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REVIEW **Open Access**

A review on solar water heating technology: Impacts of parameters and techno-economic studies

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Abstract

Background Solar water heating is a highly sustainable method of extracting thermal energy from the sun for domestic and industrial use. In residential buildings, thermal energy from a Solar Water Heater (SWH) can be used to heat spaces, shower, clean, or cook, either alone or in combination with conventional heating systems such as electricity- and fossil-fuel-based heaters. In the industrial sector, SWHs can be used in various high-temperature fluid processes, including chemical processing, manufacturing, power generation, and construction. Despite the technological advancements in water heating systems, there are still some significant technical and economic challenges that limit their widespread adoption and commercialization. Despite their potential to revolutionize the industry, these systems remain in the shadows of unsustainable water heating solutions.

Main body of the abstract This paper reviews recent selected publications on the technical and techno-economic aspects of solar water heating technology. The discussions include the effects of some parameters and components on the overall thermal efficiency of the SWHs as well as the techno-economic prospects of the technology. In addition, the paper provides the existing research gaps and recommendations for future research directions.

Short conclusion The present review paper is unique because it condenses the recent studies carried out on both the technical and techno-economic aspects of the SWHs. It provides a comprehensive framework for interested readers and researchers to gain insights into the technical and economic status of SWHs. However, it is not an exhaustive study. The information presented can aid researchers in conducting further research on the subject, as well as understanding the future of SWHs.

Keywords Solar water heaters, A review, Solar radiation, Sustainable energy, Renewable energy, Techno-economic analysis

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Background

The use of energy from fossil fuels results in the complication of climate change and the degree of environmental pollution (Eze et al. 2022). Currently, the world is fighting for a net-zero energy economy with the goal of limiting the surface temperature of the earth to below 2 °C, according to the Paris Agreement. Even so, the present mean surface temperature on the globe stands at 1.2 °C beyond the pre-industrial benchmark giving rise to heatwaves and extreme weather conditions around the globe (IEA 2023a). The rapid increase in global energy demand is attributed to the exponential growth in the population of the world, which is currently projected to reach 10 billion by 2050 (United Nations 2019), and the intense economic activities in developing countries like China, India, and Sub-Saharan Africa. The fast depletion of fossil fuel reserves has also been a major concern and is also one of the major driving factors for diverting attention towards alternative eco-friendly energy sources (Carfora et al. 2019). This growing energy demand means that the consequences of climate change will continue to intensify, given the fact that these demands have to be met. Put simply, meeting the continuously growing global energy demand while mitigating the effects of climate change to maintain a sustainable environment is one of the greatest challenges of the present generation. To alleviate this challenge and meet up with the net-zero energy target, renewable energy, and its sustainable consumption must be adopted (IEA 2022).

The provision of dependable energy that caters to the needs of the populace is not only socially beneficial but also a critical factor for the economic advancement of any nation (Suriyan et al. 2023). As a result, several alternative energy sources, particularly renewable energy sources, have been explored and considered for adoption as a viable solution (Asif et al. 2023; Sudarsan et al. 2023; Xonto'rayev 2023). Renewable energy is the "Energy derived from continuous and natural energy flows in the immediate environment" (Kerr and Kerr 2019). In order words, RE is an energy source that is replaced naturally at rates not less than the rate of use. Unlike other RE energy sources, which are indirectly linked to the sun, solar energy is fundamentally direct energy that is obtained from the sun and its use has been made possible by several technologies. Today, solar technologies have been developed and commercialized. Such technologies include solar photovoltaic and solar thermal heaters (Anand et al. 2021; Kumar et al. 2021a; Masera et al. 2023; Rosales-Pérez et al. 2023; Yadav and Gattani 2022). The sun is estimated to have about 10 billion years life span with a remaining life span of about 5 billion years (NASA 2023), which means that it can be classified as an unlimited source on the generational time scale. It is an energy source that sustains the ecosystem and offers a solution to meeting the global need for sustainable energy. Fundamentally, solar energy comes from the nuclear reactions that occur in the innermost part (core) of the sun, where hydrogen conversion into helium gives energy. In addition to its unlimited nature, solar energy is abundant in nature and is eco-friendly (Yu et al. 2022). It is one of the RE sources that the transformation from conventional energy sources to purely renewable energy relies upon. Studies by Zekry (2020) indicated that complete transformation may be accomplished in the next 40–45 years following the renewable energy components and their technological modifications. Solar energy has many applications, including power production through various means. One of the recent studies by Homadi et al. (2020) explored the possibility of power generation using solar wall technology operating on the modes of heat transfers with the use of heat energy converted from solar radiation. More applications of solar energy are found in domestic hot water use (Mabrouki et al. 2022; Zhou et al. 2022), industrial applications (Kumar et al. 2021a, b; Shoeibi et al. 2022), health institutions, and tourist centers. For domestic applications, it can be used for cooking, drying, and cooling. Solar water heater is utilized effectively in industries (Martínez-Rodríguez et al. 2022), and, arguably, is the most versatile solar energy application that can be utilized effectively in exchange with conventional (electric) water heaters. This system is described by its thermal performance and relies on the absorption, transmission, and conduction of solar radiation along with the thermal conductivity of the heat transfer fluid (Patel 2023).

The goal of this study is to highlight the recent studies on the technical and techno-economic aspects of solar water heating technology. The main text of this paper is organized as follows. Next section briefly describes the historical development of the SWH, including a general classification of the SHWs, followed by summary of water and space heating requirements in selected countries, including the prospect of using solar water to meet both domestic and industrial hot water and space heating energy demands in the the section after it. Selected recent reviews are encapsulated in following section, including the observations and recommendations provided by the respective authors, and the followed section presents selected recent studies on SWHs, including the effect of some of the important parameters such as the mass flow rate of the working fluid and the hot water storage unit on the overall performance of the system. The study then analysed the techno-economic analysis of SHW systems conducted by different researchers and based on the technical and economic studies, some research gaps were identified, conclusions were drawn, and recommendations for future research directions were outlined in conclusions' section. This review paper will open doors for more research towards this promising technology by providing readers and researchers with enabling research directions for filling the existing research gaps. The techno-economic aspect of the solar water heating technology provided in this paper will offer a great insight into the system to investors and help the government make plausible policies for energy sustainability and economic growth.

Main text

Historic development of solar water heater

SWH is a system designed to absorb solar energy and convert it into heat, which is then used to heat up and store water for later use. The history of SWH can be traced back to the early years when pots of water were kept under the sun during daylight to get it heated up for later use (Jamar et al. 2016). Today, the SWH that follows this principle is the one where the working fluid is enclosed in a metal tank that is painted black on the outside, for increased thermal absorptivity and is usually placed on the roofs of domestic and industrial buildings and tilted towards the sun to absorb solar radiation. The first designed SWH system worked but had a very low efficiency since a large amount of heat was lost for several reasons, mainly due to the lack of insulation of the water storage unit.

General classifications of solar water heaters

Solar water heaters (SWHs) are classified according to their modes of operation and configurations (Duffie et al. 2020). At times the energy from the sun is not adequate to heat up the water to the preferred temperature and in this case, an auxiliary heat powered by electricity or directly by a combustible gas is supplied. Furthermore, solar radiation may be used to directly heat up water, especially in domestic use of the solar water heating setup. However, in utility- or industrial-scale systems, the solar radiation is concentrated on a small collector panel using mirrors or lenses to improve the thermal conversion efficiency. A SWH can be configured to be either a passive or active SWH Fig. 1c and d. These two are further classified into direct and indirect SWH (Duffie et al. 2020; Jamar et al. 2016), depending on whether a secondary fluid is utilized or not Fig. 1a and b. In line with the stated aims and objectives, the detailed classifications of solar water heaters are not presented in this review. Detailed discussions on different classifications of SWHs are published in textbooks that cover the fundamentals of solar water heating.

Water and space heating energy requirements in selected countries

Water heating and air conditioning, arguably, have been the major domestic energy consumption around the world. As of 2022, water and space heating account for 45% of building energy demand globally and account for about 80% of direct CO_2 emissions (IEA 2023b). In the United States, for example, besides lighting, space heating, and air conditioning, heating of water accounts for 20% of the domestic energy consumption (IEA 2023b). In Australia and New Zealand, after space heating and cooling, water heating takes the second position in residential energy consumption (Heidari et al. 2020; Lu et al. 2021). About 48% of the energy used for heating water in these regions comes from natural gas, with 45% coming from grid electricity, 3% from LPG, and 4% from solar energy (Fragkos et al. 2021; Li et al. 2020). Furthermore, in Finland, water and space heating alone account for more than 80% of the net domestic energy use. This figure increased by 5% in 2015, giving rise to about an 8% increase in CO_2 emission every year, as projected by Hirvonen and Hirvonen (2017). In developing economies, limited data for the water and space heating energy needs exist. Mostly, conventional methods of water heating are still employed despite its huge need for SWH. For example, in South Africa, 7.2% of electricity consumption are utilized for water heating by employing 29% electric storage water heaters (Hohne et al. 2019). In West Africa, there is a huge potential for SWH due to its abundant solar irradiance however, few of this technologies have been installed and tested (N'Tsoukpoe et al. 2023), just like in Kenya where SWH is still gaining interest with 52% and 44% of passive and active SWHs installed in domestic buldings out of the few (EPRA 2022). In Egypt, there is a huge need for SWH since water and space heating account for about 62% of building energy consumption (Haghani et al. 2023).

