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Applications of different types of heat pipes in solar desalinations: A comprehensive review

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ABSTRACT

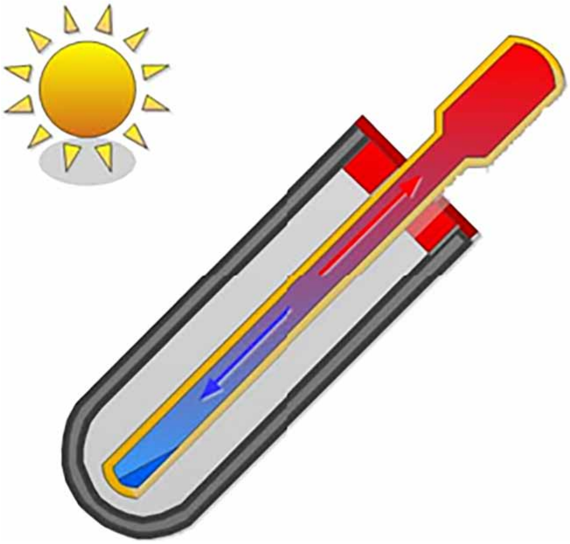
Desalination processes are energy consuming and it is required to apply clean energy sources for supplying them to prevent environmental issues. Solar energy is one of the attractive clean energy sources for desalination. In solar thermal desalination systems, different thermal components could be used for heat transfer purpose. In solar desalination technologies, heat pipe as efficient heat transfer mediums could be employed to transfer absorbed and/or stored thermal energy. The objective of this study is to review applications of heat pipes in solar energy desalination systems. Regarding the performance dependency of these thermal systems on the variety of factors, scholars have investigated these systems by consideration of the effect of different influential factors. Based on the results, it is concluded that use of heat pipes could lead to proper performance of solar desalination systems. Aside from direct transfer of absorbed heat from solar radiation, heat pipes can be applied in the storage units of solar desalination systems to keep the systems active in night-hours or low solar irradiation conditions. The overall performance of the solar desalinations systems with heat pipes can be influenced by some factors such as filling ratio and operating fluid that affect the performance of heat pipes.

Key words: desalination, heat pipe, heat transfer, solar energy, thermosyphon

HIGHLIGHTS

- Applications of heat pipes as efficient heat transfer tools are reviewed.
- Solar desalination system utilizing heat pipes for heat transfer are introduced.
- Some recommendations are provided for the upcoming studies on the use of heat pipes in solar desalination systems.

GRAPHICAL ABSTRACT



1. INTRODUCTION

For human societies, supply of fresh water is vital due to the reliance of the societies on it for survival and development (Zheng 2017). Although the majority of the earth, more than 70%, is covered by water, there is fresh water scarcity in different regions of the world since more than 95% of water is saline or in brackish form that means it is useless for drinking and agricultural purposes and only less than 1% of water resources are reachable for human (Tiwari *et al.* 2003; Chauhan *et al.* 2021). Owing to some facts like uneven distribution of fresh water in the world, requirement of water for human activities and survival, and population growth, there is increasing trend in the importance of desalination (Alhuyi Nazari *et al.* 2021). It should be noted that desalination process is energy consuming and different systems and configurations have been proposed for this purpose by use of various energy technologies (Assad *et al.* 2020; Shakouri *et al.* 2021). This energy requirement can cause some problems and issues in supply of required energy and emission of harmful gases for the environment. Current technologies used for desalination consuming fossil fuels would likely to produce water with high emission of carbon and economic cost (Zheng *et al.* 2021). In this regard, it is crucial to apply clean and energy sources and alternative technologies in a sustainable way to have secure supply of fresh water for human beings' needs and requirements.

Interest in clean and alternative energy sources is sharply increasing in the world (Taner 2021). Renewable energies, as alternatives for fossil fuels, can be used for desalination process in direct or indirect way (Anand *et al.* 2021; Vaithilingam *et al.* 2021; Kumar *et al.* 2023; Mehtari *et al.* 2024). In direct cases, renewable energy sources are generally applied in thermal systems to supply required heat for evaporation of saline water and salt removal. These systems have been investigated by different scholars (El Haj Assad *et al.* 2022). In a study by Ahsan *et al.* (2014), parameters that affect the performance of a low cost solar still were evaluated. They reported that for their considered case, daily water productivity is inversely proportional to the water initial depth in the systems. Moreover, it was noted that productivity of the still was approximately proportional to the daily solar radiation. In some studies, effect of modifications on the performance of solar desalination systems has been investigated. For example, in a study by Bataineh & Abbas (2020), impact of adding internal reflectors to the sides of solar still was investigated. They reported that adding reflectors can improve the efficiency. Another technique for performance modification of solar desalination systems is making use of storage unit (Adamu *et al.* 2023). In addition to solar, other renewable energy sources with thermal content are applicable for desalination purpose in direct way. In a study by Hu *et al.* (2023), performance of a distillation desalination technology driven by ocean and solar thermal energy was investigated. They reported that in case of applying ocean thermal energy for driving the desalination system, up to 0.7 kg/h minimum freshwater productivity was achievable while coupling it with the solar thermal energy lead to improvement in the freshwater yield. Furthermore, they observed that the proposed desalination by use of both solar and ocean thermal energy leads to 30.1% more freshwater yield compared with the single solar desalination. Aside from the direct desalination by use of renewable energies, it is possible to indirectly use renewable sources. In these systems, renewable energies are applied for power generation to supply the electricity needed for the desalinations systems, e.g. Reverse Osmosis (RO) systems (Gorjian *et al.* 2020). Performance and feasibility of these systems have been investigated by different researchers in recent decades. For instance, Ghafoor *et al.* (2020) implemented a techno-economic feasibility study on the solar-based desalination system composed of RO systems. They reported that increment in the temperature of feed water leads to elevation in the membrane productivity. Moreover, they noted that payback period for their case study in Pakistan was 1.83 years. In a study by Shafaghat *et al.* (2023), performance of a RO desalination system equipped with PV/thermal collectors for Shiraz in Iran was investigated by consideration of stand-alone and grid-connected installation. They reported that in comparison with simple grid-connected RO system, proposed system decrements emission of CO_2 by 79% and 85.7 in stand-alone and grid-conned installation, respectively. In these systems, it is possible to use more than one renewable energy technologies, as hybrid systems, to produce power and use it in RO desalination (Mito *et al.* 2019). Performance of these systems have been studied in different research works (Jiang *et al.* 2022). For instance, Elmaadawy *et al.* (2020) implemented a study on the optimal sizing and feasibility assessment of a RO system driven by hybrid renewable energy systems by consideration of technical, environmental and economic criteria. They reported that CO_2 emission from the optimal system outperforms a diesel system by 81.5%.

Heat pipes (HPs) are very efficient thermal devices operating based on a two-phase heat transfer mechanism. Effective thermal conductivity of HPs is much higher than conductive metals (Ramezanizadeh *et al.* 2019) which makes them as promising technology for heat transfer and attractive alternatives for conventional thermal mediums. HPs have been used in variety of clean and renewable energy systems for thermal management or as thermal medium to transfer energy from heat source to heat sink. As one of the most conventional application in renewable energy systems, HPs are usable in solar collectors to transfer absorbed thermal energy to the working fluid. In these systems, evaporator section of HPs are located in the absorber of collectors and heat is transferred to the condenser of the HP for the intended purpose (Alshukri *et al.* 2021, 2022). HPs are applicable for cooling of renewable energy systems need thermal management for performance enhancement. For instance, Alizadeh *et al.* (2018) proposed an approach for thermal management of solar PV cells by use of oscillating HPs to reach higher efficiency. In the proposed system, HPs were installed at the back of PV cell to transfer thermal energy from the cell in order to reduce its temperature and improve efficiency. Zhang *et al.* (2013) proposed a solar PV systems integrated with HP heat pump for water heating purpose. In their system, PV/looped HP was applied and the HP was used to transfer the absorbed thermal energy to the water tank. In another study (Mathioulakis & Belessiotis 2002), a solar domestic water heating system based on HP was introduced. In the proposed configuration, wickless loop HP was applied to transfer heat from the collector-evaporator to the tank via heat exchanger-condenser. In addition to the abovementioned applications, it is possible to use HPs to accelerate thermal energy transfer from the storage unit. Motahar & Khodabandeh (2016) applied HP in Phase Change Material (PCM) and reported dramatic enhancement in rate of both solidification and melting by use of HP. It is possible to use HPs in solar desalination systems both for transfer heat from collector or storage unit in order to modify the overall performance which is the topic of this article. HPs have been applied in different systems for desalination purposes. For instance, Zhang *et al.* (2018) proposed a thermal-driven desalination system based on low-grade waste heat with use of open loop HP.

As it was mentioned, it is necessary to develop desalination systems, particularly in regions water crisis. In regard to energy requirement for the desalination process and issues related to the fossil fuels, employment of renewable energy sources would be inevitable. Solar energy is one of the most appropriate renewable sources for water desalination and HPs are one of the most important components in some of the solar desalination systems. In this regard, it is useful to get deep insight into the applications of HPs in solar desalination systems and the factors affecting their performance. The main focus of the present review article is on the applications of HPs in solar thermal desalination systems. In the following section, different types of desalination systems are introduced and their classifications are represented. Afterwards, the use of HPs in solar desalination systems is reviewed. Finally, some suggestions are recommended for the future studies on the similar technologies and systems.

