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Hybrid Technologies for Water Heating Applications: A Review

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Highlights

- The most recent advancements in water heating technologies are discussed.
- A mathematical model for various hybrid technologies is presented.
- Various optimization methods for water heating technology are examined.
- The use of nanofluids in hybrid technology is discussed.
- Future prospects for hybrid water heating are discussed.

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Abstract

The over-reliance on fossil resources necessitates the development of a sustainable energy system. Renewable energy and efficient hybrid water heating technologies are viable net-zero energy options. The economic benefits of these hybrid technologies offer a promising prospect for widespread adoption in developing countries as a means of increasing the hot water production. These hybrid technologies are becoming increasingly popular for domestic thermal applications in remote areas to compensate for energy shortages. This paper provides an overview of hybrid renewable water heating technologies with a focus on hybrid configurations, optimization techniques, mono-particle, and hybrid nanofluids and modelling. This paper also highlights the prospects for increasing the economic attractiveness and public acceptance of such systems.

1. INTRODUCTION

Energy and water are indispensable needs of human survival. They are needed for domestic use such as water heating and drinking. Therefore, energy efficiency can reduce costs while also addressing environmental concerns. Global energy deficit is currently a major concern in the energy sector. As a result, rising energy demand drives up the consumption of fossil fuels, contributing to global warming and climate change [1]. As shown in Figure 1, conventional electric equipment dominates the heating market, accounting for 80% of total sales in 2019 [2]. Therefore, the over-reliance on fossil fuels necessitates a sustainable energy system that is eco-friendly and cost-effective. Furthermore, Furthermore, rising concerns about energy efficiency, climate change, and public health have piqued the interest of researchers, scientists, and governments in exploring hybrid renewable energy (HRE) technologies as a viable alternative to global energy insecurity [3]. Notably, an increasing number of remote areas are off-grid, and their demand for thermal load can be met using renewable energy (RE) technologies. Hence, HREs are deployable renewable energy integration systems that compensate for energy shortages. These technologies are becoming increasingly popular for rural electrification, water heating, and other applications. One major area of global interest is the use of hybrid technology in residential hot water [4–10]. Water heating is the third-largest consumer of household energy besides space heating [11–13]. According to several studies, building accounts for 42% of global energy demand [14]. Almost a quarter of this energy is used to heat bath water [15]. Despite their high energy consumption, electric water heaters predominate in a majority of households. To save costs and minimise energy usage, electric water heaters have been replaced with RE technologies. Although, the sporadic and unpredictable nature of renewable energy sources is a drawback

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that limits their optimal utilisation, resulting in a loss of hot water availability [16]. Therefore, a single renewable source is insufficient to address the issue of energy reliability. To address these issues, a combination of energy sources capable of producing hot water independently is required. In this regard, HRE technology has proven to be a promising option [17]. This scheme combines two or more renewable sources with a conventional energy source and a storage unit, which help to improve energy efficiency, and maintain hot water availability. Recently, solar PV, wind geothermal, and solar thermal collectors have been combined with water heating; however, several questions remain such as (1) what combination of RE technologies will be most effective? (2) What is the most cost-effective component sizing for RE technologies? (3) What is the most cost-effective component sizing for RE technology? and (4) how much do economic and environmental constraints influence these combinations? To answer these questions, it is necessary to consider optimization methods that address conflicting objectives functions when using this syergistic combination.

Several optimal control schemes for HRE systems with various energy sources and water heating technologies have been reviewed [17–22]. [23] proposed a predictive control for a hybrid PV/Grid/battery system, while in Langer and Volling [24], predictive control model algorithms are proposed for hybrid PV/battery/ thermal storage/heat pump water. Further, [25] presented an optimal sizing model for a combined PV/fuel-cell/wind/grid power systems. The objective functions in this model are to reduce grid costs and increase fuel-cell based on time-of-use (TOU) electricity tariffs. In Sichilalu et al. [26,27], the same author proposed a size optimization model for hybrid PV/wind/heat pump water heaters. They established an optimisation function that minimizes the costs of electricity for hot water while taking TOU into account. In another study, [28] developed a sizing model of hybrid PV and heat pump- instantaneous shower was developed. In [29] the author also used a more advanced control strategy, to ensure the efficient operation of a combined heat pump water heater-instantaneous shower systems linked to a RE system. Multi-objective optimization of hybrid energy system ased on genetic algorithms is presented in [30] while [31] proposed a discrete based model for integrated systems. Amer et al. [32], used particle swarm optimization to find the best model for a combined wind, PV, water heating systems. Other studies have examined the economic, technical, and environmental feasibility. For instance, performance assessment of hybrid PV/heat pump water heater is discussed in [33]. While Mehrpooya et al. [34] studied the economic and technical assessment of a combined solar collector/geothermal heat pump based system. Techno-economic assessment of hybrid PV-T-heat pump water heater is introduced in [35,36]. Li and Kao [37], studied the effectiveness of solar heat pump water heaters. Using TRNYS software. Also, [38] investigated the thermal energy of hybrid PV-T/storage tanks/heat pump systems. Nasruddin [39], presented an economic assessment and optimization model for hybrid PV/heat pump water heaters using a genetic algorithm. The objectives of this study are to provide an overview of hybrid renewable heating technologies, with a focus on hybrid configurations, modelling, and nanofluids and to present the use and of optimization techniques for optimal energy control of hybrid water heating systems, which has received little attention in the literature. Further, the inclusion criteria is formulated based on the concept presented in Table 1.

Table 1. *Selection and rejection criteria*

Selection Metrics	Criteria for Selection	Criteria for Rejection
Publication Year	Reviews and Articles papers published from 2012 to 2021	Review and articles published before 2012
Evaluation	Research focuses on hybrid water heating systems, heat pumps and optimization	Research includes water heating, simulation,
Comparison	Research focuses on renewable hybrid energy systems, heat pump, genetic algorithm, particles swarm optimization, nanofluids, and hybrid nanofluids	Research involves on electric water heater, thermal performance without heat pump, and optimisation of power systems.
Applications	Research focuses on heat pump water heater, optimal energy control, water heating applications, nanofluids applications in solar collector systems	Research involves on optimal sizing, thermal design, and nanofluids applications for solar energy systems

Study	Research focuses on theoretical modelling and experimental results.	Research includes short communication, case studies, and other related papers unstructured in English.

The following are the novelties of this paper:

1. A comprehensive study of recent hybrid technologies for water heating systems, their configurations, and applications was discussed.
2. Various types of optimization techniques for hybrid water heating technologies were identified and discussed. The use of genetic algorithms, particle swarm optimization, hybrid optimization, and mixed integer nonlinear programming was extensively discussed. Previous works on the application of optimization on HRWHs, as well as their comments, were also highlighted.
3. An elaborate study of the several HRES model and component mathematical models was presented. The mathematical models include photovoltaic cells, wind generators, solar thermal collectors, heat pump water heaters, batteries, and fuel cells.
4. The use of mono-particles and hybrid nanofluids in hybrid water heating systems was presented. The use of hybrid nanofluids in flat-plate collectors, evacuated tube collectors, and photovoltaic/thermal collectors was discussed.

This study aims to present the most recent developments in hybrid technology used to supplement solar water heaters and to suggest potential solutions to the challenges of hybrid technology in domestic applications. To the best of the author's knowledge, research on hybrid water heating technologies is rarely published. Several previous studies and reviews focused on SHW technologies and their future prospects. The information presented in this paper will be a valuable resource for those interested in conducting research or projects involving hybrid technologies for water heating applications. In addition, this review paper summarizes numerous key findings related the topic of discussion, it would help the readers to assimilate relevant information that suits their research. Furthermore, this review will also help researchers understand the best optimization technique to use when solving discrete-continuous variable optimization problems that may arise during the formulation of the objective function. Furthermore, identify areas that require additional research and investigate the potential use of hybrid solar thermal/heat pump water heaters in the increasing thermal generation in the majority of developing countries.