Because of this growing demads for water and space heating around the globe, many countries are embarking on many Renewable Energy (RE) development programs, and due to the importance of domestic hot water, SWH has been manufactured to minimize the rate of energy usage for this purpose and consequently reduce the corresponding direct and indirect costs. As previously mentioned, SWH is a system used for heating water for residential and industrial purposes and it has the advantage of achieving thermal requirements by utilizing the energy from the sun leading to more benefits over water heating with the use of electricity. This thermal system does not contribute significantly to greenhouse gas emissions and can be designed to have a considerably high energy conversion efficiency (Jamar et al. 2016). Recently, there have been many modifications to further enhance

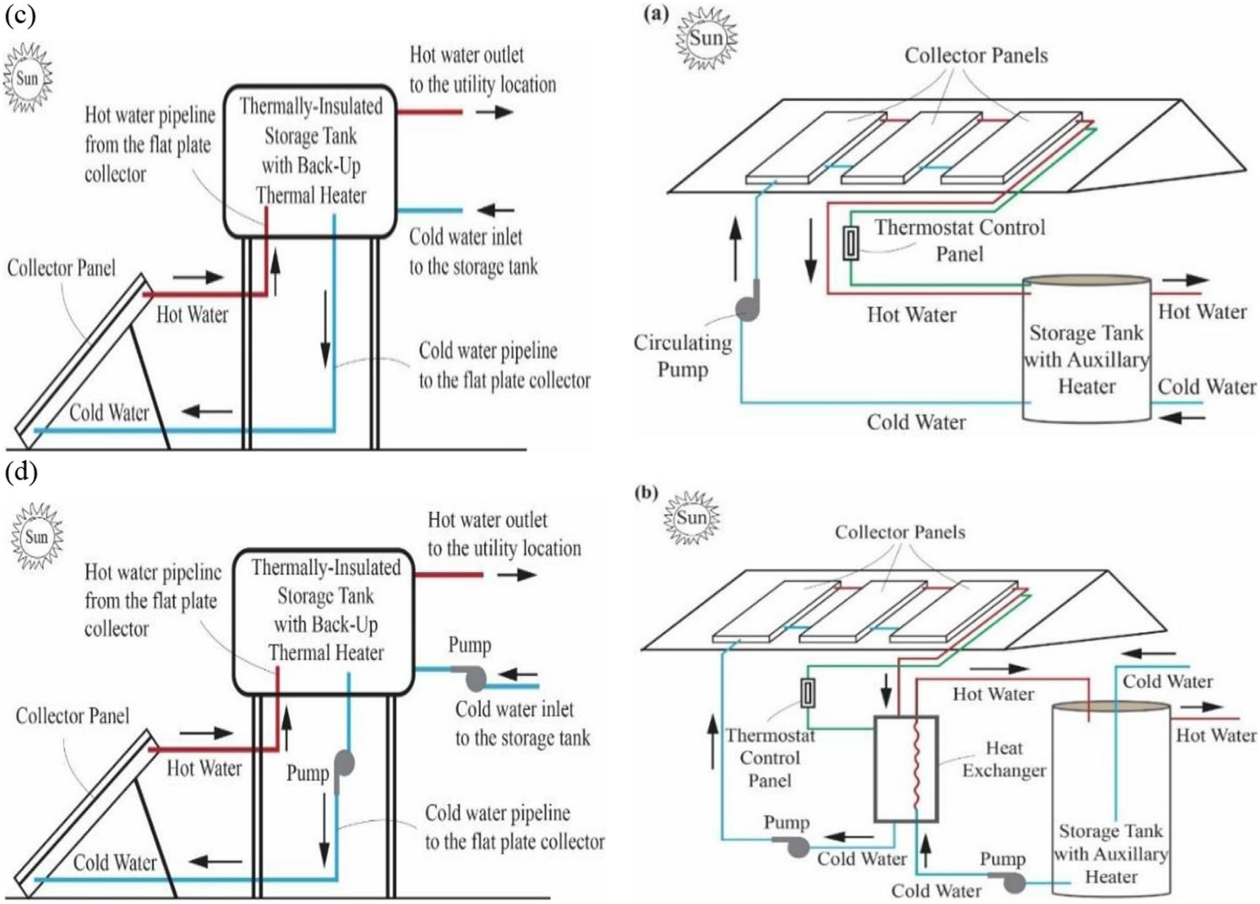

Fig. 1 Classification of the solar water heater and their working principles **c** passive, **d** active, **a** direct, **b** indirect. Alt text: A labelled drawing of the classification of solar water heating including passive on the top left, active on the bottom left, direct on the top right, and indirect on the bottom left

the thermal efficiency of the system, as discussed in the later sections of this study.

Selected recent reviews on SWH systems

SWH is a solar thermal system and these systems can be combined with other renewable energy sources for efficient fuel harnessing. For instance, studies on solar-biomass pyrolysis with an interest in the solar-thermal technologies arrangements were reviewed in Ndukwu et al. (2020). The review showed that a combination of solar energy and biomass gives fuels with a high density as required for common consumptions and this efficient production of high-density fuel is dependent on the solar-thermal system arrangement in the entire system combination. Recently, researchers have shown interest specifically in SWH and have studied it either to design and test new technology to improve the efficiency of the existing ones or simply to review the recent trends in the technology. The purpose of this literature review is to understand the recent progress that has been made in this technology, determine the gaps in knowledge, and suggest possible research to fill these gaps. Next, we discuss selected reviews on SWHs that have been carried out by some researchers.

As a result of the importance of SWH in both domestic and industrial applications, Jaisankar et al. (2011) carried out a relatively comprehensive review of this technology. The study focused on reviewing different techniques to enhance the thermal efficiency of the SWH system and in addition, to identify the current research gaps and consequently suggest solutions that can be adopted. After a series of literature reviews, the study concluded that although SWHs work under the active and passive mode, the thermosyphon (passive) is widely used in households because of its simplicity in usage without the need to apply external energy, although limited research has been dedicated to it. Also, the research found that there has been limited research in parallel flow solar collectors even though it has better performance than the series flow solar collectors and the flow distribution is not uniform in the riser tube. Furthermore, Jaisankar et al. (2011) revealed that the impact of heat losses due to convection as a result of the movement of the atmospheric air over the glazed surface has never been researched and have suggested that the use of appropriate aero profile design which can stop the movement of air over the glass surface can minimize this heat loss through convection. Another comprehensive review of solar system applications was done by Jamar et al. (2016). The authors reviewed the SWH systems and technologies as well as the components with an extensive discussion of the solar collectors. The result of this review showed that on the comparison of the concentrating and non-concentrating solar collector, the PDR type of collector, with regards to the optical optimization, reduced loss of heat, heat recovery improvement, and several solar tracking techniques is the best. The research also discovered that the effects of nanoparticles in the base liquid of the heat pipe for both the tracking and non-tracking collectors have not been observed on the commercial scale, suggesting further research to be carried out to speed up the development and injection of utility-scale SWH in the existing thermal energy mix. Gautam et al. (2017) reviewed the technical advancement, global scenario, and economic viability of SWHs. The review focused on the economic viability of SWHs in the future and discussed the technical advancement of the system, along with the research trends. The study found that SWHs have greater initial capital costs than the common water heating systems and hence proposed that future work should focus on the economic improvement of the system to make it cost-effective for both domestic and industrial applications. The study also indicated the need to adopt hybrid solar water heating systems which have been studied only on the forced circulated SWHs.

Ultimately, not so many comprehensive review articles have been published, partly due to the availability of limited studies on solar water heating systems. The reluctance of government agencies and commercial investors to fund research that would drive the advancement of these technologies, arguably, relies on the variability of the availability of solar radiation. That is, the sun's availability, like some other renewable energy sources, depends on the weather and season. The present authors strongly believe that huge progress would be made in exploring and exploiting the endless potentials and benefits of solar power when significant headway has been made in developing sustainable energy storage systems that would be used to effectively and efficiently store and release solar power during idle time and usage hours, respectively. To the authors' knowledge, the available review of SWH in the literature is presented in Table 1, including the year of publication, the focus area, and the observations and recommendations provided.

Recent advances on SWH systems

As early as 2015, the study of the SWH system has gained a tremendous interest including the consumer impacts on their dividends (Wang et al. 2015). However in recent years, studies aiming to widen the current knowledge and improve its performance have been done. A lot of progress has been made recently to advance the knowledge of SWH and improve its efficiency in the areas of collector modification, heat storage enhancement, integration with existing technologies, smart systems and controls, techno-economics studies, and hybrid systems. Few of these advances will be discussed in the following sections. Overall, improving the design of the collector in turn, enhances the performance of SWH; however, it may constitute higher costs. It is expected that future-day collectors will be more efficient than present-day collectors, and this includes the development of vacuum tube collectors, which minimize heat loss, and flat plat collectors, known to be more consistent in maintaining their performance in diverse weather conditions. Attention to these improvements is drawn mostly to the upgrading of absorbtivity of solar radiation, the prevention of heat losses, and cost-effectiveness.

