

Renewable Energy-Based Water Desalination Technologies for Arid Regions: A Review

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Abstract

Water scarcity has become a major global challenge, particularly in arid and semi-arid regions where freshwater resources are limited and demand continues to increase. Renewable energy-driven desalination technologies have emerged as promising solutions for sustainable freshwater production while reducing dependence on fossil fuels and minimizing environmental impacts. This review presents a comprehensive analysis of recent developments in major desalination technologies powered by renewable energy sources, including solar still systems, reverse osmosis, membrane distillation, humidification–dehumidification, multi-effect distillation, and concentrated solar desalination systems. Their operating principles, advantages, limitations, and recent technological advancements are critically discussed. Furthermore, the performance characteristics and application potential of these technologies in water-scarce regions are comparatively evaluated. Major challenges associated with large-scale implementation, such as high capital costs, membrane fouling, heat losses, and energy storage limitations, are also highlighted. In addition, emerging trends involving advanced materials, artificial intelligence, Internet of Things technologies, and hybrid desalination configurations are discussed as promising approaches for improving system efficiency and sustainability. The findings indicate that renewable energy-based desalination technologies offer significant potential for achieving long-term water security and sustainable water management in arid regions.

Keywords: *Renewable energy; water desalination; solar desalination; reverse osmosis; membrane distillation; humidification–dehumidification; sustainable water management.*

1. Introduction

Freshwater scarcity is one of the most pressing global challenges of the twenty-first century, with far-reaching consequences for environmental sustainability, food security, economic development, and human well-being. Rapid population growth, urbanization, industrial expansion, and increasing agricultural demand have intensified pressure on already limited freshwater resources. These pressures are particularly severe in arid and semi-arid regions, where low precipitation, high evaporation rates, recurrent droughts, and climate-related hydroclimatic extremes constrain the natural replenishment of surface water and groundwater resources [1, 2, 5–7]. Water scarcity also extends beyond local and national boundaries through global trade networks and interconnected socioeconomic systems, which redistribute water-related risks between producing and consuming

regions [3]. At the same time, groundwater depletion, deterioration of river-water quality, and increasing imbalances in major freshwater systems further threaten long-term water security [7–9]. These combined pressures adversely affect agricultural productivity, rural livelihoods, ecosystem stability, and progress toward sustainable development [4–6].

Desalination has therefore become an increasingly important option for supplementing conventional freshwater resources, particularly in coastal, remote, and water-stressed regions. Current desalination technologies can generally be classified into thermal and membrane-based processes, including multi-stage flash, multi-effect distillation, reverse osmosis, forward osmosis, and membrane distillation [10–13, 15–17]. Reverse osmosis has achieved widespread commercial deployment because of its relatively high salt

rejection, modularity, and lower energy requirements compared with conventional thermal processes, whereas multi-effect distillation remains attractive for large-scale applications where low-grade or renewable thermal energy is available [10–12,16]. Emerging technologies such as forward osmosis and membrane distillation offer additional opportunities for low-pressure operation, utilization of low-temperature heat, and treatment of high-salinity feedwater; however, membrane fouling, wetting, thermal losses, draw-solution regeneration, and limited commercial maturity continue to constrain their broader implementation [11, 15, 19].

Despite their capacity to produce reliable freshwater, conventional desalination systems remain energy intensive and are frequently dependent on fossil-fuel-derived electricity or heat. This dependence increases operating costs, greenhouse-gas emissions, and vulnerability to energy-price fluctuations. Integrating renewable energy with desalination can reduce these disadvantages and improve the environmental sustainability of freshwater production [13, 17–19]. Solar photovoltaic, solar thermal, wind, geothermal, and hybrid renewable-energy systems have consequently been investigated for powering both membrane and thermal desalination processes. Solar energy is especially relevant to arid regions because high solar irradiance often coincides geographically with severe water scarcity [18, 20–23]. Recent research has reported advances in photovoltaic-powered reverse osmosis, solar-thermal membrane distillation, nanofluid-enhanced solar desalination, thermal-energy storage, and hybrid renewable configurations [14, 18–22]. Nevertheless, renewable-energy integration also introduces specific technical challenges, including intermittent power or heat supply, energy-storage requirements, part-load operation, membrane performance under fluctuating conditions, dust accumulation on solar collectors and photovoltaic modules, and increased maintenance requirements in hot and remote environments.