2. DESALINATION SYSTEMS

In general, desalination is divided into three main processes on the basis of the applied technology for freshwater production, as shown in Figure 1. In the evaporation and condensation technologies, thermal energy is employed for vaporizing water and then condensation of vaporized water to produce freshwater. The required energy for this purpose is provided by utilizing

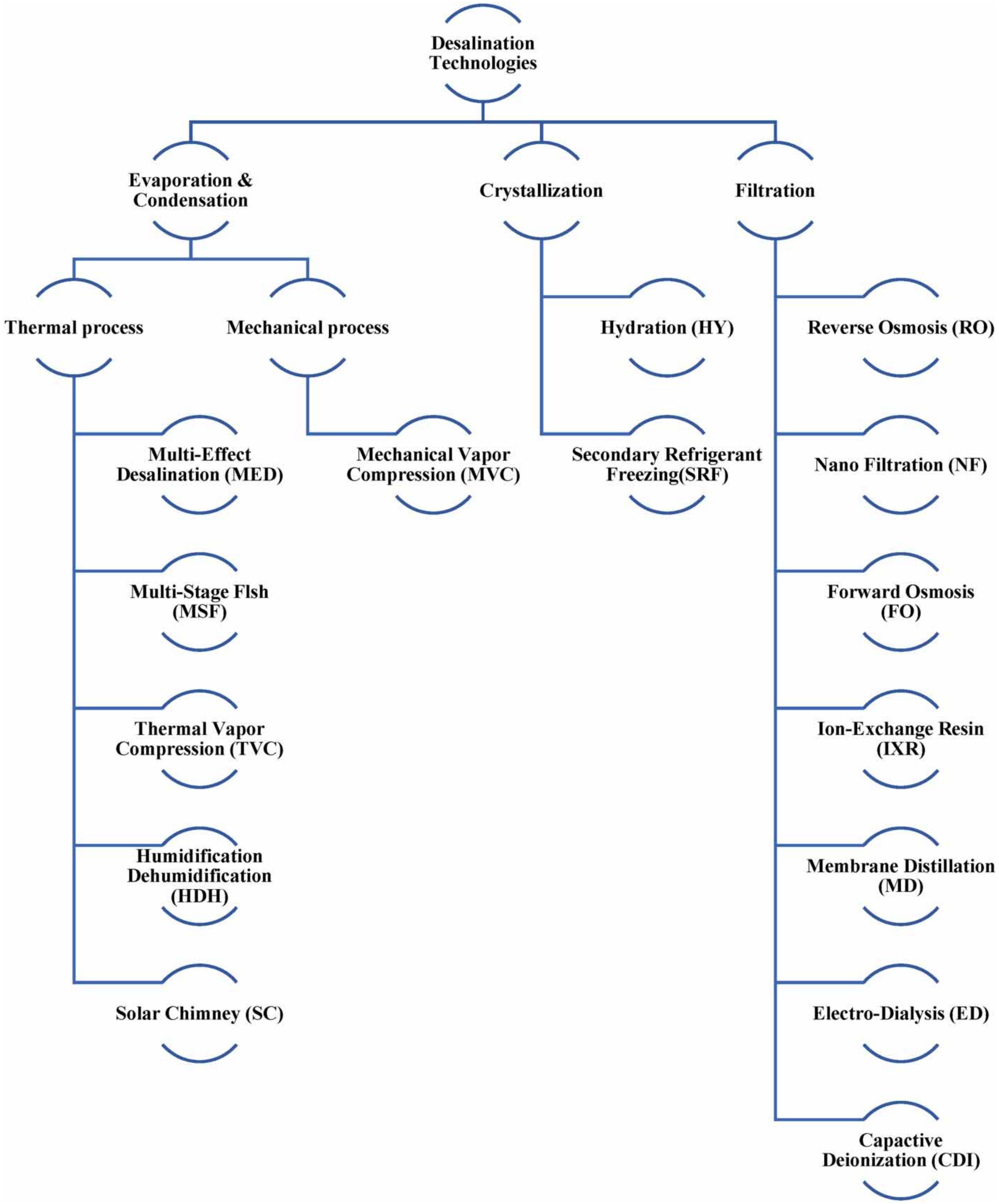


Figure 1 | General classifications of desalination technology (Adapted from Ref Curto *et al.* 2021).

heat from a thermal process or via a mechanical process. In filtration technologies, a semipermeable membrane is used in general to separate salt from water. In the category known as crystallization, freshwater is extracted by producing ice as an intermediate product (Curto *et al.* 2021). There are some requirements for these processes such as feedwater pretreatment to decrease fouling, management of brine, water post-treatment production prior to its distribution and optimization of energy utilization and production of water (Kress 2019). The most important factors determining desalination process choice are the operation and capital cost in addition to the plant capacity (Fellows & Al-Hamzah 2015). The majority of the desalination plants in the world are RO type; however, in some regions of the world such as the Middle East, thermal technologies are used in larger scale compared with RO (Mahmoudi *et al.* 2023).

In this study, the main focus is on solar-based desalination systems, which are a subbranch of thermal processes. It should be noted that aside from the technical factors that are related to the specifications of the applied technology, quality of input water plays key role in the obtained water quality (Jalihal & Venkatesan 2019). Raw water classification is provided in Table 1.

3. HEAT PIPES IN SOLAR DESALINATION

Solar energy is the most abundant renewable energy source with applicability for different energy-related purposes including power generation, cooling and heating (Wang *et al.* 2020; Hussain *et al.* 2021; Alhuyi Nazari *et al.* 2023). Thermal content of solar beams is usable for thermal desalination plants. In this regard, different architectures and systems have been introduced for freshwater production by use of thermal energy of solar radiations. In some of the proposed configurations, HPs are used as thermal mediums that are reviewed in this article.

3.1. Solar desalinations with evacuated tube collectors

Evacuated Tube Collectors (ETCs) are composed of a HP inside a tube that is vacuum sealed. Liquid-vapor phase change is used in ETCs in order to transfer thermal energy at high efficiency. The material of applied pipe which is made of copper is attached to a black copper fin, which fills the tube and creates the absorber plate of the collector. Each tube is ended at a tip made of metal that is connected to the sealed pope and works as the condenser. The thermal content of solar beams causes evaporation of the liquid, which rises due to the lower density and condensed there by heat dissipation. Afterwards, the condensed fluid is returned to the solar collector due to the gravity impact (Kalogirou 2016). Schematic of an ETC is illustrated in Figure 2. It is found that making use of HPs in ETC leads to higher temperature and efficiency output (Chopra *et al.* 2018). This cycle is repeated till there is solar energy as driving force in thermal format. In majority of the cases, water or water/ethylene glycol moves via the manifold to receive the thermal energy from the vapor condensation (Kalogirou 2016). In addition to the gravity assisted HPs, also known as thermosyphon, wick HPs can be used in these collectors (Kumar *et al.* 2017). This absorbed heat can be used as thermal source for different purposes, i.g. thermal desalination. It should be noted that in addition to direct use of produced thermal energy by ETCs for desalination, it is possible to apply the absorbed heat for driving heat-powered engine pump and use it in RO desalination (Takalkar & Bhosale 2020).

The performance of solar desalination systems with ETC have been evaluated by different scholars by consideration of various architectures and parameters. Similar to any other solar energy system, solar radiation intensity plays key role in the performance of solar desalination coupled with HPs. In a study by Jahangiri Mamouri *et al.* (2014), performance of a solar desalination based on ETC and thermosyphon was investigated. they reported that desalination rate increments when the solar radiation intensity elevates. Another factor evaluated in their work was the material of basin cover. It was reported that employment of aluminum for this purpose leads to higher desalination rate in comparison with the steel due

Table 1 | Raw water classification

Description	Salinity range TDS (ppm)
Fresh water	<1,000
Brackish water	1,000–5,000
Highly brackish	5,000–15,000
Saline water	15,000–30,000
Seawater	30,000–40,000
Brine	40,000–300,000

(TDS: total dissolved solids) (Jalihal & Venkatesan 2019)

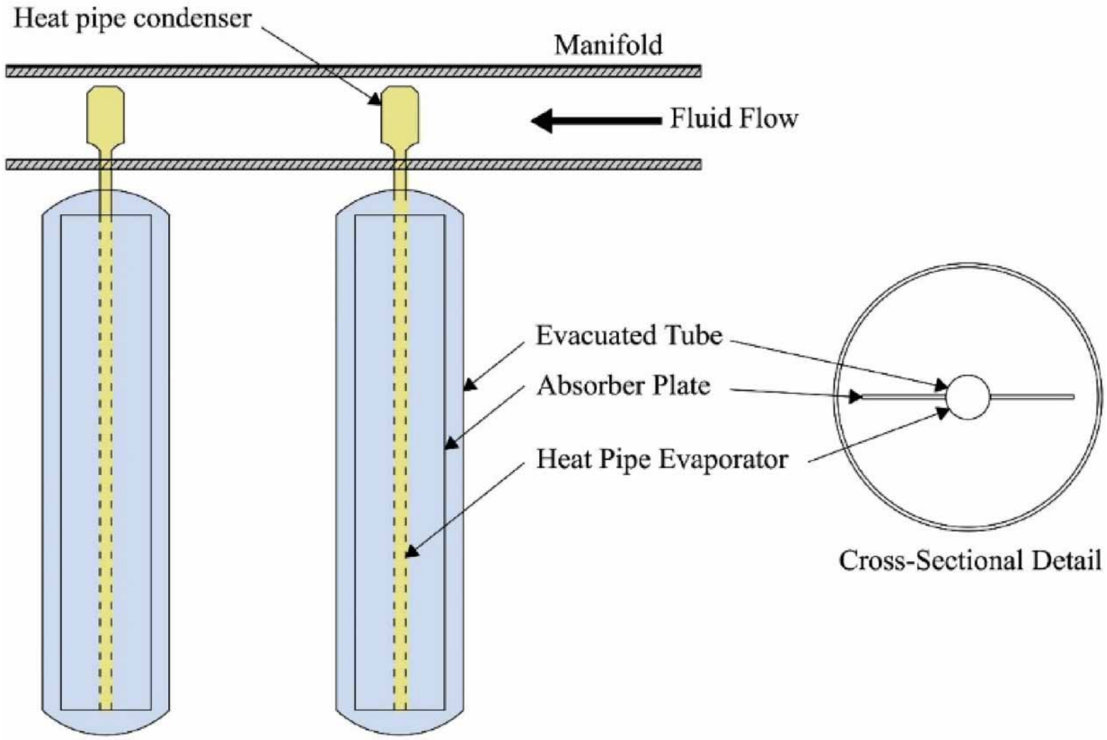


Figure 2 | Schematic of ETC (Adapted from Ref Kalogirou 2016).

