

Recent Developments of Solar Stills and Humidification Dehumidification Desalination Systems: A Review

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Abstract

Freshwater shortage refers to the ongoing depletion of available water resources. The World Economic Forum identified this issue as the most significant global risk affecting all continents based on its potential impact over the next decade. According to the United Nations (UN) world review, up to 40% of the population will be impacted by freshwater scarcity by 2030 due to climate change. Many attempts to convert seawater to potable water were made via many techniques that need a huge amount of energy, like multi-stage flash, multi-effect thermal desalination, or reverse osmosis. Some methods of seawater desalination can be executed by renewable energy. Solar desalination systems are introduced here in a comprehensive review study to show the importance of energy and cost-saving. In this study, Recent developments in solar desalination hybridization are reviewed to focus on the productivity, cost, and energy efficiency of combining solar energy and other disciplines. Hybridization aims to optimize the heat energy source, minimize the potable water cost, and maximize freshwater productivity. This review introduced modern techniques accompanied by solar desalination, like geothermal energy, concentrated solar power, photovoltaic modules, humidification dehumidification techniques, and evaporation enhancers. The estimated cost comparison between hybrid solar desalination studies is presented besides their thermal efficiency and gain output ratio. Results showed that maximum energy efficiency was 72%. It was achieved with compact flat solar still with ultra-hydrophilic glass cover. The minimum cost of one litre produced freshwater was 0.011 USD/L (about 0.17 LE/L) in the case of solar desalination with copper chips, nanofluid, and PCM.

1. Introduction

Water is a limited resource that is critical for accomplishing sustainable development goals. Water shortage refers to the ongoing depletion of available water resources and their inability to meet freshwater demands [1]. The World Economic Forum identified this issue as the most significant global risk in 2015, affecting all continents based on its potential impact over the next decade. According to the United Nations (UN) world review, up to 40% of the population will be impacted by freshwater scarcity by 2030 due to climate change and greenhouse gas emissions [2]. Water and energy are necessary components of any thriving life or society. Water and energy inefficiencies have developed due to substantial population expansion, rising quality of living, and the rapid growth of agriculture and industry [3]. Water scarcity is projected to worsen as most economic development takes place. To avoid or ease this problem, alternative sources of freshwater are explored. Solar-powered water desalination is a significant supply of freshwater, according to Eid et al. [4].

Desalination of saline water provides 97 million m³ of clean water each day to more than 300 million people globally. Water resources are critical for human survival, but substantial industrial growth and growing populations have polluted and depleted water supplies [5, 6]. The supply of freshwater is insufficient to meet the demand [7, 8] Two technologies dominate the worldwide desalination market: thermal and membrane desalination. Alhaj et al. [9]. Investigated Solar-powered Multi-Effect Desalination (MED) plant environmental assessment.

Solar-driven desalination systems employing various application techniques are viewed as a viable answer to this problem [10]. These solutions need additional effort to optimize heat gain and systems analysis [11, 12]. Numerous solar desalination techniques are viable options for producing freshwater such as, solar stills (SSs) [13, 14], multi-effect desalination (MED) [15], mechanical vapor compression (MVC) [16], Humidification and Dehumidification (HDH) [17], HDH with solar still [18], new materials [19, 20] and reverse osmosis (RO) systems [21], and hybrid desalination system [18, 22] and Capture and separation of CO₂ [23, 24]. For

instance, thermal distillation systems, like solar stills, are popular due to their simplicity of design and low cost of installation and operation. Sharshir et al. [25] illustrated a review on enhancements of solar still desalination system. The impacts of climatic conditions, procedures, and design parameters were indicated. The improvements techniques such as wick materials, reflectors, PCM also revealed. Results concluded that adding sponge cubes to the basin water increased the distillate yield significantly (up to 273%). Even without the fan, using cuprous oxide nanoparticles enhanced the production by 133.64 % and 93.87 %, respectively. Peng et al. [26] presented a review of solar stills enhancements by using new techniques of nanoparticles and porous medium (PM). Results showed that the distillate yield varied between 3: 7 kg/m². Also, nano-particle additives improved the production by 93.9% for passive SS and 285% for active SS. Sharshir et al. [27] investigated the extraordinarily effective and promising economic and environmental performance of solar distiller integrated with nanoparticles and cotton pad. Solar-powered interfacial desalination has established itself as a cost-effective and environmentally benign method of producing clean water [28]. Li et al. [29] suggested a novel desalination technique using an atomic layer deposition method. The reverse osmosis (RO) process is a widely used method of producing large amount of pure water. Electricity is the source of energy for RO [30]. The construction of a high-distillate yield desalination unit consumes little energy. So Abdelgaied et al. [31] investigated solar PV-powered hybrid desalination unit utilizing HDH and RO techniques integrated with heat recovery. The saltwater was utilized as a working fluid in a hydro-mechanical coupling. It eliminated the RO high-pressure pump in favour of a direct-drive hydraulic converter, resulting in fewer intermediate power conversions and increased efficiency [32].