2. OVERVIEW OF HYBRID RENEWABLE WATER HEATING TECHNOLOGIES

Recent research on hybrid water heating technologies for water heating has focused on sustainable energy to overcome the problems of excessive reliance on fossil fuels. Solar and wind energies are now being combined to co-generate hot water for home and industrial use. Furthermore, excellent efficiency, enhanced coefficient of performance (COP), and significant energy saving capabilities of HPWH have been integrated with renewable sources to assure high thermal reliability. Grid systems (GS), batteries, fuel cells (FC), and diesel systems (DS) are employed as backups for most hybrid systems because RE sources are inconsistent and unpredictable. Fuel cell technology has been used in place of batteries due to its high efficiency and energy storage capacity to produce hot water, along with a wind generator and a HPWH. Hybrid water heating technologies are a highly efficient heating systems that uses minimum energy cost. As a result, several hybrid configurations have been exploited, and the search for new developments continues.

2.1. Photovoltaic-Grid-Battery-Heat Pump Water Heater

This system comprises PV modules, a grid system, a battery with an inverter, and an HPWH to meet hot water and other domestic demand, as shown in Figure 1. The solar cells produce the heat energy needed to power both the HPWH 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. In South Africa, the system configuration is thriving [40].

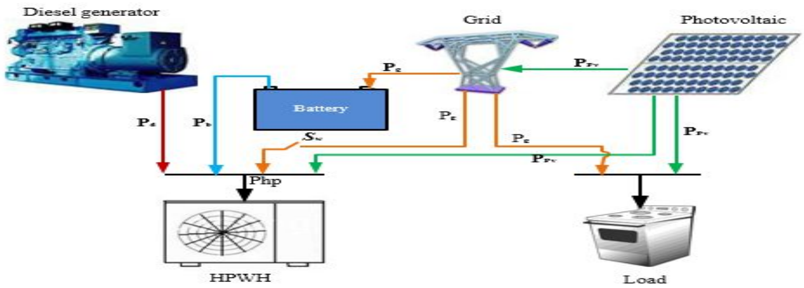

Figure 1. *Hybrid system configuration* [41] *modified*

2.2. 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 2 depicts the system configuration.

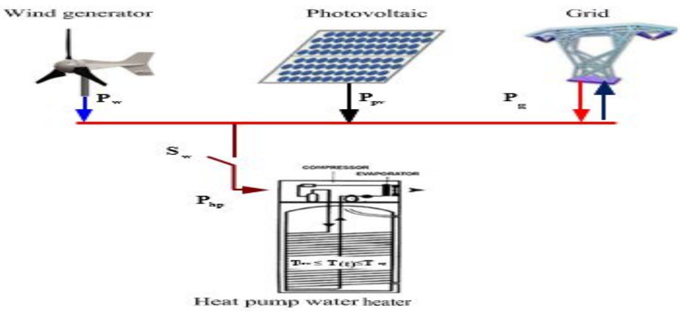

Figure 2. *Schematic of hybrid Photovoltaic-Wind-Grid-Heat Pump configuration [42]*

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

This framework comprises PV cells, wind generator, fuel cell, grid system, and HPWH (Figure 3) for generating hot water. RE sources complement each other because of their inexhaustibility. Consequently, excess solar and wind energy is used to power electrolyzes, which are then stored as a backup. The fuel cell is utilized to power the HPWH when RE sources are unavailable, guaranteeing that hot water is accessible for water heating. In the absence of RE sources, the fuel cell is engaged to power the HPWH for hot water availability.

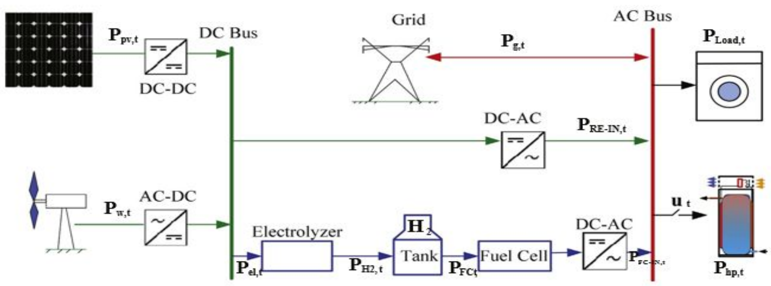

Figure 3. *Schematic of hybrid photovoltaic-wind-grid-fuel cell-heat pump water heater [43]*

2.4. Solar Thermal -Heat Pump Water Heater

In Figure 4a, the solar collector and heat pump water heater can be used interchangeably. Solar collectors have been combined with other traditional energy sources to generate hot water for domestic and industrial use. Thus, the shortcomings of solar water heating systems were mitigated by this hybrid system, allowing them to perform more efficiently. Flat plate collectors dominate the household heating market and concentrating collectors are used in industrial applications where higher temperatures are required, such as space heating or process steam generation. Such a combination allows for efficient utilization of both technologies when there is variability in solar irradiation levels; thus permitting an HPWH system to act as a heating thermal backup during demand.

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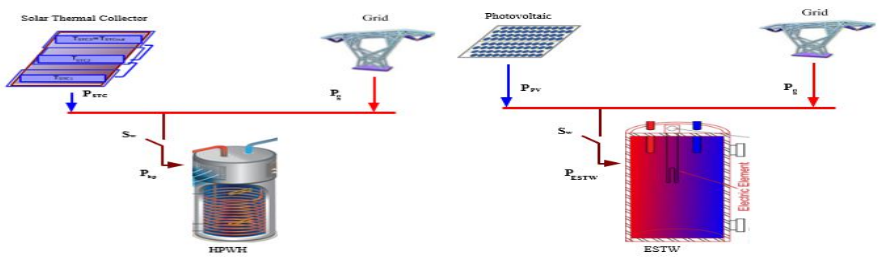

(a) Hybrid STC/grid with Heat Pump Water Heater (b) Hybrid PV/Electric Water Heater

Figure 4. *Schematic of hybrid renewable water heating technologies*

2.5. Solar -Electric Tank Water Heater

This hybrid scheme combines a solar water heater, electric water heater, and thermal storage to enhance hot water availability, as illustrated in Figure 4b. This synergistic combination ensures that the end-user has constant access to hot water. Solar water heating is a time-varying RE source that is affected by solar irradiation intensity, weather fluctuation, and the temperature of PV cells. Although, 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. Its thermal storage potential makes it a preferred option in most residential households. These hybrid systems 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 system configuration is widely accepted in nations such as South Africa, Nigeria, China, and the United Kingdom. For the sake of brevity, all reviewed studies of hybrid renewable water technologies and their configurations are summarized in Table 2.

Table 2. *Summary of literature on hybrid renewable energy water heating technologies*

Hybrid Configurations	Year	Study Type	Author/Citation
PV/GS/HPWH	2014	Mathematical	Sichalu et al. [43]
PV/STC	2013	Numerical	Shan et al. [44]
PV/HPWH	2010	Mathematical	Li and Yang [45]
STC/HPWH	2009	Experimental	Kjellson [46]
PV/STC	2021	Mathematical	Okubanjo et al. [47]
PV/GS/FC/Battery/HPWH	2016	Numerical	Ren et al. [48]
PV/STC/HPWH	2017	Mathematical	Chen et al. [49]
PV/GS/EWH/HPWH	2017	mathematical	Wanjiru et al. [50]
PV/HPWH	2018	Experimental	Bellos and Tzivanidus [51]
PV/STC/HPWH	2019	Mathematical	Herrando and Markides [52]
STC/HPWH	2013	Experimental	Panaras et al. [53]

3. MATHEMATICAL MODELLING

Several modelling approaches have adopted by researchers for sub-components modelling of hybrid renewable water heating technologies (HRHT). The following subsections are devoted to hybrid sub-components modelling.