to the higher thermal conductivity and better condensation rate on the inner surface. In a study by Jafari Mosleh *et al.* (2015), performance of desalination system composed of twin-glass ETC with parabolic through collector and HP was investigated. They applied three different volumes in the basin. In the lowest volume, the HP condenser was partly submerged in the water while in the middle value, the condenser was thoroughly submerged in water that causes higher yield in the latter case. Further increase in the volume causes increase in heat loss and consequently slight reduction in the yield. Moreover, their findings demonstrated that efficiency and production rate can achieve 22.1% and 0.27 kg/m^2.hr, respectively, in condition that aluminum conducting foils were applied in the space between the twin-glass ETC collector and the HP for transferring the thermal energy from the collector to the HP. In condition of employment of oil for this purpose, efficiency and production rate reached 65.2% and 0.933 kg/m^2.hr, respectively. Applying some modifications by adding some extra components would be an effective approach to improve the performance of solar desalinations with ETC and HPs. Shoeibi *et al.* (2022) proposed a solar desalination system by use of wind ventilator external condenser as shown in Figure 3. Their results revealed that generation of freshwater by using external condenser and ETC with HP is around 2.13 time of those conventional ones. The external condenser yield share was around 18.62% of the whole water productivity. In addition, the mitigation of carbon dioxide was around 0.51 tons and 29.19 on the basis of exergoenvironmental and environmental analysis in the proposed system with modification.

Operating fluid is among the most important factors in the performance of various kinds of HPs (Ramezanizadeh *et al.* 2018). In this regard, the overall performance of systems with HPs can be affected by the operating fluid. In a study by Fallahzadeh *et al.* (2020), performance of a Conventional Pyramid-shape Solar Still (CPSS) was compared with a Modified Pyramid-shape Solar Still (MPSS). In the MPSS, CPSS was integrated with HP solar collector in which five thermosyphons were installed in five glass evacuated tubes. For the MPSS, two operating fluids namely water and ethanol were tested in the HPs in three filling ratios including 30, 40 and 50%. They found that employment of HP solar collector leads to elevation of temperature difference between the basin water and glass cover by 30% and as a consequence, productivity improved by 62%. Furthermore, it was observed that the best performance for both working fluid is obtained in case of 40% filling ratio as

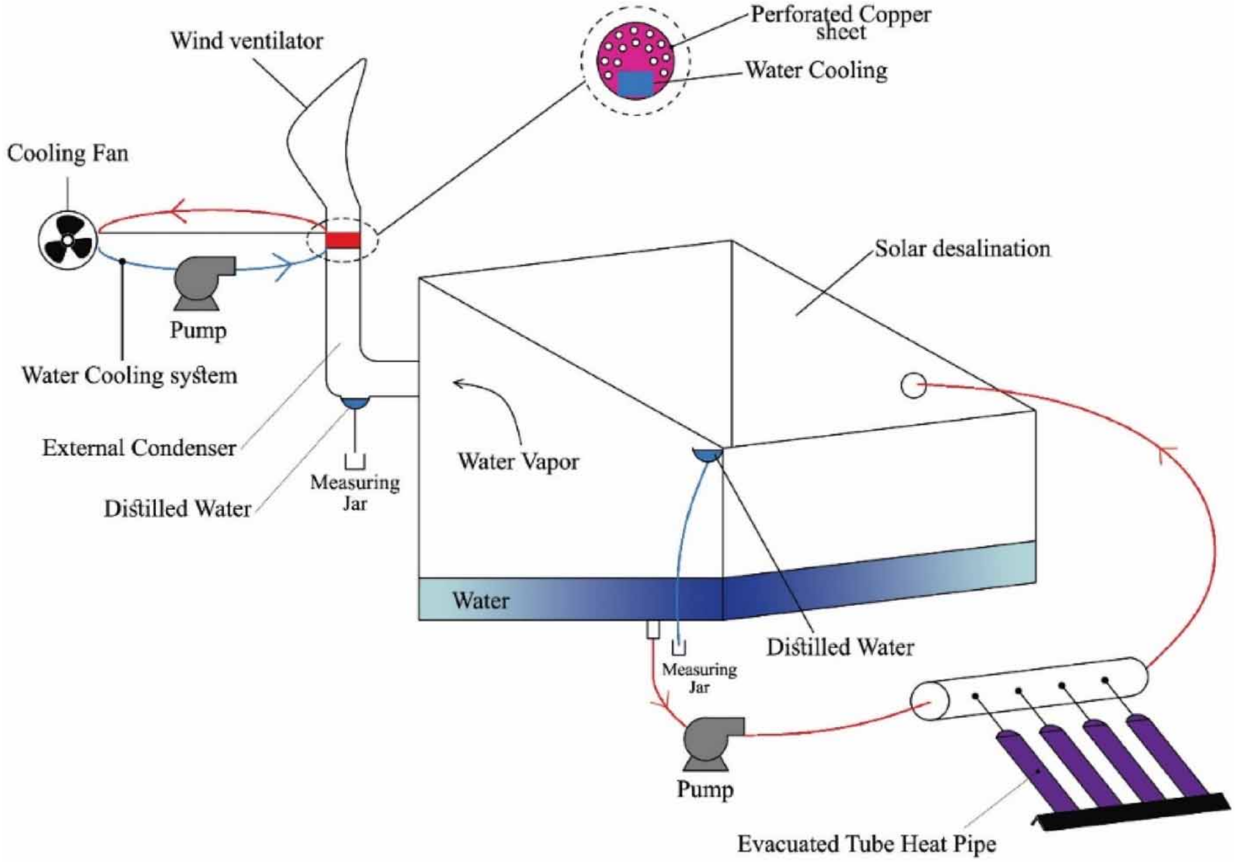


Figure 3 | Solar desalination with wind ventilator and ETC (Adapted from Ref Shoeibi *et al.* 2022).

shown in Figure 3. It was noted that making use of water in the HP can provide the best performance. In addition to productivity, exergy analysis was implemented and reported that using the collector increments the highest hourly exergy around twice that was attributed to the decreased thermal energy loss due to the existence of vacuum gap between the evacuated tubes two glass surfaces.

In another study, performance of a solar desalination with air bubble column humidifier, ETC and thermosyphon was evaluated by Behnam & Shafii (2016). Schematic of the proposed system is illustrated in Figure 4. They considered impacts of various factors such as depth of water and air flow rate into the humidifier. Three initial depths of water in humidifier including 5, 7.5 and 10 cm were considered. They reported that by elevation of water depth from 5 cm to 7.5 cm, desalination rate gradually increments since in the latter case HPs condenser were completely submerged in the water while it was partially submerged in case of 5 cm water depth. Further increase in the depth to 10 cm leads to decrement in the productivity that was attributed to the elevated heat loss. Furthermore, it was reported that in the morning times, increase in the humidifier air flow rate leads to reduction of hourly productivity rate while in the following times increase in the hourly productivity was observed. In addition to the consideration of mentioned factors, they applied a new idea by using fluids like water and oil in the space between the HPs and ETCs. They reported that by using this technique, productivity of the system and its efficiency significantly improve. The provided reason for this improvement was improvement in the convective heat transfer that leads to increment in heat transfer rate between the ETCs and applied HPs.