Progress on collector modification

Modification of solar collectors improves the absorptivitiy of solar radiation, reduce costs, and enhance durability of SWHs and few studies have shown it. For example, Pambudi et al. (2023) modified a V-corrugated zinc collector integrated with an insulator made from aluminum foil foam and embedded a thick plywood at the collector's base to enhance the collector's efficiency and minimize heat loss. The authors' concepts are shown in the Fig. 2. Using different flow rates, the study tested for the efficiency of the system at different time intervals and observed that the higher the flow rates of the working fluids, the more the efficiency, recording about 50% energy efficiency at 240 Lph. In addition, the collector efficiency improved to 61% hence suggesting the adoption of V-corrugated collectors. Similarly, Sharma et al. (2022) compared the performance of flat plate solar collectors with circular and trapezoidal corrugated absorber plate designs. The study examines thermal and exergy efficiency, overall heat loss coefficient, and heat removal factor. Results show that the trapezoidal absorber surface has better performance, with thermal efficiency increases of 8.74% and 12.85% for the circular and trapezoidal corrugated surfaces, respectively. Exergy efficiency improves by 16.88% and 23.31%, and the overall heat loss

Table 1 Chronological list of existing review papers on solar water heating (SWH) technology and observations/recommendations from authors

Author, (year)	Focus area	Observations/recommendations
Jaisankar et al. (2011)	Methodologies for thermal efficiency enhancement	More research should be carried out on thermosyphon SWH for performance enhancement
		Parallel flow should be considered
		Variable headers can be used for velocity stability in the HTF
		More research to minimize heat losses on a glazed cover
Hossain et al. (2011)	SWH collector and flow channels	Experimental research lacking in the study of SWH flow channel
		Heat distribution can be improved by the use of a night insulation cover
Shukla et al. (2013)	Progress in refrigerants	Refrigerants such as propane, NH_3, and CO_2 are under investigation for alleviation of environmental concerns
Sadhishkumar and Balusamy (2014)	Heat transfer improvement and TES	Detailed research on the heat exchange behavior of solar collectors required
		The use of twisted tape in heat transfer is common but limited in application
Wang and Yang (2014)	Loop heat pipe (LHP) for SWH application	Further development in the economic aspect and geometry are required in LHP for SWH application
		Studies under the standard test conditions are limited
Halawa et al. (2015)	Thermal performance technique investigation in three countries—Australia, Taiwan, and Japan	Further investigation to explore a novel mechanism to ensure actual test condition is simulated
		Computer models for environmental check should be developed for future studies
Jamar et al. (2016)	Collectors, Working fluids, and storage tank	Studies on the influence of nanoparticles at the base fluid of heat pipe of solar collectors are yet to be done
Kannan and Vakeesan (2016)	Opportunities, prospects, and challenges	Economic, environmental, and social factors identified as barriers in the solar industry
Gautam et al. (2017)	Technical enhancement and economic viability	The economic situation of SWH should have an important focus
		Thermosyphon-designed SWH research is limited
		Different refrigeration need to be explored for better results
Kee et al. (2018)	PCM application	For SWH, PCM temperature range of 40 – 70°C is the best
		PCM incorporated directly into the storage tank gives the best heat retention hence more research in system design and optimization is paramount
		Storage tank design needs improvement and the use of different PCM requires further exploit
Hohne et al. (2019)	SWH application in South Africa	Hybrid water heating system (heat pump, geothermal, gas-fired plants) promises high performance and should be studied
Vengadesan and Senthil (2020)	Flat plat SWH. Heat transfer enhancement	Study of hybrid nanofluids (including heat transfer enhancing materials) is limited and needs more numerical research
		Numerical analysis of porous medium with varying material and nanofluids required
		Commercial use of nanofluids for the system is not economically viable
Shamsul Azha et al. (2020)	Flat-plate type SWH. Heat transfer improvement	Heat distribution improvement using vibration approach on ETSC improves heat enhancement but is yet to be done on FPSC
		Future research to focus on the use of vibration method within infrasound acoustic range ($f < 20$ Hz)
Wei et al. (2021)	Life cycle assessment (LCA) of SWH	The LCA of SWH shows the system is economically viable. However, installation requires complex techno-economic analysis

Table 1 (continued)

Author, (year)	Focus area	Observations/recommendations
Faisal Ahmed et al. (2021)	Advances in technology	Further studies on the techno-economic analysis are required
		Forced circulation technologies are common, and natural circulation needs to be considered
		A combination of solar and fossil-fuel-powered systems should be considered
Mane and Kale (2021)	Design and performance parameters	Computer simulations on heat-resistant thermal barriers and complex geometries of collector designs such as triangular and pentagonal should be considered in future studies
		Auxiliary storage system separate from the storage tank needs to be considered
Pandey et al. (2021)	Energy, exergy, exergoeconomic, and enviro economic method for PCM application	Effects of various additions such as nanoparticles, their dimensions, and concentrations as well as the types of PCM should be considered in future research
		Further numerical analysis needs to be considered in future work
Sharma and Chauhan (2022)	Collectors, latent heat storage	Studies on the ETC type ICS-SWHS-LHS limited
		Further research on nano-enhanced PCMs required
		Comparative analysis of different configurations of SWH-LHS is needed for further understanding
Pathak et al. (2023)	PCM application	Limited optimization research on nano- based PCM
		More experimental and numerical studies recommeded

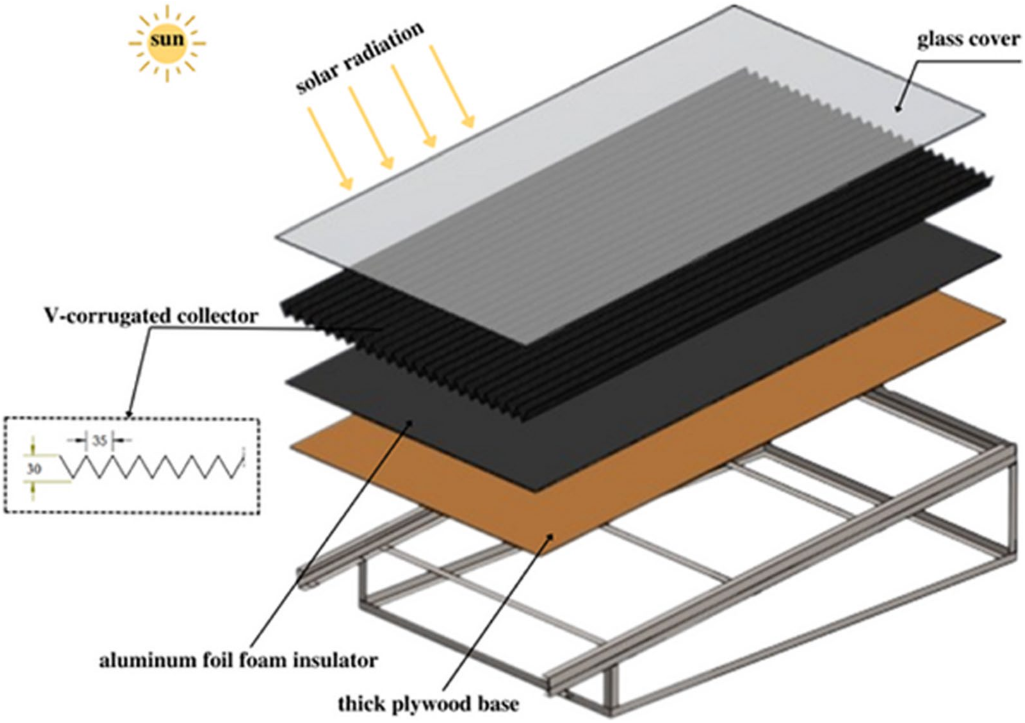

Fig. 2 V-corrugated zinc collector integrated with an insulator for heat loss minimization (Pambudi et al. 2023)

coefficient decreases for both designs, indicating their effectiveness in solar thermal applications. Patel (2023) carried out an experimental study of a SWH featuring an oval tube and fin-covered absorber plate, aiming to enhance thermal efficiency through increased surface area. The unique design with the oval tube and top–bottom cover plates leads to a quicker increase in water outlet temperature, indicating a notable improvement in thermal performance.

Progress on the use of thermal energy storage

Further to the improvement for higher absorptivity of solar radiation and cost reduction, the use of thermal energy storage has been applied previously. The most common methods include the sensible thermal storage (STS) which involves the use of thermal insulated tanks (Seyitini et al. 2023) and latent heat storage (LTS), involving the use of phase change materials (PCM) (Zhang et al. 2023a, b). LTS has several advantages such as high energy storage density, constant temperature heat release, improved efficiency, and reduced thermal losses. However, it also has some drawbacks such as high costs, limited selection of phase change materials, and low thermal conductivities (Ouali et al. 2022). On the other hand, STS is simple and cheap, and offers flexibility in storage medium and scalability. However, it has low energy density and requires high insulation (Katekar et al. 2023). In the application of SWH, Aramesh and Shabani (2023) investigated an advanced solar water heater with a phase change material (PCM), comparing it to a traditional system. The enhanced design retains a collector temperature of around 63 °C for 15 h without sunlight, outperforming the standard model. Energy storage efficiency of 75% was found for the new system, versus 57% for the conventional one. Overall thermal efficiencies are 72% and 49%, respectively. It is expected that the smart integration of these storage methods will enhance the performance of solar heaters. Recently, Elfeky et al. (2023) tested for integrated latent-sensible thermal storage tank and compared with cascaded heat storage designed in layers, with the study's work flow as shown in Fig. 3. The authors reported a capacity ratio and utilization ratio of 52.4% and 45.5%, respectively higher than that of the cascaded layers configuration. This innovative approach significantly reduces the need for large hot water storage tanks, showing better scalability and performance. Other methods of thermal energy storage such thermochemical storage and stratified water storage have been employed.

Progress on thermal efficiency enhancers

It is worth mentioning that thermal efficiency/performance enhancers have been used in different thermal systems including SWHs to boost their overall thermal performance. Schematics of some of these devices that has been put together by Balaji et al. (2017) as shown in Fig. 4. Devices such as metallic fins, nano-particles, tapes and tubes have all been employed for this purpose, however, there are still need for improvements and the application of more innovative solutions.

