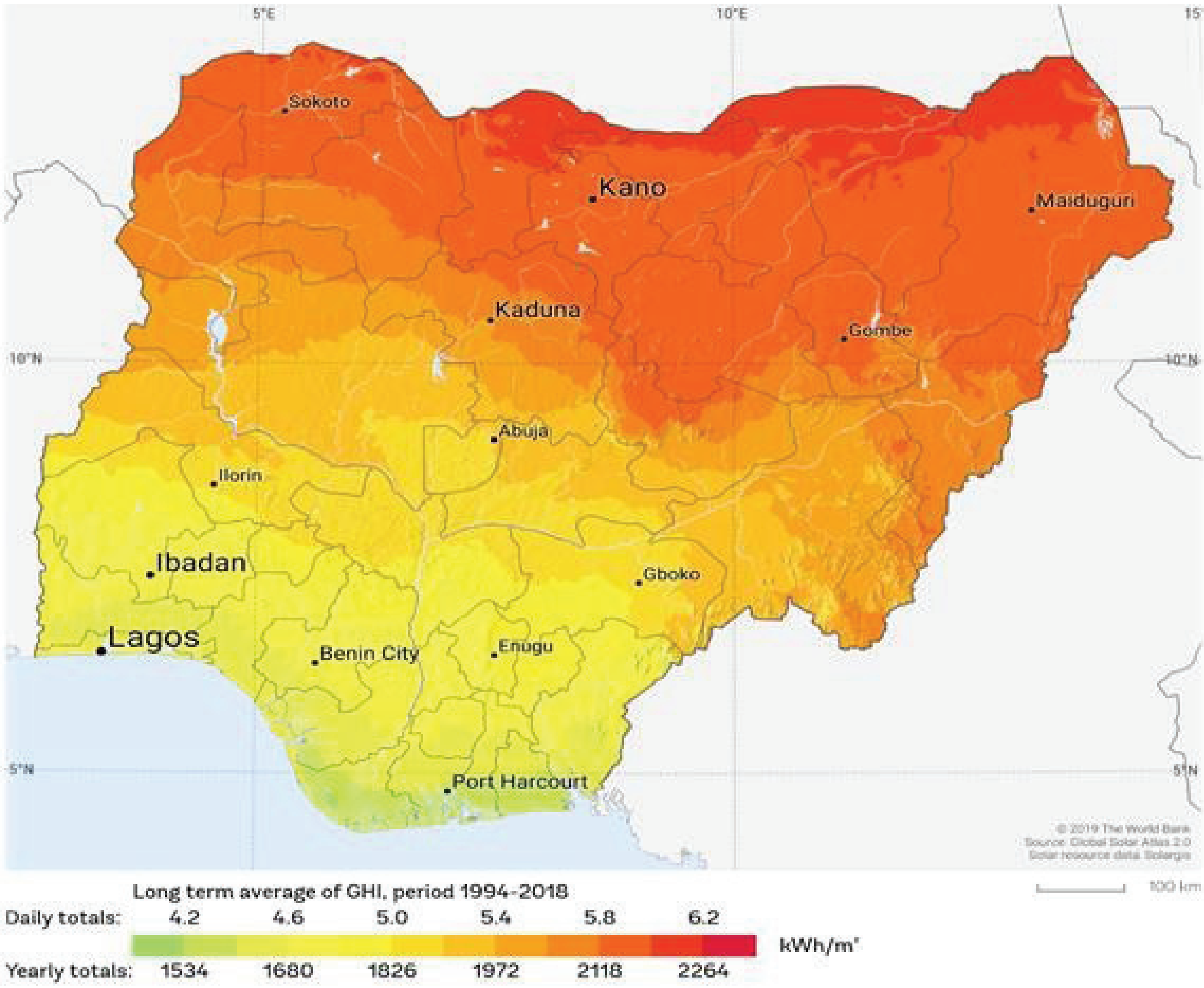

Figure 7. Annual solar Irradiation in Nigeria.

countries, including South Africa, Tunisia, Ethiopia, Kenya, Morocco, Ghana, Cape Verde, Egypt, and Tanzania[56]. South Africa dominates the solar market in Africa [57]. However, the solar water heater market in Nigeria is still nascent; and few solar water-heating applications have been deployed.

A typical SWH consists of (1) solar thermal collector, which is the principal component of SWH for harnessing thermal energy. (2) A storage tank used to keep hot water for later use, (3) a pump to circulate the heat transfer fluid within the storage tank and (5) piping that serves as a flow channel for fluid transport. SWH can be classified as active or passive. The Active SWH systems use a pump to force the working fluid to circulate [58]. This type of water heating system is classified into two types: direct (open loop) and indirect (close-loop) heating systems. They differ in the mode of transportation of working fluid [59]. Air systems and heat pump systems are examples of active systems that use force circulation. In a passive water heating system, fluid circulation depends on density difference [60], but its high thermal loss limits its widespread use. They require minimal maintenance due to absence of actuators and sensors and are inexpensive compared to active systems. The passive systems are most suitable for warm climates and are thermosiphon system or integrated collector storage (ICS) system. Hence, four types of collectors that use in solar water heating applications are the flat plate collector (Figure 9a), evacuated tube collector (Figure 9b), concentrating collectors' as shown in Figure 10. The integrated collector is a solar collector that uses both the collector and the storage tank as a thermal energy absorber, but its high thermal loss limits its widespread use.

Flat plate collectors (FPCs)

The flat plate collector (FPC) is one of the most extensively used solar collectors owing to its high solar energy absorption and diffusion. FPC is rapidly gaining wide popularity in most residential water heating systems due

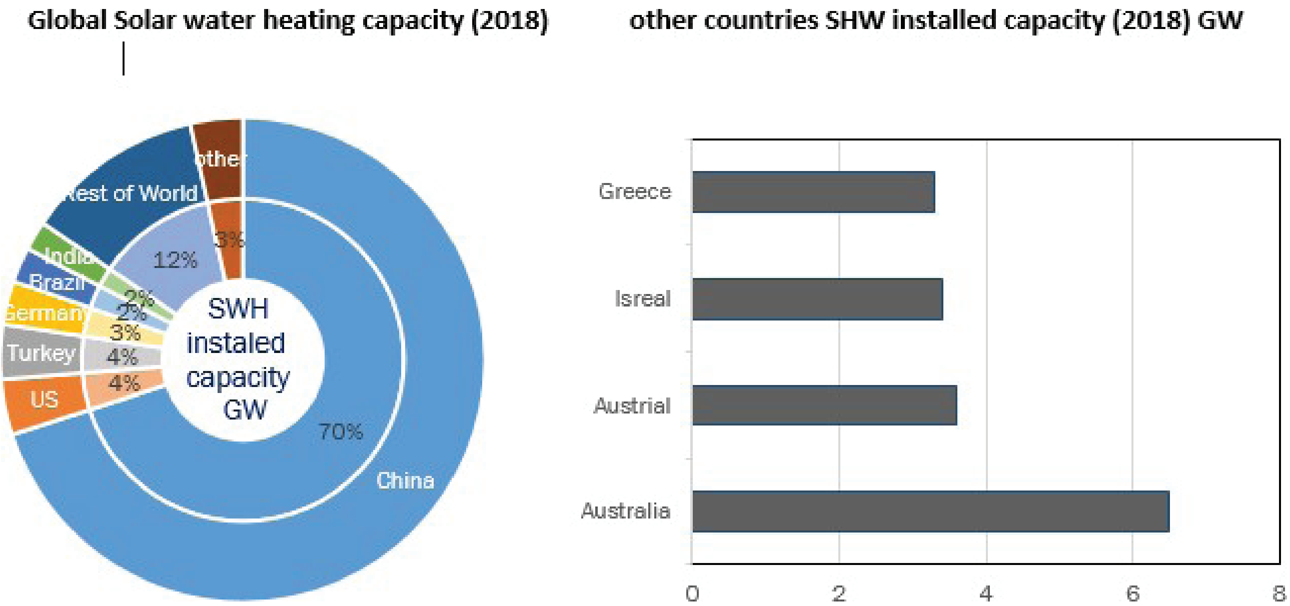

Figure 8. Global solar water heating installed.