1.1. Aim of the study

The hybridization of water desalination utilizes two or even more desalination processes to deliver more efficient techniques with minimum energy consumption and freshwater costs than any technology can produce alone. The hybrid methods offer numerous opportunities to save the cost of freshwater. Combining more than one technique with distinct methodologies makes it possible to meet various product water quality criteria [33]. For instance, imagine that the system can distillate ultrapure freshwater whereas others produce desired TDS content. For this scenario, hybridization can blend with desalinated water of varying TDS content to meet water quality criteria. Utilizing CSP in any hybrid technology has many economic and performance benefits, including reduced energy consumption, improved water quality, and potential cost savings over stand-alone systems. Abdelaziz et al. [34] investigated the review of hybrid desalination system.

1.2. Current Consequence and Literature Reviews

Numerous prior reviews discussed the historical development of solar energy driven techniques like

humidification dehumidification technique in terms of heat gain optimization and system design development. The hybrid solar HDH desalination technique with various hot stream flow rates integrated with high-frequency ultra-sound atomizer HFUA was investigated experimentally by [33, 35]. The impacts of water heights, atomizers number, and airflow rates were optimized. Results revealed that the airflow rates significantly affected system performance. The highest daily potable-water productivity, energy efficiency, and estimated cost were 7.72 kg/m², 33.840, and 0.0112 USD/L. Rahimi et al. [36] performed a review article on humidification dehumidification technique and evaluated cost per litre and system performance. Results concluded that higher temperature of humidifier's feed air and water and selecting an appropriate airflow rate leads in an improvement in distillate yield. Lawal and Qasem [37] presented a desalination device driven by renewable energy. Results revealed that optimizing system performance gain output ratio (GOR), distillate yield, and estimated cost per litre of freshwater can be accomplished by combining humidification, dehumidification, solar energy, and geothermal energy, especially for large quantity of productivity (up to 200 L/h).

The commercial technique used in remote areas and give a good solution for providing drinkable water is solar still. Essa et al. [38] developed the performance of PSS with wick-materials combined with reflectors and a cooling cycle. The modified system production rate and energy efficiency were improved compared with the Conventional one by 192% and 53%, respectively. The enhancement in distillate yield achieved by integrating SS with photovoltaic panel PV was analysed by [39]. Results concluded that the combination of the modified system had a thermal efficiency that was 25% greater than the regular one. Peng et al. [40] performed a compact flat solar distiller. The comparison of inclined solar still (ISS) with flat SS with ultra-hydrophilic glass cover were investigated. Results concluded that the modified FSS achieve higher productivity and efficiency than ISS. Singh et al. [41] evaluated a developed SS desalination system that included nano-fluid. This paper concluded that solar stills' performance and freshwater output employing nano-fluids were superior to those using traditional SS. Fang et al. [42] presented a review of saline water distillation techniques and economic feasibility in desalination plants located in China. Solar collectors are one of the most cost-efficient ways to improve the performance of steam power plants Kabiri et al. [43].

Furthermore, to adequate water quality the augmentation of membrane desalination system with solar power was recommended [34, 44]. The integration of membrane desalination (MD) systems with low-grade energy was performed by Yadav et al. [45]. Anand et al. [46] examined the augmentation of PV with numerous freshwater production techniques. The main result showed that the integration of PV/T with desalination systems significantly affected systems performance. Dixit et al. [47] discussed

MXenes' potential potable water and power distillation applications. MXenes are a unique family of (2D) materials attracting significant interest in a variety of natural, industrial, and biomedical. Lee and Jepson [48] conducted a thorough review and Service Life Evaluations on the environmental effects of distillation.