A substantial body of review literature has examined renewable-energy-powered desalination, solar desalination, membrane processes, and individual technologies [13, 18–20, 23, 24]. However, many existing reviews concentrate on a single energy source, one desalination process, or general technological developments without systematically linking technology performance to the environmental and operational constraints of arid regions. In particular, limited attention has

been given to cross-technology comparisons based on consistent quantitative indicators, such as specific energy consumption, freshwater productivity, and water-recovery ratio, leveled cost of water, technological maturity, and compatibility with variable renewable-energy supply. Similarly, arid-region-specific factors—including extreme ambient temperatures, high feedwater salinity, dust and sand accumulation, limited grid infrastructure, seasonal water demand, brine management, and restricted technical-maintenance capacity—are not always incorporated into technology-selection frameworks.

To address these gaps, this review critically evaluates six major renewable-energy-based desalination pathways: solar stills, reverse osmosis, membrane distillation, humidification–dehumidification, multi-effect distillation, and concentrated-solar-driven desalination systems. Unlike purely descriptive reviews, the present study compares these technologies using technical, economic, environmental, and deployment-related criteria, including energy demand, freshwater productivity, water-production cost, system scale, technological maturity, renewable-energy compatibility, and operational suitability for arid conditions. The review also examines how renewable-energy intermittency influences fouling, scaling, thermal losses, storage requirements, and system reliability. Particular attention is given to concentrated solar desalination, hybrid renewable-energy configurations, advanced membrane and thermal-storage materials, digital monitoring, and artificial-intelligence-assisted operation. Based on this comparative assessment, specific research priorities are proposed for improving reliability, affordability, brine management, and large-scale deployment of renewable-energy-driven desalination systems in arid and water-scarce regions.

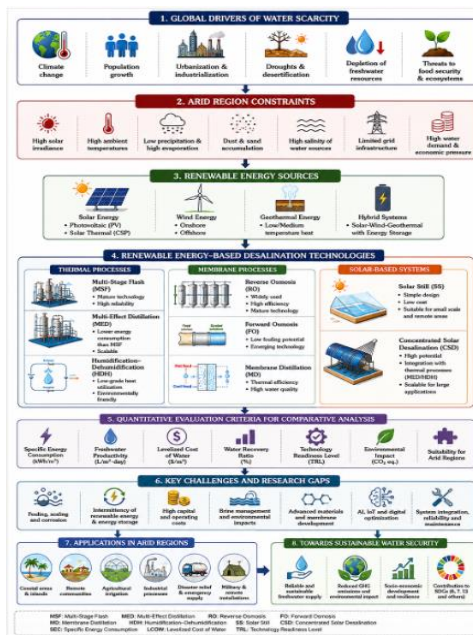


Figure 1. Conceptual framework illustrating the relationship between water scarcity, desalination technologies, renewable energy sources, and sustainable freshwater production in arid regions.

2. Classification of Renewable Energy-Based Water Desalination Technologies

Renewable energy-based desalination technologies can be classified according to both the separation mechanism and the form of energy required for operation. From a process perspective, desalination systems are generally divided into thermal, membrane-based, and solar-driven configurations. Thermal processes separate freshwater through evaporation and condensation, whereas membrane-based systems rely on selective transport driven by pressure, concentration, or vapor-pressure gradients. Solar-driven systems may operate either as direct desalination units, such as solar stills, or as indirect configurations in which photovoltaic or solar-thermal energy supplies electricity or heat to another desalination process [10–19].

Thermal desalination technologies considered in this review include multi-effect distillation (MED) and humidification–dehumidification (HDH). MED uses successive evaporation stages at progressively lower pressures, allowing latent heat to be reused and making the process suitable for coupling with solar thermal or concentrated solar power systems. HDH reproduces the natural hydrological cycle by humidifying air with heated saline water and subsequently condensing the water vapor. Because both technologies can use low- or medium-temperature heat, they are potentially suitable for integration with solar thermal, geothermal, and waste-heat resources [17, 18, 23, 34–40].