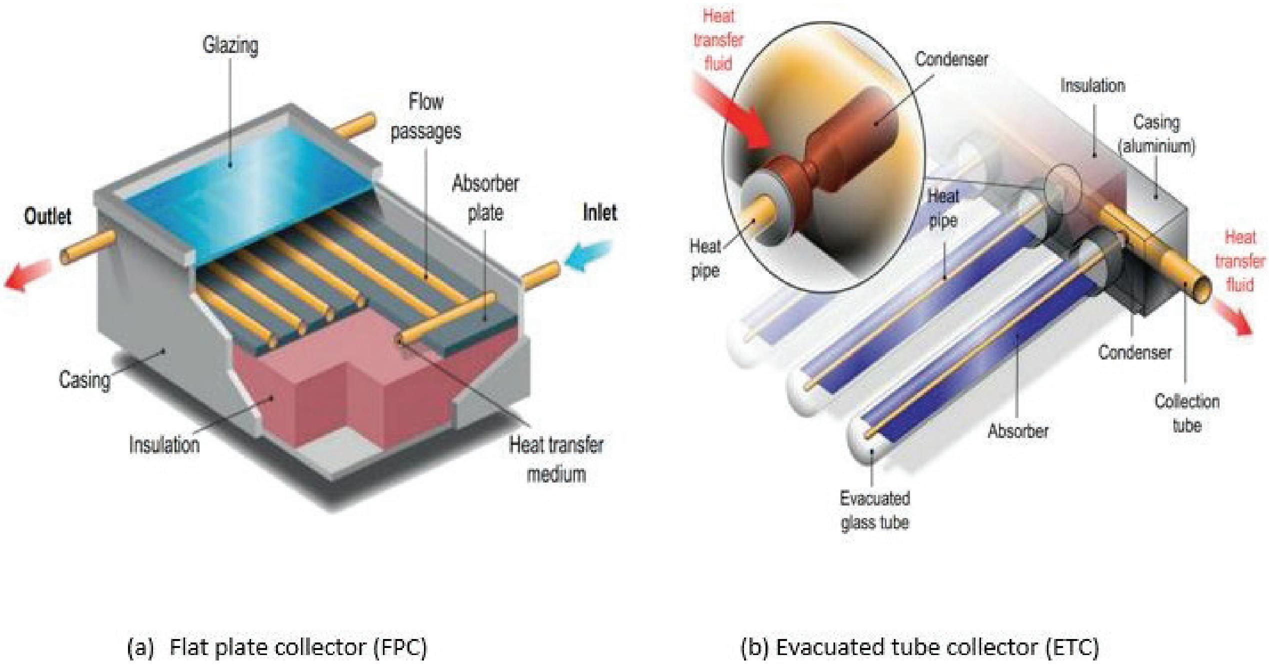

Figure 9. Schematics of (a) FPC and (b) ETC [41].

to its simplicity in design, low -cost and low maintenance. However, it has low efficiency compared to concentrating solar collectors. Flat plate collectors are most suitable for hot water at a low demand temperature of about 30–70 [61]. Based on Figure 9a, high-frequency solar radiation penetrates the collectors via glass cover, reducing heat loss by convection. The heat absorber absorbs the solar thermal energy; transfers it to the working fluid flowing through the collector via radiation. The heated working fluid is further transported to the fluid tubes for maximum absorption and later stored in a storage tank. The commonly used heat transfer fluid (HTF) are water, oil and air [62]. Water is the most widely used heat transfer fluid due to its abundant, high heat capacity, incompressibility, and high mass density. However, the limitation of water as HTF is that it freezes at low temperature with the potential of deteriorating the collector plate. Anti-freeze mixtures and phase-change liquids (low boiling point) may help prevent the collector plate from freezing.

Evacuated tube collector (ETC)

Evacuated tube collector (ETC) is a non-concentrating collector type used for high-temperature applications. ETCs have dominant benefits of excellent thermal performance and high heat removal ability over flat plate collectors [63]. Hence, it is suitable for high thermal applications, since it limits convective loss and sun-tracking deficiency associated with flat plate collectors [64]. As a result, evacuated tube collectors can thrive in cold, windy, and cloudy weather. Evacuated tube collector, as shown in Figure 9b has a metal heat pipe of low thermal conductivity embedded within a parallel arrangement of a twin glass tube to transfer thermal energy from the collector to the heat transfer fluid via convection. The twin glass tube coated with a selective light absorber for maximum absorption with minimal reflection. Also, the evacuated air between the two tubes prevent much conductive loss. The heat transfer fluid circulates around the solar collector by convection to reheat, evaporate and rise to the heat exchanger head. Hence, the transfer liquid flows through the manifold in the collector to gain thermal energy and then condenses. The condensed fluid cools down in the bottom of the heat pipe to repeat the cycle. The disadvantages of ETCs include overheating above the domestic application temperature of 100 and high upfront costs. However, ETC are an excellent choice for solar hot water for countries with unfavourable climates [65]. Table 3 compares the performance of the two most commonly used SWH systems: flat plate collector water heating (FPC-SWH) and evacuated tube collector solar water heating (ETC-SWH).

Concentrating collector (CC)

Concentrating collectors are solar thermal collectors that capture direct sunlight from a large area and concentrate it into a small absorber area. These are high-temperature application devices with the major benefits of high energy or radiation flux, excellent direct radiation tracer and heat loss optimizer. A typical concentration collector comprises two key components: (1) a receiver that is responsible for energy conversion, and (2) a concentrator for direct capturing of incident radiation. The interaction of the optical device and the absorbent surface produce high temperatures before heat conversion. Hence, solar energy is optically concentrated. Due to their limited absorption surface region, concentrating concentrators generally have more thermal energy and lower heat loss than flat plate and evacuated tube collectors. The four most adopted solar imaging concentrating collectors for hot water applications are parabolic trough collector (Figure 10a), parabolic dish collector (Figure 10b), linear Fresnel reflector (Figure 10c), and Central tower receiver (Figure 10d). The parabolic troughs are the linear focus, concentrating systems capable of producing steam or hot water at temperatures of up to 375 . They are more efficient at temperatures ranging from 150°C to 190°C and are suitable for desalination cooling and power generation. The parabolic troughs are the only concentrating systems that have reached industrial maturity with a track record of accessibility and dependability [66]. The linear Fresnel reflector (LRF) is a promising concentrating device at temperatures around 400°C. They are multi-reflector, single-axis sun trackers, and line focus collectors [67], and they used in thermal applications such as electricity generation and hot water heating systems.

Table 3. Performance Comparison of FPC- and ETC-SWH technologies

	Flat- Plate Collector SWH System	Evacuate Tube Collector SWH System
Thermal output	Moderate	Fast
Thermal performance	Poor performance at hotter temperature	Excellent performance at hotter temperature
Heat loss	High	Low
Efficiency in freezing temperature	Moderate	Low due to water freezing
Temperature range (^{o}C)	30-70	60-120
Antifreezing material	Phase change material (PCM)	Liquid-vapour phase change material
Application	Low temperature application	Low and medium applications
Heat insulating material	Polyisocyanurate insulation on collector and hot water tank	Polyurethane insulation on hot water tank
Peak absorption period	All-day long whenever the sun is hot	Optimum at noon
Annual hot water output	350 days	» 300 days
Life span	5-15 years	> 25 years
Limitation	Freezes at low temperatures, potentially deteriorating the collector plate	High initial costs and overheating above the domestic application temperature of 100.

