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Developments in solar-driven desalination: Technologies, photovoltaic integration, and processes

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ABSTRACT

The growing global demand for fresh water, coupled with the environmental impact of conventional desalination technologies, underscores the urgent need for more sustainable, energy-efficient solutions. This review provides an updated and comprehensive analysis of solar-driven desalination systems, focusing on the integration of photovoltaic (PV) and thermal (T) technologies (PV/T). It presents recent advancements in both direct and indirect solar desalination methods, highlighting how PV/T integration can enhance energy efficiency, reduce environmental impact, and improve system scalability. The paper also explores cutting-edge optimization techniques and rule-based control algorithms that significantly enhance operational performance. Compared to previous reviews, this paper offers a more detailed examination of emerging trends and addresses gaps in current research, particularly in the integration of PV/T systems. By synthesizing the latest technological developments, this review provides critical insights into the future of solar desalination, offering a clear path forward for sustainable water production and addressing global water scarcity.

Abbreviations: AI, Artificial Intelligence; AC, Alternating Current; AD, Adsorption Desalination; CdTe, Cadmium Telluride; CIGS, Copper Indium Gallium Selenide; DC, Direct Current; ED, Electrical Dialysis; EDR, Electro dialysis Reversal; ETC, Evacuated Tube Collectors; FF, Fill Factor; FO, Forward Osmosis; FPC, Flat Plate Collectors; FD, Freeze Desalination; HDH, Humidification-Dehumidification; ICS, Integrated Collector Storage; Isc, Short-Circuit Current; IWA, Invasive Weed Algorithm; IXR, Ion Exchange Resin; IoT, Internet of Things; LCOW, levelized cost of water; MBR, Membrane Bioreactor; MD, Membrane Distillation; MED, Multi-Effects Distillation; MIT, Massachusetts Institute of Technology; ML, Machine Learning; MSF, Multi-Stage Flash; MVC, Mechanical Vapor Compression; NF, Nano Filtration; NVD, Natural Vacuum Desalination; ORC, Organic Rankine Cycle; PID, Proportional Integral Derivative; Pmp, Maximum power output; PMSM, Permanent Magnet Synchronous Motor; PV, Photovoltaic; PVT, PV-thermal; RE, Renewable Energy; RO, Reverse Osmosis; SRM, Switched Reluctance Motor; SSD, Solar Still Distillation; STC, Standard Test Conditions; TDS, Total Dissolved Solids; TES, Thermal Energy Storage; TVC, Thermal Vapor Compression; VFD, Variable Frequency Drives; VC, Vapor Compression; Voc, Open-Circuit Voltage; ZLD, Zero-Liquid Discharge.

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1. Introduction

The scarcity of water is a serious problem and is a result of increasing population and development in the industrial and agricultural sectors. Water is the basis of life; its scarcity is presently affecting one-fifth of the world's population, and a quarter of the world's population faces a shortage of technology to retrieve fresh water from rivers and ponds [1]. Many regions of the world are experiencing significant and rapid increases in water stress. According to United Nations declarations of water development measures worldwide, 3.7 billion people are exposed to a lack of water. The number of affected people is expected to increase by about 5.7 billion by the year 2050 [2]. In addition, there is about 97% salt water in the oceans, according to the US Geological Survey, with approximately 3% being drinkable water. While pure water is distributed among rivers and glacial places in the Antarctic and Arctic regions at a rate of 68.7%, while surface water is 0.3%, and groundwater is 30.1%. While 87% of surface water is found in lakes, rivers, and swamps [3], the rest of the total pure water present on the surface of Earth is usable.

In 2021, natural disasters alone forced around 3 million people to quit their homes on the continent of Africa and the Middle East, according to statistics from the International Organization for Migration [4]. The fact it that 3.5 million people die per year as a result of not having access to pure, pollution-free water. This emphasizes how valuable water is as a resource for the entire planet [5]. According to statistics, by the year 2030, approximately half of the world's population will live in water-stressed areas, and certain dry and semi-arid regions will be displaced. Additionally, the continent of Africa will experience this problem more than any other location [6]. To obtain clean water in addition to the reserve stock that is provided, it is possible to purify highly saline seawater, which constitutes 97% of the total water on this earth [3]. On the other hand, brackish water usually has a salinity between 1000 and 10000 mg/L [7]. While the demand for pure water increases, seawater is used after the salts are extracted from it, and it falls under the name of seawater desalination.

The desalination of seawater is a process used to separate salt from salt water. Because of this, it may be used to produce water for drinking and other things. To achieve this, much power generation is needed [8]. The foremost desalination water plants were constructed in the late 1950s to meet the demand for freshwater caused by population growth and social concerns [2]. Science has advanced to the point where desalination using renewable energy sources may produce pure water at levels equivalent to those produced by plants using traditional sources while simultaneously lowering emissions of the greenhouse gases that contribute to global warming [9].

The goal of recent advancements in desalination systems for passive solar has been to use solar energy to produce potable clean water without the need for energy-intensive or complicated procedures. One promising method uses capillary action to bring water into contact with solar collectors in solar evaporators that float on seawater. The evaporation–condensation cycle is used by these systems which are frequently built as multi-stage solar stills to extract salt from seawater. To maximize energy efficiency, for example, Massachusetts Institute of Technology (MIT) researchers have created a system that utilizes multiple layers of evaporators and condensers [10,11]. By recycling heat released during condensation, the system's overall efficiency is increased to over 385 percent. This design could be expanded for use in coastal off-grid areas where energy sources might be limited but seawater is easily accessible.

Since salt buildup is a common problem in conventional solar desalination systems, floating solar evaporators are especially beneficial. Certain systems like the ones that MIT tested have evaporators made of capillary wick material. This permits a constant passive flow of water to the evaporating surface and encourages seawater's natural passage through the system. Furthermore, the systems can function effectively for prolonged periods of time without salt clogging because they are made to withstand high salinity levels [10–12]. Incorporating ocean-like convection principles that aid in water circulation and salt buildup prevention allows for this. Additionally, by employing inexpensive, easily accessible materials like black solar absorbers and basic capillary wicking materials, these passive systems provide a notable cost advantage that makes them more affordable for needed communities. A single unit as small as $1\ m^2$ one square meter could provide enough water for a person's daily drinking needs at a very low operating cost possibly less expensive than tap water in many areas. With further development, these systems could potentially alleviate water scarcity, especially in developing nations or isolated off-grid locations with plentiful solar energy [13,14]. Steam latent heat recovery is one of the most important methods for increasing efficiency and water production in solar desalination. The total energy required for desalination can be decreased by using systems to preheat incoming seawater using the heat from steam condensation. Solar desalination technologies that mainly rely on thermal energy to drive the evaporation process, such as Vapor Compression (VC) or Multi-Effect Distillation (MED), perform noticeably better when using this method [15]. The significance of optimizing latent heat recovery through sophisticated heat pumps and exchanger designs has been brought to light by recent studies. The system's overall efficiency can be increased by using these technologies to recycle the thermal energy from the condensing steam. The process is more sustainable when refrigeration cycles are incorporated into steam power plants, for example, because they recycle waste heat and lessen the need for cooling water [15,16].

By increasing water production rates using latent heat recovery, systems can deliver more freshwater for the same energy input. The systems become more economical and ecologically friendly by lowering energy losses which solve the problems of water scarcity and energy consumption [15,17]. There are promising opportunities for the large-scale application of solar desalination due to recent developments in material science and thermal management, which are propelling additional progress in this area.

In general, many parameters (see Fig. 1) may affect energy use and the choice of technique for desalination [18]. The heating requirements are electrical power for thermal desalination techniques, which range from 40 kWh/m^3 to 80 kWh/m^3. At the same time, for its auxiliary equipment, it uses 2.5 kWh/m^3 to 5 kWh/m^3 of power. The most commercially viable desalination plant uses an average of around 100 TWh of energy annually, which causes emissions of 60–100 Mt of CO_2 [14]. Therefore, each technology needs a robust solution to reduce its energy usage and associated emissions.

There are many different technologies for desalination associated with renewable power, and in this paper, the most common methods associated with photovoltaic energy are presented. In addition, since there is often no electricity grid in remote areas, the desalination technique using PV cells is a powerful and practical method to overcome a shortage of infrastructure [7]. Firstly, membrane and photovoltaic components for distillation are connected units that may be scaled to fulfill the need for pure water. Secondly, dry regions of the world have higher drinking water needs, and these same areas typically have strong solar energy resources [7,14]. Third, PV module prices had declined steadily by the end of 2018 [14,19]. Multiple academics and scientists have been drawn to solar energy because of its availability and potential for desalinating water. As a result, various methods are being developed to boost clean water production by utilizing solar energy. Porous media, phase change in materials, nanotechnology, thermal heating, and photovoltaics are some of the techniques used to speed up the evaporation of water in order to separate it from salts [2,20,21]. Table 1 shows a comprehensive analysis of solar-driven and traditional desalination processes.

The main topic of this paper is to discuss the technologies of solar PV desalination systems. The paper also discusses the relationship between solar energy and water desalination plant methods as well as available solar PV-powered desalination methods. (see Fig. 2) gives the layout of the paper organizational structure.

2. Processes for desalination

Desalination of water refers to various techniques that successfully disconnect dissolved minerals, such as those in brackish or salty saltwater, and provide drinkable water with a low concentration of total dissolved solids. The Netherlands' Island of Curaçao was the first location to witness a significant commitment to desalination in 1928. The first significant desalination facility was constructed in the Kingdom of Saudi Arabia in 1938. Following that, during the Second World War, the USA, as well as other nations, carried out extensive research to address military demands for clean drinking water in water-scarce locations [27,28]. The first artificial RO membranes were constructed in 1963 by Loeb and Sourirajan from the University of California. The Flash for Multi-Stage (MSF) method was being used in the Middle East to desalinate saltwater in the 1960s. However, commercial RO and ED systems started to be used during the following ten years [29,30].

Desalination systems may be divided into different categories for their energy sources: thermal, mechanical, electrical, and chemical. Another classification based on the desalination process is as follows: Examples include filtration, crystallization, and evaporation–condensation processes (see Fig. 3). Technologies for desalinating water are currently being developed. For instance, membrane distillation (MD), membrane bioreactor (MBR), forward osmosis (FO), solar chimney, greenhouse, natural vacuum, and Ion Exchange Resin (IXR). The most widely used desalination technologies are reverse osmosis (RO), (see Fig. 4), flash for multi-stage (MSF), and distillation for multi-effects (MED) (see Tables 2, 3, and 4) [22,31]. Fig. 3 displays the key desalination operations throughout the globe [31]. Also, Fig. 4 presents the global percentages for each commonly used desalination technology [5]. Also, Tables 2, 3, and 4 demonstrate all the world's main desalination processes of evaporation and condensation, crystallization, and filtration, respectively.

Saltwater is heated through thermal processes, creating water vapor that eventually condenses to create filtered water. This approach uses a thermal energy source, which can come from nuclear energy or sources of conventional energy. Flash for multi-stage (MSF), distillation for multiple effects (MED), and compression for vapor (VC), which may be

Table 1
Comprehensive analysis of solar-driven and traditional desalination processes [12,22–26].

Aspect	Solar-driven desalination	Traditional desalination
Energy source	Solar energy (PV, Solar thermal).	Electricity, Fossil fuels.
Environmental impacts	Minimal impact on the environment utilizing sources of renewable energy in 90%.	Substantial carbon emissions, and a high environmental impact in 10%.
Cost	Investment in high initial, but minimal operational in (70%).	Medium to high costs of operating in (30%).
Efficiency	Solar intensity depends on efficiency, which is generally lower than with conventional techniques (50%).	Depending on technology, efficiency is generally higher (50%).
Maintenance	Requires periodic maintenance on PV panels in (60%).	Requires maintenance high regular in (40%).
Integration techniques	Direct combined with RO, PV, and PV-thermal hybrid systems in (50%).	Combined with traditional power sources in (50%).
Recent advances	Efficiency improvement for PV cells, and hybrid PV-thermal process in (70%).	Developments in energy recovery devices and membrane technology in (30%).
Energy efficiency	Possibility of developing cutting-edge materials and highly efficient solar collectors in (60%).	Configurations low-energy, and improvements of energy recovery devices in (40%).
Water quality	Advanced desalination methods and real-time control systems in (60%).	Processes for enhanced pretreatment and control systems in (40%).
System durability	Improved materials for a longer lifespan and less upkeep in (60%).	Technologies and materials are improving durability (40%).
Opportunities for improvement	Cutting expenses, increasing out ways to lessen the environmental impact, and creating scalable systems for various capacities in (60%).	Increasing sustainability by creating cost-effective solutions and optimizing processes in (40%).

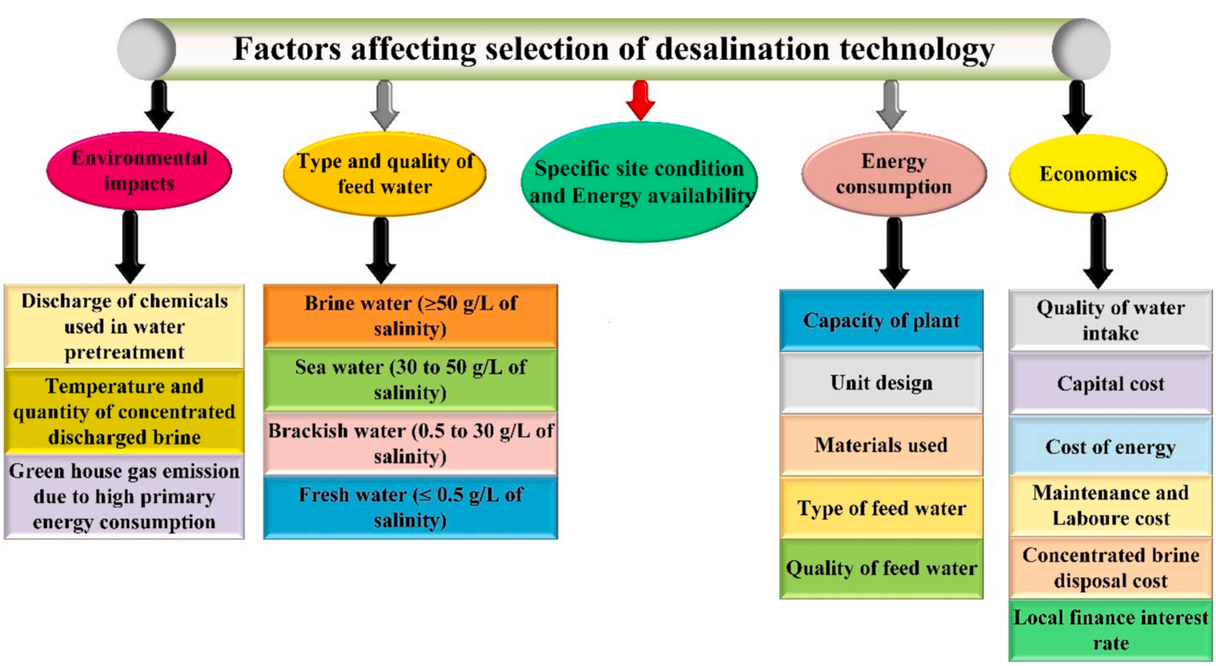

Fig. 1. Factors influencing desalination technologies [18].

thermal TVC or mechanical MVC, are examples of desalination techniques based on thermal energy. To use the MSF process, sea water must be successively evaporated and then condensed at lower pressures at each stage [30,36]. Semipermeable eclectic membranes are used in membrane processing to physically separate dissolved salts from other contaminants. They are categorized as osmosis for reverse (RO) and electrodialysis (ED). While ED is exclusively used for brackish water distillation, osmosis for reverse may be used to distill both brackish and seawater [3,31]. The summary of the main features of conventional hybrid technologies is shown in Table 5. Also, Table 6 demonstrates desalination capacity by country/region.