3.1. Photovoltaic Array

A photovoltaic (PV) cell or solar cell transforms solar energy into electricity. The PV cells are either connected as a series configuration (known as a module) or series-parallel configuration to form an array. For model simplicity, the PV model is represented by a single diode mathematical model. Solar panels with N solar cells each depend on current (I_{sp}), voltage (V_{sp}), temperature (T), and solar irradiation (G). The solar panel current and voltage are expressed as:

$$I_{sp} = I_{cell}\left(V_{spi}, T_{spi}, G\right) \tag{1}$$

$$V_{sp} = NV_{cell}\left(I_{spi}, T_{spi}, G\right) \quad . \tag{2}$$

The current, voltage, and irradiation for one single cell relate according to Equation (3)

$$I(V,T,G) = I_o \frac{G}{G_o} - I_{sat}\, e^{\frac{qv}{kT}} \tag{3}$$

where I_o is the specific cell current (A), G_o is the reference radiation (Wm^{-2}), I_{sat} diode reverse saturation current (A), k is the Boltzmann constant, q is the electron charge and T, surface temperature (K). The cumulative electric power provided by solar cells is given by Equation (4):

$$P_{sp} = \eta_{sp} A_{sp} G_{sp} \tag{4}$$

where A_{sp} , η_{sp} refer to the surface area and panel efficiency.

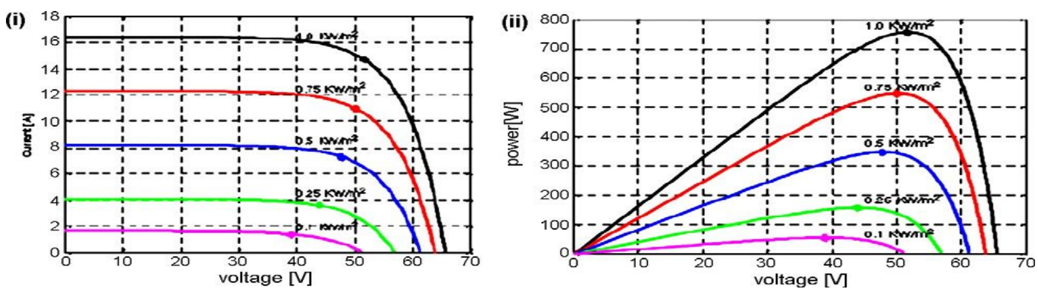

***Figure 5**. (i) Photovoltaic cell I-V curve and (ii) Photovoltaic cell P–V curve* [54]

Figure 5 depicts the power-voltage characteristic curve for a photovoltaic array functioning at a normal irradiance and temperature of 1000w/m and 25 ^{o} C, respectively. The solar irradiation G_{sp} varies with time, hence PV output depends on the solar irradiation variation, such that G_{sp} are evaluated as proposed by [55] as

$$G_{sp} = R_b\left(G_b + G_d\right) + G_d \tag{5}$$

where R_b is the tilt factor for the beam, G_b and G_d are the global and diffuse irradiation (Whm^{-2}) respectively. The theoretical relationship between the panel efficiency and the solar cell temperature is given by [56]

$$\eta_{sp} = \eta_o\left[1 - \beta_o\left(T_c - T_a\right)\right] \tag{6}$$

$$\eta_o = \eta_m \eta_{pc} \quad . \tag{7}$$

Here, η_m is the module efficiency, η_{pc} is the efficiency, T_c solar cell temperature, T_a is the ambient temperature, and β_o is the temperature coefficient.

3.2. Wind Generator (WG)

The fundamental equation governing wind energy comprises wind turbine dynamics and generator modeling. [57], uses a simplified model to explain the mechanical power produced by the wind generator

$$P_{wg} = \begin{cases} 0 & V \prec V_o \\ 0.5\eta_b \eta_{ge} \rho_a C_p A_{wg} V^3 & V_o \prec V \prec V_{rf} \\ P_{wge,r} & V_{rf} \prec V \prec V_f \\ 0 & V \succ V_f \end{cases} \tag{8}$$

where η_b and η_{ge} denote gear-box and generator efficiencies, respectively, ρ_i is the air density (kgm^{-3}), C_{pc} denotes the turbine coefficient, A_{wg}, rotor-swept area (m^2) and V is the wind speed. Also, the C_p is defined in Equation (10) as:

$$C_p = \frac{P_{out}}{P_{max}} \cdot \tag{9}$$

Here P_{out} is the wind generator output power and P_{max} is the maximum power, while V_o is the cut-in wind velocity, V_{rf} is the rated wind speed and V_f is the cut-off wind speed and P_{wgr} is the wind turbine rated power and rated wind speed V_r is expressed by [58]

$$V_r = \left(\frac{P_{wg,r}}{0.5\eta_t \eta_g \rho_a C_p A_{wg}} \right)^{\frac{1}{3}} \cdot \tag{10}$$

3.3. Solar Thermal Collector (STC)

The solar thermal collector converts solar energy into heat energy. The useful heat gain is depends on solar irradiation, temperature, heat removal factor and as expressed in [59]

$$Q_{gTc} = A_{Tc} F_R (\alpha\tau)_{TC} . G_{Tc}(t) - F_R U_L (T_h - T_i) \cdot \tag{11}$$

The isotropic diffuse model in is used to calculate the total hourly solar radiation on a slanted collector.

$$I_{TC}(t) = I_b \cos \phi_{TC} + I_d \left(\frac{1 - \cos \beta_{TC}}{2} \right) + I_g \left(\frac{1 - \cos \beta_{TC}}{2} \right) \rho_g \cdot \tag{12}$$

It is further represented in Equation (14) by [60, 61] in a temperature differential form of inlet water and the outlet water temperature

$$Q_{lTc} = m_{Tc} c_\omega (T_h - T_i) \cdot \tag{13}$$

So that in steady-state, the energy balance equation of the collector is

$$Q_{Tc} = Q_{gTc} - Q_{lTc} \cdot \tag{14}$$

The differential equation corresponding to the energy balance equation is:

$$M_S c_\omega \dot{T}_s = A_{sc} F_R (\alpha\tau) G_{sc}(t) t_h - F_R U_L (T_{co} - T_a) - m_c(t) c_\omega (T_{co} - T_{ci}) \tag{15}$$

where I_b is the diffuse solar intensity (W/m^2), I_d denotes the global solar radiation intensity, T_a is the ambient temperature, ρ_g is ground reflectivity. A_{Tc} is solar thermal collector area, G_{Tc} is hourly solar radiation on the titled collector (W/m^2), Q_{gTc} is the heat gain by the collector , Q_{lTc} is the heat loss by the collector, C_w water heat capacity, T_h is the water outlet temperature collector, T_i water inlet temperature collector, Msc is the mass flow rate, $\dot{T}_s$ is the derivative of the temperature variation of the water inside the storage tank, $\tau\alpha$ is the transmittance absorbance product. ϕ_{TC} angle of incidence, β_{TC} denotes the tilt angle of thermal collector, U_R is the overall coefficient of heat loss and, collector removal factor.

In terms of output power, Equation (16) relates the thermal power to the efficiency, solar radiation, and solar collector area as:

$$P_{sc}(t) = G_t \eta_{sc} A_{sc} \tag{16}$$

$$\eta_{sc} = \eta_{rsc} - \frac{\alpha_1}{800}(T_{sc} - T_a) - \frac{\alpha_2}{800}(T_{sc} - T_a)^2 \tag{17}$$

where A_{sc} represents the collector area, η_{sc} and η_{rsc} are collector efficiencies. T_{sc}, collector temperature, T_a the ambient temperature and α_1 and α_2 are the loss coefficients.

3.4. Heat Pump Water Heater (HPWH)

HPWH captures heat energy from the surrounding air and uses it to heat water through a working fluid. Because of their high efficiency and significant energy savings, heat pump water heaters are preferred over other electric-based water heaters. For model simplicity, only standby loss and hot water demand loss are considered. Losses due to the evaporator, compressor, and refrigerator are neglected.