Aside from the energy analysis, other analyses such as exergy, environmental, techno-economic etc have been implemented by the scholars on different energy systems to investigate different aspects of them (Taner & Demirci 2014; Taner & Sivrioglu 2017; Taner 2018a). These types of analyses have been applied for different renewable energy technologies in recent years (Ta Ner & Dalkilic 2017; Taner 2018b). It should be noted that it is possible to apply the mentioned analyses for desalination systems. In some studies, exergetic, environmental and economic dimensions of solar desalination systems applying ETCs

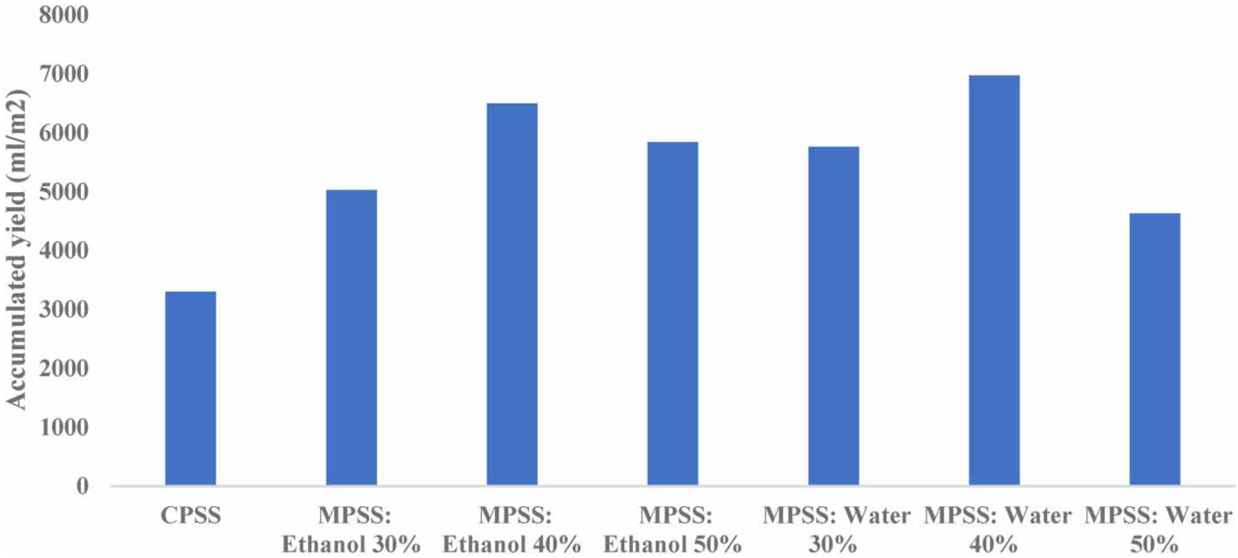


Figure 4 | Accumulated yields of the CPSS and MPSS with water and ethanol in different filling ratios (Adapted from Ref Fallahzadeh *et al.* 2020).

have been considered. In a work by Nema & Karunamurthy (2022), a novel desalination system on the basis of evacuated tube collective condenser HP, as illustrated in Figure 5, was considered for evaluation. They reported that delivered total distilled water in conditions of half-filled and three-fourth-filled water flow pipe was 8,050 ml/day and 5,925 ml/day, respectively. The highest exergy efficiency of the proposed system was 3.92%. It was noted that the freshwater economic minimum unit cost by use of the proposed system is 4.27 INR and the payback period is equal to 2.9 years. Moreover, it was found that by employment of this system, it is possible to have 4.25 kWh save in electricity and 4.16×10^{-3} tons of CO_2 equivalent per annum.

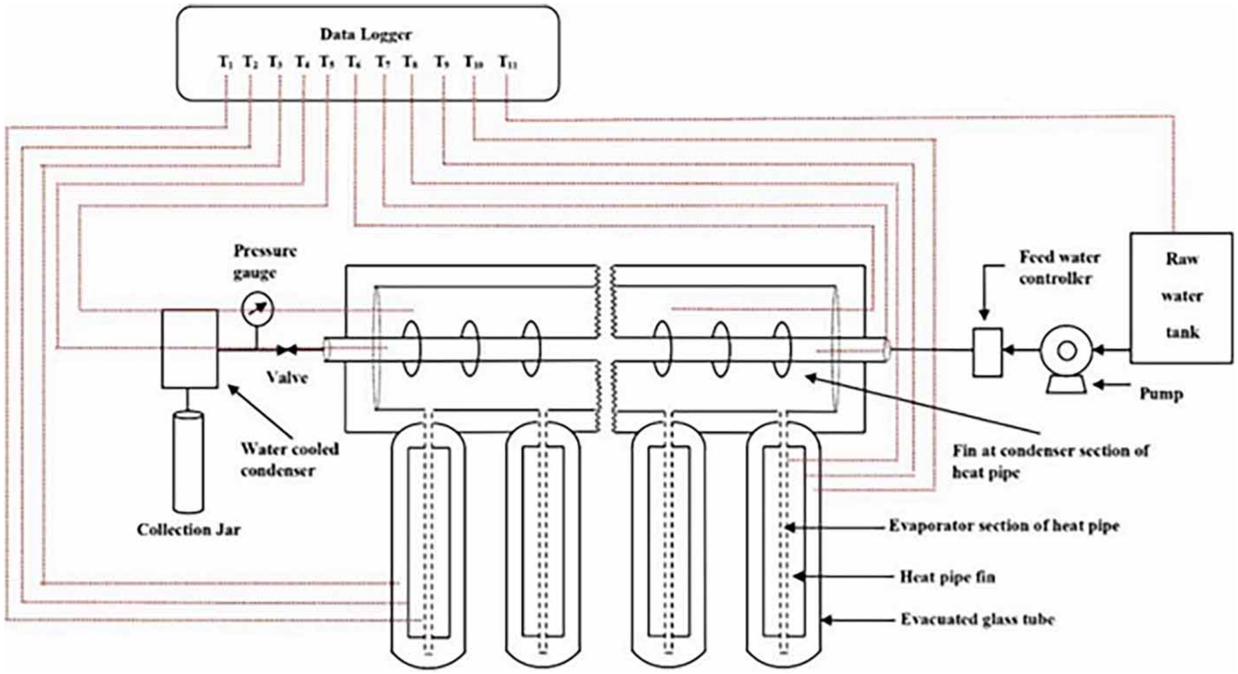


Figure 5 | Schematic of solar desalination system with evacuated tube collective condenser HP (Nema & Karunamurthy 2022).

3.2. Solar desalinations with storage unit and heat pipes

Solar has an intermittent nature and it is necessary to apply a storage unit to have active systems in night hours or daytimes with low radiation intensities. Thermal Energy Storage (TES) units can be applied in solar thermal desalination systems to extend its operating hours and overall yield. In these cases, it would be useful to employ HPs to improve heat transfer from the storage unit to water for being desalinated. In a study by Khalilmoghadam *et al.* (2021), a solar still was designed with latent heat storage unit. In the proposed system, the total solar radiation was used for heating the saline water and just the thermal energy from the vapor condensation was stored in the storage unit during the day. The dissipated thermal energy from the body of condenser was transferred to the storage and stored. After sunset, the stored thermal energy in the storage was transferred to the saline water by making use of HPs, oscillating type. Employment of this system causes prevention of water temperature drop that ensures the continue of desalination process after sunset. They reported that by using the proposed design, efficiency of the system increases to 48.5% while it is 23.7% for the conventional solar still. For their case study, in Iran, cost per liter for freshwater production was 0.0093$/l/m^2.

It is possible to have modified solar thermal desalination systems with storage unit by applying some modifications and adding some components. In a study by Faegh & Shafii (2017), a novel solar still was designed by use of external condenser that was filled with PCM (Figure 6). The system was designed in a way the contact between PCM and saline water was prevented to utilize the total radiated energy for evaporation of saline water during daytime. The produced vapor in this period, daytime, was conducted to a PCM-filled external condenser to be condensed. Vapor wasted heat in the condenser was absorbed by the PCM and stored. Consequently, PCM energy storage was just via the vapor and solar radiation was not directly used for storage. By installation of thermosyphon as thermal diode between the saline water at upper position and PCM tank at lower position, unidirectional heat transfer became possible. Consequently, in cases of this sort of solar radiation, in which saline water temperature is lower than PCM, heat was transferred from the PCM to water and it caused the desalination process to continue in the absence of solar radiation. They reported that by applying the external condenser in absence of PCM and insulating the solar still cover glass jointly results in 56% increase and utilization of PCM-filled external condenser leads to 86% increment in water yield.

3.3. Other solar thermal desalinations with heat pipes

In addition to the ETC, which were mentioned in section 3.1., other types of collectors based on HPs are applicable for desalination by use of solar energy. In a study by Aref *et al.* (2021), performance of a portable bubble basin HDH desalination unit by employment of an oscillating HP was investigated. The system was composed of bubble basin humidifier, oscillating HP dehumidifier and oscillating HP collector. In order to compare the Bubble Basin Humidifier (BBH) with Bubble Column Humidifier (BCH) type, the basin glass cover was insulated by PVC and aluminum sheet was applied to cover it. They reported that BCH-type overall efficiency was higher than the BBH-type; however, the latter one has better function in terms of the yield. The total surface in the BBH-type was higher than the other one that enables the BBH-type to receive more radiation and consequently thermal energy which causes greater yield. Furthermore, it was reported that an increment in the air mass flow rate results in yield improvement. In another study (Tanaka & Nakatake 2004), performance of a vertical multiple-effect diffusion solar still (MED) solar still coupled with solar collector based on HP was investigated. In the proposed configuration, absorbed solar energy on the collector transports as working fluid latent heat to a vertical MED still in which energy is recycled to increments the distillate productivity. It was reported that productivity of the introduced still is 13% higher than the vertical MED still integrated with a basin-type still. MED solar desalination can be proposed with other configurations. Chong *et al.* (2014), a MED integrated with HP and vacuum tube collector, as shown in Figure 7, was evaluated. Their test in outdoor condition reveals that the supply temperature of solar collector reaches 100 °C in case of 800 W/m^2 solar radiation intensity. The highest daily production of total pure water per unit area of glass cover was reported equal to 23.9 kg/m^{2}·day that was around 29% more than the basin-type MEDS. Higher efficiency of MEDS in the multiple-diffusion and evaporating process in cell of still was attributed to higher temperature gradient. This higher temperature gradient was due to the use of vacuum-tube solar collector.