3. Types of solar energy driven desalination technologies

Solar-based systems have received a lot of attention since most desalination processors require thermal and electricity input, which may be delivered by solar energy [44] (see Fig. 5). Sub-systems that fall from the main system where solar energy is collected are used to either collect heat through solar energy and supply it to a heat exchanger for a thermal desalination process or transform sunlight into electricity using photovoltaic cells to power desalination processes [6,44]. Fig. 5 shows the classification of solar-assisted desalination techniques such as photovoltaic and thermal systems.

Solar energy may be utilized in water desalination operations in two ways: the first is direct, and the second is indirect. In direct desalination processes, solar energy is used directly to produce fresh water as solar stills. These systems are best suited to areas with a daily need for clean water of less than 200 m^3/day (see Fig. 6). The second category is indirect systems, where each station is divided into two subsystems: a unit for collecting solar energy and one for desalinating water [6,45]. A PV system can convert solar power directly into electricity, while solar power concentrated (CSP) technologies can do it indirectly [45,46]. The most popular ranking between solar power systems and desalination techniques is shown in Fig. 6. The recent studies on direct and indirect solar desalination technologies are demonstrated in Table 7.

Numerous significant elements that impact the dependability and efficiency of desalination systems are included in the fundamental parameters. Maximum power output (Pmp) is the primary electrical performance metric, varying between 300 and 500 W per panel. The conversion efficiencies of new high-efficiency panels under standard test conditions (STC) range from 20 to 24 percent. While the temperature coefficient, which is crucial for coastal installations, typically ranges between −0.35 % and −0.45 % per °C, the fill factor (FF) is maintained between 0.75 and 0.82 for optimal power output [47]. For typical installations, the open-circuit voltage (Voc) should be between 35 and 45 V, and the short-circuit current (Isc) should be between 9 and 12A. These voltage and current parameters must be exactly matched to the requirements of the desalination unit.

Environmental durability criteria, which include enhanced corrosion resistance with an IP68 protection rating, specialized anti-reflective coatings that maintain greater than 98% transmittance over 15 years, and reinforced frame structures that can withstand wind loads up to 2400 Pascal, have become increasingly important [48]. Demonstrates the importance of operational integration parameters, with recent PV panels sustaining specific energy consumption of 2.5 to 3.5 kWh/m^3 of freshwater produced and consistent operating response times under variable irradiance below 1.5 s. Demonstrates how dependability metrics have become more significant in maritime environments where deterioration rates are below 0.5 % annually and lifespans are expected to exceed 25 years. New benchmarks for the ratio of performance maintained above 85 percent through the warranty period which typically lasts 20 to 25 years for premium panels applied to desalination applications have also been established acknowledging the importance of specialized coating techniques that enhance light absorption and reduce soiling in coastal environments [49].

The investment costs for solar panels used in desalination systems are special. The capital costs for desalination systems range from $0. 35 to $0. 55/watts which is about 30–40% more than that of regular PV panels [50,51]. This is because desalination systems have better corrosion protection, specialized coatings, and superior resistance to salt spray. Location technology and project size all affect how much PV panels cost to install for desalination systems. Reduction of desalination expenses has generally been demonstrated to be possible through integrating PV systems with RO technology. Because of its effective design and plentiful solar resources, PV-powered desalination in Morocco, for instance, has been able to achieve water costs as low as $1 per cubic meter. With grid-

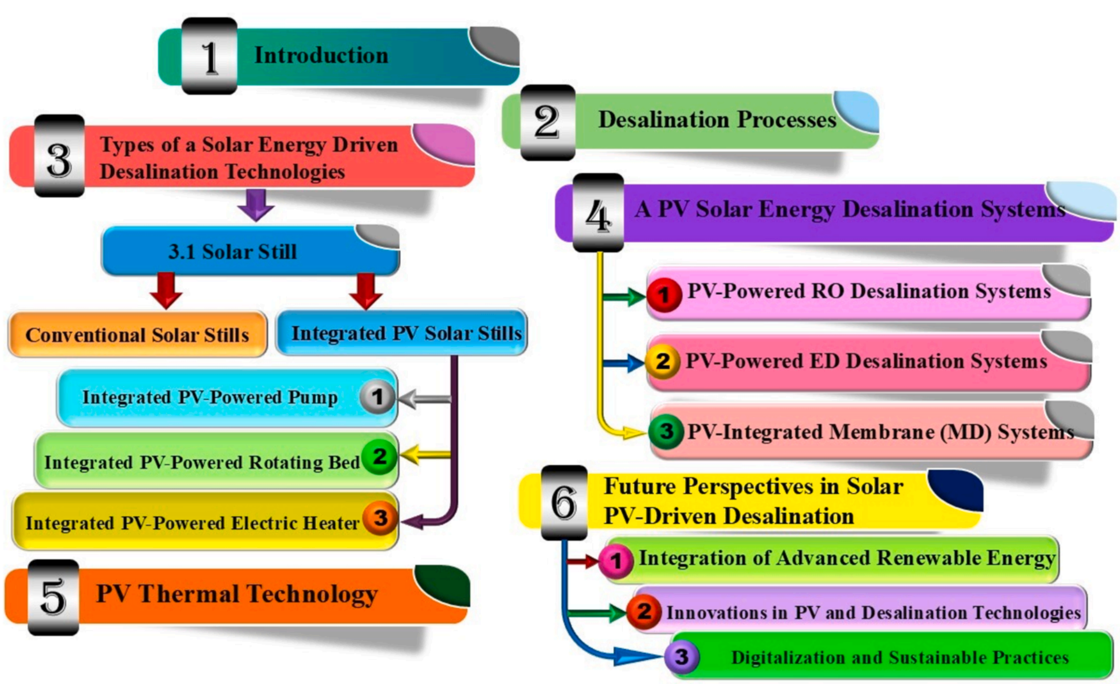

Fig. 2. Layout of the paper organizational structure.

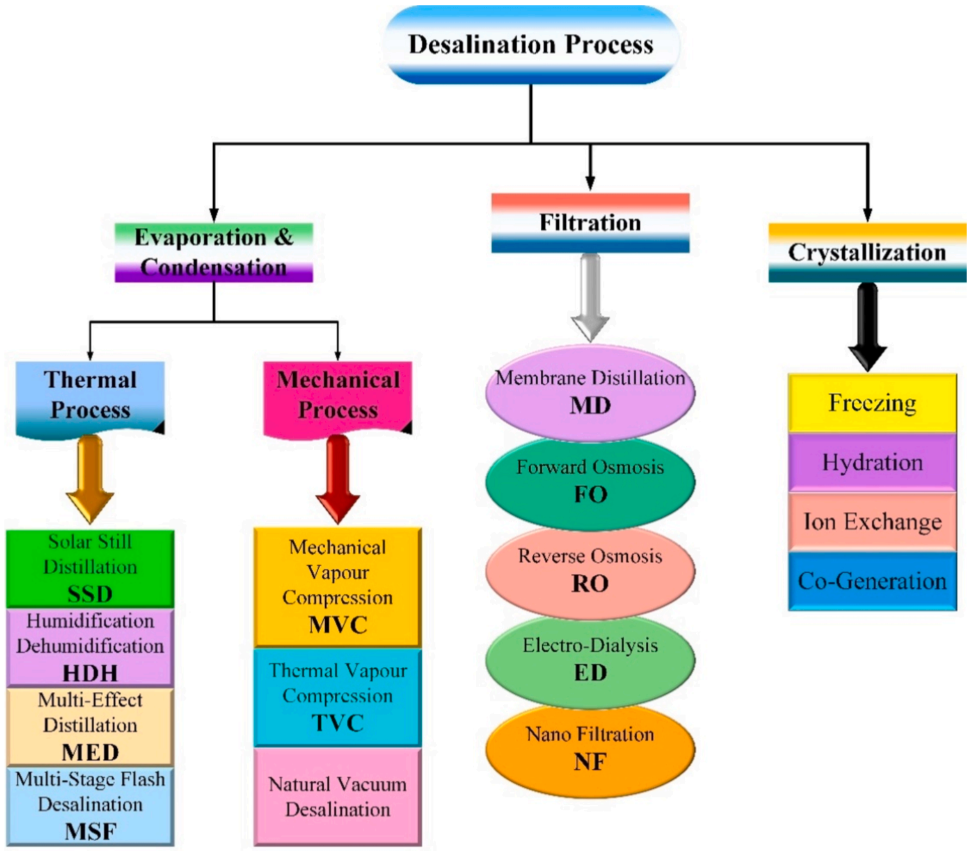

Fig. 3. Main desalinate processes around the world [31].

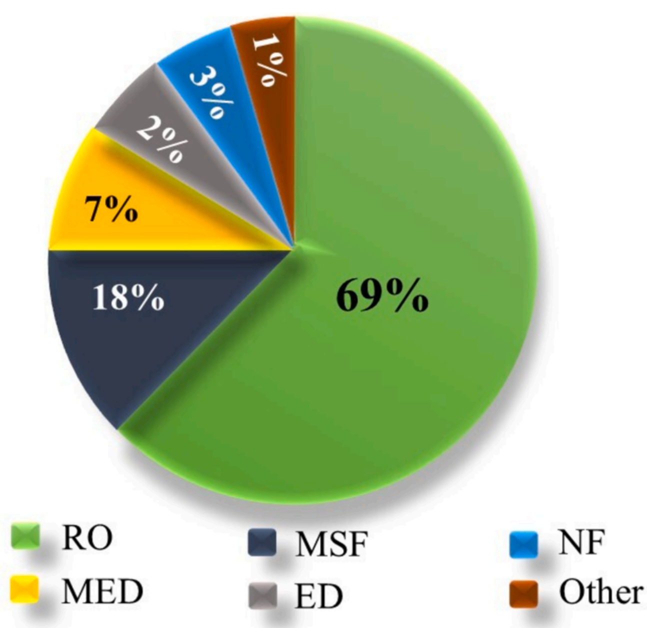

Fig. 4. Contribution of every desalination technique globally [5].

connected systems that require fewer PV panels and do not require extensive energy storage solutions initial capital costs can be further reduced [50,51]. Additionally, advancements in PV desalination systems, like the use of flexible batch electrodialysis reversal (EDR) technology, have reduced costs. By balancing energy consumption with solar availability this technique improves efficiency and reduces battery dependency. A recent study calculated that these systems' levelized cost of water (LCOW) was approximately \$1. 66 per cubic meter, a 22 percent increase over traditional methods [50–52]. These advancements show how solar energy and improved desalination technologies can be used to provide sustainable and reasonably priced solutions to the water shortage [52].

The cost of installation in coastal areas needs to be considered. Due to the complexity of marine installations, labor costs make up 12–18 % of the total investment, whereas dedicated mounting systems and safety precautions make up 15 %–20 % [50–52]. With yearly operating and maintenance costs ranging from \$18 to \$25 per kW, PV-desalination systems are significantly more expensive than traditional PV installations and necessitate more cleaning and corrosion protection measures. Freshwater produced in the combined PV-desalination system uses 3 to 4 kWh/m^3 and the entire system costs between \$2000 and \$3500 per m^3/day of desalination capacity [50–52]. These specialized systems typically pay for themselves in 6 to 9 years depending on the nature of the water shortage and energy expenses. For conventional grid-powered systems, the LCOW ranges from \$0. 90 to 1. 50/m^3, whereas for solar PV-powered systems, it ranges from \$0. 70 to 1. 20/m^3 [51,52].

Solar thermal is one of the indirect desalination systems that is categorized into heat, shaft, and electricity types. The shaft type describes a mechanical component used in solar desalination systems that is driven by thermal energy produced by solar thermal systems (see Fig. 6). Solar thermal energy can generate heat that powers turbines or engines that mechanically rotate a shaft. This rotational motion then powers pumps or compressors that are necessary for desalination processes like Electrodialysis (ED), Mechanical Vapor Compression (MVC), or Reverse Osmosis (RO) [19,46].

Even though photovoltaic panels are the desalination system's main energy source, their importance goes beyond just producing electricity.

Table 2
Summary of the desalination processes of evaporation and condensation worldwide [22,25,32–35].

Desalination process	Water production capacity (m^3/day)	Outcome	Advantages	Disadvantages	Performance efficiency (%)
SSD	1 to 500	Drinkable water	Simple design, low cost, and renewable energy	High land requirement, low efficiency	10 to 30%
HDH	1 to 500	Drinkable water	Uses low heat, simple	High energy consumption, low production capacity	20 to 40%
MED	1,000 to 15,000	High-quality drinkable water	Low energy consumption per unit, High efficiency	The required experience in operation, high initial cost	50 to 70%
MSF	10,000 to 500,000	High-quality drinkable water	Large-scale reliable, production	High capital and high energy exhaustion of cost	40 to 60%
MVC	100 to 3,000	High-quality drinkable water	Energy to efficient of small-scale operations	Complex system, high maintenance cost	70 to 85%
TVC	3,000 to 10,000	High-quality drinkable water	Uses squandering heat, the high efficiency	Limited scalability, high initial cost	70 to 90%
NVD	1 to 1,000	Drinkable water	Low energy requirement, simple design	Production of small-scale, low efficiency	20 −to 50%

Table 3
Summary of the desalination processes of crystallization worldwide [22,25,32–35].

Desalination process	Water production capacity (m^3/day)	Outcome	Advantages	Disadvantages	Performance efficiency (%)
Freezing	1 to 100	High-quality drinkable water	Low energy request for a cold zone	A complex process, the cost of high equipment	30 to 50%
Hydration	1 to 100	Drinkable water	Simple, consumption of low-energy	The capacity of low production, slow in process	20 to 30%
Ion exchange	1 to 10,000	Drinkable water, deionization	Effective to specific ions, regenerable	Specific ion exchange resins needed, high cost of operational	70 to 90%
Co-Generation	10,000 to 100,000	Drinkable water, electricity	Dual-aim, efficiency of high overall	Complex combination, high initial cost	60 to 80%

Table 4
Summary of the desalination processes of filtration worldwide [22,25,32–35].