Progress on collector coatings

Collector coatings are crucial to the overall performance of the SWH systems. The coatings are usually designed to have high solar absorptance thereby improving the solar absorption rate as well as minimizes the heat losses. In addition to this, they help in prevention of corrosion, oxidation, and degredation over time and maintains operational stability (Yao et al. 2023). Investigations have also been done on the selective coating of solar collectors in the last decade (Asaad Yasseen et al. 2022; Caldarelli et al. 2023; De Maio et al. 2022; Herrera-Zamora et al. 2020; Hu et al. 2019; Jeong et al. 2017; Liu et al. 2021; Ma et al. 2021; Motamedi et al. 2023; Müller et al. 2019; Nunes et al. 2018; Thappa et al. 2020). The main function of these coatings is to enable the substrates of the solar collectors to efficiently absorb solar radiation that is then transferred to the working fluid. These coatings can reduce the thermal emittance of collector substrates, optimizing their overall heat absorption efficiency in the process.

Lizama-Tzec et al. (2019) who were among those that recognized the difference selective coatings can make in the overall thermal performance of SWHs researched electrodeposition of glazing in the form of bright nickel/black nickel on a copper-based FPC with an aperture area of 1.74 m^2. The study compared the optical characteristics and the thermal strength of FPC with electrodeposition coating of two other FPCs with commercially available coatings—a copper oxide and a sputter-deposited PVD Ti coating. Photographs of the three FPCs, and the picture and SEM appearance of the copper fin enclosed electrodeposited bright nickel/black coatings are shown in Fig. 5a and b. Lizama-Tzec et al. (2019) reported that at temperatures below 50 °C the electrodeposition coating showed superior performance in comparison with copper-oxide-based collectors but achieved identical performance when compared with titanium-dioxide-based collectors. They went further to postulate that based on their relatively low initial capital and operational cost, the electrodeposited black nickel/bright nickel/copper FPC has proved to be commercially viable in the low-temperature SWH system market. A comprehensive review of medium-to-high temperature solar selective absorber constituents has been published and can be found in (Kennedy 2002; Selvakumar and Barshilia 2012).

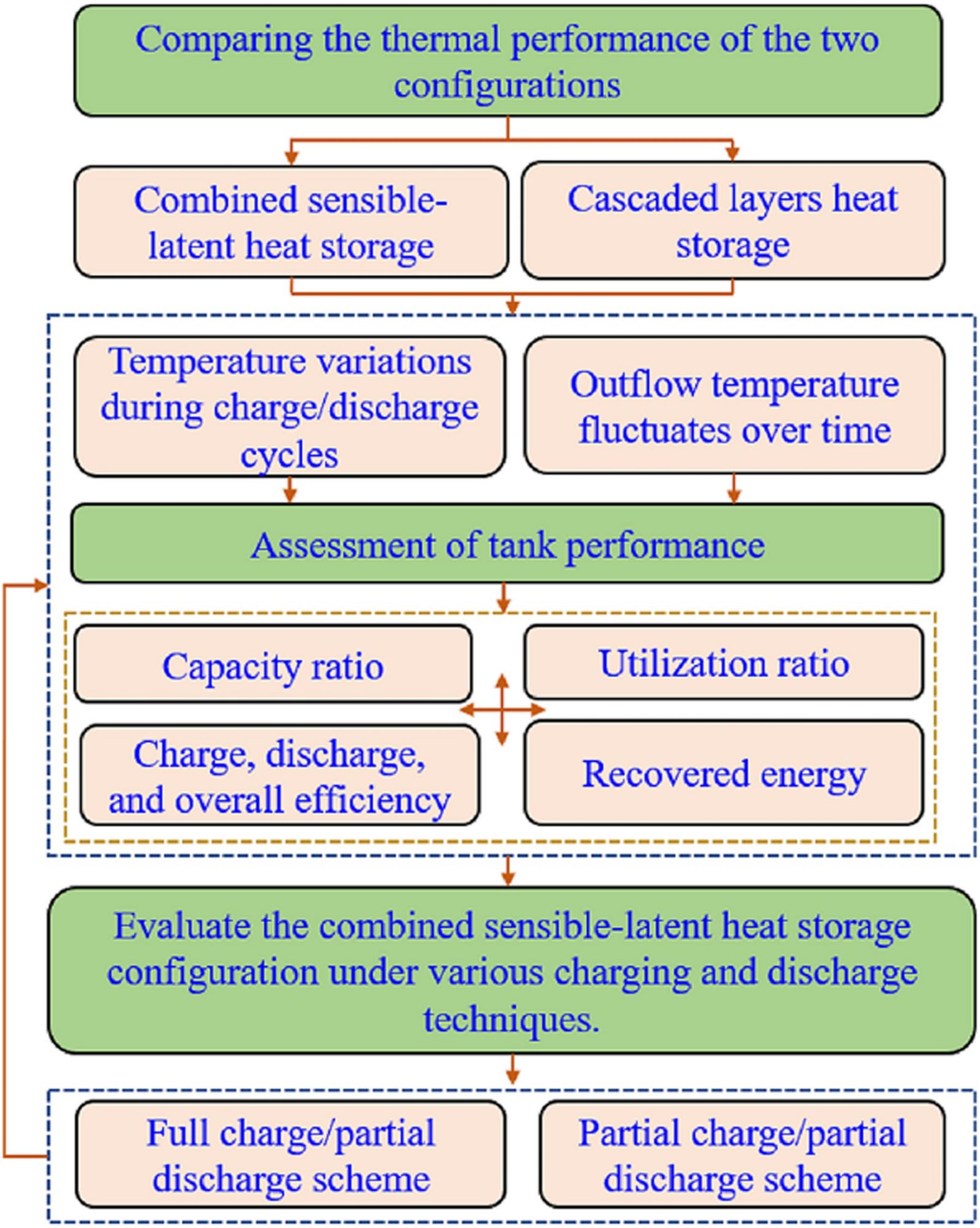

Fig. 3 Workflow for development and testing of integrated latent-sensible heat storage (Elfeky et al. 2023)

Despite the progress in this areas, the problems of low absorptivity of the collectors and heat losses still persist. It is obvious that the recent developed technologies and current research results, although could alleviate the aforementioned issues, are yet to be fully explored. It is imperative to employ more sophisticated absorbtivity and insulating materials for further thermal efficiency enhancement. Even when this is done, the working fluid, flow rates and the intermittent nature of the solar energy must be considered. For example, a more advanced thermal energy storage (TES) system could be provided for short and long-term storage of the heat absorbed by the solar collector. Thermal energy storage are primarily accomplished using the methods mentioned in Eze et al. (2023a, 2023b). In modern water heating, space heating and space cooling, TES systems such as the conventional insulated tanks, underground thermal banks, and vacuum insulated tanks are gaining advancement,

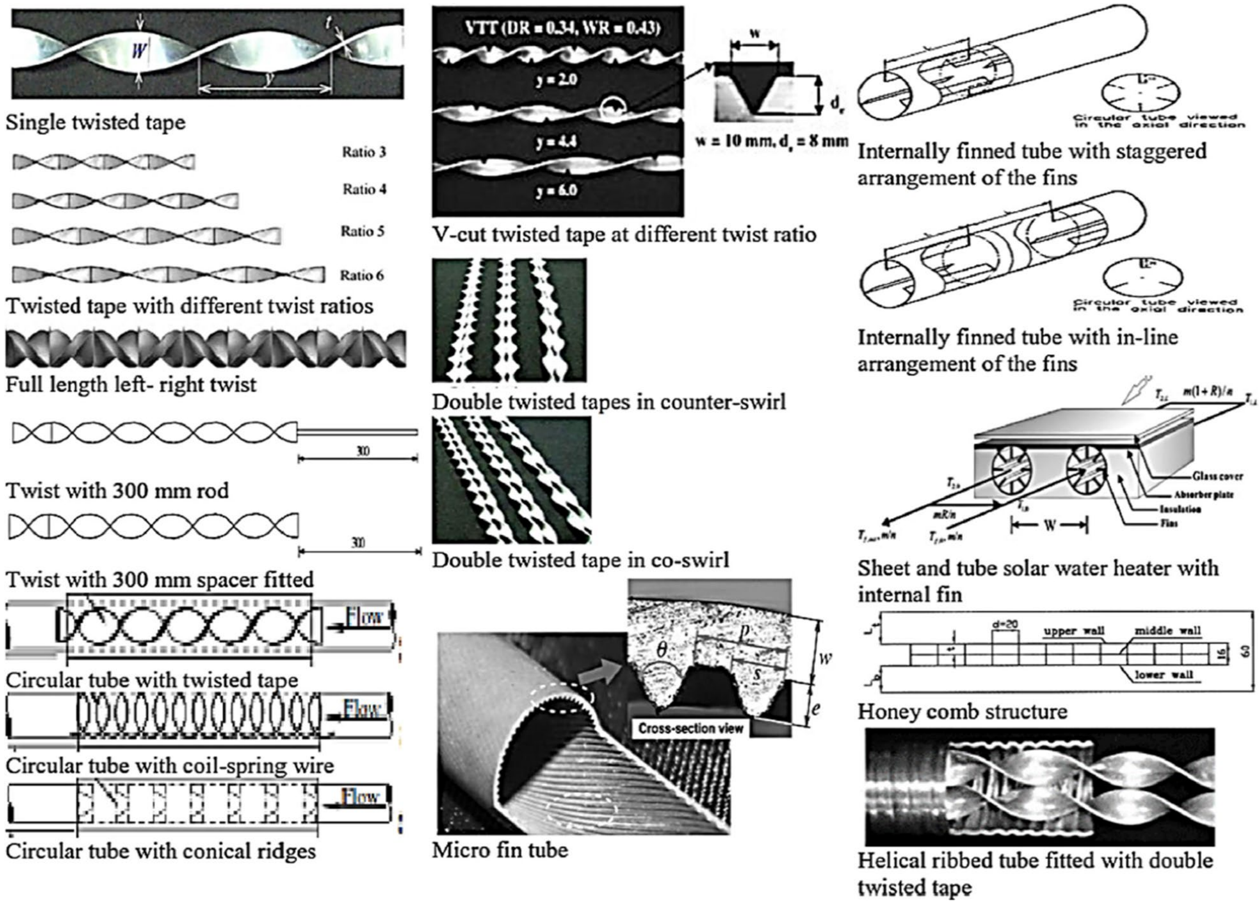

Fig. 4 Typical thermal efficiency enhancement devices (Balaji et al. 2017)

progressing up to seasonal domestic and district applications (Meister and Beausoleil-Morrison 2021; Rezapour et al. 2022; Wu et al. 2020). In addition to these methods of thermal energy storage, the phase change materials (PCM) has also become a hot topic since it has proven itself to be reliable and economical (Suwaed et al. 2023). The organic, inorganic or hybrid types of PCM has shown their abilities to yield high system performance and in combination with other methods or with other types of its kind can improve significantly in mitigating the effects of the solar time-dependency (Kurnia et al. 2022; Selimefendigil and Şirin 2022). The detailed effects of some parameters are evaluated in the next sections.