The principal membrane-based technologies examined are reverse osmosis (RO), forward osmosis (FO), and membrane distillation (MD). RO is a pressure-driven and commercially mature process that can be powered by photovoltaic, wind, or hybrid electricity systems. FO uses an osmotic-pressure gradient but requires draw-solution regeneration, which remains an important technical limitation. MD is a thermally driven membrane process that uses a vapor-pressure difference across a hydrophobic membrane and can therefore utilize solar thermal energy, geothermal heat, or other low-grade thermal sources [10–15, 19, 29–32].

Solar desalination systems form a distinct category because solar energy may be used either directly or indirectly. Direct systems, particularly solar stills, convert solar radiation into heat within the desalination unit and are generally appropriate for small-scale and decentralized water production. Indirect systems employ photovoltaic modules, solar collectors, or concentrated solar power technologies to supply electricity or thermal energy to RO, MD, HDH, or MED processes. Wind, geothermal, and hybrid renewable systems can also be combined with these technologies to improve energy availability and reduce dependence on fossil fuels [18–28].

For arid-region applications, classification by process type alone is insufficient because technology selection also depends on freshwater demand, feedwater salinity, renewable-resource availability, energy-storage requirements, infrastructure limitations, environmental conditions, and required system scale. Solar stills and HDH systems are typically more suitable for household, community, or remote applications, whereas RO and MED are more appropriate for medium- and large-scale freshwater production. MD occupies an intermediate position, offering compatibility with low-grade heat and high-salinity feedwater, but its wider deployment is still constrained by heat losses, membrane wetting, fouling, and limited commercial maturity.

Accordingly, this review classifies renewable energy-based desalination technologies into three interconnected groups: thermal processes, membrane-based processes, and direct or indirect solar-driven systems. Figure 2 summarizes this classification and shows the principal renewable-energy pathways that can be coupled with each desalination technology.

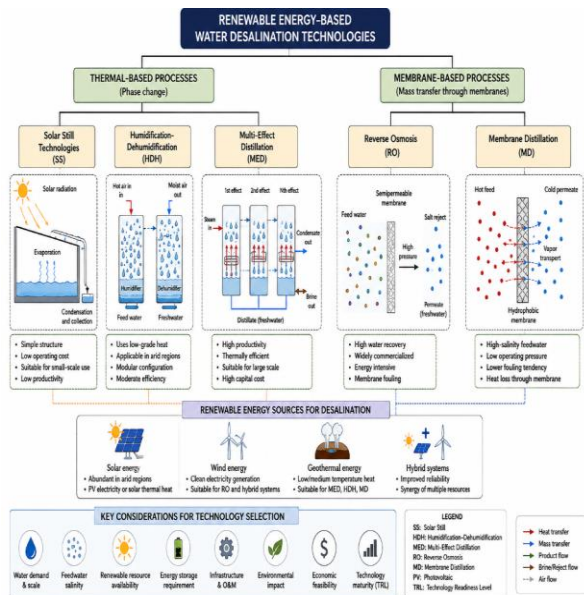


Figure 2. Classification of renewable energy-based water desalination technologies.

2.1. Solar Still Technologies

Solar stills are direct solar desalination systems that reproduce the natural hydrological cycle within an enclosed basin. Solar radiation is absorbed by saline or brackish feedwater and converted into thermal energy, increasing the water temperature and promoting evaporation. The generated vapor rises toward a cooler transparent cover, condenses on its inner surface, and flows into a collection channel as distilled water. Because dissolved salts, suspended solids, and most non-volatile contaminants remain in the basin, solar stills can produce high-quality freshwater without high-pressure pumps or complex mechanical equipment [24–27].