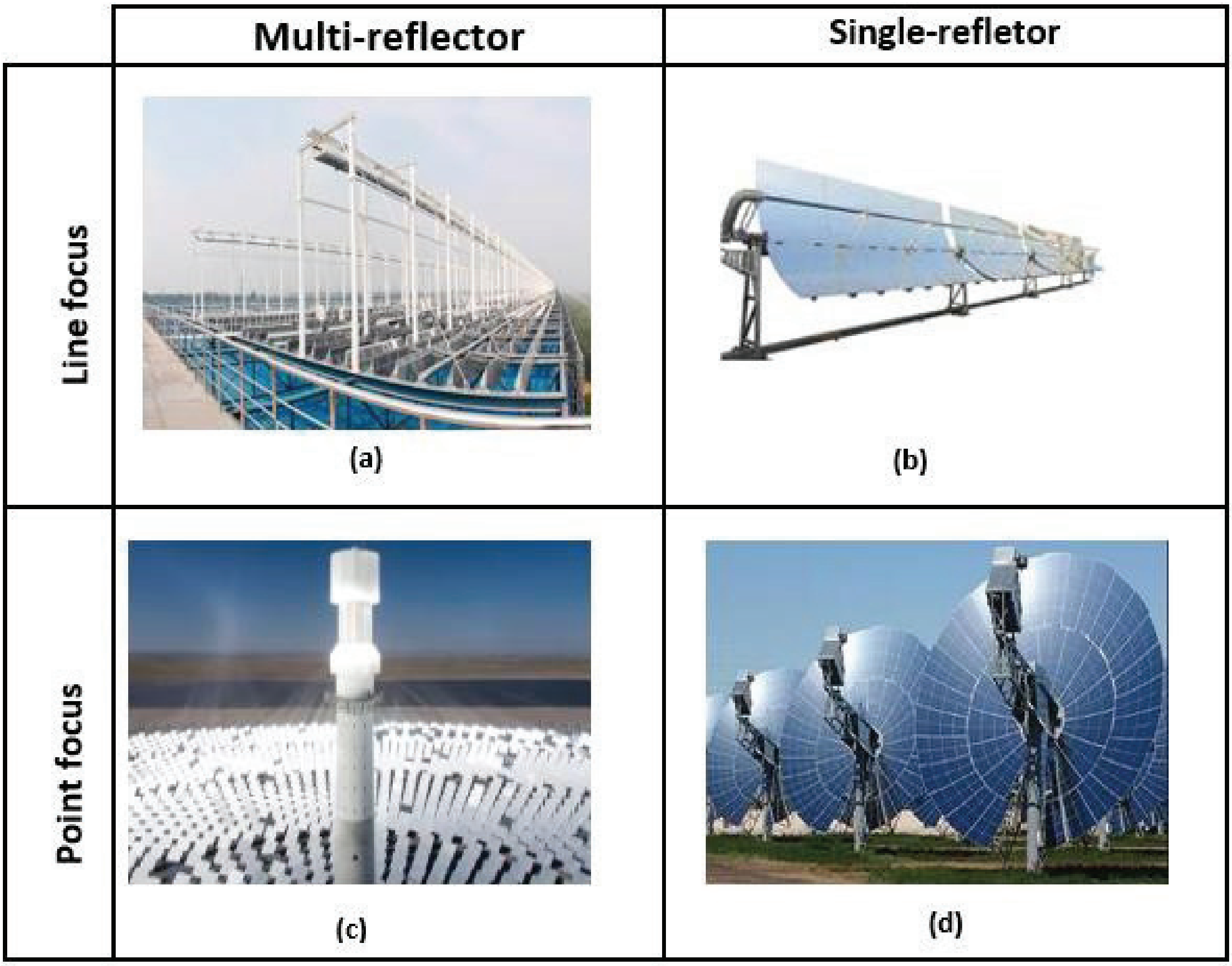

Figure 10. Pictorial representation of concentrating solar power system technologies.

In comparison to the parabolic trough collector PTC, it uses flat-curved surface reflectors that are less expensive than parabolic glass reflectors. The lower thermal efficiency is one of the major barriers to large-scale LRF adoption. The parabolic dish collectors are the point of focus based concentrating devices. They have a two-axis tracking mechanism with a mirror-like reflector and absorber in the center, similar to a satellite dish antenna. They are suitable for high-temperature applications. There are some studies in Nigeria based on collector types. Nwaji et al. [68] proposed mathematical modeling. The key parameters were bond with and riser tube temperature, and their findings show that, of the selected study areas, Sokoto has the best performance for implementing the proposed systems. [69] , investigated the feasibility of using evacuated-based solar collectors and developed a modeling framework in Nigeria. The comparative study focused on the potential for energy savings and the economic viability of using SWHs. Their study demonstrated that SWH is economically viable and recommends financial incentives to promote SWH mass-adoption. [70], investigated the effect of stretching a water tube throughout its thickness on the heat rate of a flat- plate collector. The results of the study were compared numerically and experimentally. Despite the fact that the data correlates, the experimental model has a slightly higher heat loss. [71], developed a mathematical model to calculate the best tilt angles for SWH. The study's novelty is that an automated tilting mechanism was proposed in contrast to existing methods. [72], carried out a thermal analysis of SWHs using three different refrigerants: R-134a, R12, and Ethanol. Their findings show that R-134 has the highest thermal index of the three refrigerants. Joseph et al.[73], assessed the exergy of a flat plate SWH in a few areas of Nigeria. The influence of solar radiation and time on collector outflow temperature was investigated experimentally. Their findings show that the temperature of the outflow is highly dependent on solar radiation and heating time. [74], used the "TRNSYS" modeling tool to conduct an experimental study on the thermal efficacy of flat-based SWHs. Two distinct configurations are the subject of the study. According to their findings, which demonstrate that serpentine-type has a better heat enhancement than other types. Isamotu et al. [75] investigated the influence of phase change material (PCM) on the performance index of flat-based SWHs. Two different tank storages were tested experimentally, one without PCM, and the other with a small amount of PCM. Their model results show that the storage tank containing a fraction of PCM has a higher thermal index than the storage tank containing only water.

Heat Pump Water Heater (HPWH)

The heat pump water heater (HPWH) absorbs thermal energy from the ambient air to heat water via a working fluid. Because of its high efficiency and significant energy savings, HPWHs are preferred over other electric-based water heaters. Unlike an electric water heater, which generates heat through energy conversion, heat pumps only transmit heat from one location to another. This method of heat transfer result in a higher coefficient of performance, COP. Domestic heat pumps have a COP of 2 to 4.5, so the heat pump generates 2 to 4.5 times more heat than the electricity it consumes. Heat pump water heaters can be classified into four types. Ground (Geothermal) source heat pump water heaters (GSHPWHs), air source heat pump water heaters (ASHPWHs), solar assisted heat pump water heaters (SAHPWHs) and gas-engine drive heat pump water heaters. These heat pump water heaters differ in the heat source used as an evaporator [76]. The essential components of a typical HPWH as shown in Figure 11 are the evaporator, compressor, expansion valve, and condenser. Table 4 shows several studies of the most recent advancement of HP technology in terms of applications, renewable sources integration, prospect, and performance. The comparison studies of different types of water heating systems are presented in Table 5.

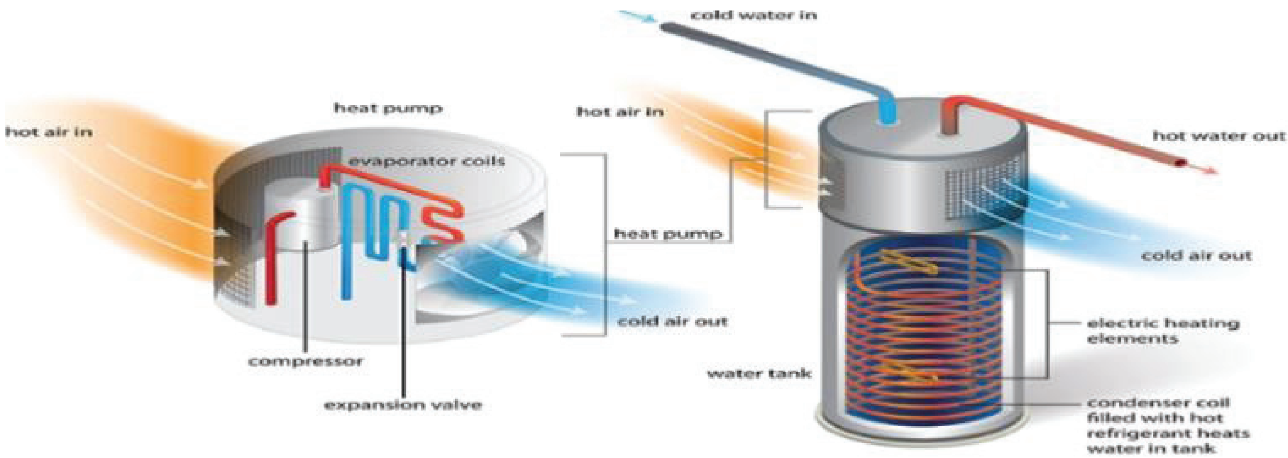

Figure 11. Heat pump water heater (HPWH).