Effects of parameters on the performance of SWH system

Effect of selected heat transfer fluids on the overall thermal performance of SWH

Some researchers have studied the effect of employing various refrigerants as working (heat transfer) fluids in solar collectors (Abed et al. 2020; Ekiciler et al. 2021; Hissouf et al. 2020; Kannaiyan and Bokde 2022; Kumar et al. 2021b; Vengadesan and Senthil 2020). The selection of the heat transfer fluid for SWH design is dependent on the application and the operating temperature requirement. Based on these, Moya (2017) categorized the working fluid for PTCs into five—thermal oils, liquid–water/steam, forced gases such as N_2, CO_2 and air, liquefied salts, and nanofluids while pointing out that these can be extended to other collector types. Among sodium fluid, supercritical CO_2, water, and air as working fluids, the liquid sodium at increased temperature (540–740 °C) performs the best (Gomaa et al. 2023). Changing these working fluids also increase the performance of parabolic trough collector (PTC), and among working fluids such as water, therminol VP-1, and molten salt, the therminol VP-1 performs best at temperature range of 320–500 K (Abed et al. 2020). Ouagued et al. (2013) studied the effects of different thermal oils on the overall thermal efficiency of a PTC under different solar settings in Algeria. Among the different oils used, Syltherm 800 proved to possess the best thermal performance. Moya (2017) also mentioned that thermal oils are not the preferred working fluids because of their numerous disadvantages which include operating temperature limitation (max. of

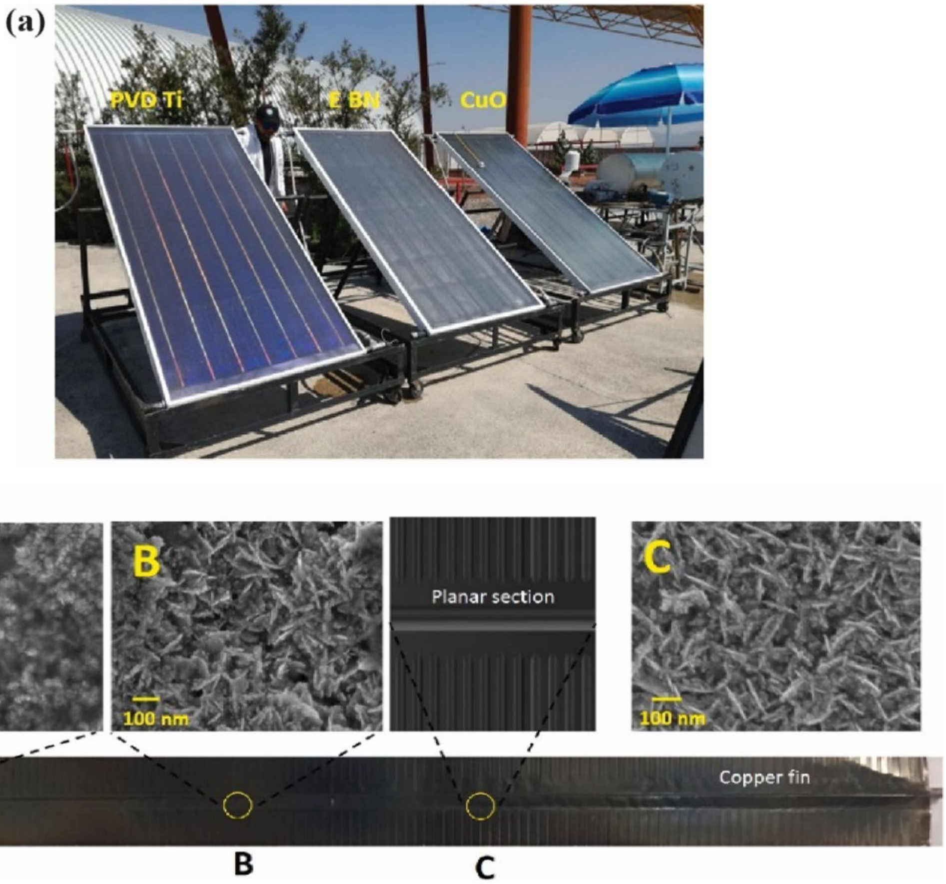

Fig. 5 **a** "Photograph of the three FPCs: PVD Ti—sputter-deposited nitrogen-doped titanium dioxide; E BN—electrodeposited bright nickel/black; CuO—copper oxide. **b** The appearance of the copper fin is enclosed with the electrodeposited black nickel selective glazing, with SEM photos shot from planar divisions of the fin as shown with alphabets A, B, and C" (Lizama-Tzec et al. 2019)

398 °C), environmental pollution, and fire dangers during oil leakage. In the same way, (Hissouf et al. 2020), showed that pure water as working fluid enhances thermal and electrical performance by 4.5% and 1.85% respectively over a glycol–water blended working fluid. To find an alternative for thermal oils, Bellos et al. (2016a, b) compared the thermal performance of a PTC when thermal oil and pressurized water were used. They found that the latter produced a superior performance than the latter due to its enhanced convective heat transfer coefficient resulting from higher thermal conductivity and dynamic viscosity of pressurized water. Montes et al. (2010) studied an exergy analysis of a PTC using thermal oil, water/steam, and molten salt, and reported that the water/steam has the best overall thermal efficiency. However, lack of a suitable 'thermal storage, complex control of the system as a result of two-phase liquid–vapor/steam flow, and decrease in high pressure because of the low density of steam at the superheated section, are the major disadvantages of adopting liquid–water/steam as the appropriate working fluid for SWHs. Compressed gases like N_2, CO_2, and air have also been tested as an alternative working fluid for SWHs because of their no fire risk and environmental pollution. CO_2 which is a greenhouse gas, however, when leaked into the atmosphere can potentially cause serious damage to the environment. Another advantage of pressurized gases is their capacity to function at elevated temperatures, and this means that efficient TES are required.

As a result of the drawbacks associated with the other working fluids, especially their low thermal conductivity, researchers came up with a way to enhance the thermal conductivity of the common working fluids by the addition of solid nanoparticles. These fluids with enhanced thermal conductivity were called nanofluids, and the size of their constituent solid nanoparticles is between 1 and 100 nm. Depending on the type of material of the nanoparticle, nanofluids are classified as either metallic or non-metallic nanofluids, and the commonly used metallic and non-metallic nanoparticles are Al, Fe, Ag, Cu, and TiO_2, Al_2O_3, carbon nanotubes (CNTs), and composite materials. The use of nanofluids in SWH applications has been carried out experimentally and numerically over the years. Menbari et al. (2016) experimentally studied the effect of CuO/Water nanofluid on the thermal performance of a 'direct absorption parabolic trough collector' (DAPTC). They reported that the thermal efficiency of the DAPTC improved from 18 to 52% when the volume fraction of the CuO nanoparticles was increased to 0.002 and 0.008%, respectively. Menbari et al. (2017) also investigated the performance of a 'direct absorption solar parabolic trough collector' (DASPTC) using a nanofluid made up of two nanoparticle types (CuO and □-Al_2O_3) in EG, water, and water/EG. They found that the thermal performance of the DASPTC was higher when water was used as the heat transfer fluid, compared to when a mixture of water/EG was used. To improve the heat transfer processes of the HTF in SWH applications by improving its thermal conductivity, Moghadam et al. (2014) performed an experiment to study the effect of Copper (II) oxide–water nanofluid on the performance characteristics of FPC under the weather condition in Mashhad, Iran. The results showed that the CuO-water nanofluid enhances the solar collector efficiency by 16.7% when compared with water alone at the maximum flow rate operation of the HTF (3kg/min). Other numerical studies on the influence of nanofluids on the thermal performance of SWHs can be found in Table 2. Also, recent comprehensive reviews on how selected working (heat transfer) fluids of solar collectors could control the total thermal performance of solar water heating system schemes can be found in Anbarsooz et al. (2020), Muhammad et al. (2016).

Effect of mass flow rate of the working fluid on the performance of the SWH

The fluid exit temperature and the overall thermal performance of SWHs are affected by the mass flow rate of the HTF during operation, and not just on their thermophysical properties. Theoritically, the higher the flow rates, the lower the temperature difference, and this evidently affects the solar-to-fluid heat transfer rate, and the consequent efficiency of the system. To back this up, Mandal and Ghosh (2020) investigated experimentally the efficiency of a two-pass SWH with a reflector in Bangladesh during the month of November. The study aimed to weigh the efficiency of this type of system based on flow rate variations. The authors collected data at various mass flow rates at 30 min intervals when solar irradiance varies between 3.8 and 6.4 kWh/m^2/day. The result of the study indicated that the efficiency rises with a rise in the mass flow rate whereas the temperature difference in the working fluid at both inlet and exit of the solar collector reduces with an increased flow rate. They also compared the thermal performance of single- and double-pass SWHs, and their data showed that the latter was more efficient than the former [see Fig. 6].