According to [62] the total standby loss $Q_s(t)$ through the tank's casing material is evaluated with Equation (18)

$$Q_S = SA_{hp}\left(\frac{t^h{}_{hp} - t_a}{\theta_{T_{hp}}}\right) \tag{18}$$

where SA_{hp} , is the surface area of HPWH's tank (m^2) while $t^h{}_{hp}$ and t_a are hot water and air temperatures, respectively , $\theta_{T_{hp}}$ is the casting thermal resistance, expressed as,

$$\theta_{hp} = \sum_{i=1}^{N} \frac{dx_i}{k_i} + h_i^{-1} \ . \tag{19}$$

Therefore, the thermal loss related to the demand for hot water is expressed in as follows

$$Q_{DS} = c_{\omega} W_d^{hot}\left(t_{hp} - t_{ic}\right) \tag{20}$$

where W_d^{hot} and t_{ic} the rate of hot water flow and the temperature of the inflow cold water. The required input power to satisfy the HPWH demand can be calculated as:

$$Q_p = COP \times P_{hp} \ . \tag{21}$$

Here Q_p signifies the HPWH heating capacity and COP denotes efficiency index.

3.5. Battery Storage (BS)

The battery is an energy backup storage device for hybrid water heating systems. The maximum discharge depth (DD), temperature, and battery capacity all influence battery sizing. The charge state (SOC) is modelled as

Charging mode:

$$SOC = SOC\ (t-1) + \frac{E_{bat}\,\eta_c}{P_{bat}} \times 100 \tag{22}$$

Discharging mode:

$$SOC = SOC\ (t-1) + \frac{E_{bat}\,\eta_D}{P_{bat}} \times 100 \tag{23}$$

where E_{bat} is the battery energy, η_C and η_D are battery efficiencies, P_{bat} the nominal capacity of the battery (Ah).

3.6. Diesel Generator (DG)

DG is a traditional energy source that is used to supplement energy when renewable energy sources are insufficient due to weather variability. It is commonly used in water heating applications as a hybrid configuration. The fuel usage of DG is presented as:

$$D_{hfc} = \alpha_{DG} P_{Dg}(t) + \beta_{DG} P_{Dgr} \tag{24}$$

where D_{hfc} the fuel usage of the diesel generator, P_{Dg} mean power of the diesel generator, P_{Dgr} power capacity of the diesel generator, $\alpha_{DG}$and β_{DG} fuel consumption coefficients.

3.7. Fuel Cells (FC)

Fuel cells are a new technology used as a storage device for hybrid water heating systems due to their long storage capacity. The chemical energy is converted to electricity energy during the energy conversion process. Using its hydrogen consumption as a measure, a fuel cell's output power is described by [63] as:

$$H_{2CFC} \begin{cases} \gamma_{FC} P_{fc} + \varphi_{fc} P_{fcr} \; if \; \dfrac{P_{fcr}}{P_{fc}} \leq \tau_{FC\max} \\ \gamma_{FC} P_{fc} + \varphi_{fc} P_{fcr} \left(1 + f_{fc}\left[\dfrac{P_{fcr}}{P_{fc}} \leq \tau_{fcmx}\right]\right)^{if \; \frac{P_{fcr}}{P_{fc}} \geq \tau_{FCmx}} \end{cases} \quad (25)$$

where $\gamma_{fc}$and φ_{fcr} are hydrogen consumption curve coefficients with the numerical values of 0.004kg/KWh and 0.05kg/KWh respectively, P_{fc} is the nominal fuel cell's output (KW), P_{fcr} is the rated power of the fuel cell , τ_{fcm}, peak fuel-cell efficiency (%), lhv_{h_2} lower heating value (KW/m/Kg) and f_{fc} is a constant. The maximum efficiency is defined as

$$\tau_{fc} = \frac{P_{fcr}}{H_{2cfc} \times lhv_{h_2}} . \quad (26)$$

4. APPLICATION OF OPTIMISATION IN WATER HEATING SYSTEMS

The optimization approach entails developing an algorithm to maximize and minimize objectives functions that are constrained by certain parameters. Several authors have developed optimization algorithms to achieve various design objectives for hybrid water heating systems e.g. minimize energy, minimize life cycle cost, minimize annual cost, minimize emissions. Maximize fuel cell output and maximize thermal output. The most widely reported techniques have been classified into three types: conventional, meta-heuristic, and hybrid optimisation. Figure 6 depicts a simplified classification of optimization methods based on the literature. Recently, there has been a surge of interest in optimization problems with continuous and integer constraints associated with the integration of HREs to address water and energy insecurity in water heating technology. Among the optimization methods, the meta-heuristic algorithm and hybrid optimization have received considerable attention. The fundamental concepts and applications of mixed integer nonlinear programming (MILNP), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and other hybrid optimization in hybrid water heating applications are examined in this paper

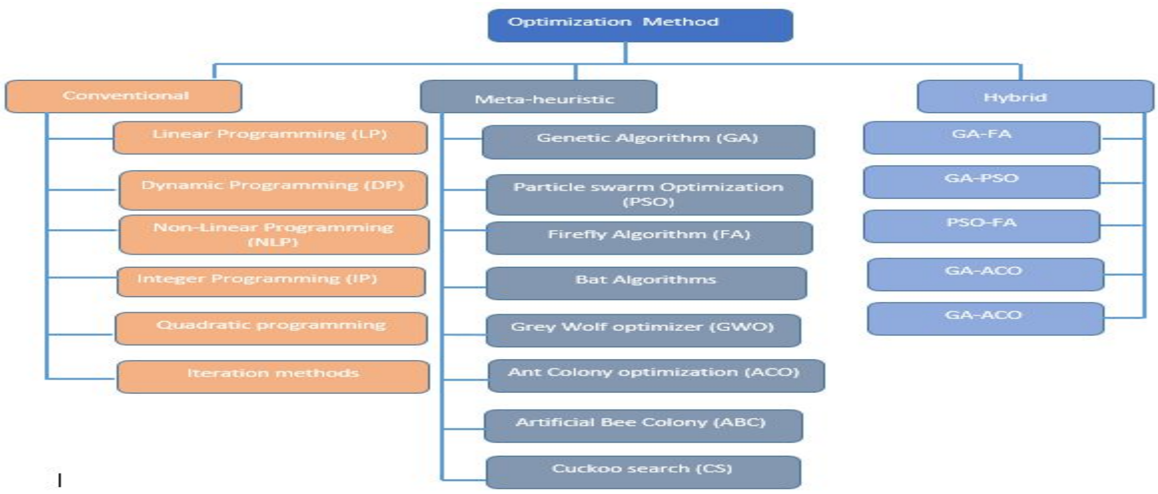

***Figure 6**. Optimization method classification*

4.1. Mixed Integer Nonlinear Programming (MINLP)

MINLPs are class of optimization algorithms that handles integer and continuous variables with nonlinearity in the objective function and constraints. For a variety of reasons, MINLP continues to garner significant attention in the engineering world. Complex engineering problems can be modelled using MINLP, and it also serves as an efficient modeling tool in the field of optimization, with the integer variable providing excellent options for discrete decisions in the MINLP optimization model. In MINLP, for example, the binary indicator variable that turns on and off a continuous variable or constraint is modelled as switching between the states of 0 and 1.. MINLP is generally expressed in general form as:

$$\min \; f^{T}(t,u)$$

Subject to the constraints:

$$g_k(t,u) \le 0, k \in J \quad (27)$$
$$t \in T$$
$$y \in Y$$

where $f: P^i \to P \quad g_k : P^i \to P^j$ are algebraic that are often represented as a recursive configurations of sums and products of a univariate function, J denotes the inequality constraint index and x, y are continuous and discrete variables. The MINLP has been adopted in many optimal decision problems in science and engineering applications, such as chemical engineering, transportation network, optimal power scheduling in electrical engineering, optimal energy management of hybrid systems, production planning, energy optimisation problems in water heating applications, application in cyber-attack, wireless bandwidth allocation and network performance optimization [64, 65]. The use of MINLP has grown in popularity as a because of recent advancements in HRE applications. Although the use of renewable sources for domestic use is not novel, the integration of renewable energy systems with HPWH has been viewed as a viable alternative for mitigating global warming. These integrated systems enable control switch to be integrated into an optimization problem as a discrete variable such that the optimization problem result in MINLP problems. As shown in Figure 7, an optimization problem in HPWH integrated with HREs entails determining the optimal solution to an objective function given a set of constraints. Table 3 depicts the hybrid configuration, algorithm application, objective function, and highlights of the MINLP algorithm in optimizing heating systems.