This study provides an in-depth review of recent advances in solar energy driven distiller integrated with other techniques for freshwater production from seawater. The main goal is to analyse the energy, exergy, and cost of one litre freshwater. The focused disciplines include the combination of one or more techniques in seawater desalination for heat source optimization, cost minimization or efficiency maximization. Another objective of this review is to examine the effect of hybridization on the freshwater production, desalinated water salinity, system performance, and cost per litre of freshwater yield. This study evaluates the performance of recent developments in the solar desalination. Another purpose is to extract and identify emerging trends and forecast future contributions, including ideas and recommendations for further research.

2. Hybrid techniques for energy source optimization

Water desalination is the important technology used in various countries throughout the world to generate freshwater [49]. The desalination process needs a thermal energy source to be done efficiently. Here, recent researches that has been conducted to optimize the energy sources will be discussed. Incorporating various energy sources includes solar energy, electrical heaters, and geothermal energy.

2.1 Solar desalination coupled with geothermal energy

Kaczmarczyk et al. [50] analysed a Novel treatment of geothermal wastewater with low-enthalpy geothermal energy. Hammadi [51] proposed modelling solar desalination augmented with geothermal energy serving as a condenser, as shown in Fig.1. SS with adjustable airflow rate and subterranean heat exchanger comprise the basic model. Results showed that the distillate yield of the proposed system was enhanced by 56% compared with traditional SS. The highest production was 7.8L/m²/day.

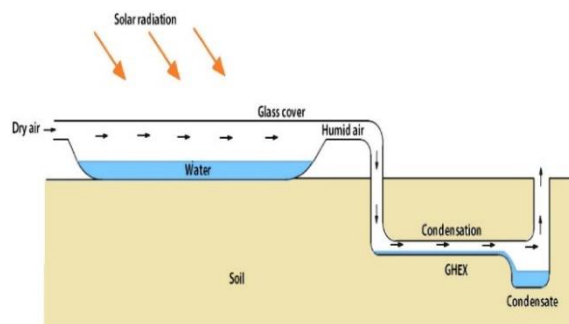


Figure 1 Geothermal energy coupled with solar still [51]

2.2 Hybrid Desalination with Concentrated Solar Power

Solar collectors are one of the most cost-efficient ways to improve the performance of steam power plants Kabiri et al. [43]. Numerous investigations have been performed to improve the performance of the conventional desalination process through hybrid desalination. Manas et al. [52] developed an integrated desalination unit with vacuum MED and MD that can efficiently produce 7m³ freshwater per 40m² solar field annually. Thakur et al. [53] demonstrated a solar desalination system using a solar still integrated with a parabolic dish concentrated collector and activated carbon pellets as heat storage, as shown in Fig.2. Results indicated that the modified system improved productivity by 85.2% compared with the conventional one. Kerme et al. [54] examined a thermodynamic model of the performance of a MED coupled with a refrigeration system. Results indicated that the modified system's exergy efficiency was increased by around 64.8%. Lu and Li [55] investigated experimentally and mathematically solar-driven MD in conjunction with PVT. Results indicated that the water yield was 23.26L/day, while the anticipated cost per cubic meter is around 18.34USD/m³.

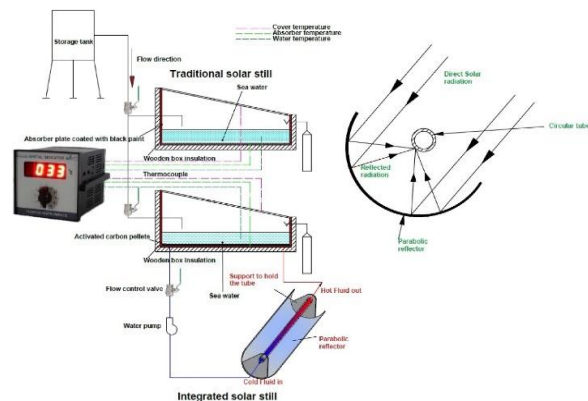


Figure 2 modified solar still [53]

Zuo et al. [56] examined a coupling between solar chimney and turbine to generate electric power using a computational analysis based on vortex theory. The suggested system can produce around 7.92136 ton/h of distillate water hourly. Mendez and Bicer [57] analysed a thermodynamically desalination plant that utilizes a solar chimney combined with water to generate electricity and freshwater. This resulted in the enhancement of performance by 8.4 %.

2.3 Hybrid solar desalination with PV modules

Essa et al. [58] illustrated a stepped solar still augmented with corrugated plate absorber and curved liners, PCM (paraffin wax) with Cu O-nanoparticles and wick material, as shown in Fig.3. The highest distillate yield of the modified system, thermal efficiency, and the estimated cost was 7L/m²/day, 59%, and 0.014 USD/L, respectively.