Table 4. Summary of the recent studied on heat pumps

Authors/Citation	Year	Areas of focus
Giti et al. [77]	2019	Review of solar-assisted ground solar water heater (SAGSH)
Hosseinirad et al. [78]	2019	Performance optimization of HPs with solar a system
Amin et al. [79]	2013	Solar-assisted heat pump water heaters SAHPWHS in Singapore
Vaishak [80]	2019	Review of the prospect of PVTSAHPS
Poppi et al. [81]	2017	Techno-economic review of solar-assisted heat pumps (SAHPS)
Siyuan et al. [82]	2020	Space heating and domestic hot water applications of solar- assisted heat pumps
Rodrigo et al. [83]	2019	The water heating application of hybrid solar heat pumps (HSHPS)
Fudholi et al. [84]	2018	Drying application of solar-assisted heat pumps (SAHPS)
Badiei et al. [85]	2018	Review of the recent development and innovation of SAHPS
Dia et al. [86]	2017	The water heating application of hybrid photovoltaic- thermal/heat pumps

Table 5. Comparison of different types of water heating systems in terms of technology, merits and demerits

Water Hating Technology	Merits	Demerits
Kerosene Water Heater	Cheap, low operating cost, cleaner source of fossil-fuel for domestic use, environmental friendly than wood water heaters	Contributes to greenhouse gas emission, emits a high level of pollution, leads to indoor air pollution due to high concentration of Co_2, $PM_{2.5}$ and PM_{10}, causes asthma, tuberculosis, cancer, and eye problems in indoor users
Wood Fueled Water Heater	The fuel cost is relatively lower than the conventional gas, oil, and ESTWHs, It is a clean renewable fuel source since the Co_2 emissions are almost neutral (0.008Kg Co_2/kWh), sustainable, replenishable form of renewable energy, serves as alternative energy source to mitigate the reliance on non-renewable fossil fuels, and an off-grid energy source; independent on electricity, oil, or natural gas	Locally, it emits high concentrations of hazardous pollutants (Co_2, H_2S, So_2, CH_4, $PM_{2.5}$, and PM_{10}), lower energy density than conventional fuel, and the use of wood stoves is associated with back drafting issues
Electric Storage Tank Water Heater	ESWH has high hot water retention capacity, requires less maintenance than other oil and gas heaters, a pollution-free source of energy because it uses electrical energy, which eliminates the problem of Co_2 emissions, and It can be strategically located everywhere within a building to reduce heat loss	ESTWHs use a significant amount of electricity to maintain hot water reliability and availability, converts electrical energy to heat energy at a high rate, occupies more space than electric tankless water heaters, and indirectly contributes to environmental pollution occupies more space than electric tankless water heaters because fossil fuels are used to generate electricity.
Electric Tankless Water Heater	ETWHs use 20% to 30% less energy than ESTWHs , its space efficient, has a low standby energy loss, provides instant access to hot water, energy conservative, has a longer service life than ESTWs and heat pump water heaters, and has an excellent synergistic combination with solar water heaters.	Limited hot water due to lack of storage tank, contributes to fossil-fuel depletion, When in use, it consumes a large amount of energy, and has a much higher operating cost than gas- fired and ESTWH heaters
Solar Water Heater	SWHs is a completely renewable resource, creates no pollution, conserves fossil fuels energy sources, energy conservative and cost-effective, and reduces carbon foot print	High upfront cost, have no multiple uses as it only heats water, Its intermittency and vulnerability to climatic change necessitates an auxiliary thermal backup, a time- varying RE source that is affected by solar irradiation intensity, weather fluctuation, and the temperature of PV cells, and SWHs freezing temperature has significant influence on its performance index
Heat Pump Water Heater	High efficiency and significant energy savings, compensates for the vulnerability of SWHs when combined with a solar PV system, generates low- emissions heat using clean energy (solar, wind, fuel cell, and hydrogen), and HPWH has a promising future in terms of energy sustainability.	HPWH has a higher start-up cost than conventional heating systems, and Cold climates cause a significant decrease in HPWH performance coefficient.

Hybrid Water Heating Technologies (HWHTs)

The growing interest in developing new heating technology to enhance hot water sustainability and overcome the weakness of solar intermittency in SWHs has resulted in a new synergetic energy source integration in solar water heating. This synergetic integration resulted in the formation of hybrid water heating technology. HWHTs are new water heating technology that combines RE sources with at least one conventional energy source and storage unit. Furthermore, these technologies contribute to higher energy efficiency, higher energy savings, lower energy consumption, thermal sustainability, and hot water availability. Hybrid water heating technologies have recently become a focus in buildings for emerging nations, particularly African countries, for a variety of reasons. One major motivation for this is to reduce reliance on fossil fuels and the resulting climate crisis. Several hybrid configurations have been studied, as shown in Table 6, but for the purposes of this paper, we will only look at six different configurations that are expected to gain future market penetration in Nigeria.

Hybrid solar/electric tank water heater (HSETWH)

Hybrid solar/electric tank water heater (HSETWH) combines a solar water heater, electric water heater, and thermal storage to boost hot water availability as illustrated in Figure 12. This synergistic combination ensures that the end-user has constant access to hot water. Solar water

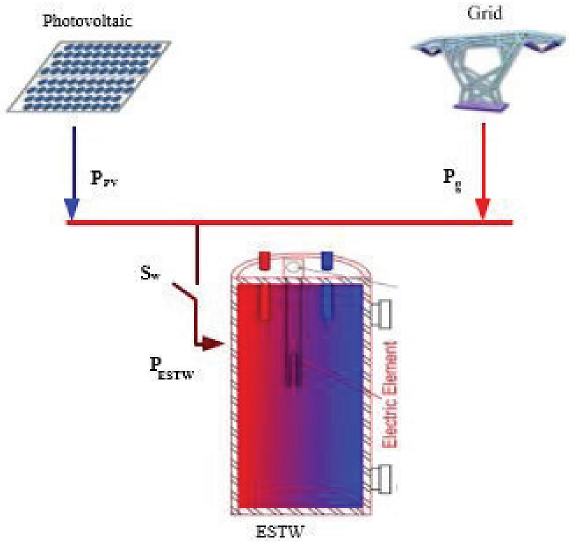

Figure 12. Hybrid solar/electric water heater [9].

Table 6. Studied on hybrid water heating technologies

Reference	Hybrid configurations	Areas of application	Location
[87]	Photovoltaic, power grid, heat pump water heater	Optimal power control	South Africa
[88]	Grid-connected, photovoltaic system, heat pump water	Optimal scheduling strategy	South Africa
[89]	Solar, electric water heater	Cost optimization	South Africa
[90]	Ground source heat pump, solar collector	Economic assessment	Denmark
[91]	Wind, grid systems, solar collector heat pump	Optimal management	Lebanon
[92]	Thermal collector, heat pump water heater	Techno-economic assessment	Finland
[93]	PV, solar thermal collector	Optimal sizing	United Kingdom
[94]	Grid, PV. Heat pump water heater	Single objective optimization	South Africa
[95]	Solar , heat pump		China
[96]	Grid systems, PV, fuel cell, battery, hot water tank	optimal energy management	China
[97]	Photovoltaic, heat pump water heater	Performance Assessment	Hong Kong
[98],	Solar thermal collector, heat pump water heater	Techno-economic assessment	Nigeria
[99]	Photovoltaic, Solar thermal collector, heat pump water	Performance analysis	Chain
[100]	Photovoltaic, grid energy, heat pump water heater	Optimal energy management	South Africa
[101]	Photovoltaic, heat pump water heater	Multi-objective optimization	Greece
[102]	Photovoltaic, wind, heat pump water heater	Optimal power control	South Africa
[103]	Photovoltaic, grid energy, battery, heat pump water heater	Optimal energy management	South Africa
[104]	Photovoltaic, wind, fuel cell, grid energy, heat pump water heater	Optimal energy management	South Africa
[105]	Solar, thermal storage tank, electric water heater	Multi-objective optimization	Brazil
[106]	Photovoltaic, electric water heater	Multi-objective optimization	China
[107]	Photovoltaic-thermal, heat pump water heater	Economic assessment	China
[108]	Photovoltaic-thermal, electric water heater	Techno-economic assessment	Portugal
[109]	Solar, wind, electric water heater	Optimal sizing	Lithuania
[110]	Solar, grid energy, electric water heater	Optimal energy management	South Africa

heating is a time-varying RE source that is affected by solar irradiation intensity, weather fluctuation, and the temperature of PV cells. Though, it is a green technology that harnesses thermal energy via a thermal collector to heat water, its intermittency and vulnerability to climatic change necessitates an auxiliary thermal backup for hot water generation. As a result, an electric tank water heater (ETWH) is combined with a solar water heater to compensate for its inconstancy while saving energy. The drawbacks of SWHs include intermittency and low efficiency due to PV cell temperature rise. The SHWs may be integrated with PHCN grid-connected systems to compensate for solar radiation inefficiency, making thermal energy available for hot water heating. HSWH are designed to turn on during off-peak hours to save money on the time-of-use tariff (TOU) while still providing optimal hot water delivery.