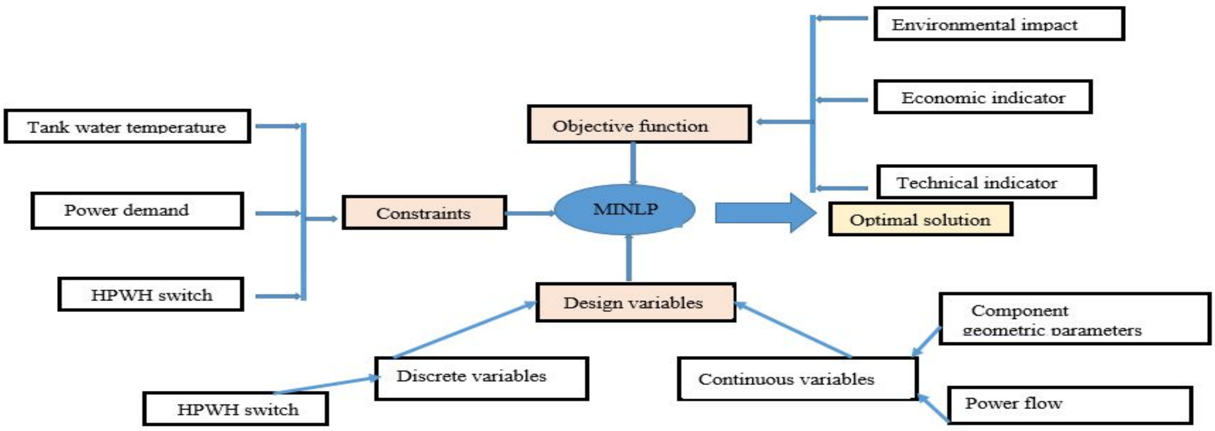

Figure 7. *MINLP optimization problem for hpwh integrating hres systems*

Table 3. *Application of MINLP algorithm for hybrid water heating systems optimization*

Citation	Hybrid Configuration	Application of the Algorithm	Objective function	Highlights/Remarks
[66]	Grid-tied/battery/PV/HPWH	Power control	Grid cost minimization	The findings indicate that the energy prices have an impact on the power scheduling strategies.

[67]	Photovoltaic-thermal heat pump water heater	Optimal sizing and economic assessment	Fuel costs, and Energy costs minimization	Replacement of fuel consumption with solar energy was suggested

4.2. Genetic Algorithms (GA)

GAs are natural evolution-based metaheuristic algorithms. GA mimics Darwin's genetic and natural selection theories in biological processes. GA began in 1975, with a well-known scientist and electrical engineering professor named John Henry Holland [68]. GA is used in many engineering fields to solve complex optimization problems because it is efficient in dealing with discrete and mixed optimization problems. GA only uses the objective function's fitness values. Figure 8 depicts the key components and process cycle shared by all GAs.

Figure 8. *Genetic Algorithm (GA) process cycle*

The first generation (initial population) of the chromosome is chosen at random in GAs. This population's chromosomes are binary string variants (0 or 1). At each generation, a tournament selection is initiated from a mating pool of parent candidates based on fitness function, so that better candidates have a better chance of survival in an environment with limited resources, and good solutions are retained while bad solutions are discarded. The tournament selection is played between tournament size "k" members, and the member with the best fitness is chosen for mating, so that each solution has two chances to play, and the best solution has two copies, while the worst solution is never chosen and other solution can have 0, 1, or 2 copies. As the tournament size increases, the selection pressure of each solution increases and the selection criteria are based on Table 4.

Table 4. *Selection criteria in ga selection stage*

Tournament size (k)	Remarks
2	The Worst solution will not be in the mating pool
3	The worst and second solutions will be excluded from the mating pool
N	The worst (n-1) solutions will be excluded from the mating pool

Crossover involves selecting two parent individuals at random from the selection pool to perform crossover, and swapping some of the parent strings to generate a new solution. The crossover of the two parents occurs at a crossover probability. Single-point crossover is frequently used in a GA to enhance the genetic variation; however, its limitations, such as poor performance, a search space confined to the current values of the decision variables, and reliance on the mutation operator for a new value of the decision variable, have led to modifications in the crossover operators. GAs have recently been used to optimize Hybrid integrated systems in water heating applications. Table 5 summarizes the most recent GA applications in water heating, with an emphasis on hybrid configuration, algorithm application, objective function, and key findings.

Table 5. *Application of GA algorithm for hybrid water heating systems optimization*

Citation	Hybrid Configuration	Application of the Algorithm	Objective function	Findings/Remarks
[69]	Wind/PV/battery/thermal collector/heat pump	Technical and Environmental evaluation	Net Present cost and environmental foot print minimization	A comparison of single-objective and multiple-objective GA
[70]	Grid-tied/PV/heat pump water heater	Optimal component sizing using GA	Grid energy cost minimization	The optimal capacity depends on the changes in the price of electricity, natural gas, SC and HP
[71]	wind/PV/ground heat pump water heater	Optimal sizing and economic assessment using GA	Cost minimization	A significant reduction in energy usage
[72]	PV/heat pump water heater	Optimizing Annualized life cycle costs using GA	Minimization of life cycle costs and comfort levels	At lower ALLC, the model provides the same level of comfort than ASHP configuration.
[73]	PV/wind/battery/heat pump water heater	Techno-economic assessment	Annualized cost minimization	The GA optimizer and the HORMER software were compared.
[74]	PV/ battery/natural gas/boiler/heat exchanger/Ground heat pump water heater	Optimal sizing and economic assessment	Total annual costs and CO_2 emission minimization	The model constraints, focus on energy balance, solar fraction and solar collector space
[75]	Grid-system/Solar collector/Electric water heater	Economic analysis using GA	Life cycle cost minimization	The optimization problem is solved using a GA.

4.3. Particle Swarm Optimization (PSO)

PSO is a swarm intelligence-based metaheuristic optimization algorithm. As shown in Figure 9, it belongs to the metaheuristic optimization class. It mimics the swarming behaviour of social insect colonies and fish flooding. PSO was developed as a social behaviour model by Kennedy and R. Eberhart in 1995. Since it was introduced in 1995 at the International Conference on Neural Networks in Australia, many applications have used it to resolve optimization issues. The concept of PSO is based on artificial life and evolutionary computation [76]. The key elements of PSO are the fitness of each particle, fitness of the swarm, and velocity and position updates. PSO bases its search for a better solutions on inertia, prior experience, and social influence [77]. PSO, like GA, starts by randomly initializing the population. Unlike GA, solutions are assumed with randomised velocity. Each solution in PSO is referred to as a particle. These particles change position by adjusting their velocity to identify optimal environmental parameters. Subsequently, the velocity of the particles is updated to find the optimal solution. PSO has been identified as a prominent and widely used algorithm for addressing optimisation problems in a various of fields because of its simplicity and rapid convergence. The use of PSO has grown at an exponential rate in the fields of engineering and computer science. Furthermore, the use of PSO in other fields of science and social science research is becoming more common. The increasing trend in PSO publications from 100 publications in 2002 to thousands of publications in 2019 [78]. This demonstrates that research on this topic has grown rapidly in the academic domain over the last two decades. Over 5000 publications on PSO have been recorded over the last decade. Table 6 summarizes the most recent PSO applications in water heating applications, with an emphasis on hybrid configuration, algorithm application, objective function, and key findings