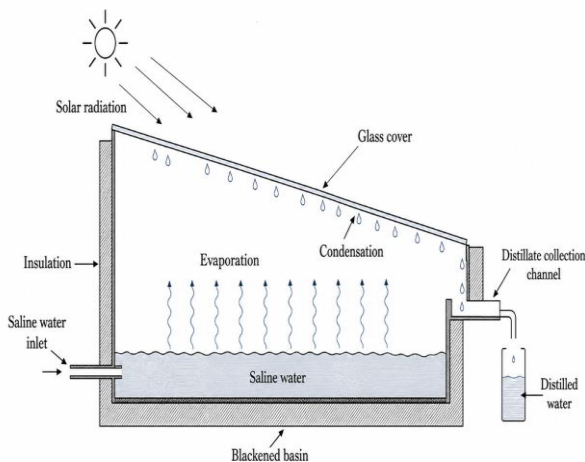


Figure 3. Operating principle of a conventional solar still, showing solar-energy absorption, feedwater evaporation, vapor transport, condensation on the transparent cover, distilled-water collection, and brine retention

Figure 3 illustrates the principal heat- and mass-transfer processes in a conventional single-slope solar still. Incident solar radiation is transmitted

through the transparent cover and absorbed by the basin liner and feedwater. Freshwater production is governed by the temperature difference between the heated water surface and the condensing cover. Consequently, solar irradiance, basin-water depth, absorber properties, cover inclination, ambient temperature, wind speed, feedwater salinity, and internal heat losses strongly influence daily yield and thermal efficiency [24–27].

Solar stills are commonly classified as passive or active systems. Passive solar stills depend exclusively on incident solar radiation and natural convection. They are structurally simple, inexpensive to operate, and suitable for household or community-scale applications, but their freshwater output is generally low and varies with weather conditions. Active solar stills incorporate supplementary components, such as external solar collectors, photovoltaic-thermal modules, circulation pumps, condensers, reflectors, or auxiliary heating devices, to increase the temperature difference driving evaporation and condensation. These modifications can improve productivity, although they also increase capital cost, operational complexity, and maintenance requirements [24–28].

Recent performance-enhancement strategies can be grouped into four main categories. The first involves geometrical and thermal modifications, including optimized basin depth, stepped or inclined absorbers, fins, wicks, rotating elements, and external reflectors. These approaches increase the effective evaporation area, improve heat transfer, or reduce thermal inertia. The second category concerns advanced absorber and interfacial materials, including black coatings, porous media, nanostructured surfaces, and photothermal materials designed to localize solar energy near the evaporation interface. The third category includes nanofluids and nanoparticles, which may enhance solar absorption and thermal conductivity. The fourth consists of thermal-energy-storage materials, especially phase-change materials, which store excess daytime heat and release it during periods of reduced solar radiation, thereby extending water production beyond peak sunshine hours [14,24–29].

Although many experimental studies report productivity improvements from these modifications, the reported gains are highly dependent on climatic conditions, system geometry, water depth, material concentration, and test duration. Therefore, percentage enhancements obtained from different studies should not be

compared without normalizing for baseline design and local solar irradiance. In addition, nanofluids, phase-change materials, and hybrid heating systems may introduce added cost, material-degradation risks, pumping requirements, or maintenance needs that are often overlooked when only freshwater yield is considered. A rigorous assessment should therefore include not only daily productivity but also thermal efficiency, exergy performance, water-production cost, embodied material impacts, and long-term reliability.

The suitability of solar stills for arid regions is linked to their ability to operate off-grid under high solar irradiance and with minimal technical infrastructure. They can support isolated households, small communities, emergency water supply, and remote agricultural or coastal applications. However, arid environments also impose specific constraints. Dust accumulation can reduce solar transmission through the cover, high ambient temperatures may decrease the temperature difference available for condensation, saline scaling can degrade absorber surfaces, and irregular feedwater supply can interrupt operation. These factors require periodic cleaning, appropriate cover-cooling strategies, durable materials, and simple brine-management arrangements.

Artificial intelligence and machine-learning techniques have recently been explored for predicting freshwater yield, optimizing operating parameters, and supporting real-time control. Nevertheless, their practical value depends on the availability of sufficiently large, representative datasets and should not be overstated for simple passive systems. At present, the most actionable research priorities are standardized outdoor testing, long-duration durability assessment, low-cost thermal storage, improved condensation, dust-resistant surfaces, and techno-economic comparison of active and passive configurations under representative arid-region conditions.