Table 2 Summary of articles that carried out studies of the effect of nanofluids on the performance of SWHs

Author, (year)	Type of study	Observation
Sokhansefat et al. (2014)	Numerical	Heat transfer coefficient enhanced with the presence of nanoparticles but decreased with an increased operating temperature of the absorber tube hence, the application of nanoparticles achieves reduced heat transfer areas in PTC systems
Mwesigye et al. (2015)	Numerical	The thermal efficiency of the receiver improved by nanofluids up to 7.6%
		Conclusively, beyond certain Reynolds numbers application of nanofluids becomes thermodynamically undesirable
Bellos et al. (2016a, b)	Numerical	Thermal oil with nanoparticles showed the best working fluid performance compared to pressurized water as a result of high-pressure level demand
		The study further revealed that the wavy collector design improved the average efficiency by 4.55%, but increased the pressure losses
Mirzaei (2017)	Experimental	Efficiency decreases as HTF decreases
		CuO nanofluid provides better improvement than the Al_2O_3
Mwesigye and Meyer (2017)	Numerical	The optimal flow rate of about 22.5 m^3 h^{-1} was achieved for all the considered nanofluids and parameters
		Huge potential for energetic and exergetic performance improvement with high concentration ratios was also observed
Genc et al. (2018)	Numerical	Nanoparticles were more effective at flow rates below 0.016 kg/s on the exit temperature of FPCs. The method of analysis was recommended for PV/T systems
Mohammed et al. (2021)	Numerical	Hybrid nanofluids showed superior thermal performance and boosted the thermal efficiency of the PTSC by 11.5%. The results were recommended for PTSC industry further development
Thulasi et al. (2021)	Numerical	The thermal performance of a SWH was enhanced with Epsom salt. The study indicated that 92% thermal efficiency higher than the 82% common SWH efficiency was observed

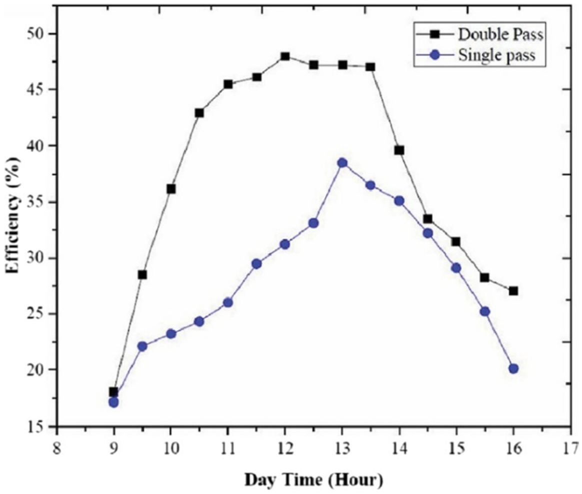

Fig. 6 Thermal efficiency versus day for the single-pass and double-pass SWHs (Mandal and Ghosh 2020)

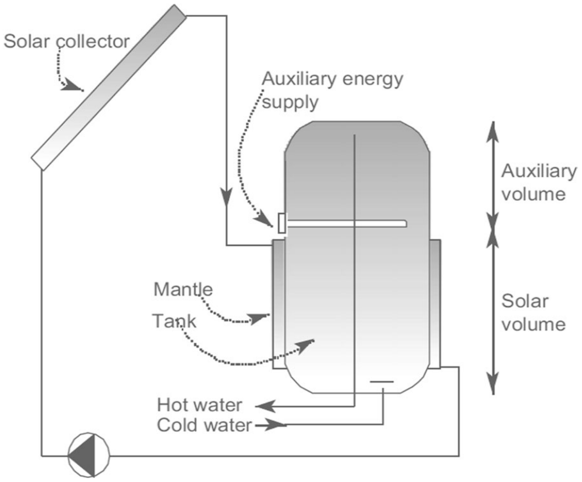

Fig. 7 Schematic of low-flow domestic SWH system centered on mantle tank (Cabeza 2021)

Effect of the hot water storage unit on the performance of SWHs

In most cases, standard hot water tanks are integrated into solar collectors, and the problem of this component is the rate of heat loss through conduction, convection, or radiation and imbalance between hot water supply and demand (Balali and Stegen 2021; Tahiri et al. 2023; Xu et al. 2022). Designed solar tanks for TES particularly are manufactured in lesser numbers and this constitutes their high costs (Cabeza 2021). The hot water storage system is also a major determinant of the price of SWHs and studies have shown that the mantle tank is the best domestic solar water system (Zhang et al. 2023a, b) and this include for a recent analysis of the use of hot water tanks for district heating and cooling (Roncal-Casano et al. 2023). Figure 7 shows the typical mantle tank for low-flow domestic water heating. The tanks are appropriate for domestic water heating up to 20 m^2, having a tank capacity of 1000-L. Note that in some cases, pumps are used to enhance the mixing of cold water and hot water in the storage tanks to improve their performance (Patel et al. 2012).

For large domestic SWHs, thermal energy storage tanks having an inlet stratifier and external heat exchangers are preferred (Cabeza 2021). The function of the inlet stratifier is to direct the hot water leaving the heat exchanger to a level with the same temperature in the tank. The integration of the inlet stratifier was predicted to enhance the overall thermal performance of large-scale domestic SWHs, and this was validated by Furbo et al. (2005a, b) in their study of a 336-m^2 low-flow SWH system centered on this hot water storage design, which to date remains the large-scale domestic SHW system with the highest thermal performance in Denmark (Cabeza 2021).

Improvemet and future modification of the hot water storage unit

Some researchers have suggested that smart solar hot water tanks are required to further improve the performance of SWHs (Løvstakken 2022; Lyden and Tuohy 2022). Even as far back as 2005, an investigation on smart solar water storage tanks for residential applications reported that the annual thermal efficiency of home solar hot water technologies with smart thermal energy storage tanks was 5–35% greater than that of a conventional solar hot water system (Furbo et al. 2005a, b). This study also claimed that the overall performance and the cost ratio have a possibility of being improved by 25% when a smart solar tank is used as a substitute for the conventional type. Conventional hot water tanks often allow cold water to enter the tank while hot water is still present, and vice versa for seasonal hot water storage. This process consumes more energy as the system has to heat or cool the water again, making it inefficient. However, a smart water tank, as conceptualized and shown in Fig. 8, can improve the thermocline properties of the hot water in the tank, reducing heat loss and improving reheat time (Li et al. 2022). This tank can also automatically adjust to varying hot water demands, in terms of temperature and volume, making it suitable for unknown and variable hot water consumption. This feature reduces the size of solar water heating systems and tank volumes (Cabeza 2021).

Modeling and control of SWHs: future direction

Due to variations of solar radiation at every location because of factors such as cloud cover, air pollution,

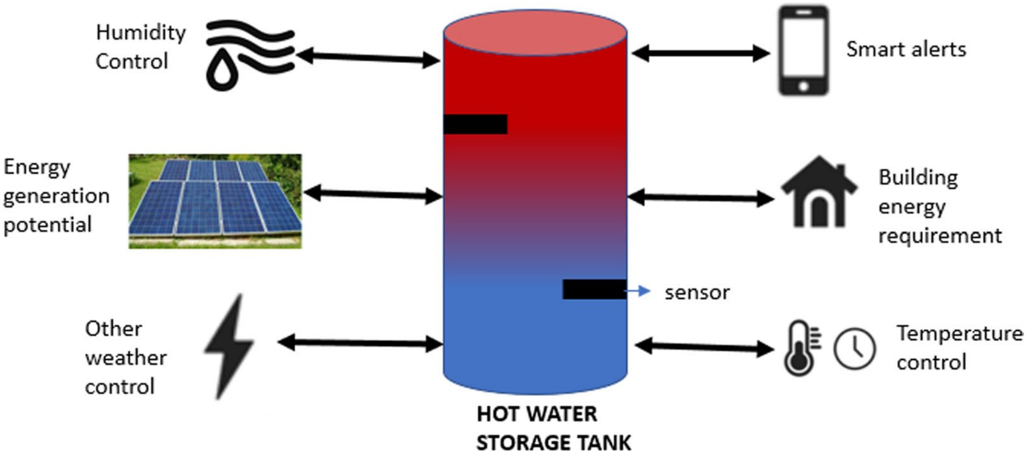

Fig. 8 Conceptualised smart hot water tank

seasonal all change, and even abrupt climate change, SWHs must be designed to optimize their overall thermal efficiency by adjusting their mode of operations based on the existing solar radiation (Yadav et al. 2022). Developing an advanced control algorithm to regulate fluid flow can reduce system operation, cost, and improve efficiency. Recently, the modification of the SWH system using the problem-solving method under working conditions was carried out by Obstawski et al. (2020). The study found that one of the limitations of solar water heaters (SWHs) is the inability to control the volume flow rate of the working fluid in accordance with the system's operating conditions. To address this issue, it in necessary to develop a technique that compares the characteristics of an analog model with a digital model to determine how solar systems behave in different working environments. An example of a control method, where the energy generation from the solar PV/PVT are monitored for more efficient system was conceptualized and tested as shown in Fig. 9 (Hachchadi et al. 2023).