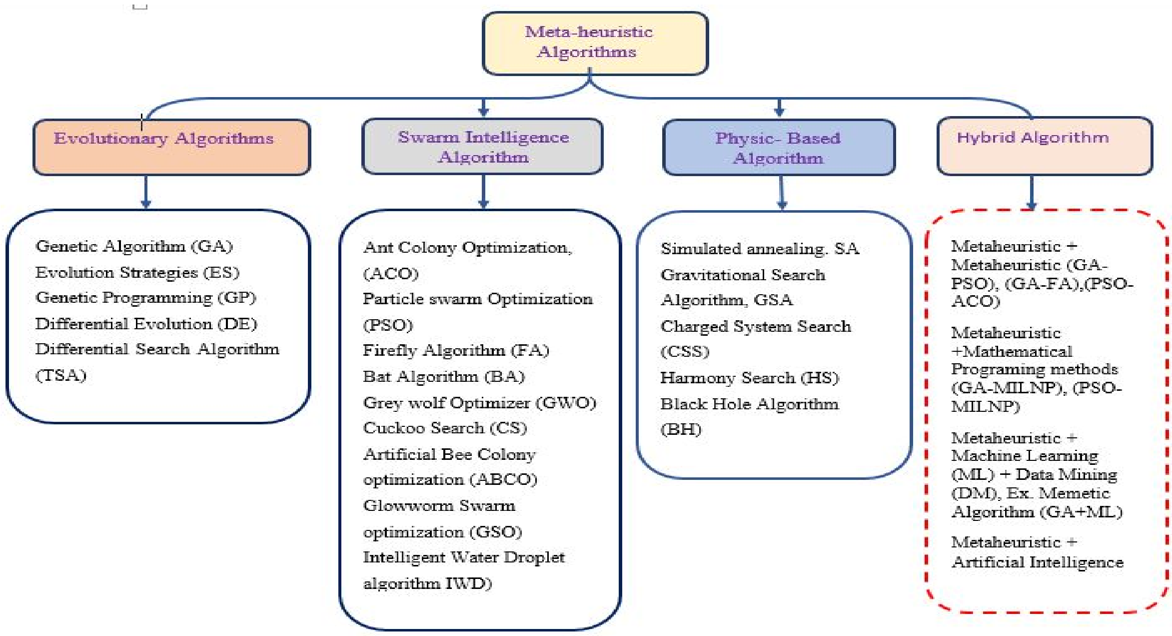

Figure 9. *Metaheuristic-based Algorithm*

Table 6. *Application of the PSO algorithm to hybrid water heating systems optimization*

Citation	Hybrid Configuration	Application of the Algorithm	Objective Function	Findings/Remarks
[79]	solar thermal collector/ PV/heat pump water heater	Optimal size and configuration	Minimizes the Energy cost and power grid demand.	It uses multi-objective PSO various optimal solutions were obtained for each objective function
[80]	Water heating systems	Mathematical model based on PSO	minimizes the total life cycle cost	An enhanced PSO model is formulated.
[81]	PV/Fuel cell// heat pump water heater	Economic evaluation of combined systems using PSO	Minimizes the life cycle cost (LCC)	Reduced energy costs
[82]	Solar thermal/Ground source heat pump water heater (GSHPWH)	Multi-objective PSO model	Minimize the energy costs.	Multi-objective PSO-based model

4.4. Hybrid Optimization (HO)

Hybrid optimisation is a meta-heuristics algorithm based on combinatorial optimisation. It uses the distinct strengths of combined algorithms to improve the algorithm efficiency, decrease search time, and improve effectiveness [83]. The HO is designed to address the shortcomings of a single meta-heuristic algorithm. Figure 9 depicts several combinatorial approaches developed and classified. Hybrid optimisation is effective in a diverse range of engineering domains for solving complex optimisation problems. It has been used to mitigate the issues of fast convergence and local stagnation associated with metaheuristic optimisation [84] . Recently, HO has emerged as a prominent and widely used method for solving multi-objective optimisation problems in HREs. Hybrid water heating technology is one of the emerging areas of application with the increasing use of HO. Various combinatorial optimisation algorithms have been proposed to address optimisation issues in hybrid water heating systems, including the hybrid algorithm of GA and SQP [85], hybrid algorithms of SSO and PSO [86], fuzzy-based hybrid SSO algorithm [87],hybrid algorithms of PSO and ACO [88], hybrid algorithm of firefly (FFO) and PSO [89], hybrid algorithm of

PSO and Hooke-Jeeves (PSO/HJ) [90], hybrid algorithm of MILP and GA [91], hybrid algorithm of PSO and GA [92], hybrid algorithms of GA and MILP.

5. APPLICATION OF NANOTECHNOLOGY IN WATER HEATING SYSTEMS

5.1. Nanofluids in Water Heating Systems

The growing interest in developing new thermal fluid materials to enhance the thermal properties of working fluids and increase the collector's efficiency in heating applications has resulted in a new discovery in the field of nanotechnology. Nanofluids are a novel class of fluids formed by suspending nanoparticles in a base fluid (e.g. water) to increase the working medium's or fluid's energy transport property [93]. Several types of nanofluids have been reported and classified as metal (Zn.Al, Ni, Fe, Ti, Cu, Au and Ag), metal oxides (CuO, SiO_2, TiO_2, ZnO.Al2O3, Fe_3O_4), metal hybrids , nitrides (AiN, SiN, TiN,ZrN, HfN) and carbon based nanofluids (SWCNT,MWCNT,GNP, graphene, diamond and graphite). Water's low thermal conductivity of limits its use as a working fluid. The desire to reduce heat loss, increase the energy transport property, and improve the transfer property of solar thermal collectors has prompted several researchers [94, 95] to explore the impact of nanofluids in water heating technology.

5.2. Hybrid Nanofluids in Water Heating Technology

The synergetic combination of two or more nanomaterials with conventional fluid has recently been applied to minimise the weakness due of low thermal conductivity and stability issues associated with single nanofluids [96]. This synergistic combination results in the formation of hybrid nanofluids. Hybrid nanofluids are classified based on their nanocomposition [97],which a mixture or composition of ceramics, polymers (polymer-CNT,polyester-TiO_2) and metal nanocomposites. Due to their superior performance, hybrid nanofluids are a better candidate for heat transfer applications than working fluids. Scholars and researchers have recently shown a keen interest in using hybrid nanofluids in water heating technology. Solar collectors, as shown in Figure 10, have been identified as a critical component for harnessing thermal energy in water heating applications. Several authors have used various collectors to investigate the effect of hybrid nanofluids on collector efficiency, heat transfer rate, thermal conductivity, and viscosity.

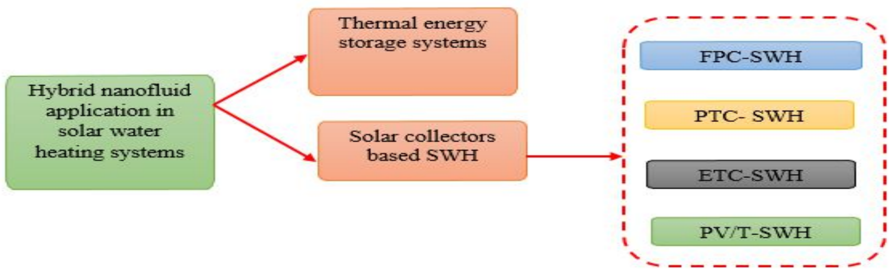

Figure 10. *Hybrid nanofluid applications*

Harrabi et al. [98], examined a techno-economic evaluation of three different heating technologies using a hybrid of aluminum oxide Al_2O_3/water and MWCNT/water nanofluids. The experimental results show that using hybrid nanofluids improves solar water performance and significantly reduces the payback period. It was also demonstrated that the use of water and 0.06 percent Al_2O_3 reduced CO_2 emissions.