Hybrid solar distillation with photovoltaic panels comprises heating the saltwater before it enters the

solar still by passing it over the photovoltaic panel's front surface. [59] conducted an experimental study on a SS integrated with PV, porous medium and seawater preheating. The results indicate that increasing the preheating of seawater by 40%, 50%, or 60% boosts the freshwater yield by 10%, 15%, or 20%, respectively. Additionally, it improves energy efficiency by 8.20%, 13%, and 20%. Mehdiabadi et al. [60] quantitatively examined the double slop SS coupled with PV and PCM. The goal of the study is to calculate the proposed system's exergy efficiency. The maximum freshwater yield and produced electricity are determined to be $6.5\text{kg}/\text{m}^2/\text{day}$ and $470\text{Wh}/\text{m}^2/\text{day}$, respectively. 38.1 % was the highest daily efficiency through the study.

Manokar et al. [61] investigated the effect of mass flow rate on improving inclined solar still obtained with a photovoltaic panel. The influence of various water flowrates on freshwater yield, thermal efficiency, and estimated cost per one litre was examined. Results indicated that the maximum yield occurs at the lowest flowrate, yielding $3.7\text{kg}/\text{day}$. An experimental study on an inclined solar still equipped with a PV and PCM accomplished through cover cooling was conducted by Kabeel et al. [62]. The goal of the study is to calculate the system's performance when the flow of water entering the cover cooling system was partially or wholly opened. The proposed system produced $12.29\text{ L}/\text{m}^2$ and $14.17\text{ L}/\text{m}^2$ of cooling when the lid was partially or entirely opened.

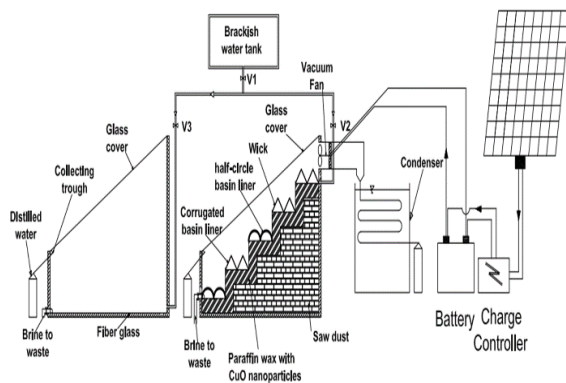


Figure 3 proposed solar still [58]

3. Hybrid solar desalination for freshwater yield maximization

3.1 Solar still

A glass solar still is a typical simple solar device for converting salty or brackish water into drinkable water [53, 63]. There are many types of solar stills such as pyramid solar still [64, 65], solar still with nanomaterials [27, 66], tubular solar still [67, 68]. A convex tubular SS coupled with wick and nanocomposites was investigated experimentally by Essa et al. [69] as shown in Fig.4. The wick materials utilized were (jute cloth and cotton wick); the nanocomposites were TiO_2 and graphene. Results showed

that using wick and nano-composites significantly affects TSS performance. The utilization of a convex absorber improved the vaporization surface area by approximately 21.3%. Employing jute cloth in conjunction with the CVTSS increased freshwater yield by 114% and 92.5%, respectively.

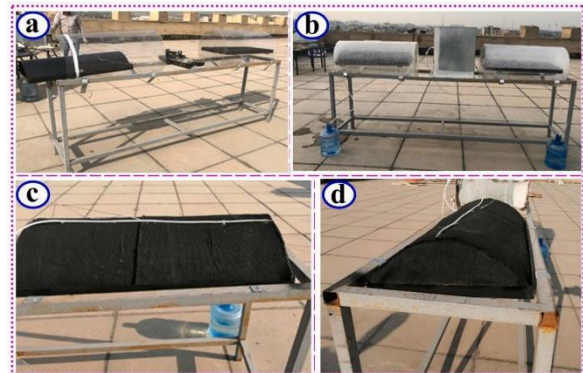


Figure 4 convex tubular solar still [69]

Elshamy et al. [70] performed an experimental investigation of the performance of SS integrated with an absorber having circular parabolic shape to increase absorber surface area. The highest productivity and lowest estimated cost were $2.31\text{ kg}/\text{m}^2.\text{day}$ and $0.00278\text{ USD}/\text{L}.\text{m}^2$. Alawee et al. [71] presented a new technique of PSS using wick materials. The proposed system's main aims are to enhance the performance of pyramid solar still by using (cotton wick and jute wick) at different cracks/cords. Results illustrated the highest performance of the proposed system at 25 cords, with an increment in distillate yield of 122% and 118% above CSS when jute and cotton wick respectively. Additionally, the maximum thermal efficiency was 53 % compared to 34.5% for the CSS.