Desalination process	Water production capacity (m^3/day)	Outcome	Advantages	Disadvantages	Performance efficiency (%)
MD	1 to 1,000	High-quality drinkable water	Temperature for low operating, high repudiation of contaminants	Low flux, possible membrane contaminates	40 to 70%
FO	1 to 5,000	Drinkable water	Consumption of low energy, recovery for high water	Complex pull solution recovery, membrane contaminates	60 to 80%
RO	100 to 500,000	High-quality drinkable water	High efficiency, consumption of low energy	Membrane contaminates, disposal cost of high brine	35 to 45%
ED	1 to 10,000	Drinkable water	Low energy exhaustion for brackish water	Feedwater of limited salinity, membrane contaminates	40 to 60%
NF	1 to 100,000	Drinkable water	Take off multivalent ions, operation for low-pressure	Does not take off monovalent ions, the membrane contaminates	40 to 60%

Table 5
Summary of the main features of conventional hybrid technologies [25,34–38].

Hybrid technology	Components	Main features	Water production capacity (m^3/day)	Outcome	Advantages	Disadvantages
RO with MSF	Membrane (RO) + Thermal (MSF)	Integrate thermal and membrane processes	10,000 to 20,000	High-quality drinkable water	Consumption of reduced energy, and improved efficiency	Complex operation and maintenance, high initial cost
RO with MED	Membrane (RO) + Thermal (MED)	Warms feed water using thermal process waste heat	8,000 to 15,000	High-quality drinkable water	Efficiency of higher overall, and costs to lower energy	Requires high-quality waste heat sources
MSF with MED	Thermal (MSF) + Thermal (MED)	Used a heat from MSF brine to MED process	5,000 to 10,000	High-quality drinkable water	Utilization for better energy, recovery for increased water	Consumption of high-energy
ED with RO	Membrane (ED) + Membrane (RO)	Utilize RO of initial desalination, followed by ED of nomination	1,000 to 5,000	High-clean water	Reduced brine disposal issues, recovery of high water	Membrane contaminates, high operational cost
RO with VC	Membrane (RO) + Thermal (VC)	VC of further concentration, RO of primary desalination	3,000 to 7,000	High-clean water	High purity water output, Reduced energy consumption	Complex system, cost of high capital

System efficiency, energy optimization, and sustainable water production are all significantly impacted by the solar panel configuration. These solar panels enable a decentralized eco-friendly water treatment solution in addition to powering the desalination process by directly converting solar radiation into electrical energy. Utilizing PV technology demonstrates a thorough process of desalinating water in which

Table 6
Desalination capacity by country/region (2016/2024) [39–43].

Country/Region	2016 (m^3/d)	2018 (m^3/d)	2020 (m^3/d)	2022 (m^3/d)	2024 (m^3/d)	Annual growth rate (%)
Saudi Arabia	3,300,000	4,000,000	5,200,000	6,500,000	7,500,000	17.1%
UAE	1,500,000	2,100,000	2,700,000	3,300,000	4,000,000	18.2%
USA	1,000,000	1,200,000	1,400,000	1,600,000	1,800,000	12.0%
China	600,000	750,000	900,000	1,100,000	1,300,000	16.6%
Kuwait	500,000	600,000	750,000	900,000	1,100,000	17.1%
Spain	400,000	500,000	600,000	700,000	800,000	16.7%
Australia	350,000	420,000	500,000	600,000	700,000	18.0%
India	300,000	400,000	500,000	600,000	700,000	21.3%
Egypt	200,000	300,000	450,000	650,000	900,000	25.0%
Row (Rest of World)	5,500,000	6,200,000	7,000,000	8,000,000	9,000,000	10.5%

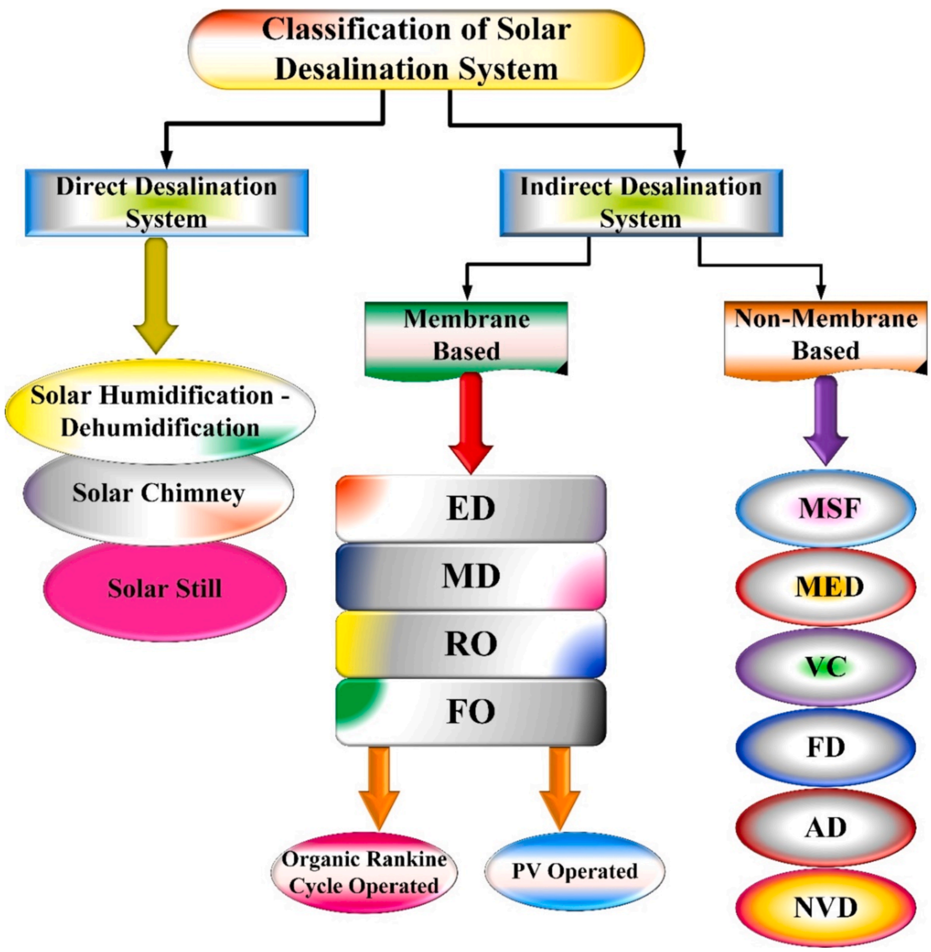

Fig. 5. Classification for a solar desalination system [44].

environmental sustainability, energy production, and system performance are all closely related. This approach shows how water scarcity issues can be mitigated by renewable energy, particularly in remote or off-grid locations with little access to traditional electricity infrastructure [53,54]. When choosing PV panel technology the effectiveness and efficiency of solar desalination systems are greatly impacted. While polycrystalline silicon panels offer a more affordable option with somewhat lower efficiency (15%–18%), monocrystalline silicon panels have a high conversion efficiency (18%–22%), making them perfect for areas with little solar radiation [53,54]. Thin-film technologies such as copper indium gallium selenide (CIGS) panels and cadmium telluride (CdTe) panels exhibit exceptional performance in high-temperature settings while sustaining steady electrical output under trying circumstances [53,54]. More solar radiation from reflected surfaces can be captured by sophisticated bi-facial PV panels, boosting the system's overall energy yield by 10 % to 30 %. Additionally, new technologies with quick efficiency gains and cheaper production costs, like perovskite solar cells, show promise. By facilitating a more effective conversion of solar energy into drinkable water, these panel variations have a direct impact on the water production rates, energy consumption, and overall sustainability of the desalination system.

The organic Rankine cycle is a closed thermodynamic cycle used for power production from low to medium–high temperature heat sources ranging from 80 to 400°C and for small-medium applications at any temperature level.

3.1. Solar chimney

The solar chimney is considered one of the direct desalination processes based on thermal energy. The thermal energy from the sun is

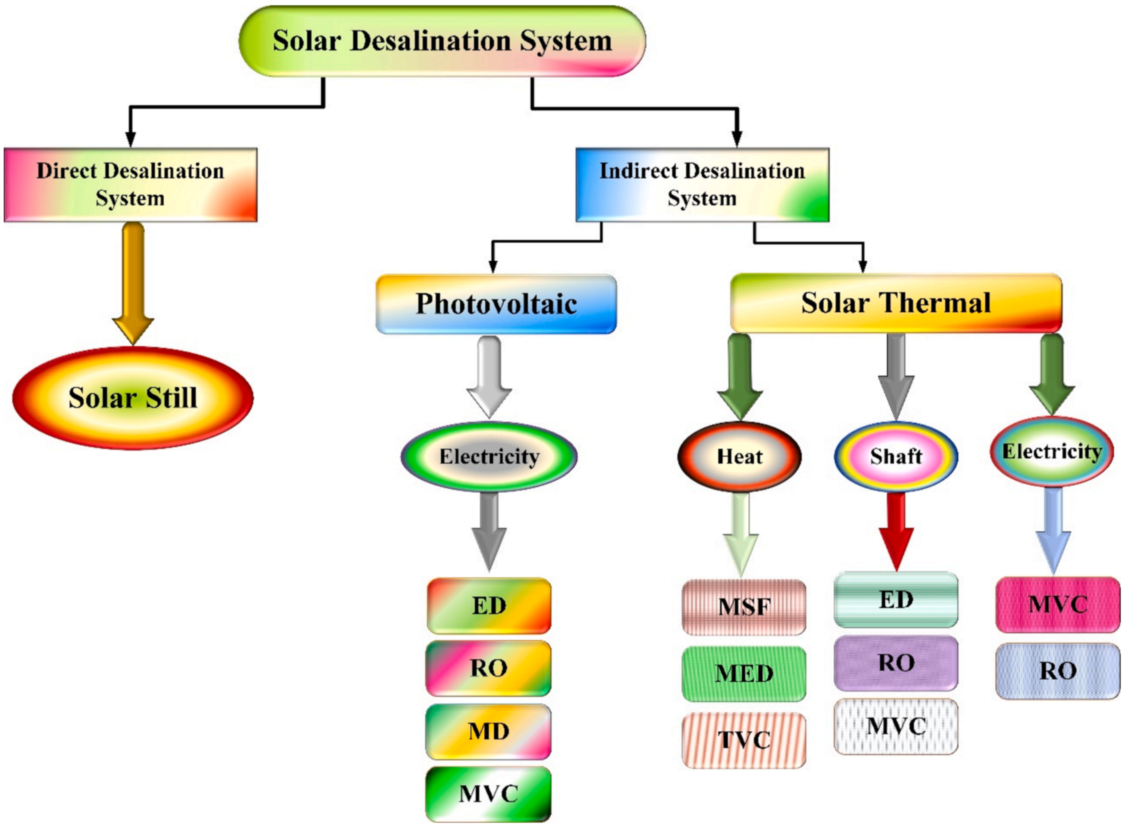

Fig. 6. Integration for desalination technology with solar energy system [46].

Table 7
Recent studies on direct and indirect solar desalination technologies powered by nanoparticles [55–63].

Solar desalination technology	Year	Location	Design	Main findings	Efficiency improvement
Direct solar desalination	2019	Egypt	still	Increased evaporation rate, enhancement of efficiency thermal	Increase efficiency by 25%
Direct solar desalination	2020	USA	Solar still	Increased evaporation rate, enhancement of heat absorption	Increase efficiency by 30%
Indirect solar desalination	2020	Saudi Arabia	Solar-powered RO	Improvement of membrane performance reduced fouling	Increase water output by 22%
Direct solar desalination	2021	Australia	Solar distillation unit	Higher production rate for water, increased of thermal conductivity	Increase water output by 35%
Direct solar desalination	2021	Brazil	Solar still	Increased evaporation rate, enhancement of heat absorption	Increase efficiency by 33%
Direct solar desalination	2022	UAE	Solar pond	Increased temperature gradient, absorption of enhanced solar energy	Increase thermal efficiency by 40%
Indirect solar desalination	2022	Eastern China	Hybrid PV-thermal system combining ORC and RO.	Improved thermal energy utilization and increased water production.	Preheated feedwater in RO systems lessens energy exhaustion by up to 25%.
Indirect solar desalination	2023	Coastal regions, China	RO system of PV-powered devices for energy recovery	Efficiency of Enhanced energy, increasing water recovery, and reducing operational costs.	Devices for energy recovery reduced energy consumption by 20% to 30%.
Direct solar desalination	2023	Spain	still	Higher heat to absorption, improved evaporation rate	Increase efficiency by 28%
Indirect solar desalination	2024	Japan	MD	Reduced energy consumption, improved distillation rate	Increase efficiency by 30%

converted into kinetic energy and then electrical energy by a solar chimney using a turbogenerator. A solar chimney is primarily composed of a long chimney, a turbine a generator, and large-diameter sunlight collectors. Glass and plastic sheets which are used to make the most popular kinds of collectors, act as greenhouses by retaining heat and warming the ground underneath (see Fig. 7). This permits heated air to pass down the chimney by producing a temperature differential between the air inside the system and the outside air. The kinetic energy of the flowing air causes the turbine, which is placed beneath the chimney, to rotate and produce electricity. Below a solar chimney collector cover the integrated system consists of a blackened annular basin filled with saline water and a rock bed power storage unit [44]. An angled glass cover is placed over the basin. When solar radiation heats the air and water, the air passes through a chimney to produce electricity, and the water evaporates to create distillate. Water produced from an 8-hour-per-day plant would cost $2. 23 USD/m^3, less than the water produced using any other technology. The schematic representation of the system is shown in Fig. 7.