This synergistic combination provides the end-user with continuous access to hot water. However, there is a trade-off between the thermal outputs and the cost of electricity. Consequently, these hybrid systems required control optimization to perform optimally. [110], presented energy control scheme of a thermostat-based heaters. An optimal control hybrid system was introduced in order to to reduce electricity cost and energy consumption of the conventional water heaters. A cost savings of about 43.99% was economically conserve with the use of hybrid heating system. [111], developed a simulation model to compare the energy savings potential of resistive-based water heater with the hybrid solar/electric water heater. It is noted that the hybrid system has reduced energy intake than the EWHs. [89], presented a mathematical model of hybrid solar/electric system that can be used to curtail the grid energy cost of an electric-based water heater. Further, recommends the use of optimal control for effective utilization of the proposed system. [112], compared the energy-cost saving potential of a resistive-based heater with the HSWH using Matlab optimization tool. The model result shows that the HSWH is more energy conservative and energy effective than EWHs.

Photovoltaic-thermal water heater (PV/TWH)

A photovoltaic-thermal collector (PV/T) is a hybrid of a solar thermal collector (STC) and a photovoltaic cell (PV). The hybrid system serves two purposes: generate heat for domestic water heating applications and electricity for household needs. Only a portion (about 6%-18%) of incoming solar irradiation is converted into electricity in standalone photovoltaic systems with the rest transformed into heat energy, which overhears the PV cells, resulting in temperature rises and low electrical efficiency [108]. As a result, the cooling mechanisms extract the wasted heat energy in PV/T systems for hot water applications [113]. The primary goal of a PV/T water heater is to maximize thermal output while minimizing electrical output. Thus, a need for synergy between electrical output and thermal output is required depending on the end-user requirements. The most commonly used HTFs in PV/TWH hybrid collectors are air, water, and nanofluids. As shown in Figure 13, the PV/T system is a combination of series-connected solar panels and a thermal collector that produces both heat and electricity at the same time. Thermal collectors serve as heat exchangers, absorbing thermal energy. The inlet of cold water supplied to the collector system via a circulating pump and heated, while thermosiphon assists in the circulation of water throughout the system, which also helps in transporting heater water to the storage tank. Okubanjo et al. [114], presented a simulation model of a hybrid PVT system in Nigeria to address the issue of energy deficit in buildings. The influence of six key parameters on

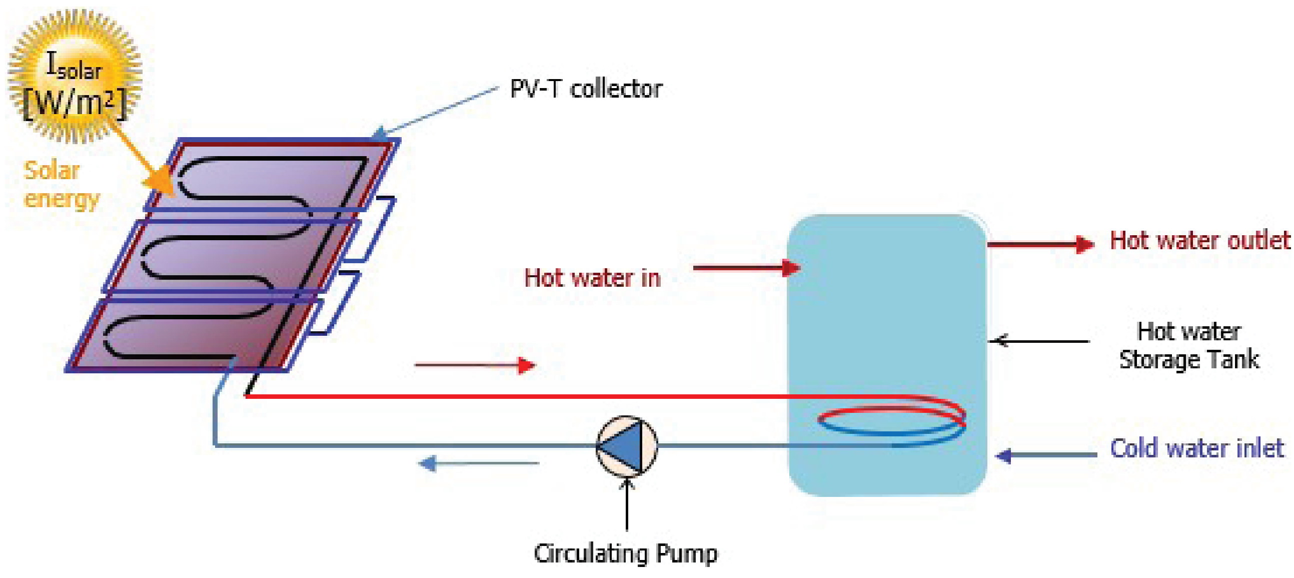

Figure 13. Photovoltaic-thermal water heater.

the performance of the hybrid system was investigated. The study utilizes a cooling system to convert waste heat into usable heat energy for domestic use. Their findings indicate that the hybrid system has a stronger affinity for improving both the electricity and heat requirements of buildings. As a result, it also suggests that PV/TWH be used to combat energy insecurity in Nigeria.

Hybrid solar/heat pump water heater (HSHPWH)

Hybrid solar/heat pump water heater (HSHPWH) is an emerging energy transition technology for sustaining hot water production. It is a hybrid system configuration that combines a solar thermal collector and a conventional heat pump water heater to supplement water heating. They are also known as solar-assisted or solar boosted heat pump water heaters. HSTHPWHs compensate for the shortcomings of conventional solar water heaters since the system can use a HPWH and solar thermal water heater interchangeably. This hybrid system is reliable and energy-efficient than a heat pump water heater or a standalone solar water heater. The solar thermal energy heats the refrigerant and transfers the heat from the refrigerant cycle to the upper heat exchanger in the storage tank, shown in Figure 14.

Okubanjo et al. [115] proposed an HSHPWH mathematical model that can be used to reduce grid energy costs in Nigeria using the mixed integer nonlinear programming optimization solver. The hybrid system's economic assessment was compared to electric water heaters as the energy baseline. Their optimal model result shows that hybrid systems reduce energy consumption and grid costs. Furthermore, the use of HSHPWH in Nigeria is expected to revolutionize energy use in buildings. [116], investigated the techno-economic feasibility of using hybrid solar/HP water heaters to address the issue of energy conservation in Nigeria. The study focuses on five economic comparative metrics, with existing EWHs serving as a heating baseline. The comparative analysis shows that the use of hybrid systems has economic advantages over existing heating systems in terms of cost savings and energy consumption, with the proposed hybrid system saving nearly 46.8% of the cost. It also recommends that transition to hybrid renewable technologies as a sustainable pathway to energy sustainability. Okubanjo et al. [117] presented a model-based simulation of hybrid solar/HP system using "MATLAB". Their findings indicate a strong preference for the hybrid system application in Nigeria in order to reduce reliance on non- renewable fuels, lower electricity costs, and sustain the ecosystem.

Photovoltaic-Wind-Grid-Fuel cell-Heat Pump Water Heater

The framework shown in Figure 15, comprises PV cells, wind generator, fuel cell, grid system, and heat pump water heater for producing hot water. Therefore, renewable energy sources complement one another due to their infinite supply. As a result, excess solar and wind energy is used to power electrolyzes, which are then stored for backup purposes. In the absence of renewable energy sources, the fuel cell is used to power the HPWH, which provides hot water.