Abdelgaied et al. [72] improved TSS performance utilizing PCM's square and circular hollow fins. Results demonstrated that conventional TSS production was $4.15\text{ kg}/\text{m}^2/\text{day}$; however, hollow square fins enhanced the production to $5.52\text{ kg}/\text{m}^2/\text{day}$, with an increment of 33%. Additionally, hollow circular fins enhanced production by $6.11\text{ kg}/\text{m}^2/\text{day}$ with an increment of 47.2%. Furthermore, the combination of PCM with hollow circular fins improved the distillate yield to $7.89\text{ kg}/\text{m}^2/\text{day}$ with an increment of 90.1%. Abdelaziz et al. [73] developed TSS utilizing carbon black (CB) nano-fluid on wick material augmented with v-corrugated aluminium basin as shown in Fig.5. Results concluded that utilizing a v-corrugated aluminium absorber resulted in a 21.4% increase in production rate and a 23.18% increase in energy efficiency compared to conventional TSS. Additionally, the cost of traditional TSS was reduced by 22.47% compared with a modified system that included a wick, CB nano-fluid, PCM, and aluminium sheet.

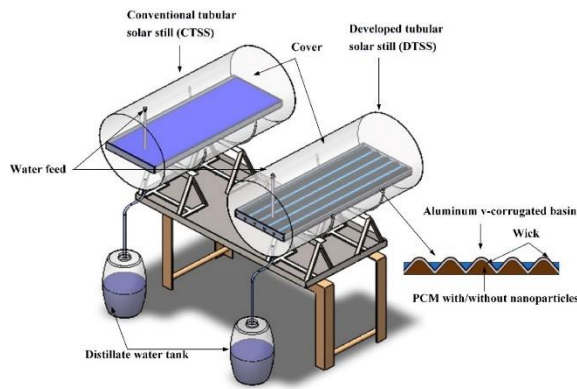


Figure 5 Tubular solar still [73]

Thakur et al. [53] developed a solar desalination system incorporating a solar still, a parabolic dish focused collector, and heat storage using activated carbon pellets. The upgraded method increased production by 85.2 % when compared to the conventional system. Younes et al. [74] conducted an experimental study of stepped SS using v-corrugated and an absorber with half-barrel shape integrated with wick material and PCM (paraffin wax) with CuO-nanoparticles. The distillate yield of corrugated and a half barrel SS compared with CSS enhanced by 134 % and 124 %, respectively.

Panchal et al. [75] improved the conventional solar still CSS performance using a blackened absorber plate augmented with different Graphite powder concentrations. Results revealed that 20% and 40% of graphite powder concentration improved productivity by 10.5 and 17%, respectively. Sharshir et al. [76] demonstrated the enhancement of tubular SS through the use of a cost-effective nano-based mushroom. The enhancement of TSS performance via blacked carbon nanoparticles on the absorber base. The significance of using mushrooms to achieve high solar absorption, capillary action, and surface heat localization. Peng et al. [40] performed a compact flat SS with high performance. The inclined SS with flat one with ultra-hydrophilic glass cover was investigated. Results concluded that the modified FSS achieve higher productivity and efficiency than ISS.

The conclusions section should come in this section at the end of the article, before the acknowledgements.

3.2 Water flashing evaporation and HDH hybridization

Kabeel et al. [77] examined the performance of HDH desalination system coupled with cellulose paper and natural or forced air circulation, experimentally. The hybrid solar HDH desalination technique with various hot stream flow rates integrated with high-frequency ultrasound atomizer HFUA was investigated experimentally [33] as shown in Fig.6. The impacts of water heights, atomizers number, and airflow rates were optimized. Results revealed that the airflow rates significantly

affected system performance. The highest distillate yield, energy efficiency and estimated cost were 7.72 kg/m²/day, 33.84, and 0.0112 USD/L, respectively. The highest distillate yield was 23.6 kg/h with a feedwater temperature of 90 °C. Additionally, they observed that raising hot water flowrates improves humidification efficiency [78].