Flat plate solar collectors are other type of collectors that have been applied for variety of solar thermal applications. It would be possible to apply flat plate solar collector with HPs as additional unit to improve performance of solar still. In a study by Kargar Sharif Abad *et al.* (2013), a novel configuration composed of two sections, solar still and flat plate collector with oscillating HP was proposed. Although Cost Per Liter (CPL) of the active system, with use of HP, was just 8% higher than the passive system without HP, its production rate was much more than passive type by around 75%.

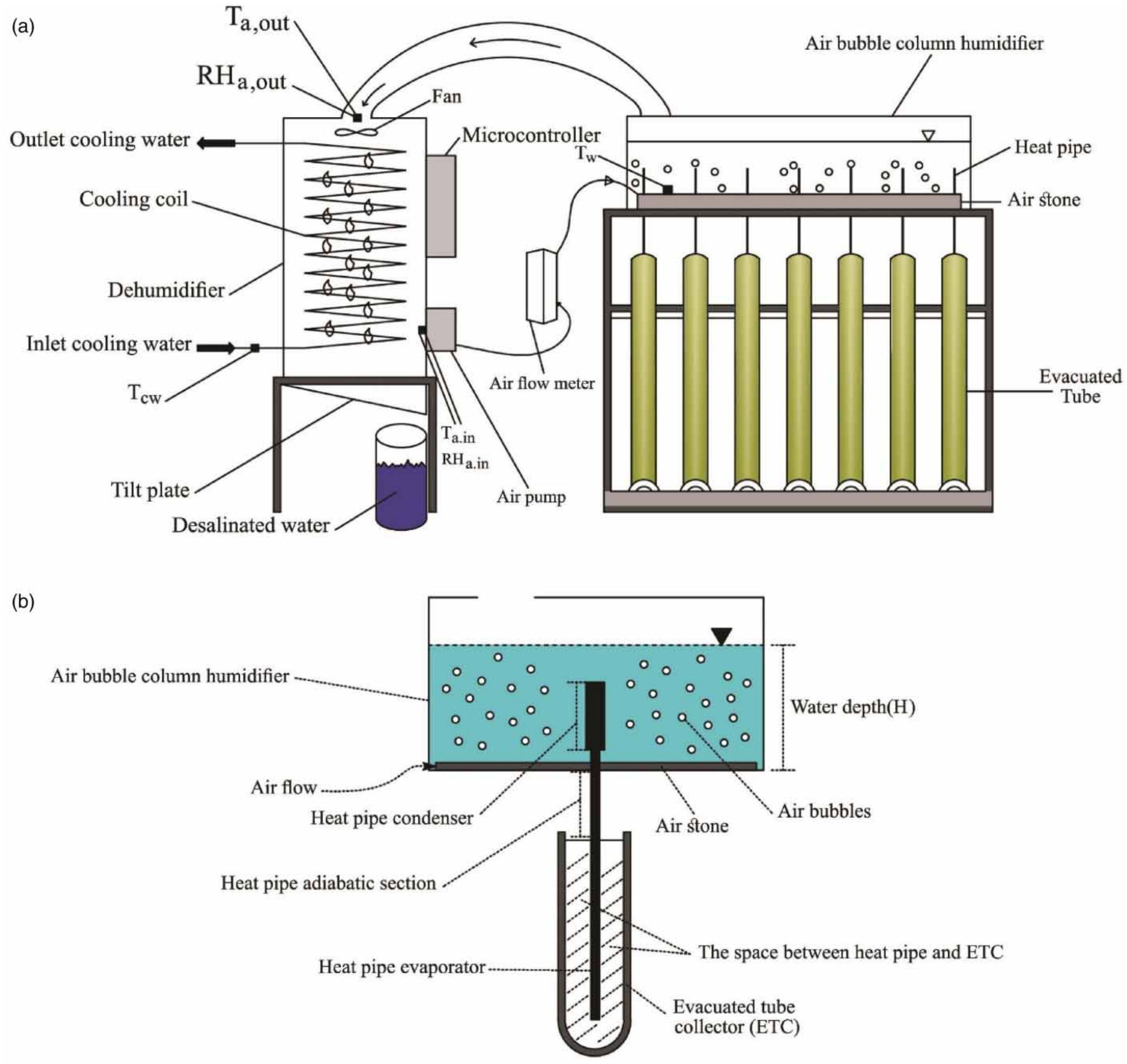


Figure 6 | (a) Experimental setup schematic and (b) ETCs and HPs schematic (Adapted from Ref Behnam & Shafii 2016).

Performance of solar PV cells would be degraded by temperature elevation (Alizadeh *et al.* 2020). In order to resolve the issues associated with the temperature increase of PV cell, different techniques have been introduced (Maleki *et al.* 2020). The removed heat from the solar cells can be applied for other purposes such as heating. In a study by Hooshmand *et al.* (2018), a system, as shown in Figure 8, was proposed to use the removed thermal energy for desalination. Four scenarios were considered in their research work. In the 1st scenario, active solar still in absence of fan was considered. The 2nd scenario was use of passive solar still in absence of fan, the 3rd scenario was employment of active solar still with fan and the 4th scenario considered active solar still with mirror and in absence of fan. In the 1st scenario, tray, thermosyphon HP and PV module was applied to analyze the performance by recovering dissipated thermal energy from it by the HP. In the 2nd scenario, tray and basin was employed with utilization of any additional component. In the 3rd scenario, impact of existence of a working fan on the performance of system with basing, thermosyphon HP and PV module was assessed and in the last scenario, mirror was considered to emphasize its impact on the function of the system. They reported that owing to the higher irradiated surface, PV module and basin, the overall amount of produced water was more for active system, 1st scenario, that the passive

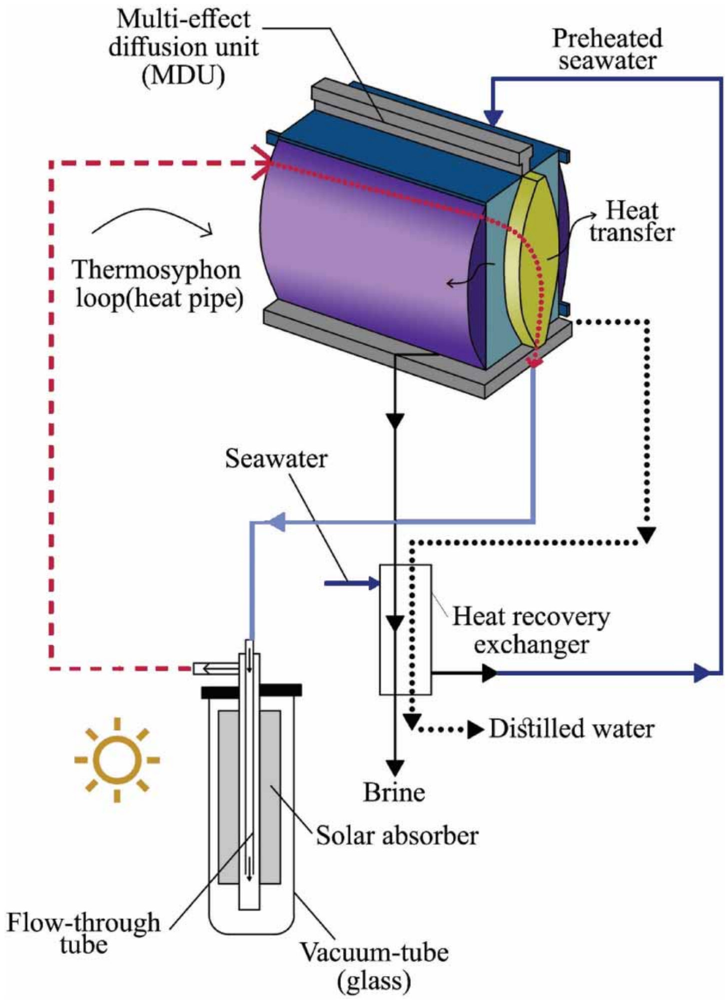


Figure 7 | Schematic of multiple-effect diffusion solar still with HP (Adapted from Ref Chong *et al.* 2014).

one, 2nd scenario. However, regarding the higher thermal resistance and HP utilization, the maximum yield of passive system, 0.406 kg/m^2.hr, was higher than the active one, 0.292 kg/m^2.hr. In addition, they noted that use of fan in the active system results in higher yield owing to the enhancement of heat transfer. As it was anticipated, employment of mirror leads to improvement in yield and power generation for the active system.

Aside for the mentioned configurations, it is possible to integrate solar desalination systems with other thermal components and equipment to have improved production. In a study by Rastegar *et al.* (2020), two solar desalinations, namely passive and active were compared. In the active configuration, thermosyphon HPs were used to recover heat from hot exhaust gases. Hourly variation in the distilled water production rate at various day time revealed that active system is around 2.06 times higher than the passive systems. The mean exergy and thermal efficiency of the solar still in active mode was improved by 41% and 65.5%, respectively, in comparison with the passive systems. According to the economic analysis, mean CPL value for the active system is 32% higher than the passive system. At the base case, exergoeconomic parameters for the active and passive types were 0.25 kWh/$ and 0.32 kWh/S, respectively, while at the worst case, these values were 0.11 kWh/S and 0.12 kwh/$, respectively.