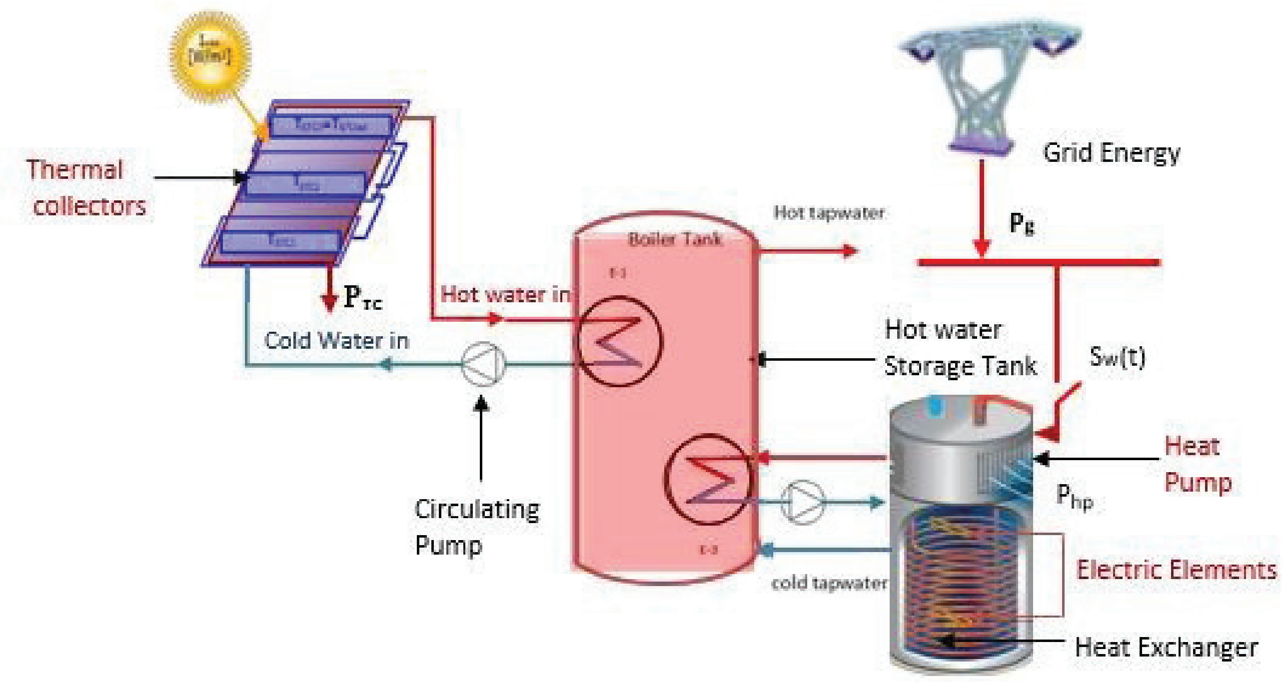

Figure 14. Schematic solar/ heat pump water heater (HSHPWH).

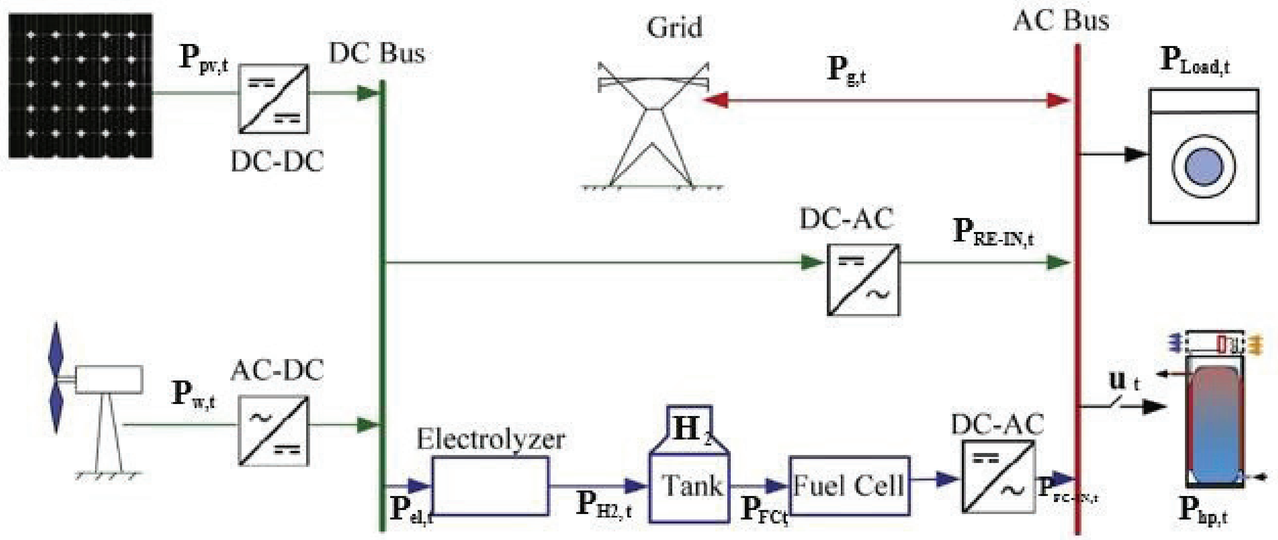

Figure 15. Schematic of hybrid photovoltaic-wind-grid-fuel cell-heat pump water heater [104].

[104], presented an optimal control strategy of fuel cell, wind, and photovoltaic renewable energy source integrated with grid system so as to meet the thermal load demand. In this model an optimal cost function was developed to minimize energy cost and maximize fuel cell output regarding time- of-use electricity tariffs as key control parameter. [118], developed an optimization model for a heat pump water heater integrated with both wind and photovoltaic-grid connected system. He established an optimization function to minimize the cost of electricity consumption for domestic hot-water taking into account the time-of-use tariff. The results reveal a significant energy savings and greenhouse gases emission reduction in comparison with the conventional system using fossil fuels and the control strategy is proven too more efficient and reliable than the existing thermostatic control of the devices. In another study an optimal control model of a grid tied photovoltaic integrated system for a hybrid heat pump water-instantaneous shower was developed for application in areas with erratic power supply [119]. The findings showed that about 23.4% daily energy can be saved, and daily water saving up to 191 can as well be achieved through the proposed control model.

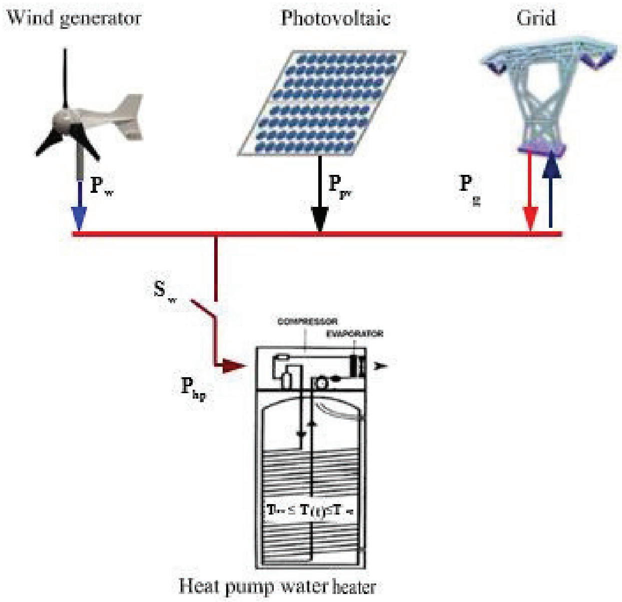

Figure 16. Schematic of hybrid Photovoltaic- Wind-Grid-Heat Pump configuration [88].

Photovoltaic-Wind-Grid-Heat Pump Water Heater

This system configuration is made up of photovoltaic cells, wind generator, grid system, and HPWH. The photovoltaic cells (PV) and wind work together to compensate for each other's inconsistencies. Hence, HPWH sources its power from these RE sources. Surplus electricity is created and fed into the grid. When the heat pump's combined output is insufficient to fulfil thermal demand, grid power is used to supplement it. Figure 16 depicts the system configuration.

A more advanced control strategy, model predictive control for effective operation of combined HPWH and instantaneous shower tied with renewable system was adopted in [119]. The control model was formulated to achieve optimal operation of both the heat pump water heater and the instantaneous shower and to adequately meet hot water demand at low energy and water consumption. In addition, an optimal controller was designed to operate a HPWH powered using integrated energy system.

This controller led to energy and cost savings from renewable energy systems. The grid was designed to accept excess power from the renewable sources through an appropriate feed-in-tariff [120]. A numerical and experimental study on the performance of a heat- pipe solar photovoltaic heat pump system was investigated in [99]. The author further formulated a mathematical model based on quasi-steady state distributed parameter for heat pump respectively. The capacity of the heat pump and the number of PV collectors are optimized to improve the system performance based on the mathematical model. The performance of a combined solar system, wind with heat pump for small house in United Kingdom was investigated [121]. In their work, a conventional on-off controller and a multi-variable model predictive controller (MPC) were compared for different climatic conditions. The outcome of the research reveals that MPC performed better than the conventional on-off controller in terms of thermal comfort, energy saving, cheap night tariff benefit.

Photovoltaic-Grid-Battery-Heat Pump Water Heater

As shown in Figure 17, the system comprises photovoltaic modules, a grid system, a battery with an inverter, and heat pump water heater to meet hot water and other domestic demand. The solar cells produce the heat energy needed to power both the heat pump water heater and load. However, the grid system only operates when the output of the solar energy is not sufficient to fulfil the thermal demand. The end-user has constant access to hot water because of this synergistic combination. The motive of this system is to create surplus power using photovoltaic cells, with the extra energy fed to the grid to earn returns and other incentives.