Overall, solar stills offer important advantages, including simple construction, low operating pressure, limited dependence on external electricity, and suitability for decentralized freshwater production. Their principal limitation remains low areal productivity, which restricts their economic competitiveness at large scale. Accordingly, solar stills are best viewed as context-specific solutions for small and remote applications rather than universal alternatives to high-capacity desalination technologies such as reverse osmosis or multi-effect distillation.

2.2. REVERSE OSMOSIS DESALINATION

Reverse osmosis (RO) is the most commercially mature and widely deployed membrane-based desalination technology. The process applies hydraulic pressure greater than the osmotic pressure of the feedwater, forcing water molecules through a semipermeable membrane while retaining most dissolved salts, suspended contaminants, and organic compounds. Compared with conventional thermal desalination, RO generally requires less energy, offers high salt rejection, and can be implemented in modular configurations ranging from small decentralized units to large municipal plants [10–12].

A typical RO desalination system consists of feedwater intake, pretreatment, high-pressure pumping, membrane modules, energy-recovery devices, post-treatment, and concentrate-discharge units. Pretreatment removes suspended solids, microorganisms, and scale-forming compounds before the feedwater reaches the membrane. The high-pressure pump provides the main driving force for separation, while energy-recovery devices capture hydraulic energy from the pressurized brine stream and transfer it back to the feed or pump system. Post-treatment is subsequently required to stabilize the permeate, restore essential minerals, and ensure that the product water meets the intended quality standards [11,12].

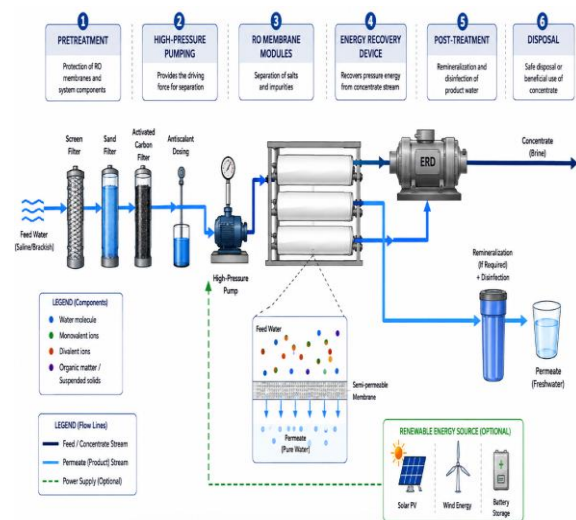


Figure 4. Schematic configuration of a renewable-energy-powered reverse osmosis system, including feedwater pretreatment, high-pressure pumping, membrane separation, energy recovery, permeate post-treatment, and brine management.

The performance of an RO system is commonly evaluated using salt rejection, permeate flux, water-recovery ratio, specific energy consumption, membrane lifetime, and water-production cost. Modern seawater RO plants equipped with efficient pumps and energy-recovery devices

typically operate at significantly lower electricity demand than earlier systems, although actual performance varies with feedwater salinity, temperature, recovery ratio, membrane condition, and plant scale. Brackish-water RO generally requires lower operating pressure and energy than seawater RO because of its lower osmotic pressure. Therefore, quantitative comparisons between studies should distinguish seawater, brackish water, and high-salinity feed applications rather than reporting a single representative value [10–12, 16].

Recent developments in RO technology have focused on higher-permeability and fouling-resistant membranes, improved pretreatment, optimized module design, and more efficient energy-recovery systems. Thin-film composite membranes, nanocomposite materials, hydrophilic surface modifications, and anti-fouling coatings have been investigated to enhance water permeability, salt selectivity, chemical resistance, and operational stability. However, improvements in membrane permeability do not automatically lead to proportional system-level energy savings because pressure requirements are also governed by osmotic pressure, concentration polarization, hydraulic losses, and recovery targets [11, 12].

RO is especially compatible with electricity-generating renewable-energy sources. Photovoltaic, wind, and hybrid systems can supply the electrical power required by pumps, pretreatment units, sensors, and control equipment [13, 19, 20]. Photovoltaic-powered RO is particularly attractive in arid and remote regions because high solar availability often coincides with severe freshwater scarcity and limited grid access. Modular PV–RO systems can support decentralized supply for isolated communities, farms, emergency facilities, and small industrial users. Wind–RO and solar–wind hybrid configurations may provide greater energy continuity where wind and solar resources are seasonally or diurnally complementary.