With the combination of modeling and experimental studies Liu et al. (2017) designed an improved water-in-glass (WIG) SWH, made of an evacuated tube with the use of High-throughput Screening (HTS) artificial

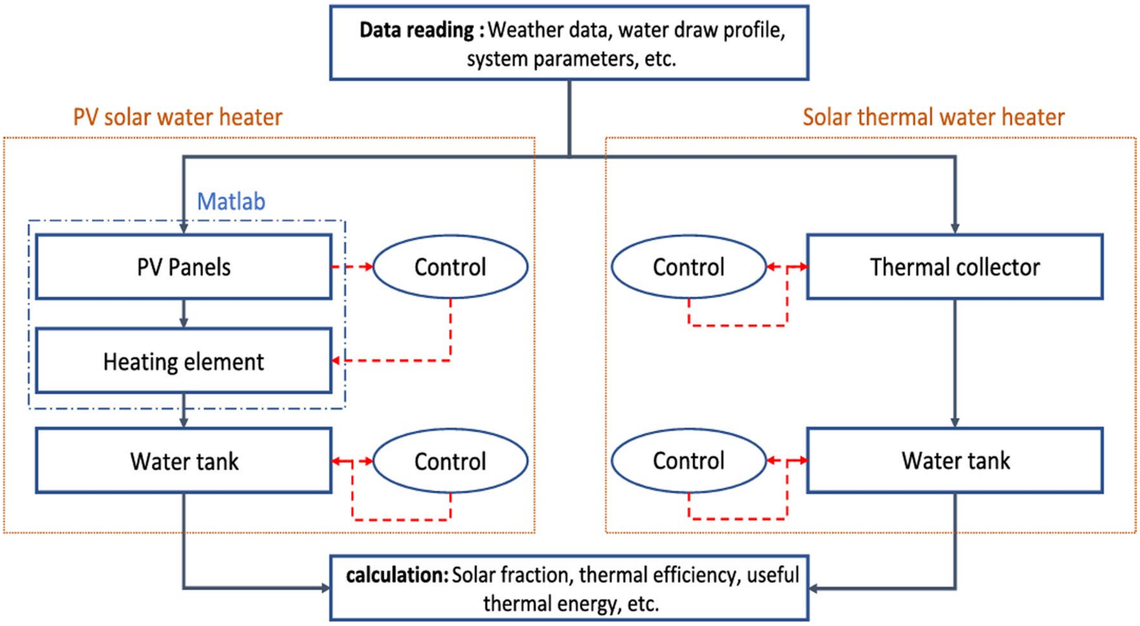

Fig. 9 Concept of solar water heating system with control method (Hachchadi et al. 2023)

neural network machine learning. Comparative analysis of the results indicated that both the ANN model and the experimental results showed improved heat collection rates. This study is a proof that HTS approach can be used to improve the design of water-in-glass SWHs taking into consideration both extrinsic and intrinsic characteristics and the heat absorption rates. The working principle of water-in-glass evacuated tube SWH (WET –SWH) has been discovered to be different during nocturnal and diurnal periods (López-Núñez et al. 2022). There is a tendency for FPC, ETC collectors to experience a reverse flow during the night and this occurrence affects the thermal characteristics of the systems; hence the thermal evaluation of WET –SWH was carried out experimentally in Tang and Yang (2014) at night for validation of the hypothesis. The result showed that the temperature in the flow channel is always lower than the temperature of the water in the storage tank and the ambient temperature, as well as the temperature expected if there is no reverse flow. In addition, the study found that the reverse flow in SWHs occurs at night and reduces their thermal performance by taking between 8 and 10% total energy loss in the SWH system. Further to this, the flow rate is found to be dependent on the collector's angle of tilt.

The studies on modeling and control is very crucial in the optimization of SWH technology. If systems are able to operate smartly through advanced control strategies by sensing on its own the low, moderate and mild weather conditions, no doubt that their efficiencies will be enhanced. At this stage where seasonal capturing and storing of solar energy for commercial and domestic use is of the greatest interest, a complex configuration and advanced control strategies may be required. Through this application, the absorptivity of the collectors maybe improved. Additionally, the inter-seasonal charging and discharging of the water storage systems will be performed efficienty and surplus energy generation in the case of solar PVT systems may be utilized more efficiently.

Techno-economic analysis of solar water heating technology

Due to the huge part that the economic viability of projects and processes play in sustainable development, some researchers, over the past decade, have ventured into the techno-economic aspects of solar water heating to compare their benefits over conventional heating systems when deployed for domestic and industrial applications. Material availability and cost, existing energy policies and incentives, and most importantly, the annual average solar radiation availability in different countries are the reasons varying deductions and conclusions have been drawn on the commercial viability of solar water heating. The techno-economic analyses takes into account various factors, including the initial capital cost, operational and maintenance expenses, grid energy expenditures, salvage value, and inflation rate throughout the economic lifespan of the project. In other words, techno-economic analyses are often presented as case studies.

More to this includes the study by Tian et al. (2018) who carried out a techno-economic investigation of a combined solar heating plant [see Fig. 10] using a valid computer model known as TRNSYS-GenOpt to develop a novel approach that optimizes the hybrid solar system based on the Levelised Cost of Heat (LCOH) and taking into account the system designs specifications and components. The study showed that the LCOH can be minimized by 5–6% using solar collectors in district heating systems and the PTCs are economically viable for such systems, especially in Denmark.

In a Namibia-based research, the net-present-value (NPV) financial approach was used to determine the payback periods of solar water heating systems (SWHs) (Dobreva and Kwarikunda 2024). The results indicated that SWHs had payback periods of 11.6 and 13.5 years in Dobreva's and Kwarikunda's studies, respectively. Additionally, fully paid upfront SWHs were associated with a high return on investment ranging from 8 to 11%. However, loan-financed SWHs yielded negative returns on investment with payback periods extending beyond the lifespan of these systems according to their findings.The literature highlights that solar water heating systems have cost-saving benefits compared to fossil fuel-based heating systems. For instance, Zhang et al. found that implementing a hybrid solar/heat pump system in Nagarze County, China resulted in significant savings of approximately NGN 865,668.80 or 46.8% compared to previously utilized baseline heating methods (Zhang et al. 2023a, b). The study concluded that the optimized system combining a concentrated solar district heating system with a water-to-water heat pump demonstrated significantly improved performance compared to using a single unit system. Specifically, the solar fraction and levelized cost of heat (LCOH) were enhanced from 53.26% and 0.2750 CNY/kWh to 74.17% and 0.2297 CNY/kWh respectively for an expansive heating area of 200,000 m^2. In fact a more detailed study conducted on the techno-economic and environmental impact of two distinct solar water heaters for evaluation of their effects on reduced emissions and cost-savings in homes was recently studied by Agyekum et al. (2024). The results revealed that depending on the location at which either flat plate (FPC) or evacuated tube (EPC) SWHs were installed,

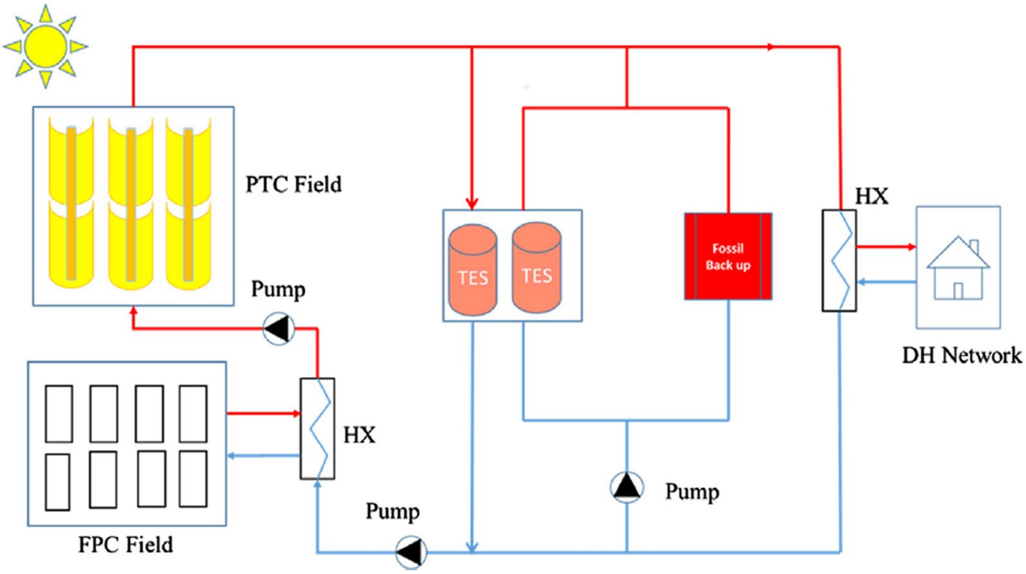

Fig. 10 Process diagram of the hybrid solar thermal system (Tian et al. 2018)

payback periods ranging from 3.2 to 4.4 years for FPC systems and 3.5 to 4.3 years for EPC systems could be achieved respectively. Additionally, levelized energy costs were found to vary between 7.47 and 9.62 cents/kWh for FPC systems and between 7.66 and 9.24 cents/kWh for EPC systems based upon where the SWH system was situated. Annual cost savings associated with implementing an FPC system ranged from $486 to $625 while those associated with an ECP system ranged from $529 to $638 depending on geographical location of installation. Moreover, Agyekum et al. contends that the utilization of SWH technology can result in a substantial reduction of CO_2 emissions, with evacuated tube systems achieving an impressive annual decrease of 75–77%, while flat plate systems can still yield a significant decline ranging from 69 to 76% per year. Furthermore, an extensive techno-economic analysis conducted in India has demonstrated the economic viability of solar water heating technology, with remarkably low levelized cost of heat and payback period values (Chopra et al. 2023). The study optimized the technical performance of SHW by implementing a Monte Carlo Technique (MCT) and Multi-energy/economic relations to identify the most suitable location for installing solar water heaters based on high solar radiation. This strategic approach significantly reduced the ratio of annual energy demand to annual solar radiation, resulting in mean values for Levelized Cost of Water Heating (LCWH), Net Present Value (NPV), and Payback Period (PP) at 5.14 INR/kWh, 663,788.48 INR, and 5.84 years respectively. It was observed that MCT provided more accurate forecasts by considering a range of states according to their probability; thus increasing efficiency while maintaining precision.