In Table 2, the reviewed works are summarized.

4. FUTURE STUDIES

In section 3, the research works focus on the desalination systems utilizing various types of HPs were reviewed. There are some points and ideas that can be considered in the future studies. For instance, owing to the significant role of working

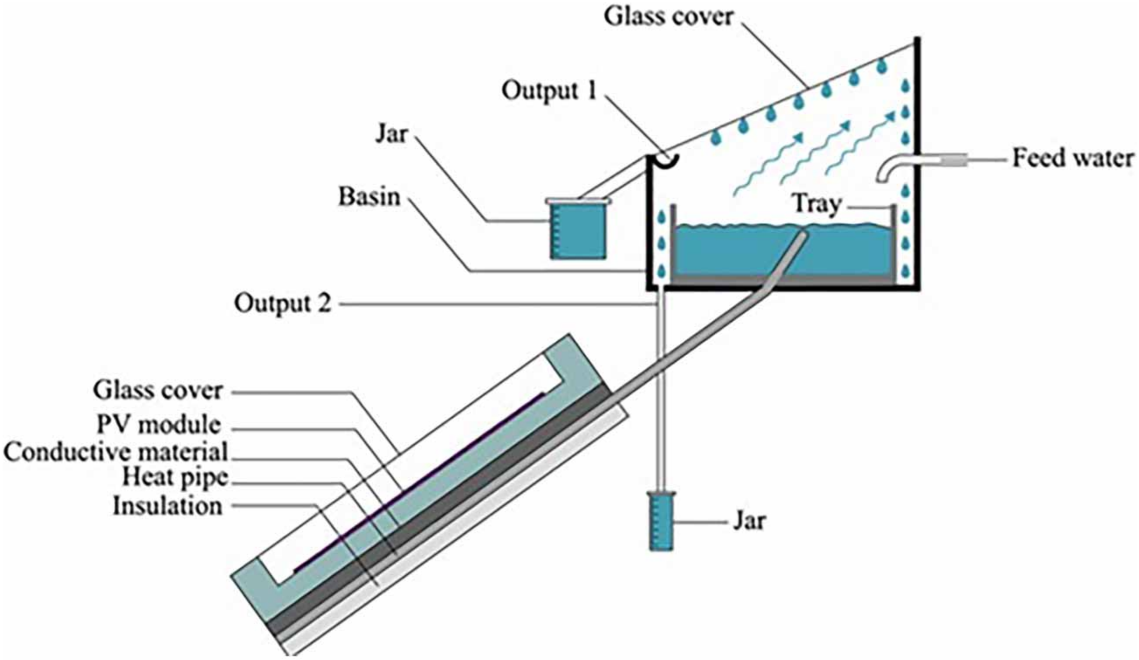


Figure 8 | Solar desalination by use of HP and solar PV cells (Adapted from Ref Hooshmand *et al.* 2018).

fluids on the performance of HPs and consequently the overall performance of the solar desalination systems, it would be useful to evaluate more operating fluids. Studies have shown that there is high potential for nanofluids to improve performance of various HPs (Su *et al.* 2015; Nazari *et al.* 2019). In this regard, nanofluidic HPs can be applied in solar desalination systems to have higher productivity. In addition to the operating fluid, structure of HPs, i.g. channels geometry and connections in oscillating HPs (Ebrahimi *et al.* 2015), are influential on the performance. It is suggested to apply HPs with modified structures in the solar desalination systems in upcoming works. Wick HPs, due to the assistance of capillary force in the fluid movement, are less sensitive to the orientation and could be attractive options for the solar desalination with collectors installed in near horizontal orientation. It should be noted that there are various structures for wick of HPs (Khalili & Shafii 2016) and it is possible to use HPs with modified wick to have better overall performance. Aside from the mentioned factors, dimensions of the HPs and lengths of different sections, i.g. adiabatic, condenser and evaporator, are involved in the performance of HPs. It can be a useful idea to consider different lengths and dimensions to reach the optimal case by consideration of technical and economic factors. Moreover, regarding the applicability of HPs for heat recovery systems (Abdelkareem *et al.* 2022), more cases can be considered for heat recovery to use the recovered energy in the solar thermal desalination systems. In cases of applying HPs in thermal energy storage unit of solar desalinations, it is possible to consider making use of fins for heat transfer improvement. It should be mentioned that PCMs' heat transfer with finned HPs can be affected by different factors such as fins' length and spacing (Tiari *et al.* 2015) that should be considered in the design process to have the most efficient system.

5. CONCLUSIONS

Benefits in use of renewable energy sources instead of fossil fuels are motivator for transition towards use of these sources in different energy consuming processes such as desalination. HPs are among the efficient thermal devices with applicability in solar thermal desalination systems. In this study, solar desalination systems with HPs are reviewed and the key findings can be outlined as follows:

- HPs could be used in the collectors, heat recovery units and thermal energy storage components of the solar desalination systems.
- Overall performance of solar desalination systems is affected by the characteristics of applied HPs and their thermal performance.

Table 2 | Reviewed works summaries

Reference	System	Important Conclusions
Jahangiri Mamouri *et al.* (2014)	Solar desalination with ETC and HP	Using more conductive material for the basin leads to increase in the yield.
Jafari Mosleh *et al.* (2015)	Solar desalination with ETC with parabolic through and HP	Using oil instead of conductive aluminum foils in the space between the twin-glass and HP leads to higher yield and efficiency.
Shoeibi *et al.* (2022)	Solar desalination with wind ventilator external condenser	Using external condenser has benefits in terms of productivity and carbon dioxide mitigation.
Fallahzadeh *et al.* (2020)	Pyramid shape solar still with evacuated tube collector	Using water in the HPs led to better performance compared with ethanol in the optimal case.
Chong *et al.* (2014)	Multiple-effect diffusion solar still (MEDS) with vacuum glass collector and HP	Performance of the designed MEDS was better than basin-based MEDS.
Behnam & Shafii (2016)	Solar desalination with ETCs, air bubble column humidifier and HPs	Adding fluids like water and oil in the space between the HPs and ETCs leads to improvement in the performance.
Nema & Karunamurthy (2022)	Solar desalination with evacuated tube collective condenser with HP	Payback period of the proposed system was 2.9 years.
Khalilmoghadam *et al.* (2021)	Solar still with storage unit and oscillating HP	Making use of the storage unit with HP leads to remarkable increment in the productivity.
Faegh & Shafii (2017)	Solar still with storage unit and thermosyphon	Applying PCM-filled external condenser leads to 86% increase in water yield.
Aref *et al.* (2021)	Bubble basin HDH with oscillating HP	BBH system had higher yield than BCH system due to higher surface area regarding the use of glass cover.
Tanaka & Nakata (2004)	Vertical MED with HP solar collector	Making use of MED coupled with the solar collector resulted in higher productivity in comparison with the vertical MED coupled with basin type still.
Kargar Sharif Abad *et al.* (2013)	Solar still with flat plate collector and oscillating HP	Making use of active desalination systems leads to 8% increase in CPL and around 75% elevation in production.
Hooshmand *et al.* (2018)	Solar PV with thermosyphon and solar still	Use of active systems provided higher yield than the passive system.
Rastegar *et al.* (2020)	Integrated solar still with heat recovery system from hot gases	Using an active system leads to higher thermal and exergy efficiency.

- Gravity-assisted or thermosyphon HPs are proper devices for being used in the storage unit of solar thermal desalination regarding their ability in provision of unidirectional heat transfer.
- Employment of HPs with collectors in a solar still can lead to improvement in the productivity.
- Adding external condenser for the solar desalination systems could provide much more productivity.
- Improvement of heat transfer between the collector and HPs by using some techniques such as adding oil in the gaps between the tube and glass would improve the overall performance.

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AUTHOR CONTRIBUTIONS

H.B. Bacha: Writing original draft, analysis, supervision. M.A. Nazari: Writing original draft, finding references. Ullah and Shah: Revision, data gathering.

DATA AVAILABILITY STATEMENT

All relevant data are included in the article.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdelkareem, M. A., Maghrabie, H. M., Sayed, E. T., Kais, E. C. A., Abo-Khalil, A. G., Al Radi, M., Baroutaji, A. & Olabi, A. G. 2022 Heat pipe-based waste heat recovery systems: Background and applications. *Thermal Science and Engineering Progress* **29**, 101221. https://doi.org/10.1016/j.tsep.2022.101221.

Adamu, N. I., Biswal, D. K., Pulagam, M. K. R. & Rout, S. K. 2023 Performance analysis of solar desalination system with thermal energy storage materials. *Materials Today: Proceedings* **74**, 801–807. https://doi.org/10.1016/J.MATPR.2022.11.173.

Ahsan, A., Imteaz, M., Thomas, U. A., Azmi, M., Rahman, A. & Nik Daud, N. N. 2014 Parameters affecting the performance of a low cost solar still. *Applied Energy* **114**, 924–930. https://doi.org/10.1016/J.APENERGY.2013.08.066.

Alhuyi Nazari, M., Salem, M., Mahariq, I., Younes, K. & Maqableh, B. B. 2021 Utilization of data-Driven methods in solar desalination systems: A comprehensive review. *Frontiers in Energy Research* **0**, 541. https://doi.org/10.3389/FENRG.2021.742615.