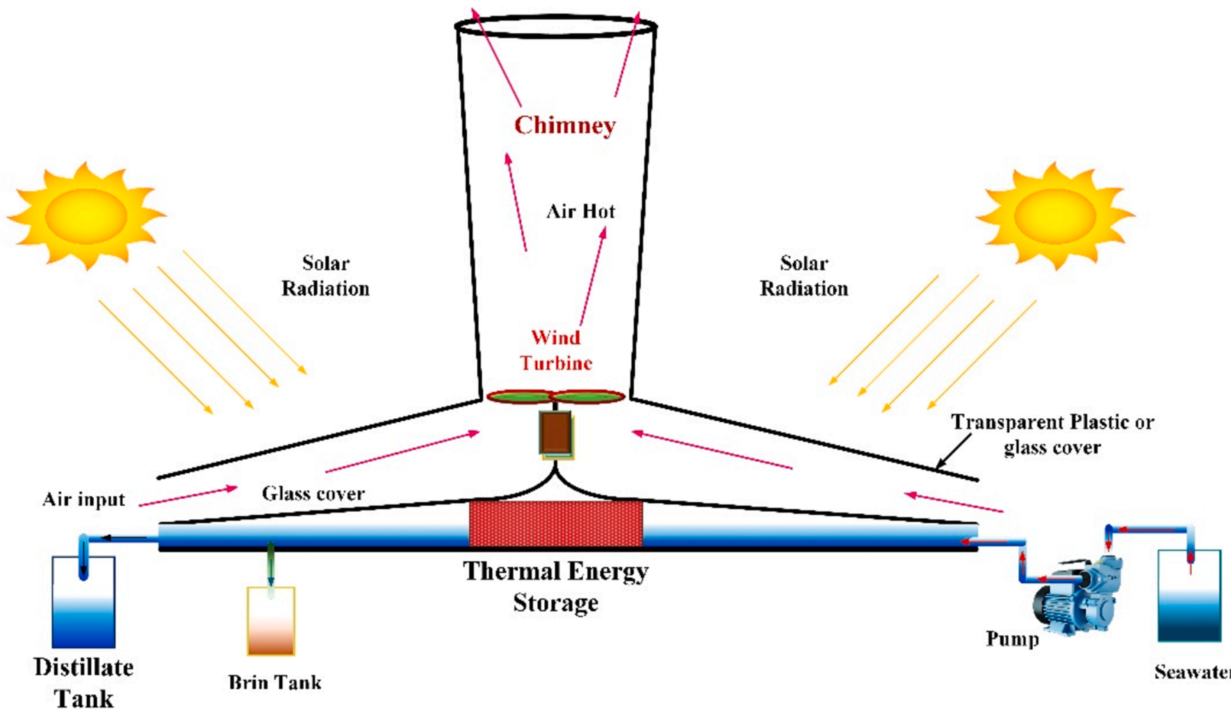

Fig. 7. Desalination system of basin type combined with solar chimney [44].

3.2. Solar still

Distillation is the oldest method of water purification. Whereas thermal distillation employs heat to transform salt water into pure water, it may be fueled by different energy sources. This process involves heating any type of water to the boiling point and producing steam, which is then condensed into pure water. The procedure may be used with saltwater, brackish water, or any other type of water [44].

A solar still comprises a basin filled to a specific depth with brackish or seawater and topped with sloped glass to allow solar radiation and evaporation to pass through more easily. The solar radiation heats the black lining to heat the salt water, which causes evaporation. The water vapor condenses down the inclined glass cover because of the changes in partial pressure and temperature, and it is then appropriately collected at the bottom [19].

3.2.1. Conventional solar stills

Impure water is retained outside the collected area, evaporated by sunlight falling on glass in typical solar stills, where the form of heat for solar power is initially employed to raise the water temperature and give the essential energy to shift the liquid to vapor [44]. Where the vapor of water is formed on the inside surface and drips down, and it is collected in a pure water basin, as shown in Fig. 8 However, a procedure that has a great chance of resolving some of the issues with traditional systems is the coupling of a photovoltaic unit with solar stills [46].

Utilizing sunlight, a solar desalination system also known as a

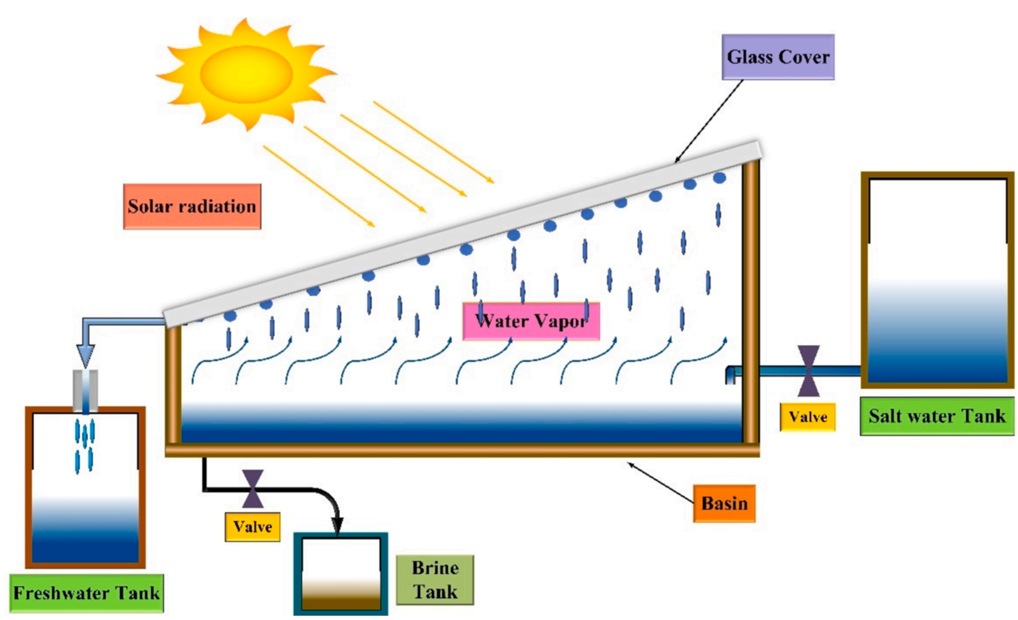

Fig. 8. Diagram of a conventional solar still [46].

traditional solar still converts saltwater into freshwater. Saltwater is first stored in a tank before being released into a tiny basin. Because solar light heats the saltwater in the basin it evaporates (see Fig. 8). A tilted glass cover above the basin retains heat, improving evaporation by producing a greenhouse effect [26]. The cooler inside surface of the glass cover is where the water vapor condenses as it rises. Gravity causes the condensed freshwater to run down the glass, where it is gathered for use in a freshwater tank. Where, the residual brine, or concentrated salt water, is emptied into a different brine tank of disposal [46]. Although this technique is an economical and environmentally responsible method of producing freshwater, its effectiveness is dependent on the amount of sunshine present, as shown in Fig. 8 However, a procedure that has a great chance of resolving some of the issues with traditional systems is the coupling of a photovoltaic unit with solar stills.

3.2.2. PV integrated based on solar stills

The sunlight for the distillation process is used for heating, mainly to evaporate, while the photovoltaic modules can provide electricity that can help various distillation technologies. Several solar PV technologies are displayed, as are distillation processes for solar power. The following equation must incorporate energy generation efficiency in order to calculate the overall thermal efficiency (η_{th}) of a solar PV distillation system [46]:

$$\eta_{th} = \frac{\text{Energy used to evaporate water}}{\text{Total Solar Energy Input}} \tag{1}$$

Where, the useful energy used to evaporate water is represented by the numerator ($M_w * h_{fg}$). At a specific latent heat of vaporization, this is the energy required to turn a mass M_w of water into vapor [46].

$$M_w * h_{fg} \tag{2}$$

The entire amount of solar energy incident on the PV module and solar still combined is represented by the denominator $((G_s*A_s) + (G_s*A_{PV}))$.

$$((G_s*A_s) + (G_s*A_{PV}) \tag{3}$$

$$G_s*(A_s + A_{PV}) \tag{4}$$

$$\eta_{th} = \frac{M_w * h_{fg}}{G_s*(A_s + A_{PV})} \tag{5}$$

Where: M_w is the water condensation rate (kg/s), h_{fg} is the vaporization's latent heat (J/kg), and A_s the basin region (m^2), G_s is solar irradiance (W/m^2), A_{PV} is the PV unit area (m^2).

3.2.2.1. Integrated PV-powered pump.

The hydraulic power needed for desalination systems depends on various characteristics that must be specified during system design. Therefore, the following equation may be used to estimate hydraulic size [46]:

$$\boldsymbol{P_{pump}} = \frac{\boldsymbol{\rho * g(h + \Delta H) * Q}}{\boldsymbol{\eta_p * \eta_e}} \tag{6}$$

Where: $-\boldsymbol{P_{pump}}$ (W) is the amount of power needed to pump water for system requirements, $\boldsymbol{\rho}$ (kg/m^3) are a density of water, $\boldsymbol{g}$ (M/S^2) is the traditional acceleration because of gravity, $\boldsymbol{h}$ (m) is total main pumping, $\Delta\boldsymbol{H}$ (m) is losses for the hydraulic, $\boldsymbol{Q}$ (m^3/s) is the amount of flow, $\boldsymbol{\eta_p}$ is the efficiency of the pump, $\boldsymbol{\eta_e}$ are the efficiency of a motor for electricity.

A solar still for distilled apparatus for off-grid use has been proposed. The model comprised a 0.57 m^2 surface of a 500-watt PV module and a pump lifting for water on 72.5 m underground, all combined with a typical still solar with a 1.25 m^3/day capacity to distill salt water [46,64]. The suggested design is illustrated schematically (see Fig. 9) [46]. In this illustration, a solar-powered desalination system that combines photovoltaic (PV) technology with a traditional solar still is used to purify brackish or saline water. A solar panel converts sunlight into electricity and powers a pump that transports salty groundwater into a desalination chamber. Table 8 also compares motors suitable for powering pumps in PV systems. Water desalination systems work at different speeds and do not require electrical energy storage. Due to a variety of developments, including falling photovoltaic energy costs and the development of specially designed inverters for solar pumping and photovoltaic water pumps, the purpose of this study is to develop and comprehensively evaluate variable-speed pumping and desalination systems coupled with direct photovoltaic energy [70]. Simulations are used every hour throughout the year to evaluate the system's

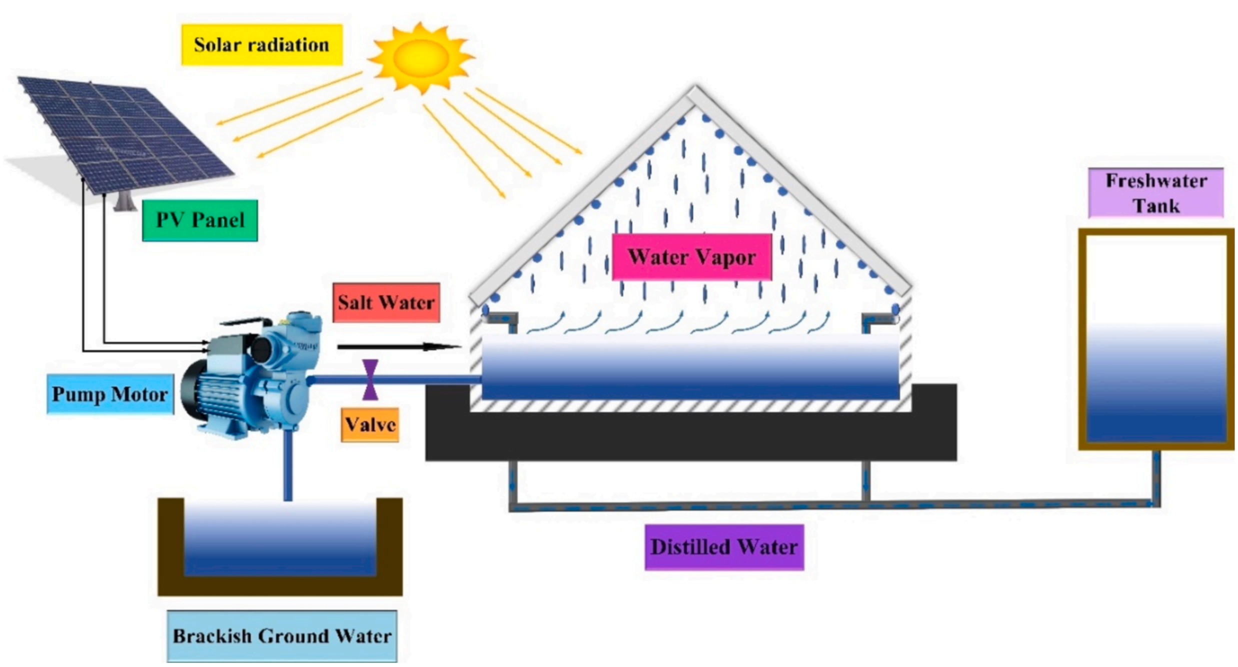

Fig. 9. Combining the solar still and a photovoltaic system to power a water pump [46,64].

Table 8
Comparison of motors suitable for powering pumps in PV systems [65–69].

Motor type	Power range	Advantages	Disadvantages
DC brushless motor	0.1 kW to 100 kW	Long lifespan, control of good speed and low maintenance, high efficiency	Complex wiring requires a controller and a higher initial cost
DC brushed motor	0.01 kW to 5 kW	Easy of control, simple design, and low cost	Reduced lifespan, increased maintenance because of brush wear and decreased efficiency
Permanent magnet synchronous motor (PMSM)	0.1 kW to 200 kW	Excellent speed control, high efficiency, and dependability	Requires complex controller, Expensive and more complex than DC motors
Induction motor (AC)	0.1 kW to 1 MW	Robust, low-cost, dependable, and low maintenance	Reduced efficiency is less effective at partial loads, and PV systems need an inverter
Switched reluctance motor (SRM)	0.5 kW to 500 kW	High efficiency, strong, easy construction, and good of variable speeds	High vibration and noise complicated control and less well-known technology
Step motor	0.01 kW to 10 kW	Simple control without feedback and precise position control	Unsuitable for high-power applications, low efficiency, and problems with heating at high speeds
Synchronous reluctance motor	0.1 kW to 500 kW	Excellent for variable speed, high efficiency, and no need for permanent magnets	Expensive, complex control and less developed technology

performance while optimizing the architecture.

Initially, a PV panel converts sunlight into electricity to power a pump that transports salty groundwater into a desalination column. Where the water inside the chamber is heated by solar radiation, promoting evaporation. By providing a transparent sloping surface for the vapor to cool and condense into droplets of distilled water the triangular shape aids in the condensation process. At the bottom of the chamber, the distilled water is gathered and transferred to a freshwater storage tank [64]. This system is sustainable and energy efficient because it uses renewable solar energy to power the pump and desalinate. It functions particularly well in environments with high solar radiation levels and limited freshwater availability. This concept combines desalination with renewable energy to offer a practical solution for the limited water supply in remote or off-grid locations.

Fig. 10 depicts the overall system for designing and modeling the system structure. An economic analysis is performed to determine pumping, desalination costs, payback periods, rate of return, internal consumption, and overall costs [70]. Also, several case studies are evaluated to demonstrate the feasibility of PV, diesel, and variable speeds for pumping in Jordan Valley agriculture using desalination systems [70]. Table 9 depicts an overview of some outdoor small-scale PV-membrane brackish desalination systems for drinking water. Total dissolved solids (TDS) are the total amount of solids dissolved in the water, including soluble hydrogen carbonate ions, chloride salts, sulfates, calcium, magnesium, sodium, potassium, volatile solids, and non-volatile solids. Its concentration will affect the taste of drinking water.