Shehata et al. [79] developed an SDS using an HDH apparatus with a solar water collector and an HFUA as a hot water sprayer. The employment of HFUA results in a high level of humidification efficiency, with relative humidity soon reaching 100 %. The study concluded that the proposed system improves the freshwater production rate by 14.6%. The cost was calculated as 0.0144USD/L.

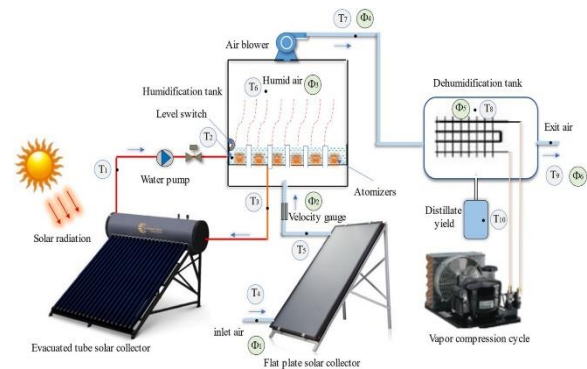


Figure 6 Solar desalination coupled with HDH technique [33]

3.3. Evaporation enhancement integrated with solar desalination

Evaporation enhancer refers to technology that raises the humidity to increase the rate of dehumidification, such as HFUA which is used as a humidifier. An experimental examination of a single slop SS combined with HFUA was performed by El-Said and Abdelaziz [78]., as presented in Fig. 7. The researchers evaluated the impact of the number of atomizers, the water height, and the feedwater salinity on freshwater productivity. Results indicated that the redesigned system's highest yield and thermal efficiencies were 4.410 kg/m² and 55.75 %, respectively.

El-Said et al. [80] conducted an experimental study of a hybrid desalination system utilizing tubular SS and liquid saturated porous material. Vibrator was employed inside wire mesh screening, generating forced vibrations to break the boundary layer in brine. The results indicated the upgraded method of producing 4.2 kg/m² of distillate water, a 34 % increase over the standard system, with 0.0309 USD/kg.m². Aly et al. [81] proposed an enhanced evaporator design for Multi-Effect Distillation (MED) to decrease thermal losses and the evaporator's surface area. Results indicated that the new techniques saved the capital cost and reduced the footprint by 20%, 65%, respectively. Kandeal et al. [82] investigated an experimentally SS desalination unit integrated with copper absorber base coated with nanofluid NF and PCM in three cases. Results

indicated that all cases revealed the good performance, and modified SS with copper absorber base coated with nanofluid NF and PCM is the best case.

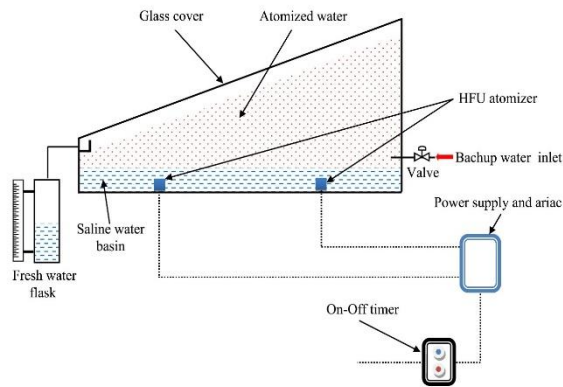


Figure 7 single slop SS combined with HFUA [78]

4. Hybrid solar desalination to optimize water quality

Water quality refers to the quantity of saline in water; also, desalinated freshwater must meet the World Health Organization's WHO standards. While distillation water is not suitable for drinking, it is employed in industry. This section focuses the usage of RO coupled with PVT since it provides a suitable salt content while also increasing freshwater production. Son et al. [83] investigated the synergetic benefits of energy utilization in hybrid desalination by combining (MED) with an adsorption cycle (AD). The upgraded system is capable of producing around 10 m³ of distillate water each day. The suggested system delivered production (0.236 g/L of TDS) with saline-water salinity (34,718 mg/L of TDS).

The reverse osmosis (RO) process is a widely used method of producing pure water. Electricity is the source of energy for the RO [30]. The construction of a high-distillate yield desalination unit that consumes little energy has proven difficult. So Abdelgaied et al. [31] investigated solar PV-powered hybrid desalination unit utilizing HDH and RO techniques integrated with heat recovery. The saltwater was utilized as a working fluid in a hydro-mechanical coupling and eliminated the RO high-pressure pump in favour of a direct-drive hydraulic converter, resulting in fewer intermediate power conversions and increased efficiency [32]. Solar-powered interfacial desalination has established itself as a cost-effective and environmentally benign method of producing clean water [28].