Alhuyi Nazari, M., Rungamornrat, J., Prokop, L., Blazek, V., Misak, S., Al-Bahrani, M. & Ahmadi, M. H. 2023 An updated review on integration of solar photovoltaic modules and heat pumps towards decarbonization of buildings. *Energy for Sustainable Development* **72**, 230–242. https://doi.org/10.1016/J.ESD.2022.12.018.

Alizadeh, H., Ghasempour, R., Shafii, M. B., Ahmadi, M. H., Yan, W.-M. & Nazari, M. A. 2018 Numerical simulation of PV cooling by using single turn pulsating heat pipe. *International Journal of Heat and Mass Transfer* **127**, 203–208. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2018.06.108.

Alizadeh, H., Alhuyi Nazari, M., Ghasempour, R., Shafii, M. B. & Akbarzadeh, A. 2020 Numerical analysis of photovoltaic solar panel cooling by a flat plate closed-loop pulsating heat pipe. *Solar Energy* **206**, 455–463. https://doi.org/10.1016/j.solener.2020.05.058.

Alshukri, M. J., Eidan, A. A. & Najim, S. I. 2021 Thermal performance of heat pipe evacuated tube solar collector integrated with different types of phase change materials at various location. *Renewable Energy* **171**, 635–646. https://doi.org/10.1016/J.RENENE.2021.02.143.

Alshukri, M. J., Kadhim Hussein, A., Eidan, A. A. & Alsabery, A. I. 2022 A review on applications and techniques of improving the performance of heat pipe-solar collector systems. *Solar Energy* **236**, 417–433. https://doi.org/10.1016/j.solener.2022.03.022.

Anand, B., Shankar, R., Murugavelh, S., Rivera, W., Midhun Prasad, K. & Nagarajan, R. 2021 A review on solar photovoltaic thermal integrated desalination technologies. *Renewable and Sustainable Energy Reviews* **141**, 110787. https://doi.org/10.1016/J.RSER.2021.110787.

Aref, L., Fallahzadeh, R. & Madadi Avargani, V. 2021 An experimental investigation on a portable bubble basin humidification/dehumidification desalination unit utilizing a closed-loop pulsating heat pipe. *Energy Conversion and Management* **228**, 113694. https://doi.org/10.1016/j.enconman.2020.113694.

Assad, M. E. H., AlShabi, M. A., Sahlolbei, A., Hmida, A. & Khuwaileh, B. 2020 Geothermal energy use in seawater desalination. In *Proceedings Volume 11387, Energy Harvesting and Storage: Materials, Devices, and Applications X*, p. 1138716. https://doi.org/https://doi.org/10.1117/12.2566527.

Bataineh, K. M. & Abbas, M. A. 2020 Performance analysis of solar still integrated with internal reflectors and fins. *Solar Energy* **205**, 22–36. https://doi.org/10.1016/J.SOLENER.2020.04.059.

Behnam, P. & Shafii, M. B. 2016 Examination of a solar desalination system equipped with an air bubble column humidifier, evacuated tube collectors and thermosyphon heat pipes. *Desalination* **397**, 30–37. https://doi.org/10.1016/J.DESAL.2016.06.016.

Chauhan, V. K., Shukla, S. K., Tirkey, J. V. & Singh Rathore, P. K. 2021 A comprehensive review of direct solar desalination techniques and its advancements. *Journal of Cleaner Production* **284**, 124719. https://doi.org/10.1016/J.JCLEPRO.2020.124719.

Chong, T. L., Huang, B. J., Wu, P. H. & Kao, Y. C. 2014 Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe. *Desalination* **347**, 66–76. https://doi.org/10.1016/J.DESAL.2014.05.023.

Chopra, K., Tyagi, V. V., Pandey, A. K. & Sari, A. 2018 Global advancement on experimental and thermal analysis of evacuated tube collector with and without heat pipe systems and possible applications. *Applied Energy* **228**, 351–389. https://doi.org/10.1016/J.APENERGY.2018.06.067.

Curto, D., Franzitta, V. & Guercio, A. 2021 A review of the water desalination technologies. *Applied Sciences (Switzerland)* **11**, 1–36. https://doi.org/10.3390/app11020670.

Ebrahimi, M., Shafii, M. B. & Bijarchi, M. A. 2015 Experimental investigation of the thermal management of flat-plate closed-loop pulsating heat pipes with interconnecting channels. *Applied Thermal Engineering* **90**, 838–847. https://doi.org/10.1016/J.APPLTHERMALENG.2015.07.040.

El Haj Assad, M., Nooman Almallahi, M., Abdelsalam, M. A., Alshabi, M. & Almallahi, W. N. 2022 Desalination Technologies: Overview. In: *2022 Advances in Science and Engineering Technology International Conferences, ASET 2022*. https://doi.org/10.1109/ASET53988.2022.9734991.

Elmaadawy, K., Kotb, K. M., Elkadeem, M. R., Sharshir, S. W., Dán, A., Moawad, A. & Liu, B. 2020 Optimal sizing and techno-enviro-economic feasibility assessment of large-scale reverse osmosis desalination powered with hybrid renewable energy sources. *Energy Conversion and Management* **224**. https://doi.org/10.1016/j.enconman.2020.113377.

Faegh, M. & Shafii, M. B. 2017 Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes. *Desalination* **409**, 128–135. https://doi.org/10.1016/J.DESAL.2017.01.023.

Fallahzadeh, R., Aref, L., Gholamiarjenaki, N., Nonejad, Z. & Saghi, M. 2020 Experimental investigation of the effect of using water and ethanol as working fluid on the performance of pyramid-shaped solar still integrated with heat pipe solar collector. *Solar Energy* **207**, 10–21. https://doi.org/10.1016/J.SOLENER.2020.06.032.

Fellows, C. M. & Al-Hamzah, A. 2015 Thermal Desalination: Current Challenges. In: *Mineral Scales and Deposits: Scientific and Technological Approaches*, pp. 583–602. https://doi.org/10.1016/B978-0-444-63228-9.00023-1.

Ghafoor, A., Ahmed, T., Munir, A., Arslan, C. & Ahmad, S. A. 2020 Techno-economic feasibility of solar based desalination through reverse osmosis. *Desalination* **485**. https://doi.org/10.1016/J.DESAL.2020.114464.

Gorjian, S., Ghobadian, B., Ebadi, H., Ketabchi, F. & Khanmohammadi, S. 2020 Applications of solar PV systems in desalination technologies. *Photovoltaic Solar Energy Conversion* 237–274. https://doi.org/10.1016/B978-0-12-819610-6.00008-9.

Hooshmand, P., Shafii, M. B. & Roshandel, R. 2018 An experimental study of a solar hybrid system to produce freshwater from waste heat of photovoltaic module by using thermosyphon heat pipes. *Energy Conversion and Management* **158**, 9–22. https://doi.org/10.1016/J.ENCONMAN.2017.12.043.

Hu, Z., Wang, J., Huo, E. & Zhang, C. 2023 Investigation of a distillation desalination system driven by solar and ocean thermal energy. *Desalination* **559**, 116649. https://doi.org/10.1016/J.DESAL.2023.116649.

Hussain, M. I., Lee, G. H. & Kim, J. T. 2021 A comprehensive performance characterization of a nanofluid-powered dual-fluid PV/T system under outdoor steady state conditions. *Sustainability* **13**, 13134. https://doi.org/10.3390/SU132313134.

Jafari Mosleh, H., Mamouri, S. J., Shafii, M. B. & Hakim Sima, A. 2015 A new desalination system using a combination of heat pipe, evacuated tube and parabolic trough collector. *Energy Conversion and Management* **99**, 141–150. https://doi.org/10.1016/J.ENCONMAN.2015.04.028.

Jahangiri Mamouri, S., Gholami Derami, H., Ghiasi, M., Shafii, M. B. & Shiee, Z. 2014 Experimental investigation of the effect of using thermosyphon heat pipes and vacuum glass on the performance of solar still. *Energy* **75**, 501–507. https://doi.org/10.1016/J.ENERGY.2014.08.005.

Jalihal, P. & Venkatesan, R. 2019 Advanced desalination technologies. In: *Sustainable Water and Wastewater Processing*, pp. 93–131. https://doi.org/10.1016/B978-0-12-816170-8.00004-1.

Jiang, Y., Zhao, J. & Tong, Z. 2022 Optimum design of a solar-wind-diesel hybrid energy system with multiple types of storage devices driving a reverse osmosis desalination process. *Processes* **10**. https://doi.org/10.3390/pr10112199.

Kalogirou, S. A. 2016 *Nontracking Solar Collection Technologies for Solar Heating and Cooling Systems*. Elsevier Ltd. https://doi.org/10.1016/B978-0-08-100301-5.00004-7.

Kargar Sharif Abad, H., Ghiasi, M., Jahangiri Mamouri, S. & Shafii, M. B. 2013 A novel integrated solar desalination system with a pulsating heat pipe. *Desalination* **311**, 206–210. https://doi.org/10.1016/J.DESAL.2012.10.029.

Khalili, M. & Shafii, M. B. 2016 Investigaing thermal performance of a partly sintered-wick heat pipe filled with different working fluids. *Scientia Iranica* **23**, 2616–2625.

Khalilmoghadam, P., Rajabi-Ghahnavieh, A. & Shafii, M. B. 2021 A novel energy storage system for latent heat recovery in solar still using phase change material and pulsating heat pipe. *Renewable Energy* **163**, 2115–2127. https://doi.org/10.1016/J.RENENE.2020.10.073.