3.2.2.2. Rotating bed for a PV-powered integrated. A new design pushes a rotating vertical wick internal to a stationary device in the form of additional evaporation surfaces alongside standard sump distillation units, as shown in Fig. 11. Where the rotating component decreases the tension of the surface and incorporates the freelancer evaporation process within the evaporation technology of forced [19,46]. Scientists are interested in studying the thickness of the film of water in the distillation apparatus because it is one of the most significant factors affecting the evaporation process, followed by the amount of clean water produced by the distillation apparatus [19]. This can be done by developing various designs or controlling the factors affecting its productivity.

The effect of solid drum movement was studied at changing speeds inside the distillers. They also studied the performance of a distillation device using solar water heaters with the addition of an external capacitor and how its performance differs from traditional [19,75]. At a speed of 0.1 rpm by 350%, their upgraded solar still's productivity was experimentally improved compared to the traditional distillation

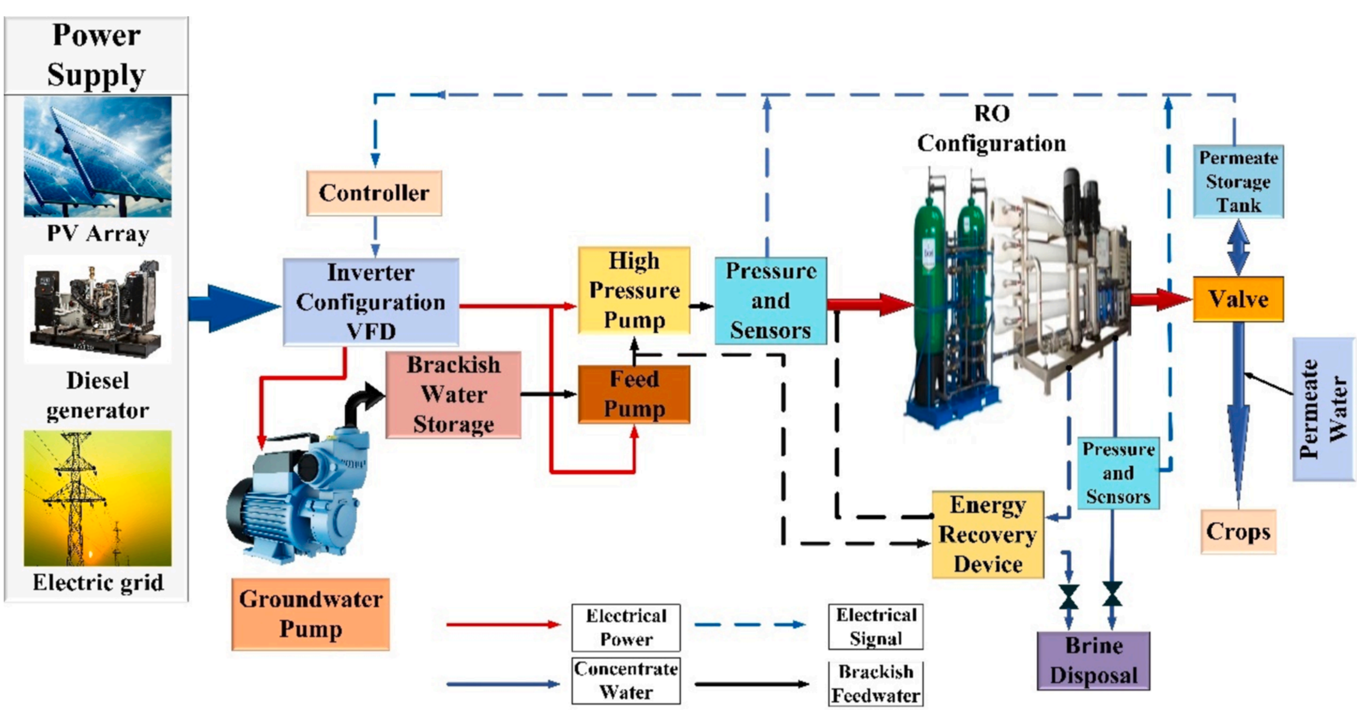

Fig. 10. Modeling architecture illustrating the various configurations [70].

Table 9
Overview of some existing outdoor small-scale PV-membrane brackish desalination [71–74].

System	System (A)	System (B)	System (C)	System (D)	System (E)	System (F)
Location	Jordan Valley, Jordan	Western Australia	Rajasthan, India	Cape Town, South Africa	Baja California, Mexico	California, USA
Configuration	PV + RO + Switched Reluctance Pump	PV + UF + RO + DC Brushed Pump	PV + NF + AC Induction Pump	PV + UF + NF + Step Motor	PV + RO + PMSM Pump	PV + RO + DC Brushless Pump
PV capacity	1.0 kW	1.2 kW	1.3 kW	1.3 kW	1.4 kW	1.5 kW
Motor power rating	1.0 kW	1.0 kW	1.5 kW	1.4 kW	1.2 kW	1.2 kW
permeate capacity	1.5 m^3/d	1.8 m^3/d	2.2 m^3/d	2.0 m^3/d	2.0 m^3/d	2.5 m^3/d
Feed water TDS	<2,200 ppm	<3,000 ppm	<2,500 ppm	<2,800 ppm	<1,500 ppm	<2,000 ppm
recovery rate	42%	40%	50%	46%	48%	45%
specific energy consumption	3.8 kWh/m^3	4.0 kWh/m^3	3.0 kWh/m^3	3.6 kWh/m^3	3.2 kWh/m^3	3.5 kWh/m^3
product water quality	< 550 ppm	< 600 ppm	< 450 ppm	< 500 ppm	< 500 ppm	< 500 ppm
Operating conditions	Sunlight: 6–8 hrs/day, Ambient temp: 15–35°C	Sunlight: 4–5 hrs/day, Ambient temp: 15–40°C	Sunlight: 6–7 hrs/day, Ambient temp: 15–40°C	Sunlight: 4–6 hrs/day, Ambient temp: 15–40°C	Sunlight: 5–6 hrs/day, Ambient temp: 15–40°C	Sunlight: 5–6 hrs/day, Ambient temp: 15–40°C
Performance	Robust and stable, uptime of 87%	Repeated maintenance, uptime in 80%	Dependable and 90% uptime	Accurate control, uptime in 85%	High efficiency, uptime in 88%	Stabilized performance, uptime in 85%

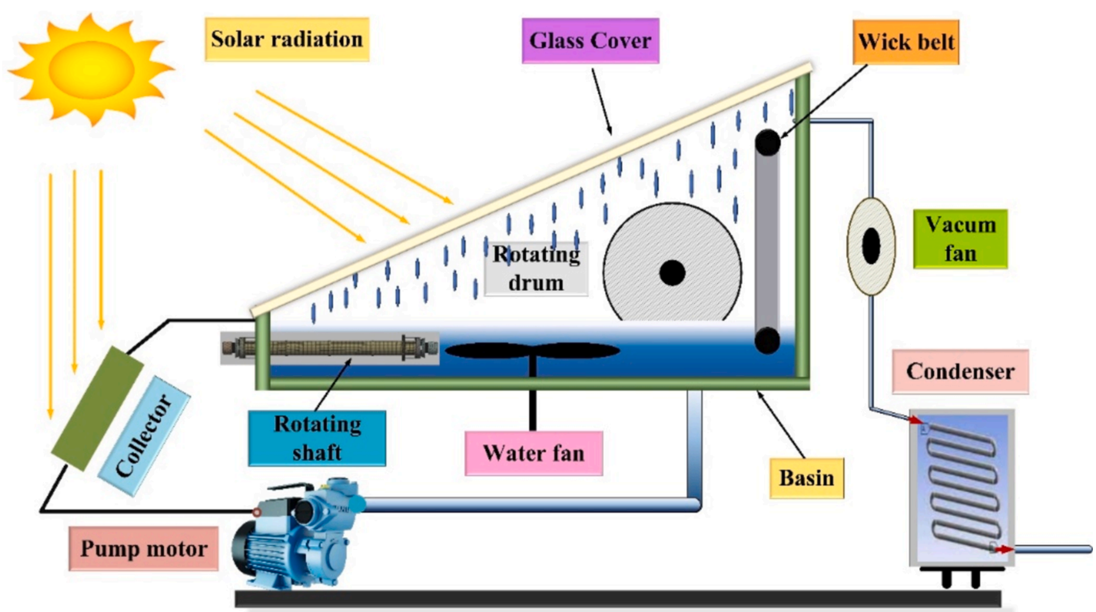

Fig. 11. A diagram of in the distiller's a rotating component [19,46].

machine. Moreover, they reported 85.5% effectiveness by adding external capacitors, water heaters for solar, and nanofluids, as shown in Fig. 12.

A new design for the rotary drum inside the traditional distiller, as shown in Fig. 13 at these values (0.02, 0.05, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, and 4.0 rpm) the speed for drum was investigated. Some effective improvements include adding PV cells to operate a DC motor and reflectors for internal use to minimize static heat loss, with the impact of employing wicks and nanoparticles for cylinders [19]. At a speed of 0.1 rpm, the results revealed a 296% improvement compared to a traditional distiller. Also, Table 10 illustrates a simple comparison of different solar stills with rotating parts.

3.2.2.3. Integrated PV-powered electric heater. Photovoltaic is used in the HDH (humidification, desalination, and dehumidification) system. This design used a pump to move water between the tank, heat exchanger, and humidifier. It was powered by a series of PV cells. The saline water is supposed to be heated first in the exchanger for heat by exiting the heat contained in the vapor for water. The heater raised its temperature to the necessary evaporation temperature when it reached a humidifier. During dehumidification, the air exchanged its inherent temperature with a heat exchanger on the cold surface and produced pure water [46].

In this study, at the bottom of a humidifier, next to the sensor for a temperature that shows the water's temperature, a 3500 W auxiliary heater has been installed (see Fig. 14). Also, a ventilator with a 5.9 m/s speed was fixed to the HDH [82]. Results show the highest productivity of 0.873 kg/m^2 every day of clean water was achieved at an evaporation heat of 64.3°C, as evidenced by the production increase following the use of forced convection, as shown in Fig. 14.

In this study [83], a solar still with PV energy was designed and operated to desalinate water continuously, 24 h a day, in Gharbia Governorate for Tanta, Egypt. The heater for electric water (EWH) was placed inside the basin to heat the water in the basin at night and in the early morning to achieve continuous water desalination (see Fig. 15). The period from 2 May to 11 August, for using continuous desalination of water during a 24-hour period, the experimental findings showed that the cumulative productivity for distillation water ranged between

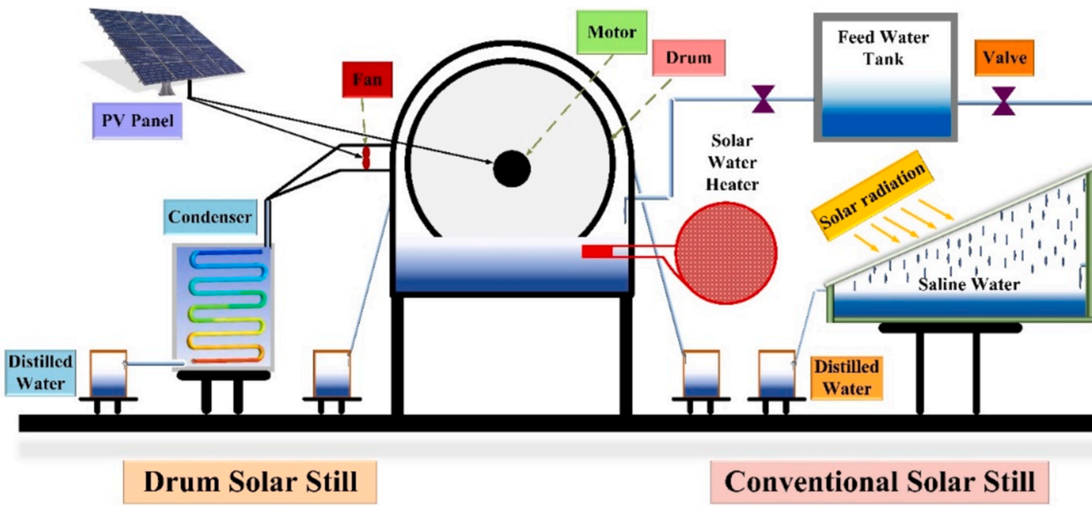

Fig. 12. A conventional and modified solar still diagram [19,75].

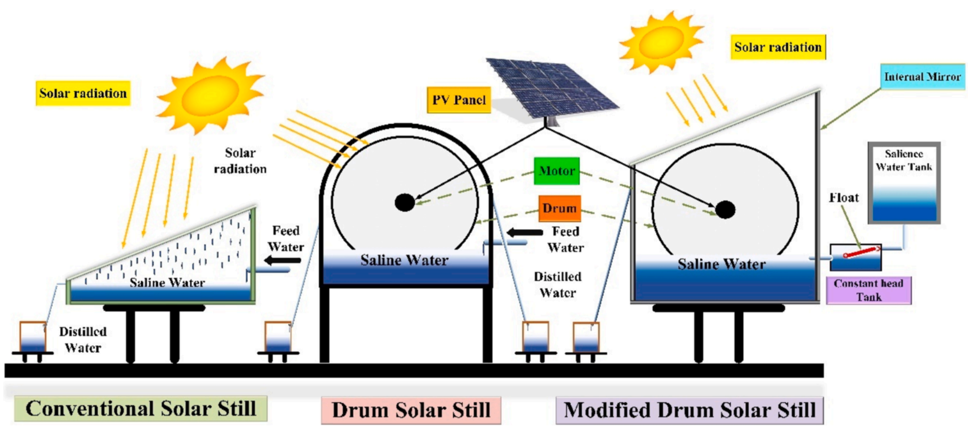

Fig. 13. A diagram for the modified drum in the distiller [19].

Table 10
A simple comparison of different solar still with rotating parts [76–81].