An optimal sizing model of hybrid solar energy and wind generator is used in [122] to power HPWHs in energy-scare areas. Furthermore, an optimal model of a HPWH powered by an integrated energy system is proposed in [76]. An optimal control strategy for power dispatch of the grid tied photovoltaic (PV) - battery-diesel system to power heat pump water heaters (HPWH) is developed in [123]. The battery is used as storage of cheaper-to-buy off peak grid energy dependent on the time-of-use (TOU) electricity tariff while the DG is a backup power source. The aim of the model is to minimize energy and fuel cost while maximizing PV energy trade-off for incentives. This optimized model resulted in energy and cost savings. A combined solar thermal pump with seasonal energy storage and diesel power backup for both space heating and domestic hot-water in cold climate region is proposed by [95]. The performance analysis for the proposed system and the energy backup revealed a significant energy saving and adaptability of the proposed system to perform efficiently in a cold region than the existing system. Further, [124] developed an hybrid model predictive control strategy to minimize the cost of electricity of a grid tied photovoltaic (PV) - battery-diesel heat pump water heater.

Summary of related studies on water heating systems

Several studies have suggested various techniques of improving the efficiency of water heating technologies. Alongside is the adoption of hybrid system configurations in increasing efficiency and optimizing cost of electricity. Recently, the integration of renewable sources of energy

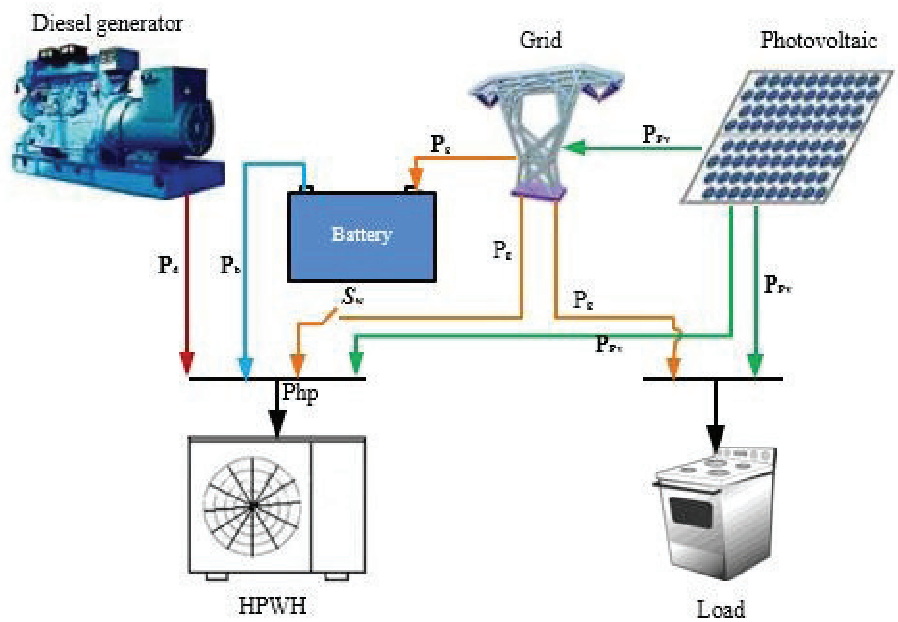

Figure 17. Hybrid system configuration [87].

with heat pump technology towards increased renewable production of hot water has been explored. Furthermore, several studies focused on design, modelling, simulation, energy, and exergy analysis, techno-economic analysis, experimental analysis, review of conventional heating systems, hybrid configurations, as well as control strategies (control optimization) to further explore system parameters. Table 7 shows the summary of relevant papers related to water heating systems with respect to source authors, technology used, and types of study and key findings

Table 7. Highlights of related studies on various water-heating technologies classified by study type /technology/ contribution

Reference	Citation	Technology	Highlights
Dannemand et al.	[125]	PV/T water heater	The simulated results show about 0.58, 1.51, and 0.75 fraction improvement in thermal, electrical and renewable energy respectively
Giovanni et al.	[126]	PV/Tl water heater	The result shows about 4236KWh/y energy savings and a payback of 2 to 6 years.
Calise et al.	[127]	PV/T water heater	Energy-economic analysis was examined. Comparison of parameter selection with optimization methods.
Diwania et al.	[128]	PV/T water heater	A comprehensive review of PV/T technology was examined.
Nwaji et al.	[129]	PV/T water heater	The performance of the collectors was examined regarding their usage in different countries and the prospect, technical improvement, and societal constraints were highlighted.
Huan et al.	[130]	Solar water heater	Comparative analysis of the serial and parallel expansion of SAHP was conducted based on seasons indirect
Jaisankar et al.	[131]	Solar water heater	Review of various water heater techniques with an emphasis on thermal efficiency improvement
Oussama et al.	[132]	PV/T water heater	Thermal and electrical enhancement of existing PV/T systems through anti-reflective, low-emissivity coating collector.
Mohammad et al.	[133]	Solar water heater	The result of the model shows that the collector surface area has a significant effect on absorber plate temperature.
Kong et al.	[134]	Heat pump water heater	The development of a control strategy for direct expansion of solar-assisted HPWH
Khani et al.	[127]	Photovoltaic-thermal water heater	Parameter estimation of electrical and thermal efficiencies based on single and bi-objective optimization.
Nwaji et al.	[129]	PV/T water heater	The optimized model shows an overall cost saving of about 44% compared to conventional water heating systems.
Albostan et al.	[135]	PV/T water heater	The proposed model is more economically feasible than the existing fossil-fuel-based system but has a longer payback period.
Sichilalu et al.	[123]	Heat pump water heater	The optimized model shows that 114.06KWh of energy can be saved daily with a maximum cost saving of 68.09%.
Chen et al.	[136]	Heat pump water heater	The optimal COP of the proposed system was 4.97.
Badescu et al.	[137]	PV/T+ HPWH	The COP of the hybrid model is higher than that of the standalone heat pump model.
Glembin et al.	[138]	Solar thermal water heater	Optimized control of solar heat supplied by integrated systems.
Jamar et al.	[139]	Solar water heater	Recommended the need for nanofluids in the heat pipe.
Raghad et al.	[140]	SHW	Further research into the limitation of integrating PV/T with heat pump.
Wang et al.	[141]	PV/T heat water pump heater	Optimized model shows about 41.5% energy savings, a 16% increase in market penetration, and a short payback period.
Weeratunge et al.	[142]	Heat pump water heater	Proposed mixed integer optimization method. Optimized model shows an improvement in peak shaving and operating cost reduced by 7.8%

Reference	Citation	Technology	Highlights
Herez et al.	[143]	PV/T heat water pump heater	Concept, benefits, and classification were reviewed.
Allouhi et al.	[144]	SWH	Compared the life cycle cost for four different solar water heaters.
Hohne et al	[145]	Solar/electric water heater	Presented optimal energy management for hybrid solar water heating systems in South Africa.
Hohne et al	[9]	Water heating systems	A survey of domestic water heating technologies in terms of usage, improvement, initial investment, payback period, and shortcomings in South Africa. The survey identifies existing research gaps and proposes concepts for energy management and cost savings
Herrando et al	[93]	Photovoltaic-thermal water heater	Techno-economic analysis of PV/T systems to determine average yearly system performance for distributed electricity and hot water production in the UK.
Aliyu et al	[146]	Solar water heater	The review identifies and recommends key policies, incentives and programmes to encourage large-scale deployment of the SWH
Lv et al	[147]	PVT/T heat pump water heater	Micro-grid energy performance analysis was presented
Mohanraj et al	[148]	Solar-assisted heat pump water heater	A survey of SAHPs focusing on system configurations, modelling, system performance, economic benefits, and environmental constraints
Yueh-heng Li et al	[149]	Solar-assisted heat pump water heater	Proposed a Taguchi optimization strategy for a dual-solar heat pump water heaters.
Bai et al.	[107]	Photovoltaic-thermal water heater	Proposed a mathematical model for hybrid PV/T water heater in greenhouse application. The proposed model was cost effective than existing fossil-fuel based system. Although, the payback is longer than expected.
Pierrick et al.	[150]	Photovoltaic-thermal water heater	Energy and exergy assessment of photovoltaic-thermal water heater were presented.
Abhishek et al.	[151]	Solar-assisted heat pump water heater	A survey of recent developments and various improvement methods of solar-assisted heat pump water were identified and presented.
Sichilalu et al	[103]	Heat pump water heater	Proposed an optimal control model for an integrated system with heat pump water heaters. The optimized model shows about 41.5% energy savings and a short payback period.
Zakaria et al.	[79]	Solar-assisted heat pump water heater	Compared the performance analysis for three different system configurations of solar/heat pump water heaters. Evaporated collector based configuration has higher efficiency than the other configurations.
Wanjiru et al.	[100]	Heat pump water heater	Developed a model predictive control strategy for HPWH and instantaneous shower powered by integrated renewable systems.
Okubanjo et al	[115]	Hybrid solar/ heat pump water heater	An optimal control model of solar thermal heat pump water heater was proposed. The proposed model aims to reduce grid energy costs by optimizing the switching control of the heat pump water heater.
Okubanjo et al	[116]	Hybrid solar/ heat pump water heater	The techno-economic assessment of a hybrid solar/heat pump system in addressing the issue of energy conservation was examined.