Renewable integration nevertheless creates additional operational challenges. Fluctuating solar and wind generation can cause variable feed pressure, permeate flux, recovery ratio, and membrane loading. Frequent start–stop operation may increase fouling risk, reduce pump efficiency, and accelerate component degradation. These effects can be mitigated through battery storage, water storage, variable-speed drives, intermediate pressure control, and hybrid power management. In many cases, storing produced water is more economical than storing large quantities of electricity, but the preferred strategy depends on

demand patterns, storage volume, energy price, and local infrastructure.

Membrane fouling, scaling, and biofouling remain major limitations of RO systems. These phenomena increase transmembrane pressure, reduce permeate production, raise cleaning frequency, and shorten membrane life. The severity of fouling depends on feedwater quality, pretreatment effectiveness, recovery ratio, temperature, and operating continuity. Advanced pretreatment, membrane-surface modification, periodic cleaning, real-time monitoring, and predictive maintenance can reduce these impacts, although they add cost and operational complexity [11, 12].

Brine management represents a second major environmental concern. RO produces a concentrated reject stream containing elevated salt concentrations and residual treatment chemicals. Direct marine discharge may alter local salinity and affect sensitive ecosystems if dilution and dispersion are inadequate. Inland plants face greater constraints because evaporation ponds, deep-well injection, crystallization, or zero-liquid-discharge approaches can be expensive and land intensive. Accordingly, the environmental performance of renewable-powered RO should not be assessed solely through reduced carbon emissions; concentrate disposal, chemical use, intake impacts, and membrane replacement must also be considered.

Arid-region conditions create both opportunities and constraints for RO deployment. High solar irradiance supports photovoltaic power generation, while high ambient temperature can increase membrane permeability and reduce feedwater viscosity. However, elevated feedwater temperature may also reduce salt rejection, accelerate biological growth, and increase scaling tendencies. Dust accumulation can lower photovoltaic output, and limited maintenance capacity can compromise pretreatment and membrane cleaning. Appropriate technology selection should therefore consider feedwater quality, solar and wind resources, local technical capacity, storage requirements, brine-disposal options, and the intended scale of water production.

Overall, RO offers the strongest combination of technological maturity, modularity, high water recovery, and compatibility with renewable electricity. Its principal limitations are sensitivity to feedwater quality, membrane fouling, dependence on effective pretreatment, and environmental challenges associated with concentrate disposal. For arid and water-stressed regions, renewable-powered RO is therefore most

suitable where reliable pretreatment, energy-management systems, maintenance capacity, and responsible brine-management strategies can be provided.

2.3. Membrane Distillation Technologies

Membrane distillation (MD) is a thermally driven separation process in which a hydrophobic microporous membrane permits the transport of water vapor while preventing the passage of liquid water and non-volatile dissolved salts. The driving force is the vapor-pressure difference generated by a temperature gradient between the hot saline feed and the cooler permeate side. Unlike reverse osmosis, MD does not rely primarily on high hydraulic pressure and can therefore operate using low-grade thermal energy. This characteristic makes it particularly suitable for integration with solar thermal systems, geothermal resources, industrial waste heat, and hybrid renewable-energy configurations [19, 22, 23, 29–31].

The performance of MD depends on the coupled transfer of heat and mass across the membrane. Feed temperature, temperature polarization, membrane pore size, porosity, thickness, hydrophobicity, module geometry, flow velocity, and feedwater salinity all influence vapor flux and thermal efficiency. Although the process can theoretically achieve very high rejection of non-volatile salts, practical performance is reduced by conductive heat loss, concentration polarization, membrane wetting, scaling, and fouling. Therefore, high salt rejection alone is insufficient for evaluating MD; permeate flux, specific thermal-energy demand, gained output ratio, membrane lifetime, and long-term wetting resistance must also be considered [29–31].