Solar still type	Year	Location	Daily yield (L/m^2/d)	Observations (Conditions)	Improvement and efficiency (%)
Rotating drum solar still	2019	India	4.2 L/m^2/d	Ambient temp 30 to 40 °C, and high solar intensity	Improvement in 32%, efficiency in 61%
Rotating wick solar still	2020	Egypt	3.8 L/m^2/d	Ambient temp 25 to 35 °C, and high humidity	Improvement in 28%, efficiency in 57%
Rotating Cylindrical solar still	2021	India	4.9 L/m^2/d	Ambient temp 25 to 35 °C, wind speed moderate	Improvement in 36%, efficiency in 66%
Rotating disc solar still	2022	USA	3.4 L/m^2/d	Ambient temp 20 to 30 °C, The wind speed low	Improvement in 22%, efficiency in 52%
Rotating basin solar still	2023	Oman	3.9 L/m^2/d	Ambient temp 30 to 40 °C, conditions of clear sky	Improvement in 30%, efficiency in 58%
Rotating cone solar still	2024	China	4.6 L/m^2/d	Ambient temp 25 to 35 °C, and low humidity	Improvement in 34%, efficiency in 63%

10,631 to 12,087 m^{-2} day^{-1}. The productivity improvement of stationery solar with 24-hour continuous water desalination ranged from 159.3 without EWH to 177.9% compared to still solar with EWH. Also, water desalination's overall efficiency is improved by 27.9-31.3%. The diagram for the solar still for distillation employing a water heater and a PV module is shown in Fig. 15.

In this study, a combination system with a solar greenhouse attached is suggested to improve the efficiency, performance, and productivity of solar distillation [84]. Following the findings, a hybrid still connected to a PCC may generate 110 L/mˆ2 daily. Were the water in a combination still in PCC's basin is 140°C and 100°C, successive. The many sources of mixing temperatures in one system are the reason for this. Where value for efficiency to production and performance for the system is measured at 160% and 100 L/m^2, successively (see Fig. 16). Despite the detrimental impact of climatic conditions, the results demonstrate that the temperature is 70°C also production for clean water is 50 L/m^2 per day during January. Additionally, the findings indicated that the temperature inside the water was 120°C at 2 PM and 110°C at 6 PM, respectively. As a result of the PV system's independence, the temperature dropped gradually. With combination stills and PCC coupled, it increased production for high temperatures up to 100 L/m^2. Finally, it was found that the performance of the proposed hybrid is higher than that of a solar still without a capacitor. The suggested system, the hybrid distiller coupled with a PV system, is shown in Fig. 16. Table 11 illustrates solar distillation using a water heater coupled with a solar PV panel.

4. PV solar energy desalination systems

The conventional PV system comprises PV modules, charger controllers, batteries, and a DC/AC inverter [35]. Grid-connected (on-grid)

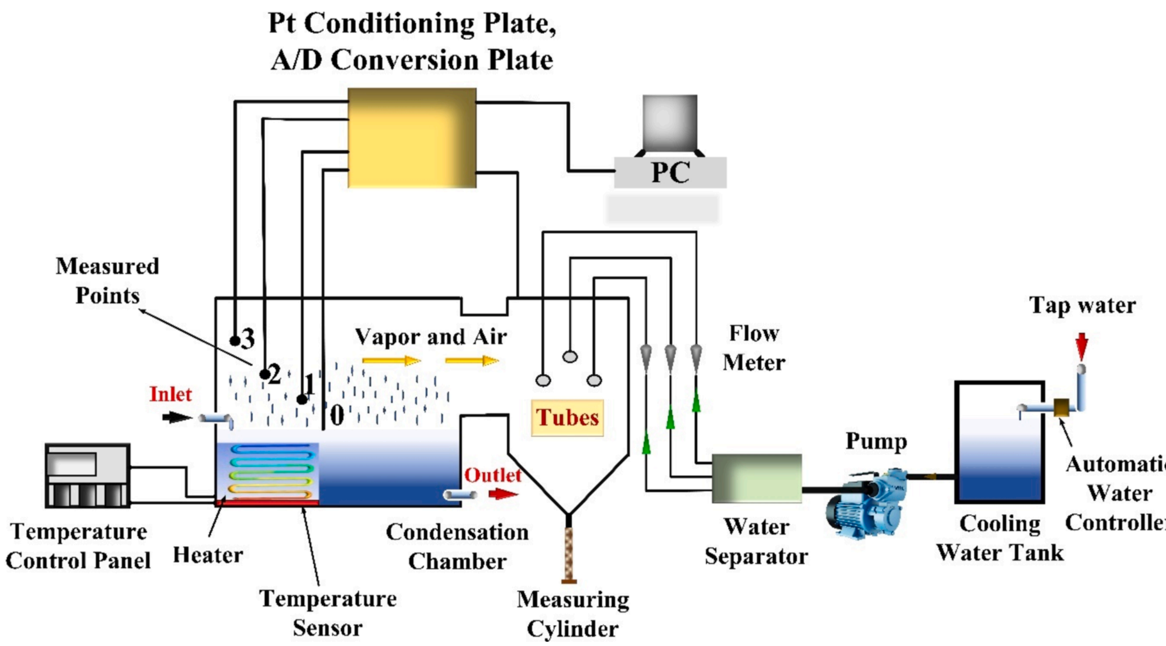

Fig. 14. A diagram showing the setup for experimental [82].

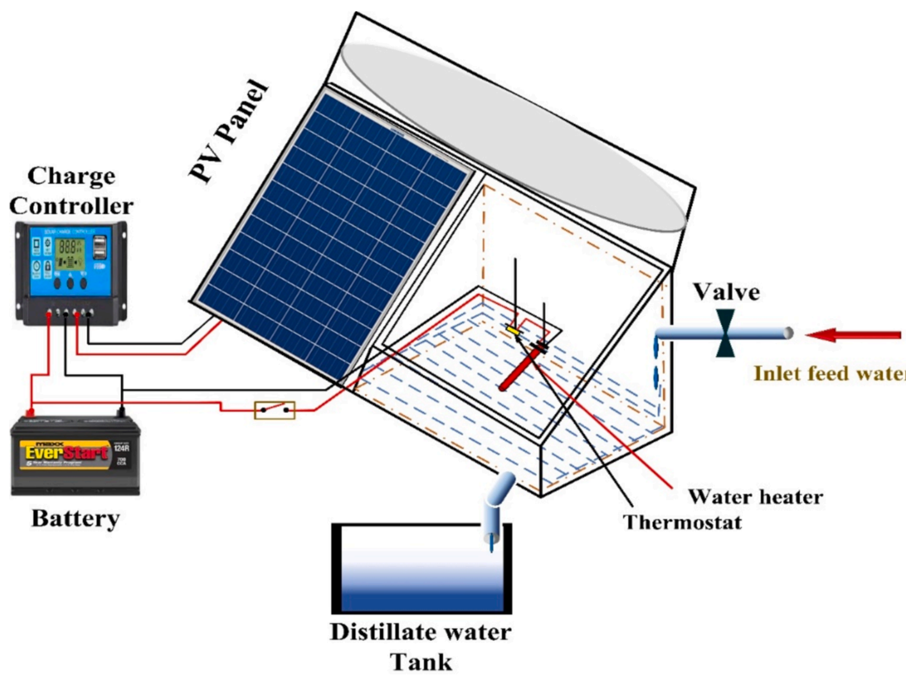

Fig. 15.D. iagram of solar still distillation using a water heater coupled with a solar pv panel[83].

and standalone (off-grid) PV systems are the two main categories of solar systems. For grid-connected systems, DC electricity generated by the photovoltaic cells is sent through a converting device and then to an electrical distribution system, as shown in Fig. 17.

A stand-alone PV system cannot convert energy for the grid but can be used for direct connection by batteries, as shown in Fig. 18. The PV system is modified, due to the high capital expense and running cost of batteries, to operate without batteries by connecting the PV directly to the DC motor-driven pump or via a supercapacitor as an electrical regulator [90]. Utilizing desalination for PV-powered methods is a great option for supplying water to small and medium-sized settlements located in isolated and remote places with abundant solar radiance and seawater [46]. Table 12 depicts a comparison of the energy storage technologies that are suitable for applications in small-scale PV systems.

4.1. PV-powered RO desalination systems

The systems for reverse osmosis contain five main pieces of equipment: a supply system, pretreatment filters, high-pressure pumps, an RO membrane, and a post-treatment system. To raise efficiency and increase the amount of clean water it produces, a PV power system would be a good choice for supplying the RO desalination method with the required energy. Many studies have been conducted in this regard. The diagram view for the typical PV-RO desalination technique is shown in Fig. 19.

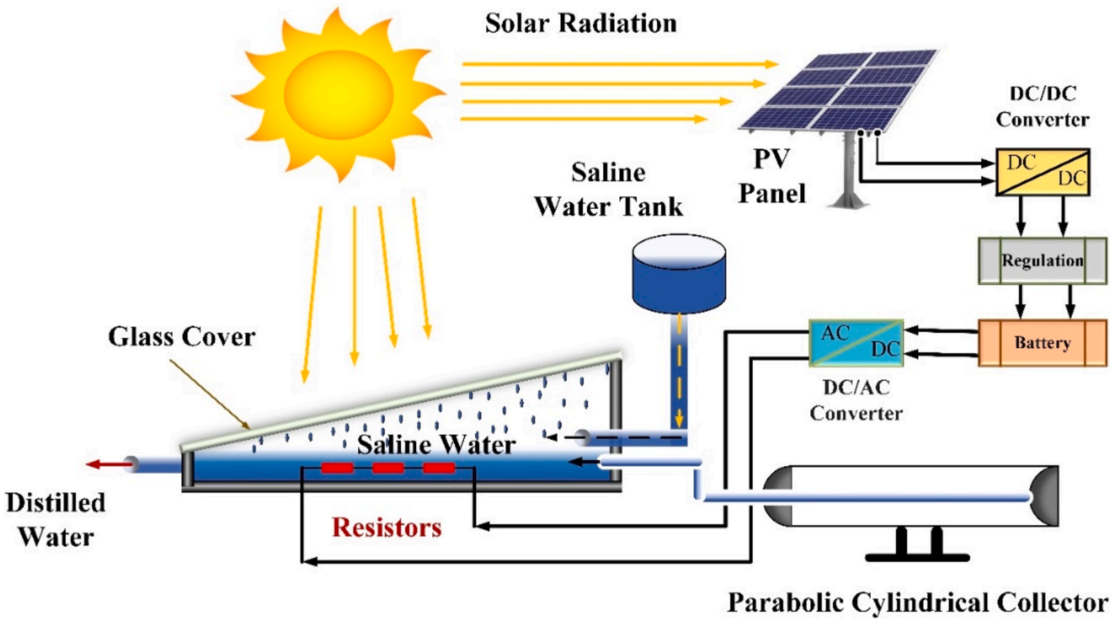

Fig. 16. Hybrid distiller coupled with a PV system [84].

Table 11
A solar distillation uses a water heater and a solar PV panel [85–89].

Heater type	Capacity range	Advantages	Disadvantages
PV with flat plate collectors (FPC)	100 to 500 L/day	Robust, cost-effective, and simple design	Less effective in colder environments, lower efficiency compared to ETC
PV with evacuated tube collectors (ETC)	150 to 600 L/day	High efficiency works well in a cloudy and colder climate	More complex maintenance, more expensive
Thermosiphon systems	100 to 300 L/day	Low maintenance, cost-effective, no need for pumps	Used small-scale applications, only installation angle and height differential are key factors
Integrated collector storage (ICS)	100 to 200 L/day	Combined collection and storage, compact design	Limited capacity, lower efficiency
PV with active pumped systems	200 to 1000 L/day	Suitable for large-scale applications, higher control overheating	Required electricity of pumps, higher initial cost
Solar PV-thermal (PVT) systems	200 to 500 L/day	Generates both heat and electricity, efficiently utilized for space	Complex installation and maintenance, higher cost

PV and RO are highly modular and scalable, and one of the best solutions for desalination driven by renewable energy, especially in remote regions, is a PV-RO unit increasing total system efficiency by 5 to 10% [95,96].

Fig. 20 shows the diagram for ideal PV-RO water desalination. Used the RO process to get pure water; the requirements were 1 ton of oil per year for order product 1 m^3 of clear water per day.

Additional techniques, including solar tracking, modification of tilt angle, and cleaning of PV unit systems, were included to successfully boost the efficiency of a PV-RO-driven desalination system. When continuous tracking was added to a PV-RO desalination unit, it increased by 43%-62% respectively [99]. According to one study, a standalone PV system has the highest initial investment costs, but the lowest ongoing costs compared to a PV system combined with other power sources like the grid or diesel [100]. According to different research, depending on the applied pressure, utilizing the buffer tank to permeate enhanced productivity by anywhere between 28% and 36% [101]. Finally, another study has demonstrated that the productivity of a PV-RO system can be maintained by using a supercapacitor as a power regulator between a PV system and a pump [102,103].

This paper has a for-performance assessment of a PV-RO system's energy output. To define the cost per liter for distillate production and implementation for the economic and technical feasibility of the RO desalination unit, 500 L/h from seawater for a 5 kW DC/AC converter for a 2-kW photovoltaic system was used [104]. The PV-RO desalination plant was operating between 9:00 a.m. and 5:00 p.m. during the winter, and the findings revealed that 40 % of the power used was supplied by the PV system and 60% by the grid, while the opposite was true during the summer. The findings also indicated that tracking for the PV system increased PV energy by 15 to 20%, while cooling of the photovoltaic panels increased PV power by 5 to 10%.

This study considered the whole PV-RO desalination system's subsystems, including the centrifugal pump, induction motor, PV generator, and RO membrane [105]. Under different climatic conditions, by using an algorithm of invasive weed (IWA) for maximum power point tracking of the photovoltaic subsystem, a fuzzy control optimum was designed, and to control the motor-pump in the subsystem, it used a fuzzy-PID control unit and a fuzzy controller was used for speed and pressure control. The controller controls the valves of the RO subsystem. Table 13 illustrates the water cost of PV-coupled RO desalination units.

4.2. PV-powered ED desalination systems

The electrodialysis (ED) technique removes salt from saline water and uses many compartments separated by membranes to exchange cations and anions. Positive and negative ions travel via cation exchange membranes and ion exchange membranes, respectively, while the polarity of DC is applied by the cathode and anode. These ions then collect in a specific compartment and are released as brine. To prevent the accumulation of salt inside membranes, polarity reversal is often performed every 20 min [44,109]. The resulting flow rate of a unit of ED is given by the following equation [44]:

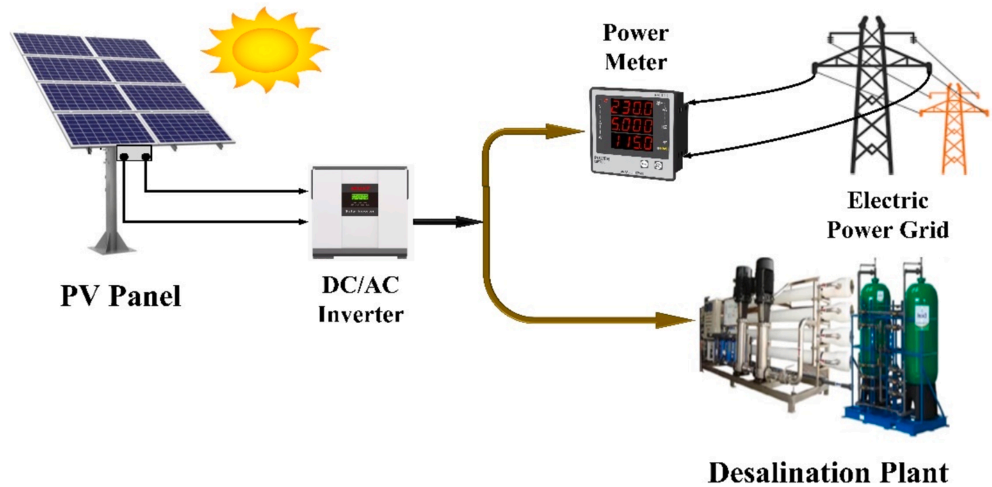

Fig. 17. Diagram for a PV-powered, on-grid desalination plant [46].