Kress, N. 2019 Desalination Technologies. In: *Marine Impacts of Seawater Desalination*, pp. 11–34. https://doi.org/10.1016/B978-0-12-811953-2.00002-5.

Kumar, S. S., Kumar, K. M. & Kumar, S. R. S. 2017 Design of evacuated tube solar collector with heat pipe. *Materials Today: Proceedings* **4**, 12641–12646. https://doi.org/10.1016/J.MATPR.2017.10.075.

Kumar, L., Soomro, J., Khoharo, H. & El Haj Assad, M. 2023 A comprehensive review of solar thermal desalination technologies for freshwater production. *AIMS Energy* **11**, 293–318. https://doi.org/10.3934/ENERGY.2023016.

Mahmoudi, A., Bostani, M., Rashidi, S. & Valipour, M. S. 2023 Challenges and opportunities of desalination with renewable energy resources in Middle East countries. *Renewable and Sustainable Energy Reviews* **184**, 113543. https://doi.org/10.1016/J.RSER.2023.113543.

Maleki, A., Haghighi, A., El Haj Assad, M., Mahariq, I. & Alhuyi Nazari, M. 2020 A review on the approaches employed for cooling PV cells. *Solar Energy* **209**, 170–185. https://doi.org/10.1016/j.solener.2020.08.083.

Mathioulakis, E. & Belessiotis, V. 2002 A new heat-pipe type solar domestic hot water system. *Solar Energy* **72**, 13–20. https://doi.org/10.1016/S0038-092X(01)00088-3.

Mehtari, N., Kahani, M. & Zamen, M. 2024 Simulation of a low-capacity solar MSF desalination unit for a steam power plant by thermoflow software. *Renewable Energy Research and Applications* **5**, 259–268. https://doi.org/10.22044/RERA.2023.13347.1231.

Mito, M. T., Ma, X., Albuflasa, H. & Davies, P. A. 2019 Reverse osmosis (RO) membrane desalination driven by wind and solar photovoltaic (PV) energy: State of the art and challenges for large-scale implementation. *Renewable and Sustainable Energy Reviews* **112**, 669–685. https://doi.org/10.1016/j.rser.2019.06.008.

Motahar, S. & Khodabandeh, R. 2016 Experimental study on the melting and solidification of a phase change material enhanced by heat pipe. *International Communications in Heat and Mass Transfer* **73**, 1–6. https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2016.02.012.

Nazari, M. A., Ahmadi, M. H., Sadeghzadeh, M., Shafii, M. B. & Goodarzi, M. 2019 A review on application of nanofluid in various types of heat pipes. *Journal of Central South University* **26**, 1021–1041. https://doi.org/10.1007/s11771-019-4068-9.

Nema, G. & Karunamurthy, K. 2022 A novel solar desalination system based on an evacuated tube collective condenser heat pipe solar collector: A thermo-economic and environmental analysis. *Frontiers in Mechanical Engineering* **8**, 1–16. https://doi.org/10.3389/fmech.2022.959286.

Ramezanizadeh, M., Alhuyi Nazari, M., Ahmadi, M. H. & Açıkkalp, E. 2018 Application of nanofluids in thermosyphons: A review. *Journal of Molecular Liquids* **272**, 395–402. https://doi.org/10.1016/J.MOLLIQ.2018.09.101.

Ramezanizadeh, M., Alhuyi Nazari, M., Ahmadi, M. H. & Chau, K. 2019 Experimental and numerical analysis of a nanofluidic thermosyphon heat exchanger. *Engineering Applications of Computational Fluid Mechanics* **13**, 40–47. https://doi.org/10.1080/19942060.2018.1518272.

Rastegar, S., Kargarsharifabad, H., Rahbar, N. & Shafii, M. B. 2020 Distilled water production with combination of solar still and thermosyphon heat pipe heat exchanger coupled with indirect water bath heater – experimental study and thermoeconomic analysis. *Applied Thermal Engineering* **176**, 115437. https://doi.org/10.1016/J.APPLTHERMALENG.2020.115437.

Shafaghat, A. H., Eslami, M. & Baneshi, M. 2023 Techno-enviro-economic study of a reverse osmosis desalination system equipped with photovoltaic-thermal collectors. *Applied Thermal Engineering* **218**, 119289. https://doi.org/10.1016/J.APPLTHERMALENG.2022.119289.

Shakouri, O., Assad, M. E. H. & Açıkkalp, E. 2021 Thermodynamic analysis and multi-objective optimization performance of solid oxide fuel cell–Ericsson heat engine–reverse osmosis desalination. *Journal of Thermal Analysis and Calorimetry* **145**, 1075–1090. https://doi.org/10.1007/S10973-020-10413-7/METRICS.

Shoeibi, S., Kargarsharifabad, H., Rahbar, N., Khosravi, G. & Sharifpur, M. 2022 An integrated solar desalination with evacuated tube heat pipe solar collector and new wind ventilator external condenser. *Sustainable Energy Technologies and Assessments* **50**, 101857. https://doi.org/10.1016/J.SETA.2021.101857.

Su, X., Zhang, M., Han, W. & Guo, X. 2015 Enhancement of heat transport in oscillating heat pipe with ternary fluid. *International Journal of Heat and Mass Transfer* **87**, 258–264. https://doi.org/10.1016/j.ijheatmasstransfer.2015.04.002.

Takalkar, G. & Bhosale, R. R. 2020 Evacuated tube heat pipe solar collector for Encontech engine-driven reverse osmosis solar desalination. *International Journal of Energy Research* **44**, 12460–12473. https://doi.org/10.1002/ER.5414.

Tanaka, H. & Nakatake, Y. 2004 A vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector. *Desalination* **160**, 195–205. https://doi.org/10.1016/S0011-9164(04)90009-4.

Taner, T. 2018a Energy and exergy analyze of PEM fuel cell: A case study of modeling and simulations. *Energy* **143**, 284–294. https://doi.org/10.1016/J.ENERGY.2017.10.102.

Taner, T. 2018b Economic analysis of a wind power plant: A case study for the Cappadocia region. *Journal of Mechanical Science and Technology* **32**, 1379–1389. https://doi.org/10.1007/S12206-018-0241-6/METRICS.

Taner, T. 2021 The novel and innovative design with using H2 fuel of PEM fuel cell: Efficiency of thermodynamic analyze. *Fuel* **302**, 121109. https://doi.org/10.1016/J.FUEL.2021.121109.

Ta Ner, T. & Dalkilic, A. S. 2017 A feasibility study of solar energy-techno economic analysis from Aksaray City, Turkey. *Journal of Thermal Engineering* **3**, 1–1. https://doi.org/10.18186/JOURNAL-OF-THERMAL-ENGINEERING.331756.

Taner, T. & Demirci, O. K. 2014 Energy and economic analysis of the wind turbine plant's draft for the Aksaray City. *Applied Ecology and Environmental Sciences* **2**, 82–85. https://doi.org/10.12691/aees-2-3-2.

Taner, T. & Sivrioglu, M. 2017 A techno-economic & cost analysis of a turbine power plant: A case study for sugar plant. *Renewable and Sustainable Energy Reviews* **78**, 722–730. https://doi.org/10.1016/J.RSER.2017.04.104.

Tiari, S., Qiu, S. & Mahdavi, M. 2015 Numerical study of finned heat pipe-assisted thermal energy storage system with high temperature phase change material. *Energy Conversion and Management* **89**, 833–842. https://doi.org/10.1016/j.enconman.2014.10.053.

Tiwari, G. N., Singh, H. N. & Tripathi, R. 2003 Present status of solar distillation. *Solar Energy* **75**, 367–373. https://doi.org/10.1016/J.SOLENER.2003.07.005.

Vaithilingam, S., Gopal, S. T., Srinivasan, S. K., Manokar, A. M., Sathyamurthy, R., Esakkimuthu, G. S., Kumar, R. & Sharifpur, M. 2021 An extensive review on thermodynamic aspect based solar desalination techniques. *Journal of Thermal Analysis and Calorimetry* **145**, 1103–1119. https://doi.org/10.1007/s10973-020-10269-x.

Wang, Y., Kamari, M. L., Haghighat, S. & Ngo, P. T. T. 2020 Electrical and thermal analyses of solar PV module by considering realistic working conditions. *Journal of Thermal Analysis and Calorimetry* 1–10. https://doi.org/10.1007/s10973-020-09752-2.

Zhang, X., Zhao, X., Xu, J. & Yu, X. 2013 Characterization of a solar photovoltaic/loop-heat-pipe heat pump water heating system. *Applied Energy* **102**, 1229–1245. https://doi.org/10.1016/J.APENERGY.2012.06.039.

Zhang, X., Liu, Y., Wen, X., Li, C. & Hu, X. 2018 Low-grade waste heat driven desalination with an open loop heat pipe. *Energy* **163**, 221–228. https://doi.org/10.1016/j.energy.2018.08.121.

Zheng, H. 2017 General problems in seawater desalination. *Solar Energy Desalination Technology* 1–46. https://doi.org/10.1016/B978-0-12-805411-6.00001-4.

Zheng, Y., Caceres Gonzalez, R. A., Hatzell, K. B. & Hatzell, M. C. 2021 Large-scale solar-thermal desalination. *Joule* **5**, 1971–1986. https://doi.org/10.1016/J.JOULE.2021.07.005.

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