Improving the economic feasibility of SWHs

It is noteworthy that the implementation of integrated systems, such as hybrid system shown in Fig. 10 or photovoltaic-thermal (PVT) systems, which incorporate solar PV panels with heat extraction and cooling designs, has been reported to enhance both the efficiency and economic feasibility of solar water heating systems (Awad et al. 2023). Moreover, Compound Parabolic Collectors (CPCs) have been shown to surpass flat plate collectors in terms of auxiliary power consumption and economic viability (Azad Gilani and Hoseinzadeh 2021). In particular, integrated systems exhibit a shorter payback period in comparison to singular systems according to Azad Gilani and Hoseinzadeh (2021). An evacuated tube collector based solar water heater demonstrated an energy payback time of 1.14 years at the ETC tilt angle of 15, exemplifying this principle. The maximum carbon credit earned falls within the range of $291.51–$1166.03. The aforementioned solar water heater displayed varying payback times ranging from 1.67 to 2.26 years depending on different tilt angles; however, it was found that a minimum value was achieved for ETC with a tilt angle of 15 while maintaining experimental uncertainty variation within the bracket of 0.161% and 0.254%. This solidifies the fact that unique circumstances and location play pivotal roles in determining the differing payback periods associated with solar water heaters overall. In India, the period for recouping the investment in a solar water heater spans from 2.5 years when substituting an electric geyser to 6.5 years when replacing a gas geyser (Dhiman and Sachdeva 2021). In Romania, the duration for recovering the initial cost of installing solar water heaters ranges between 6.8 and 8.6 years with overall savings amounting to €805-€1151 over a quarter-century (Farooq and Zhang 2022; Şerban et al. 2016). Conversely, in Taiwan, residential solar water heaters have shorter payback periods when supplanting electricity as compared to utilizing conventional fuel (Lin et al. 2016). Hohne et al. (2018) did a financial analysis of a hybrid SWH system centered on a regulator and optimal governor using a numerical approach. The input data for use in developing the model for the study were obtained from local weather stations in South Africa, taking into consideration the thermal energy need for a medium-populated household, i.e., about 3 occupants. Hohne et al. (2018) reported the possibility of approximately 84.39% savings during the cold (winter) period and 15.50% during the hot (summer) season with a yearly savings of R532.32 (32.86%).

Zainine et al. (2017) in a case study carried out energy performance and financial investigation of an existing SWH system simulating different values of the fluid flow rate in south Tunisia using TRNSYS. The system comprises both primary and secondary circuits with an integrated model of a mechanical pump for its energy consumption evaluation. The simulation outcomes were compared with a real-time experiment and the results indicated that the best flow rates values that would yield the maximum annual useful energy were 10 kg/h m^2 and 15 kg/h m^2 for the primary and secondary circuits, respectively. Zainine et al. (2017) concluded that it is more economically viable when the auxiliary heater of SHW is a gas heater than when it is a conventional electrical heating system.

Hossain et al. (2016) also presented investigation results on the thermal and economic analysis of what they claimed to be a cheap enhanced flat plate SWH with the parallel two-side serpentine flow in Malaysia. They claimed that their system yielded higher thermal efficiency than those investigated by other authors. They went further to report that their SWH system is economically attractive to conventional electric-based water heaters, based on their fiscal analysis carried out using MATLAB. A more comprehensive review of the economic viability and market trends on SWH can be found in Gautam et al. (2017).

Based on the reviewd literature, the payback period, return on investment, salvage value, and other economic indicators may differ based on the geographic location of implementation and various variables present in each individual scenario under consideration, such as system design. The economic indicators of solar water heaters are indicated in Fig. 11 with formulas for their calculations explained in detail in Eze et al. (2022).

The existing techno-economic analyses have shown that SWHs, either as stand-alone systems or together with other water heating systems as hybrid systems, can be developed and implemented to be economically attractive, especially in the regions with significant average annual solar irradiance. To see widespread acceptance and installation of this technology, national and international government agencies/organizations responsible for driving renewable energy development should come up with renewable energy policies that recognize SWHs as a sustainable alternative to conventional hot water systems and also put in place incentives that would facilitate the commercialization of the technology.. Such incentives include huge government subsidies on SWHs and attractive feed-in tariffs (in the case of the regions with district hot water systems). This will drive the adoption of this technology, even to the remote areas where there is no national grid or the extension of national grid may not be economically feasible. Adopting this technology also have huge environmental benefits, especially towards mitigating climate change.

Conclusions

A fundamental review of solar water heating has been carried out in this study with a focus on highlighting and describing this renewable energy technology, including its merits and demerits. The review further discussed the historic development of SWHs and described the types of SWHs and their important

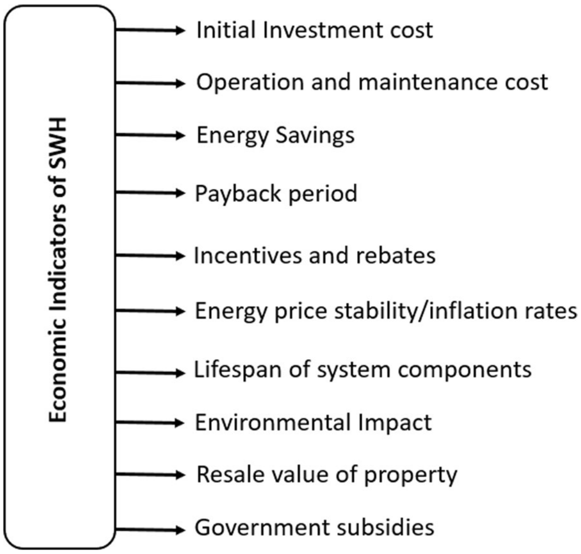

Fig. 11 Economic indicators of SWH

components—solar collectors, storage tanks, and heat transfer fluids. Four important types of solar collectors in water heating technologies were highlighted and described extensively in this study. Recent reviews and recent research advances on this system were carried out, and the following gaps have been found:

- Although the use of fins was attempted to enhance the thermal efficiency of SWHs, limited research has been done in this area. Since it was found that the thermal efficiency of this system can be improved by maintaining the temperature of the fluid in the storage tanks. This study suggests the use of computational fluid dynamics (CFD) to analyze the heat transfer profiles in the heat transport channels and the storage tanks. The result would suggest ways the temperature of the fluid can be kept constant.
- Seasonal thermal energy storage, the use of smart tanks, and underground thermal energy storage are currently an unavoidable topic. In future study, the present study recommends the application of more sophisticated and an advanced control strategy to implement an inter-seasonal SWH and storage for a seasonal use.
- Numerical and experimental analysis of combined systems such as solar collectors, heat pumps, and thermal energy storage for water heating is limited in the literature. This study recommends the addition of PCM within the storage tank for heat retention enhancement and provision of solutions to the diurnal-nocturnal behavior of solar energy especially in the application of domestic space heating and cooling.
- It has been discovered that thermal stratification in storage tanks affects the charging and discharging of PCMs when they are incorporated. This study recommends the positional integration of PCMs in the thermal energy storage tank to provide a solution to the existing thermal barriers.
- Detailed analysis of the Levelized cost of heat (LCOH) and the life cycle analysis (LCA) of various designs of SWH is limited in the literature. The analysis of these factors will enable a proper understanding of the economic benefits of the installation and use of SWH systems.
- To further explore the opportunities and impeding factors in the adoption of SWH, especially in the developing countries, this study recommends in the future research, to use the Analytical Hierarchy Process (AHP), Fuzzy-TOPSIS, and Data Envelopment Analysis (DEA) methodologies to assess the choice selection of consumers, and possibly use the quality function deployment (QFD) strategy to promote a fast uptake of the technology.
- Government spending in terms of active funding and investment into R&D programs should be recognized as crucial to making progress in substituting conventional unsustainable electricity- and/or liquid/solid fossil-based heating systems. This would make a significant contribution to reducing global energy poverty and mitigating climate change.
- The economic viability of SWHs has been a major consideration for investors' participation in driving market development of the SWH technologies. Recent studies on the economic investigation of SWHs reveal a paucity of country and regional techno-economic-based research that would highlight more economic indicators that could be optimized to achieve more return on investment (ROI). In addition, this would attract further investments and influence government policies toward supporting greater investor participation.

Abbreviations

AHP	Analytical Hierarchy Process
ANN	Artificial Neural Ntework
CFD	Computational Fluid Dynamics
CNTs	Carbon Nanotubes
CPC	Compound Parabolic Collector
DASPTC	Direct Absorption Solar Parabolic Trough Collector
DEA	Data Envelopment Analysis
EPC	Evacuated Plate Collector
FPC	Flat Plate Collector
HTF	Heat Transfer Fluid
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCOH	Levelized Cost of Heat
LCWH	Levelized Cost Water Heating
LHS	Latent Heat Storage
LTS	Latent Thermal Storage
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
PCM	Phase Change Materials
PDR	Parabolic Dish Reflector
PTC	Parabolic Trough Collector
PV/PVT	Photovoltaic/Photovoltaic Thermal
QFD	Quality Function Deployment
RE	Renewable Energy
RIO	Return on Investment
STS	Sensible Thermal Storage
SWH	Solar Water Heating
TES	Thermal Energy Storage
WET–SWH	Water-in-glass Evacuated Tube–Solar Water Heater

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Author contributions

FE: Conceptualization, methodology, writing—original draft; ME: formal analysis, writing—review and editing; UJA: writing—review and editing; ORN: writing—review and editing; JO: supervision, writing—review and editing; JM: supervision, writing—review and editing. All authors have read and approved the manuscript.

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Competing interests
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