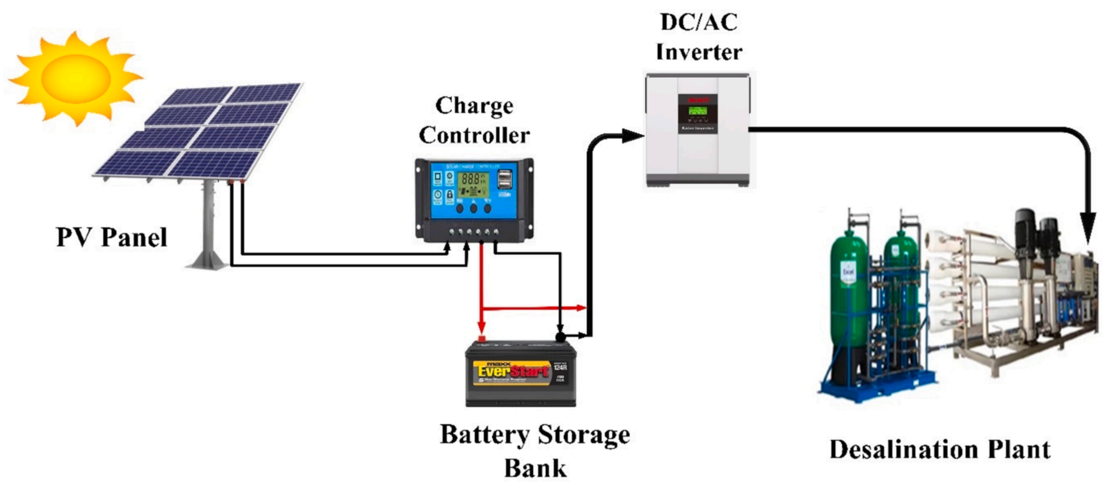

Fig. 18. Diagram for a PV-powered desalination plant that is off-grid [46].

$$Q = \frac{\eta^* I_C^* CP}{F^* \Delta N} \tag{7}$$

where: Q Rate of product flow (m^3/s), η Efficiency of current (%), I_C Current (A), CP is the number for cell pairs, F Constant of Faraday's, ΔN A normality between change in feed source and product.

The salts remove % in ED unit is given by Stover [38]:

$$SR = \frac{(C_f - C_p)}{C_f} {}^*100 \tag{8}$$

where: SR Salt removal (%), C_f Concentration of feed (mol/m^3), C_p Concentration of product (mol/m^3).

Fig. 21 explains a schematic perspective for a solar PV-ED system. It is preferred to use electrodialysis combined with PV since, for the electrodes, the direct current (DC) power it requires, and low-pressure pumps can be driven by DC/AC energy under various environmental conditions [46]. Electrolytic reversal (EDR) technology is like ED technology except that the electrodes reverse their polarity periodically over time, thus changing the current flow path [110]. The total energy needed for an ED plant is 1.50 to 4 kWh/m^3, and the price of water from a PV-ED desalination system ranges from US dollars 5.80 to 16/m^3. For PV-EDR units with capacities smaller than 100 m^3/day, energy consumption is 3 to 4 kWh/m^3, and the price of brackish water purification is US$10.40 to US$11.70/m^3 [110,111].

4.3. PV- powered membrane distillation systems

The membrane distillation (MD) technology operates by varying the vapor pressure over a hydrophobic microporous membrane. The advantages of this technique include its capacity to produce high-quality water using waste-grade heat. Fig. 22 illustrates the technique for MD desalination [46,112]. All these procedures have direct contact with the membrane surface during hot brine feeding [44]. Fig. 23 depicts the key characteristics of each membrane-based distillation method, and Fig. 24 depicts an example of the membrane distillation technique of a solar collector [44]. Taking into both the slow development and high cost of water produced, the impediments of development, and the application of large-scale PV-powered MD techniques [113], numerous PV-powered MD systems have been used in various nations, including Saudi Arabia, China, Spain, Singapore, Mexico, the United States, and Australia [114]. Taking into both the slow development and high cost of water produced, the impediments of development, and the application of large-scale PV-powered MD techniques [113], numerous PV-powered MD systems have been used in various nations, including Saudi Arabia, China, Spain, Singapore, Mexico, the United States, and Australia [114]. The solar PV-powered MD technique is shown in Fig. 25 in both aided and stand-alone modes [44].

In this paper, in India, an integrative evaluation of the PV-powered MD technique was carried out [115]. Through the experiments done by researchers, it was found that a PV-based MD technique might be a

Table 12
Comparison of the energy storage technologies that are suitable for application in small-scale PV systems [91–94].

Energy storage technology	Charge/ Discharge cycles	Lifetime (years)	Self-discharge rate/day	Energy density (Wh/kg)	Operating temperature range (°C)	Advantages	Disadvantages
Lead-acid batteries	300–700+	3 to 7	5–10	30–50	150 to 300	Easy to recycle, mature technology, low cost, high reliability	Low energy density, high maintenance, short cycle life
Lithium-Ion batteries	1000–5000+	5 to 15	1–3	150–250	−20 to 60	Low self-discharge rate, high energy density, low maintenance, long cycle life	Limited resource availability (lithium), high cost
Flow batteries	5000–10000+	10 to 20	0.1–1	20–80	0 to 40	High safety, long cycle life, discharge rate, good for long-duration storage.	High cost, low energy density, complex system (pumps and flow management).
Sodium-Ion Batteries	1000–3000+	5 to 15	0.1–0.5	100–150	−10 to 60	Good performance in cold temperatures, abundant raw materials (sodium), and lower cost than lithium-ion.	Shorter cycle life, lower energy density than lithium-ion
Supercapacitors	100–000+	10 to 20	0.01–0.1	5–10	−40 to 65	Fast charge/discharge rates, high power density, extremely long cycle life	High cost/unit of energy stored, self-discharge rate can be higher than batteries, low energy density
Flywheel energy storage	100–000+	10 to 20	0.1–1	100	−30 to 40	Fast response time, long cycle life, high power density, low maintenance	Energy loss due to attrition, mechanical complexity, high initial cost
Thermal energy storage (TES)	N/A (Heat storage)	20 to 30	N/A	N/A (variable)	−50 to 400 (depending on)	Long lifetime, high capacity, wide temperature range, low environmental impact	Complex insulation requirements require large space, limited by temperature gradient requirements.

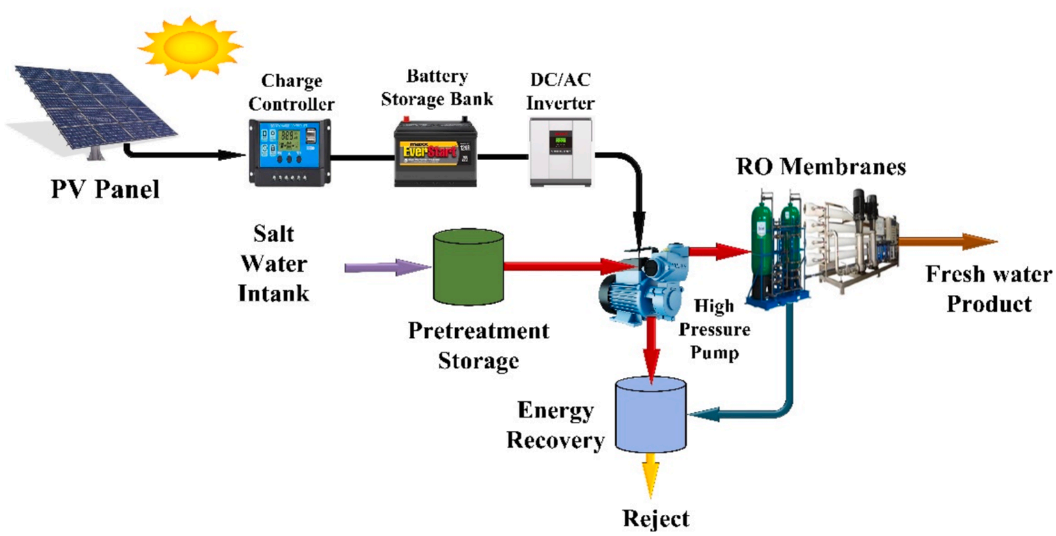

Fig. 19. Shown the diagram view of a PV-RO desalination system [46].

promising technology to address the need for pure water in remote places. According to the results, PV-MD technology can have a thermal efficiency of up to 95% compared to 83% for traditional systems. Table. 14 shows the water cost of RE-coupled desalination units.

5. PV thermal technology

In current research on PV-aided systems of solar desalination, most researchers have highlighted utilizing panels of PV mainly as a supplementary source of electrical energy to processes of power desalination, such as RO. However, there is an important gap in the study of hybrid systems that also use the energy of thermal (waste heat) produced by panels of PV for desalination. This integrated method could enhance the efficiency of overall desalination by using both thermal and electrical outputs rather than depending solely on electrical PV power. Systems that combine collectors of thermal photovoltaic (TPV) or PV-thermal (PVT) modules are progressively known for their probable to harness waste heat for thermal processes of desalination such as TVC and MED, which could prime for more sustainable solutions and energy-efficient [121,122].

Integration of solar-powered hybrid systems that use PV panel waste heat to support thermal desalination has been suggested in recent studies. These systems are useful because they use PV panel's thermal and electrical energy to produce water continuously and around the clock, even in the face of fluctuating solar conditions. In certain configurations, for example, PV is used to generate electricity while heat is also used for processes like adsorption desalination, which work best at lower heat levels (about 50°C) [121]. Particularly in isolated locations with strong solar radiation, this dual-energy strategy can greatly lessen the need for additional external thermal sources, increasing the system's affordability and environmental friendliness.

The performance optimization of such hybrid systems is also the

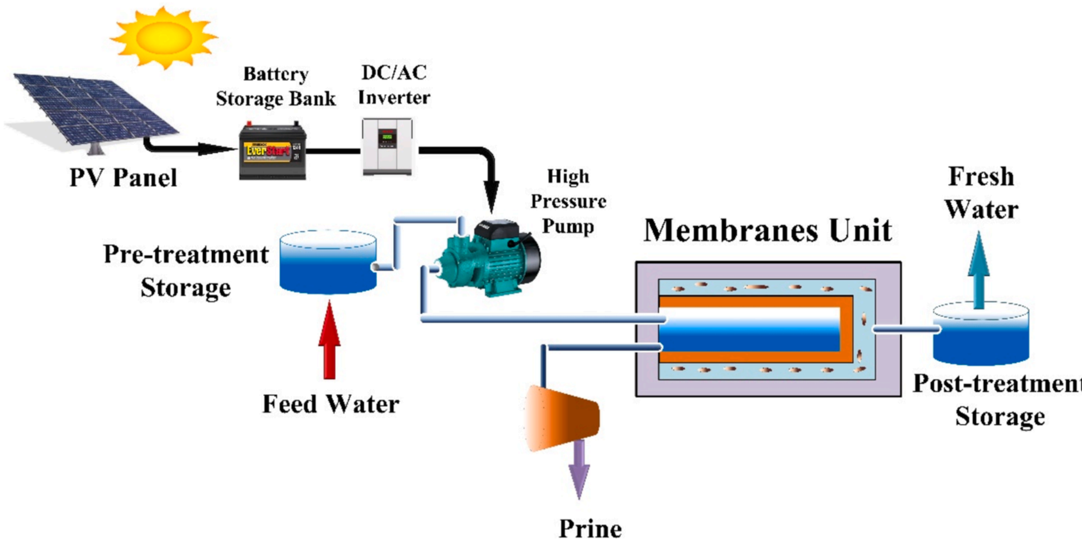

Fig. 20. Diagram of a typical PV-RO powered desalination plant [97,98].

Table 13
Water cost of PV coupled RO desalination units [106–108].

Type of system	Water cost ($/m^3)	Capacity (m^3/day)
Solar PV-powered RO (Masdar Institute)	1.50	0.8
Small-scale PV-RO (Case Study)	1.75	1
Hybrid PV/T-RO	1.30	3.8
Solar PV-RO with Energy Recovery Device	1.40	5
PV-EDR (Flexible batch)	1.66	6

subject of theoretical and experimental studies. To increase water production and system efficiency, for instance, different adsorbent materials are being investigated for the desalination of solar adsorption cooling systems, which combine cooling and desalination [122]. These advancements imply that solar desalination technologies could undergo a revolution thanks to the combination of waste heat and electrical power, increasing their efficiency and adaptability to various environmental conditions. Therefore, to optimize the potential advantages of combined thermal and electrical energy use in solar desalination, future research should improve these hybrid systems and evaluate their practicality.

6. Future perspectives in solar PV-driven desalination

The future of solar PV-driven desalination looks promising with several advancements. Integrating hybrid systems, such as combining solar PV with wind, biomass, or geothermal energy, ensures a reliable and steady power supply, making it ideal for remote and off-grid areas. Advanced solar technologies, including tandem and perovskite solar cells, improve efficiency and reduce energy consumption, even under low radiation conditions. Innovations in desalination, like hybrid processes such as membrane distillation (MD) and forward osmosis (FO), reduce energy use and are well-suited to small-scale applications. Digital technologies, like machine learning and the Internet of Things (IoT),

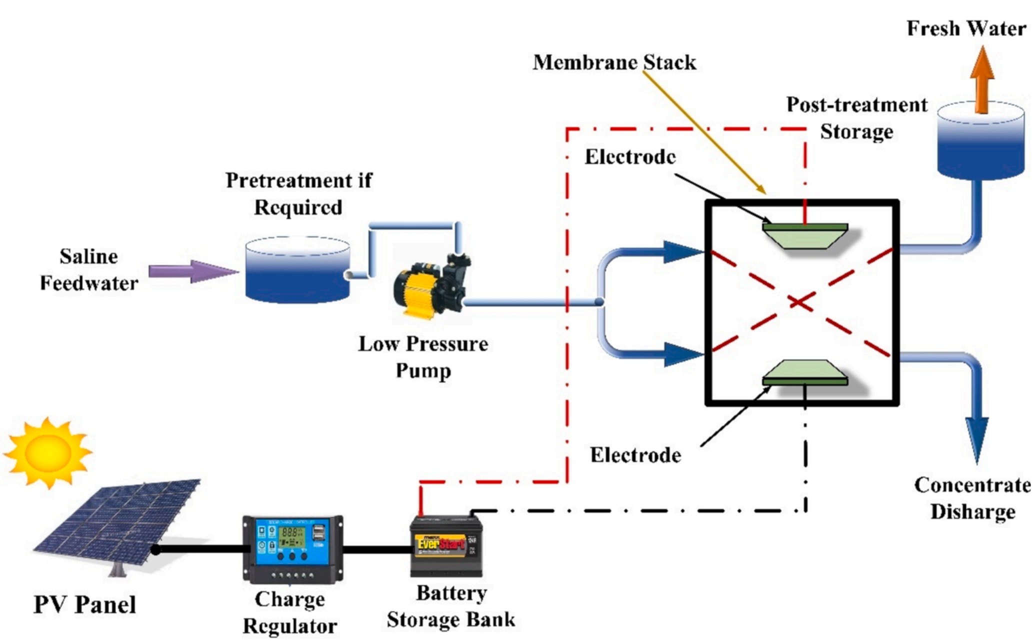

Fig. 21. A PV-powered electrodialysis system's schematic [46].