[99] investigated the performance of a PV/T-based water heater using Al_2O_3/ZnO/H_2O hybrid nanofluids combined with an ethylene glycol surfactant. Al_2O_3 and ZnO had mass concentrations of 0.05 wt percent, and their respective particle sizes ranged from 5 nm to 30 nm, respectively. The authors discovered that using hybrid nanofluids improved the system efficiencies significantly. Hossein [100] investigated the thermal properties of four different hybrid nanofluids: Ag-MgO/H_2O, TiO_2/Cu/H_20, Al_2O_3-CuO/H_2O, and Fe_3O_4-carbon/H_2O. The weight percentage was used as performance metrics in the study. Among the four

hybrid nanofluids mixtures tested, the Ag-MgO/H_2O hybrid nanofluids was found to be the most efficient heat carrier fluid. Wole-osho [101] investigated the use of a hybrid Al_2O_3/ZnO/water nanofluids in a PV/T-based solar water heater. The experiment is based on thermo-physical properties. It was discovered that a mixture ratio of 47 percent Al_2O_3 increased the system efficiencies, with a 34% improvement in a PV/T collector. [102] used a hybrid SiO_2-CuO/water nanofluids to study the thermal efficiency of an evacuated tube based collector. It was found that the heat flux of a CuO/water hybrid nanofluids is greater than that of SiO_2. Although the ratio of SiO_2 increases fluid circulation, it contributes a poor thermal performance compared to CuO nanofluids. Furthermore, the combinational use of hybrid SiO_2 and CuO nanofluids eliminates precipitation issues while increasing the heat transfer in ETC-based water heaters.

Hybrid nanofluids in flat-plate collector

Okonkwo [103] suspended hybrid Al_2O_3/Fe/water and Al_2O_3/water nanofluid to enhance the heating efficiency of a flat plate collector. The results show that the thermal efficiency of hybrid Al_2O_3/Fe/water nanofluids decreased significantly by 1.8% compared with water. Verman [104] reported on the use of hybrid nanofluids in a flat plate collector. In terms of thermal efficiency and exergy, hybrid MgO nanofluids performs better than hybrid cow/water and MWCTs/water. Tahat [105] investigated the impact of different volume fractions on a flat plate collector performance using hybrid Al_2O_3/CuO/water nanofluid and noted a 45 % improvement in thermal efficiency over water. Huang [106] investigated the effects of CuO,/Al_2O_3,/water hybrid nanofluids on four different collector types. The energy, exergy, and environmental assessments of these nanofluids were analyzed, and it was discovered that the flat plate collector is a better candidate in terms of energy, exergy, and cost. Farajzadeh et al. [107] investigated the thermal efficiency of a flat plate collector based on an Al_2O_3/TiO_2/water hybrid nanofluids. Al_2O_3/water and TiO_2/water nanofluids samples were compared with hybrid Al_2O_3/TiO_2/water nanofluids with different particle volume fractions. The authors reported that hybrid Al_2O_3/TiO_2/water outperformed single Al_2O3/water or TiO2/water nanofluids in terms of thermal efficiency while costing less. It was also noted that using hybrid nanofluids of Al_2O_3/TiO2/water can lower costs while increasing collector efficiency.

Hybrid nanofluids in evacuated tube collector

The thermal coefficient of an evacuated tube collector was investigated by [108] using the hybrid nanofluid MWCNTs/ Al_2O_3/water. Hybrid nanofluids increase the exergy of ETC. Rashid [109] investigated the effects of TiO_2/H_2O nanofluids and a finned electronic curtain on an evacuated tube collector. The effect of different TiO_2 particle volume concentrations without the addition of an electronic curtain was observed. The use of TiO_2/H_2O particles with a particle size of 50 nm without an electronic curtain reduces system performance more than the use of an electronic curtain augmented with TiO_2/H_2O particles with a particle size of 50 nm. The effect of volume concentration and nanoparticle shape on evacuating U-tube collector thermal efficiency was studied an using Al_2O_3/CuO/water nanofluid [110]. The nanofluids were created using various concentrations, nanoparticle shapes, and mass flow rates. The experimental results show that a volume concentration of 4 % Al_2O_3/CuO/water nanofluids with brick nanoparticle shape has the highest collector efficiency. The use of hybrid MoS_2/Ag/H_2O nanofluids for ETC efficiency improvement is reported in [111]. It is further proved that the use of composite nanofluids at various particle volume concentrations increases the heat transfer rate.

Hybrid nanofluids in parabolic trough collector

[112] investigated the effect of mass fraction and nusselt number on the thermo-physical properties of the hybrid CuO-Al2O3/water parabolic trough collector. The use of hybrid Ag/MgO/water nanofluids enhanced thermal stability and the collector's performance. [113] improved the thermal fluid properties of a parabolic based collector using hybrid Al_2O_3/WO_3/H_2O nanofluids. The impact of particle volume concentration was examined experimentally, and a volume mixture of 0.04 Al_2O_3/WO_3 hybrid nanofluids demonstrated better thermal enhancement of 0.39 percent of thermal energy and 0.385 percent of exergy energy. The impact of various fluids on the parabolic trough collector efficiency was investigated by [114] using CuO/Al_2O_3/water hybrid nanofluids. CuO and Al_2O_3 volume concentrations were held constant, while mass flow rates for CuO and Al2O3 were 0.012kg/s and 0.0224kg/s, respectively. At flow rates of 0.102kg/s

and 0.0224kg/s, the CuO/water nanofluids outperformed Al_2O_3 nanofluids in terms of thermal performance.

Hybrid nanofluids in photovoltaic/thermal collector

Humphrey et al. [115] reported the use of ternary CuO/MgO/TiO_2 nanofluids in photovaltaic-thermal, PV/T collector. The use of ternary nanofluids resulted in increased thermal, electrical, and energy efficiencies. CuO/MgO/TiO_2 nanofluids have lower pressure loss and pumping power than hybrid Al_2O_3-ZnO nanofluids Wole-Osho et al., investigated the effects of mass flow, particle volume concentration, and temperature on PV/T collectors using Al2O3/ZnO/water hybrid nanofluids. The use of hybrid Al_2O_3/ZnO/water increased the thermal efficiency by 91% and improved the overall collector performance by 34%. Karaaslan et al. [116] numerically investigated the impact of hybrid Fe/CuO/water on photovoltaic-thermal collectors under the influence of inlet fluid velocity. The hybrid nanofluids improved system efficiencies while reducing pressure loss dramatically. Han et al. [117] improved the efficiency of hybrid PV/T collectors using hybrid Ag/SO_4/water and Ag/SiO_2/water nanofluids. The experimental model was subjected to various particle volume concentrations, and the results show that despite having a lower electrical output, Ag/SO_4/water outperforms Ag/SiO_2/water. As a result, Ag/SO_4/water hybrid nanofluids is a better candidate than Ag/ SiO_2/ water nanofluids for enhancing thermal/electrical efficiencies.