5. System performance assessment

To adequately analyse the proposed system's feasibility. Various parameters are frequently utilized to evaluate desalination system performance, such as energy and exergy efficiencies, GOR, and the produced water price.

5.1. Energy efficiency

Thermal energy analysis was investigated to determine the desalination system's efficiency reported by [33] as follows:

$$\eta_{En} = \frac{\dot{m}_{dis} \times h_{fg}}{I_t A_{ct} + E} \quad (1)$$

where: \dot{m}_{dis} is the freshwater yield (kg/s), h_{fg} Refers to the latent heat in kJ/kg, while I_t refers to the solar radiation in W/m².

A_{ct} refers to the area of collector surface in a square meter. E is the power consumption through the system.

The term h_{fg} was analyzed as follows, Kabeel et al. [65].

$$h_{fg} = a_1 + a_2 T_w + a_3 T_w^2 + a_4 T_w^3 + a_5 T_w^4 \quad (2)$$

where T_w is the water temperature, and the terms a_1, a_2, a_3 and a_4 are determined from the following correlations:

$$\begin{aligned} a_1 &= 2.5 \times 10^6, & a_2 &= -2.37 \times 10^3, & a_3 &= 2.68 \times 10^{-1}, \\ a_4 &= -8.1 \times 10^{-3}, & a_5 &= -2.08 \times 10^{-05} \end{aligned}$$

5.2. Exergy efficiency

The exergy efficiency of the desalination process indicates how well energy is utilized. Exergy efficiency provides an estimation of the system's maximal (qualitative) useable energy output with the ambient conditions [84]. Exergy is described as available useful work. Exergy is the system's quality, and its environment depends on both the system and its surroundings. The exergy efficiency is calculated as follows [85]:

$$\eta_{Ex} = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{\frac{\dot{m}_{dis} L}{3600} \left[1 - \left(\frac{T_a}{T_{w, tr}} \right) \right]}{A_{ct} I_t \left[1 - \frac{4}{3} \left(\frac{T_a}{T_s} \right) + \frac{1}{3} \left(\frac{T_a}{T_s} \right)^4 \right]} \quad (3)$$

5.3. Gain Output Ratio (GOR)

GOR is the energy or mass ratio used in thermal desalination processes. GOR is the energy ratio between latent heat and the net heat input to the system. This metric is essentially an indicator of the water production's effectiveness and the system's heat recovery impact [86]:

$$GOR = \frac{\dot{m}_{dis} h_{fg}}{\dot{m}_{fw} c_{p, fw} (T_{fw, in} - T_{fw, o})} \quad (4)$$

where \dot{m}_{dis} is the desalinated water flow rate, and \dot{m}_{fw} is the feedwater flow rate.

Many researchers from the above review have formulated equations concerning energy and exergy efficiency besides GOR. The corresponding outputs are shown in Table 1.

Table 1: GOR and Energy & exergy efficiencies comparison

Ref.	Categories	(GOR)	(η_{en}) %	(η_{ex}) %
El-Said et al. [80]	SS with nanofluid and PCM	—	58	—
Kandeal et al. [82]	MED and absorption cooling	—	90	26.7
Son et al. [83]	SS with carbon black nanoparticles	—	42.25	4.36
Sharshir et al. [76]	SS with nano-based mushrooms	—	54	4.9
Sharshir et al. [27]	SS with cotton hung pad and CuO	—	51	5.9
Peng et al. [40]	Compact flat SS	—	72	—
El-Said et al. [33].	HDH- HFUA	1.54	33.84	1.43
Essa et al. [69]	Convex tubular solar still with nanocomposites	—	33 - 50	—
Manokar et al. [61]	SS with PV	—	34.2	—
Kabeel et al. [62].	SS with PCM	—	—	31.8
El-Said & Abdelaziz [78]	SS with ultrasound waves techniques	—	41.34	—
Elshamy et al. [70]	SS with circular parabolic absorber	—	41.7	3.021
Abdelgaied et al. [72]	TSS with fins	—	70.2	—
Abdelaziz et al. [73]	SS with aluminium basin, wick, and nanofluid	—	40.9	—
Essa et al. [58]	Stepped SS with PCM	—	59	—

6. Economic aspects

The cost-effective feasibility of an energy system is critical in determining the project's product cost and return on investment. It mitigates project risk. The cost estimate of hybrid desalination is dependent on a number of variables [87]: the start-up cost, the interest payments, the yearly output of production, the maintenance cost, the system's life, and the system's terms of quality and price. Table 2 summarizes the different cost estimates for several types of desalination techniques.