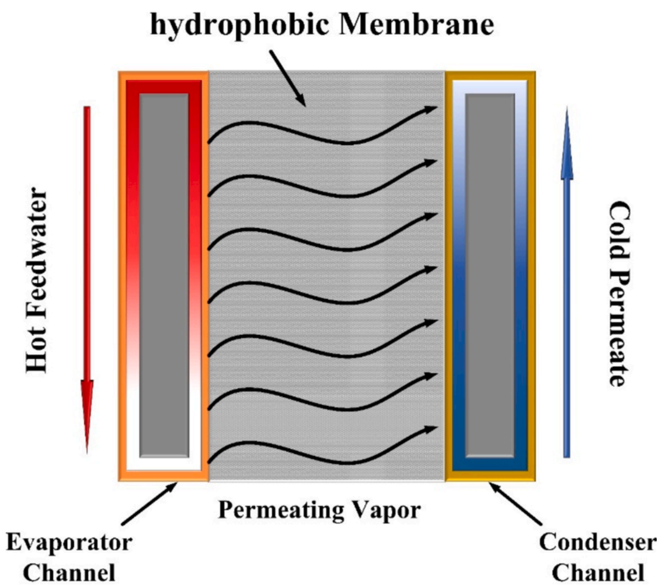

Fig. 22. Working principle of membrane distillation technology [46,112].

enhance system performance, minimize downtime, and lower operational costs. Sustainable practices like zero-liquid discharge (ZLD) and brine crystallization help minimize environmental impacts while recovering valuable by-products. Additionally, policies and incentives, including green certifications and government subsidies, promote the adoption of solar PV desalination, making it more economically viable for municipalities and industries (Table 15).

6.1. Integration of advanced renewable energy systems

A major brave in solar PV-powered desalination is the unpredictability of solar energy. Hybrid renewable energy systems are being investigated as a potential remedy for this problem. These systems offer a steady power source that can continuously run desalination operations by combining solar PV with geothermal wind or biomass energy. To store excess energy generated during the hours of maximum solar radiation, sophisticated microgrid technologies are also being developed. Lithium-ion and flow batteries are examples of these technologies for energy storage. These microgrids are particularly crucial for off-grid or remote applications with restricted access to conventional electricity. Another exciting field of study is the direct coupling of PV systems to reverse osmosis (RO) via variable frequency drives (VFDs). VFDs further lower costs by removing the need for intricate energy management systems and enabling RO plants to function effectively with variable energy inputs.

6.2. Innovations in PV and desalination technologies

Solar-powered desalination is becoming more feasible thanks to advancements in next-generation photovoltaic technologies. Perovskite-based panels and tandem solar cells, which have higher conversion efficiencies than conventional silicon cells, can potentially lower the cost and environmental impact of solar energy systems. Additionally, in areas with high albedo surfaces like deserts, bi-facial solar panels, which capture sunlight from both sides, are proving to be very effective. These developments are ideal for meeting the energy requirements of desalination systems [90–100].

In desalination technology, forward osmosis (FO) and membrane distillation (MD) are two low-energy substitutes for conventional reverse osmosis. Using osmotic pressure differences FO uses a lot less energy than RO to pull water through a semi-permeable membrane. In a similar manner, MD distills water using thermal energy, which can come from direct solar thermal systems or waste heat. These technologies are especially useful for decentralized or small-scale applications [44–48]. Additionally, hybrid systems that combine membrane and thermal processes are being developed, providing a way to minimize energy consumption and maximize water recovery.

6.3. Digitalization and sustainable practices

Integrating digital technology makes solar PV-driven desalination systems smarter and more effective. Real-time fault detection, plant

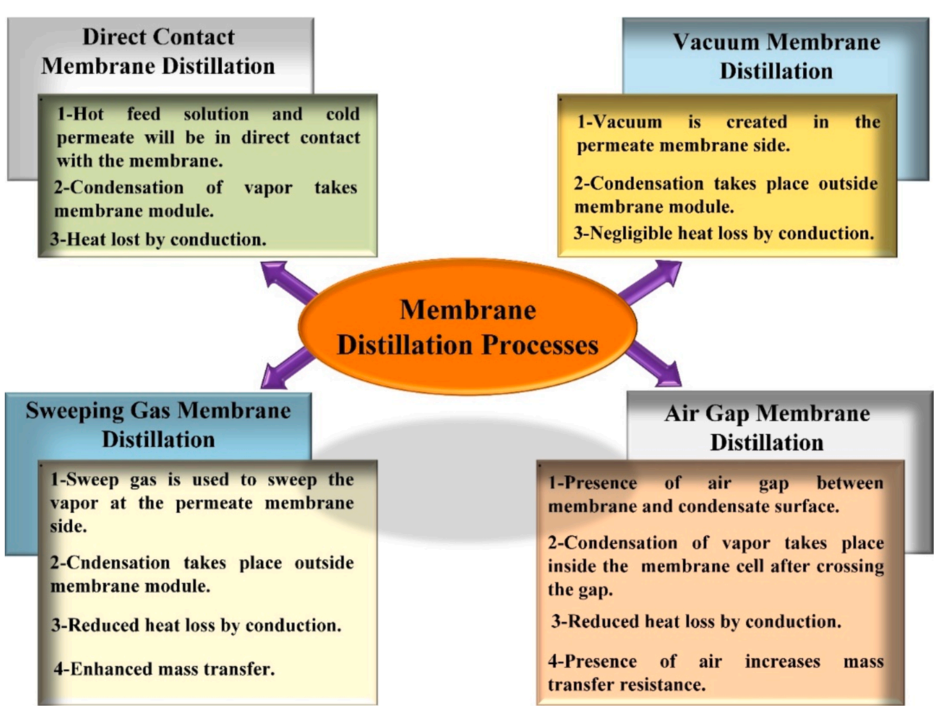

Fig. 23. Types of membrane distillation processes [44].

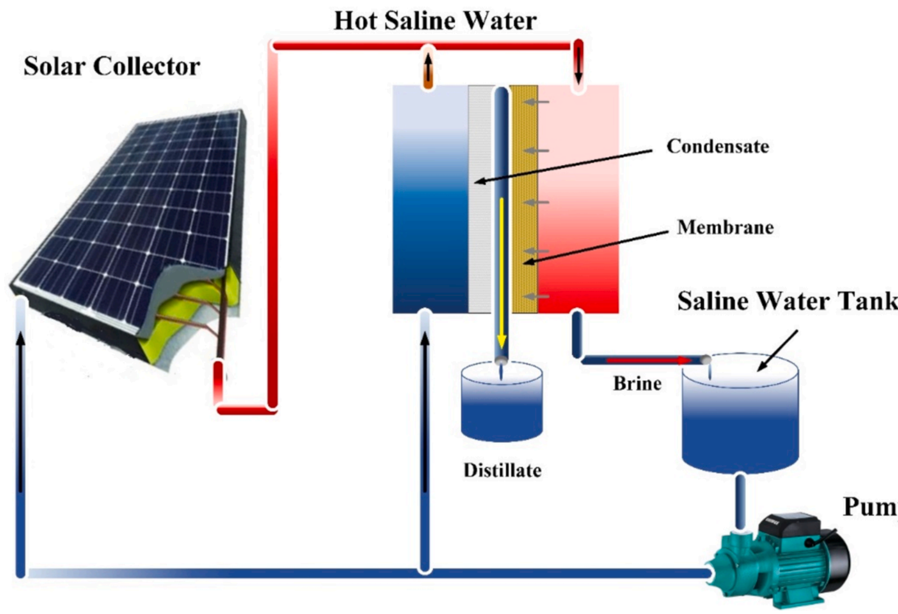

Fig. 24. Solar powered membrane distillation unit [44].

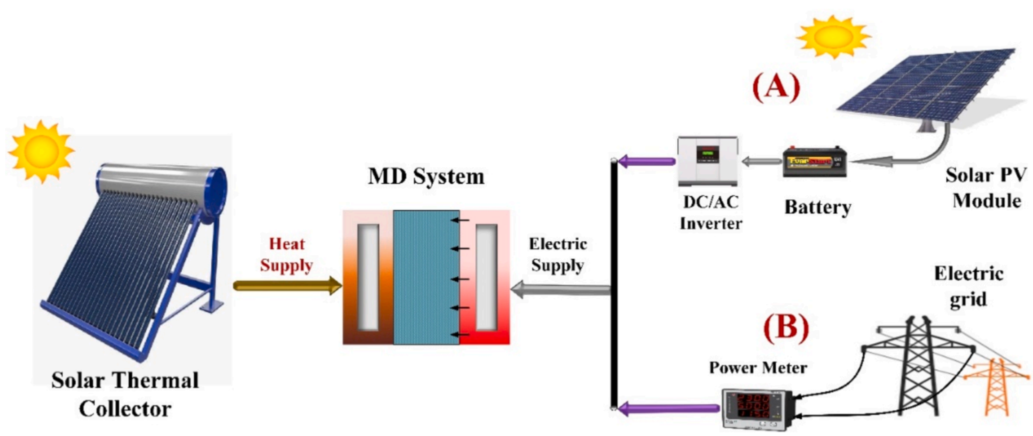

Fig. 25. A view of a PV-powered driven MD system in: (A) Stand-alone system, and (B) assisted system [44].

Table 14
Water cost of RE-coupled desalination units [116–120].

Type of system	Water cost ($/m^3)	Capacity (m^3/d)
Solar Still System	$1.00	50
Biomass-RO System	$0.60	300
Wind-SWRO System	$0.55	500
Geothermal-MSF System	$0.75	800
PV-RO Hybrid System	$0.45	1000

operation optimization, and energy demand prediction are all being accomplished with the help of artificial intelligence (AI) and machine learning (ML). For example, machine learning algorithms can forecast maintenance requirements by analyzing historical data on energy and water production, lowering unscheduled downtime and operating expenses. By facilitating the remote gathering and analysis of operational data, the Internet of Things (IoT) further improves system monitoring and guarantees consistent performance even in geographically scattered plants [90–122].

From a sustainability standpoint, brine disposal's environmental effects are a major worry. Zero-liquid discharge (ZLD) technologies are the focus of future systems. These technologies recover all water, turning brine into usable salts or other byproducts. This strategy reduces environmental damage and generates new sources of income. Developments in policy frameworks and incentives like government subsidies, green certifications, and carbon credits are helping industry and municipalities adopt solar PV-powered desalination systems. Due to its combination of technological, financial, and environmental benefits, solar PV-driven desalination is positioned as a crucial element for achieving water security in a robust and sustainable manner [45–49]. Table 15 outlines future outlooks and the latest improvements in Solar PV-driven desalination.

7. Conclusions

Desalination-based solar energy is a particularly viable choice in isolated or distant places with a scarcity of fresh water and a high potential for solar energy due to the high cost of or absence of connection to the power grid. This paper provides an overview of the main components of water desalination processes. Besides, the paper describes the classification of desalination systems according to their energy source, which included thermal, electrical, mechanical power, and chemical. This review studies the benefits of integrating PV solar power with desalination methods such as solar stills, humidification-

Table 15
Future Outlooks and latest improvements in solar PV-driven desalination [90–105].

Aspect	Description	Benefits
Integration of hybrid systems	Integrating wind with solar PV, biomass, or geothermal power, microgrids of advanced and batteries.	Guarantees a steady dependable power supply making it perfect for remote and off-grid applications.
Advanced PV technologies	Solar cells for tandem, bifacial modules, and perovskite panels for high efficiency.	Reduces energy and cost consumption, increases power output even for low radiation conditions.
Innovations in desalination	Adoption of hybrid processes, MD and FO.	Reduces energy consumption, appropriate for decentralized and small-scale applications.
Digital technologies	ML/AI for predictive maintenance and optimization, IoT of real-time control.	Enhance efficiency, lowers costs for operational, and lessen downtime.
Sustainability practices	Zero-liquid discharge (ZLD) systems and brine crystallization.	Minimizes environmental effects, retrieve valuable by-produce.
Policy and incentives	Green certifications, carbon credits, and government subsidies.	Promotes adoption and better economic viability for municipalities and industries.

dehumidification, reverse osmosis, membrane distillation, multi-effect distillation, and flash for multi-stage. Moreover, this paper provides an overview of PV-powered desalination systems, which are mechanical processes powered by solar energy. Therefore, they are quite suitable to be integrated with desalination processes that entirely or partially consume electricity, such as RO, ED, MD, and even solar distillation systems. According to the global percentage of commonly used desalination technologies, RO is considered the most widely used desalination technology. This work aims to give readers a deep study of the use of solar PV-powered desalination systems, with an emphasis on developing future trends based on reviewed scientific study findings. Due to high energy costs, the broad usage of PV-desalination technology remains limited. In this, the following solutions are proposed to improve the energy efficiency of these systems:

- Using an algorithm to determine the efficacy of a PV-powered desalination plant depending on its installation location and the amount of available solar radiation.
- Determine a standard variation range for PV-powered desalination facilities across various parameters, including temperature, feeding pressure, capacity, and water concentration.
- Conduct more experiments to optimize the performance of solar PV-powered desalination plants to make them more efficient and cost-effective.

CRediT authorship contribution statement

Mohamed El-Sayed M. Essa: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hemdan S. El-sayed:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elwy E. El-kholy:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mohammed Amer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mahmoud Elsisi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Uzair Sajjad:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. **Khalid Hamid:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – review & editing. **Hilmy El-sayed Awad:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing 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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Data availability

Data will be made available on request.

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