5.3. Future Outlook for Hybrid Water Heating Technologies

Transitioning from traditional fossil fuels to an efficient heating technology powered by renewable energy sources could make a significant contribution to low-carbon transitions. Hybrid renewable solutions for water heating applications can reduce GHG emissions to meet climate targets, improve energy access, increase energy security, address energy poverty, and maximize socioeconomic gain. Furthermore, advances in research and development have resulted in the discovery of new materials for improving the thermal rate of collectors and thermal storage devices by utilizing phase change materials, nanofluids, and composite materials [118]. Further research on advanced thermal transport fluids is required to improve working fluid efficiency and thermal performance of solar collectors. The use of hybrid technologies in water heating systems has recently grown exponentially [119, 120]. Despite the significant advantages offered by hybrid technologies in terms of thermal enhancement, lower grid energy costs, and efficiency improvement. Certain issues confront hybrid technology applications, limiting their applicability, and their potential solutions are as follows:

Economic issues such as the high cost of hybrid system purchase, installation, and maintenance limit the widespread adoption of hybrid technologies. In South Africa, for example, economic barriers have prevented people from using hybrid water heating technologies (HWHTs) to a large extent [121]. Despite various incentive schemes offered to consumers, a study conducted in India identified low natural gas prices as one of the major barriers impeding widespread implementation of HWHT [122]. Low off-peak electricity and gas prices in Australia also impede mass adoption of HWHTs [123]. Hybrid technologies may gain widespread acceptance as a result of cost reductions and an increasing proclivity for local adoption. Furthermore, through incentives, grants, and the establishment of pilot programs, the government can increase support for hybrid water heating technologies, resulting in a favourable perception of this technology. This could spark a massive revolution in the near future, necessitating additional investments in hybrid technology. For instance, strong local support for solar/hybrid technologies has revolutionized the SWH industry in China and significantly accelerated the country's transition to zero energy in buildings [124]. For example, the South African government has made significant investments in these technologies through tax credits, other forms of financial incentives, and the enforcement of bylaws to promote solar/hybrid technologies in new and existing buildings. These mechanisms have fueled the adoption of hybrid technologies and SWH industry [125].

Another crucial issue that has contributed significantly to the low penetration of HWHTs is technical challenges. These challenges include optimal control and thermal storage issues. HWHTs necessitate an advanced control system for optimal utilization. Such systems require special attention in HWHTs [126]. Several studies have used the Time-of-use (TOU) pricing strategy to develop control strategies that minimize the system's objective function, with a focus on grid energy cost minimization. Khakimova developed hybrid predictive control based on TOU to reduce electricity costs through hybrid renewable energy systems for water heating applications. Sichilalu [127] presented an optimal control strategy based on TOU in order to reduce energy costs and maximize fuel cell output. Wanjiru [128] presented a TOU pricing strategy for a grid-connected hybrid photovoltaic system. Future research in the areas of optimal control and energy-efficient management systems for improving hybrid technology could reduce overall system costs.

The issue of storing renewable energy sources with an effective storage technology has emerged as a result of the unprecedented energy demand in the use of hybrid technologies However, the large size, high cost, and huge thermal loss associated with thermal storage can be reduced by using phase change materials (PCMs). The PCM has a high energy storage density as well as thermal energy storage [129]. These transport fluids can help to solve the problem of low density, instability, and discontinuity of solar radiation in solar/hybrid technologies. Further research should be directed towards mitigating the issues with phase change material in water heating applications, so that these advancements can help revolutionise the performance of hybrid water-heating technologies. Beih et al. [130] demonstrated in their study that using PCM in solar/hybrid technologies for water heating applications increased heat retention capacity while decreasing energy consumption and CO_2 emissions [131]. Another study conducted in India found that PCM improved the thermal conductivity of solar/hydroelectric water heaters. A solar/hybrid water heater integrated with PCM nanocomposite outperforms a traditional system without PCM in terms of efficiency [132]. Thermal storage combined with solar/hybrid technologies using nanofluids/hybrid nanofluids as heat transfer fluid is another viable alternative solution for storing energy in hybrid technology applications. This fluid is critical in increasing the efficiency of solar/hybrid storage systems. Several applications of nanofluids and hybrid nanofluids in thermal enhancement of solar/hybrid technologies have been thoroughly investigated and discussed in this study. Future research should concentrate on increasing the thermal efficiency of hybrid water heating technology by utilizing phase change, nanofluids, and composite materials.

6. CONCLUSION

This paper presents a review of hybrid technology in water heating applications. Studies on the current state of hybrid technology, optimisation methods, component modelling, nanofluids and hybrid nanofluids application were comprehensive examined. 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 have rarely reported. The authors draw the following conclusions from the literature reviewed in this study:

- Studies on hybrid technology, such as the combination of solar, wind, or generator power with electric water heaters, have been numerically and experimentally investigated in heating applications. However, there have been few studies on the use of hybrid solar thermal collectors with heat pump water heaters.
- Studies have shown that there is a need to conduct extensive research on the use of hydrogen and fuel cells to supplement energy security.
- The use of MINLP, GA, PSO, and HO in the solution of single and multiple optimization problems in hybrid technology for water heating systems has gained significant popularity for solving single and multiple optimisation problems.
- Research has revealed that discrete- continuous variables optimization problems in hybrid water heating systems require a high level of optimal solution.
- GA is an excellent optimisation technique for solving discrete optimization problems, while a PSO is used for multimodal functions with continuous variables. However, PSO can be improved to solve MINLP optimization problems.
- Several studies have proposed an improved PSO for solving mixed variable problems with both discrete and continuous variables. Kitayama [133] proposed an enhanced PSO with a penalty function and an augmented objective function to solve MINLP problems with discrete variables.

Yang [134] also introduced an improved PSO. The improved PSO included a penalty and sigmoid functions to solve MINLP with equality and inequality constraints..

- Hybrid solar heat pump water heaters and the use of the MINLP algorithm is rarely reported.
- It has also been discovered that the mathematical model for hybrid solar thermal collector water heater is rarely addressed in the literature.
- Studies have shown that with the optimal hybrid controller design, hybrid water heating technologies have a significant potential to sustain continuous hot water delivery, cut costs, and reduce emissions.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

NOMENCLATURE

A_{sp} Solar panel or photovoltaic cell area [m^2]

A_{sc} Solar thermal collector surface area [m^2]

A_{wg} Rotor swept area [m^2]

C_{ω} Water heat capacity of water [J/kg/^oC]

C_p Power coefficient of the turbine

E_{bat} Battery energy

D_{hfc} Fuel usage of diesel generator

G_b, I_b Diffuse solar radiation intensity [W/m^2]

G_d Horizontal global solar radiation intensity [W/m^2]

G_{TC} Heat gain by collector [ ]

I_{cell} Photovoltaic cell current [A]

I_d Global solar radiation intensity.

$k_i h_i^{-1}$ Thermal conductivity coefficient

LHV_{H2} Lower heating value [Kw/m/kg]

M_s Mass flow rate inside the storage tank [kg]

P_{bat} Nominal capacity of the battery [Ah]

P_{Dg} Mean power of the diesel generator

P_{Dgr} Power capacity of a diesel generator [KW]

P_{wg} Wind turbine mechanical power [KW]

P_{wgr} Wind turbine rated power [KW]

$P_{\max}$ Wind turbine maximum power [KW]

P_{out} Wind turbine output power [KW]

T_C Solar panel temperature [^oC or K]

T_{ic} Inlet cold water temperature [$^oC or K$]

T_h Water outlet temperature [$^oC or K$]

SA_{hp} Surface area of HPWH's tank

T_{hp}^{t} Hot water temperature [^oC or K]

V_f Cut-off wind speed

V_{rf} Rated wind speed

V_o Cut-in wind speed

V_{sp} Solar panel voltage [V]

W_d^{hot} Hot water demand flow rate [litre/hour]

Greek letters

η_c Charging efficiency

η_D Discharging efficiency

$\eta_{fc_{max}}$ Maximum efficiency

η_m Module efficiency

η_{pc} Power conditioning efficiency

η_{sc} Solar thermal collector efficiency

η_{scr} Reference solar collector efficiency

ρ_a Air density [kg/m^3]

ρ_g Ground reflectance

$\tau\alpha$ Transmittance absorbance product

τ_{fcmax} Peak fuel cell efficiency [%]

ϕ_{TC} Angle of incidence on titled angle of solar collector [radians]

β_{TC} Tilt angle of solar collector [radians]

β_o Temperature coefficient

F_R Collector removal factor

U_R Overall heat loss coefficient

α Loss coefficient

α_{DG}, β_{DG} Fuel consumption coefficient

α_{FC}, β_{FC} Hydrogen consumption curve coefficient [kg/KWh]

Q_{hp} HPWH output power [KW

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