The total costs (TC) can be calculated as follows:

$$TC = C_{op} + C_{main} + C_{fx} \quad (5)$$

where C_{op} refers to operation cost, which includes labour, material handling, and energy while C_{main} is the maintenance cost and C_{fx} refers to fixed charges. It can be determined as;

$$C_{fx} = af \times C_c \quad (6)$$

where C_c refers to capital cost and a is the factor of amortization [33]

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (7)$$

where i , is the annual interest percentage and n is the system lifetime.

The freshwater production cost C_{prod} is calculated considering 365 days/year as follows [35]:

$$C_{prod} = \frac{TC}{f \times 365 \times \sum_{i=1}^{RT} \dot{m}_{dis}} \quad (8)$$

Table 2: Comparison of cost/one litre of desalinated water for previous studies

Ref. No.	System Category	Maximum productivity L/m ² /day	Estimated cost USD/L
Kandeal et al. [82]	SS with nano fluid and PCM	6.52	00.011
Sharshir et al. [76]	SS with nano-based mushrooms	5.5	0.025
Sharshir et al. [27]	SS with Cotton hung pad and CuO	4.23	0.015
Peng et al. [40]	Compact flat SS	7	—
El-Said	HDH- HFUA	7.72	0.0112

et al. [33].			
Essa et al. [69]	Convex tubular solar still with nanocomposites	4.2 - 9	0.012 – 0.017
El-Said & Abdelaziz [78]	SS with HFUA	4.411	0.012
Elshamy et al. [70]	SS with circular parabolic absorber	2.31	0.0021
Abdelgaied et al. [72]	TSS with fins	7.89	0.009
Abdelaziz et al. [73]	SS with aluminum basin, wick, and nanofluid	5.92	0.0164
Essa et al. [58]	Stepped SS with PCM	7	0.014

7. Conclusions and recommendations

This review study presented recent developments of solar stills and humidification and dehumidification solar desalination systems to focus on energy, exergy, and economic analysis. The main introduced disciplines include the combination of more than one technique in seawater desalination for heat source optimization, cost minimization or efficiency maximization. From the reviews and comparisons, the main results can be concluded as follows:

- 1-The distillate yield can be increased by using geothermal energy to condensate freshwater, leaving the solar still with a production improvement of 56% compared with traditional SS. The highest production was 7.8 L/m²/day.
- 2-Stepped solar still augmented with corrugated plate absorber and curved liners, PCM (paraffin wax) with Cu O-nanoparticles and wick material increases the distillate yield and thermal efficiency of solar still to 7 L/m²/day, 59% respectively with estimated cost 0.014 USD/L.
- 3-Utilizing PCM's square and circular hollow fins and utilizing carbon black (CB) nano-fluid on wick material augmented with v-corrugated aluminium basin draws a 21.4% increase in production rate and a 23.18% increase in energy efficiency compared to conventional TSS.

4-The maximum reached energy efficiency was 72%. It was achieved with compact flat solar still with ultra-hydrophilic glass cover.

5-The minimum cost of one litre produced freshwater was 0.011 USD/L (about 0.17 LE/L) in solar desalination via copper chips, nanofluid, and phase change material.

It is recommended to extend research in renewable energy hybridization with other desalination systems to minimize the cost of one litre of freshwater to meet the population's growing needs. Other recommendations include utilizing phase change material to store additional solar heat throughout the day or using nanoparticles to enhance heat transfer. It is also recommended to use stepped or corrugated absorbers to maximize absorption. Wick materials and mirrors are also recommended because they improve the evaporation and absorb thermal energy. Finally, the optimum and recommended humidifier is because it creates a rapid humid air with 100% relative humidity.

Nomenclature

Symbols

A	Area, m^2
a	Amortization factor, %
C	Cost, \$.
f	System availability.
I	Solar intensity, W/m^2 .
i	Yearly interest rate (%)
\dot{m}	Flow rate, kg/s .
n	Number of years
TC	Cost total, USD

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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