It is important to emphasize that few of these systems are in existence while others are emerging technologies that are expected to steadily gain future market penetration in Nigeria.

Techno-economic Aspects of Water Heating Technologies

Cost has long been identified as a key motivator in the user preference on the use of heating technology. Hence, the economic sustainability of heating technology has been a focus of interest in users' selection criteria. Other factors like market price, energy cost, CO_2 emission, repayment period, climate conditions and degree of thermal needs also influence the user decision. Furthermore, there is a strong desire to examine the techno-economic viability of various water heating technologies to guide users' decision making on heating investment. Table 8 compares the costs and benefits of various water heating technologies.

REMARKS AND FUTURE PROSPECTS

The energy consumption in buildings, particularly for hot water production has seen a rapid global renewable transition. As result, a diverse range of hybrid system configurations has emerged as viable alternative to fossil-fuel-based water heating technologies. The integration of solar water technology with other energy sources has as a promising prospects in mitigating environmental carbon footprint, climate crisis, and high energy cost. HWHTs are an emerging domestic heating technologies with enormous potential for energy and cost savings. Such systems are yet in use and there is little literature on hybrid water heating applications in Nigeria. Therefore, the adoption of hybrid technology has a significant role to play in contributing to African's sustainable development goals while addressing energy consumption in residential buildings. Nigeria is

Table 8. A cost-benefit analysis of various water heating technologies

Techno logy	Initial capital cost ($)	Useful life span (years)	CO_2 emission rate H M L N	Energy- cost savings	Repayme nt period (years)	Highlights in the context of the Nigerian scenario
KWH	15-45		High	Low	Nil	Kerosene, at $1.85/litre, is more expensive than wood logs and ESWH electricity charges.
WFHW	10-36	10-15	High	Moderate	Nil	WFHW is highly susceptible to Co_2 pollution.
ESWH	81-115	8-12	Moderate	Moderate	Baseline case	ESWHs have a high energy cost. It has higher maintenance costs
ETWH	68-170	5-9	Moderate	Moderate	3-7	ETWHs have higher operating costs than ESWHs.
SWH	226-800	8-20	Neutral	Moderate	2-4	SWHs have an increased start - up costs than ESWHs. An additional thermal backup is required for hot water sustainability.
HPWH	158-295	8-15	Low	Moderate	5-9	HPWH is a highly efficient than electric or gas water heaters.
HSET WH	236-395	15	Moderate	Moderate	4-6	HSETWHs have higher operational costs than ESWHs. ESWH is a backup heating technology that consumes a lot of energy at a high cost.
PV/TW H	N/A	9-15	Neutral	Moderate	9-11	PV/TWH has a higher initial cost than ESWHS.
HSHP WH	900-1500	6-10	Neutral	High	2-3	The use of HPs makes the HSHPWH more expensive to install than ESWHs, but it has economic benefits over SWHs or ESWHs in terms of hot water sustainability, energy, and cost savings. HSHPWHS has a remarkable payback period than other technologies.

* H- High, M-Moderate, L-Low, and N-Neutral

endowed with a vast array of fossil fuel resources and solar potential, but fossil energy resources dominate her thermal energy needs. For several decades, many households rely on alternative fuels such as biomass/fuel wood consumption and kerosene fuel/ LP gas to meet their thermal demand. Although fossil-fueled heating technologies have significant cost, affordability, and accessibility advantages, the following anthropogenic activities limit their merits.

- There has been widespread concern about health-related issues associated with the use of these technologies, with thousands of women and children being particularly vulnerable to indoor air pollution caused by wood fuels and kerosene heaters.
- With the use of wood and kerosene fuels, there is a rising trend in the production of harmful pollutants.
- There has been a rapid increased in cardiovascular dysfunction with use of these technologies.
- Co_2 emissions and other high-concentration pollutants have increased, changing the climate. One of the main drawbacks of electric water heaters (EWH) is the large amount of electrical energy consumed to meet the required hot water demand, as well as the high grid energy costs. These have sparked a great deal of interest in the use of renewable technology, such as solar water heaters (SWHs). Amidst this, solar irradiation intermittent and low efficiency due to PV cell temperature rise have been identified as limitations to the use of solar water heaters. However, a mismatch between solar energy and user energy consumption, as well as the variability of solar radiation throughout the day, results in an energy demand supply gap. One potential solution to these issues is to explore the use of hybrid systems, which would replace conventional heating technology, such as electric water heaters, with a more energy efficient heat pump water heater. The heat pump acts as a thermal backup for solar water heater, compensating for solar vulnerability through grid energy at the lowest cost. As a result, grid energy consumption for water heating are reduced, and the shortcomings of SWH are offset by this hybrid system.

In an attempt to promote clean energy, future adoption of hybrid technologies in Nigeria should be viewed as a positive step toward a sustainable path to zero carbon by 2050. Hybrid systems is not a new technology, its concepts remain relatively unexplored in some developing countries. These technologies offer significant advantages in terms of increased reliability, thermal enhancement, lower grid energy costs, and efficiency improvement Furthermore, hybrid technologies promote energy conservation and renewable energy system efficiency. The use of hybrid systems is a new energy-saving strategy for reducing reliance on fossil-fuel technology and improving energy security. Prioritizing government support for hybrid technologies will benefit the country's energy supply. In addition, when combined with advanced control, hybrid technologies will provide a cost-effective, energy-efficient solution to the problems of excessive energy consumption, high grid energy costs, and SWHs Shortcomings. More importantly, SWH awareness in Nigeria requires public awareness at multiple levels, including awareness campaigns, press releases, radio shows, and newspaper articles, in order to promote sustainable energy for all. Solar water technologies face high upfront investment costs in most developed countries. The South African government, for instance, has made significant investments in these technologies through tax credits and other forms of financial assistance. As a result, the country's energy supply has improved to the point where surplus energy is now sold to the electric grid to generate revenue A similar approach in Nigeria, on the other hand, could spark a massive revolution for hybrid water heaters.

CONCLUSION

This paper presents a review of the current state of water heating systems. Studies on the current state of art, prospects of hybrid technology, progress on HWHTs, barriers and policy recommendations were highlighted. Several studies have explored the use of solar water heating in domestic applications. However, studies on the use of hybrid technology in water heating applications are rarely reported. The authors draw the following conclusions from the literature reviewed in this study:

- SWHs applications in Nigeria have increased slightly in recent years.
- In spite of the renewable energy plan and the 2030 goal, the SWH technologies are at a nascent stage in Nigeria.
- Nigeria has a long-established renewable energy policy, but lacks incentives measures and other financial schemes that can motivate and promote public acceptance of both SWHs and HWTHs.
- There has been a lack of competitive investment environment to promote SWHs and related hybrid technologies in Nigeria.
- The hybrid water heating systems are an emerging technologies that many citizens are unaware of, and there is a significant literature gap for this technology and related technologies in Nigeria.
- The high initial costs of SWHs and HWHTs have stifled the rapid growth and adoption of these technologies in Nigeria. There is an urgent need for financial incentives to encourage public recognition of these technologies through government intervention.
- ESTWs have higher grid energy costs than biomass/ wood /kerosene heaters. One potential solution to this is to explore the use of hybrid technology, which would replace conventional heating technology with a more energy-efficient energy source such as HPs.

- The use of hybrid technologies has the potential to compensate for solar vulnerabilities by using grid energy at the lowest cost, resulting in lower energy consumption.
- In Nigeria, acquiring technology has taken precedence over local development. As a result, intensive research and collaboration between universities, energy centers, and engineering professional bodies should be launched to investigate future materials that can improve thermal storage and provide new insights into fuel cells and hydrogen production.

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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