Figure 5 presents the four principal MD configurations: direct-contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweeping-gas membrane distillation (SGMD). In DCMD, the hot feed and cold permeate streams are in direct contact with opposite sides of the membrane. This configuration is structurally simple and generally provides relatively high permeate flux, but conductive heat transfer through the membrane can reduce thermal efficiency. In AGMD, an air layer separates the membrane from the condensation surface, thereby limiting heat conduction but also increasing mass-transfer resistance. VMD applies a vacuum on the permeate side to remove vapor and can provide high flux, although it requires additional equipment and careful control to prevent pore wetting. In SGMD, a carrier gas removes the transported vapor, reducing conductive heat loss but increasing downstream condensation and gas-handling requirements [29–31].

Recent research has focused on membrane modification, module optimization, heat recovery, and treatment of highly saline streams. Nanostructured, composite, and superhydrophobic membranes have been developed to improve vapor permeability, liquid-entry pressure, anti-fouling behavior, and resistance to wetting. Materials such as graphene-based structures, silica particles, carbon nanotubes, and metal-organic frameworks have been investigated as membrane additives or surface modifiers. However, improvements observed under laboratory conditions do not always translate into durable full-scale operation because nanomaterial stability, pore blockage, coating delamination, fabrication cost, and long-term exposure to complex feedwaters remain unresolved concerns [29–31].

Membrane distillation-crystallization has also emerged as a potential pathway for simultaneously recovering freshwater and valuable salts from concentrated streams. By continuing water removal beyond conventional recovery limits, this configuration may support brine concentration, resource recovery, and near-zero-liquid-discharge strategies. Nevertheless, crystallization near the membrane surface can intensify scaling, reduce vapor flux, and increase cleaning requirements. Its practical viability therefore depends on controlling nucleation, crystal growth, supersaturation, and membrane-surface interactions [32].

The compatibility of MD with renewable heat is one of its main advantages. Solar thermal collectors can provide the low- to medium-

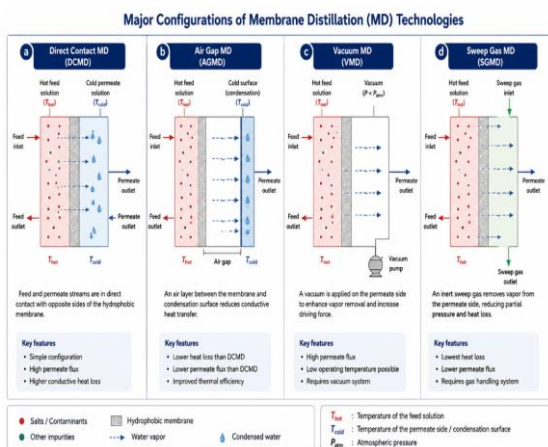


Figure 5. Principal membrane-distillation configurations: direct-contact membrane distillation, air-gap membrane distillation, vacuum membrane distillation, and sweeping-gas membrane distillation, showing the corresponding vapor-transport and condensation pathways.

temperature heat required by the feed loop, while photovoltaic electricity can operate circulation pumps, sensors, and control systems. Geothermal energy and industrial waste heat can also support more continuous operation where available. Hybrid configurations that combine MD with solar collectors, thermal-energy storage, or photovoltaic-thermal modules may improve operating stability and extend production beyond daylight hours [19,22,23].

Renewable-powered MD nevertheless faces several system-level challenges. Variations in solar irradiance can cause fluctuations in feed temperature, vapor-pressure difference, and permeate flux. Repeated thermal cycling may affect membrane integrity and increase the risk of wetting. Moreover, the thermal-energy requirement of MD can remain substantial when heat recovery is inadequate. Consequently, the apparent use of “free” solar or waste heat does not automatically guarantee economic competitiveness. A complete assessment must include collector area, thermal-storage capacity, pumping energy, heat-exchanger effectiveness, membrane replacement, and water-production cost.

For arid-region applications, MD offers several potential benefits. It can treat high-salinity water, operate at relatively low pressure, and use abundant solar thermal energy. These features make it attractive for remote communities, inland brackish-water treatment, industrial brine concentration, and hybrid systems coupled with solar ponds or waste-heat sources. However, high ambient temperatures may reduce the temperature difference available for condensation, while dust accumulation on solar collectors can lower thermal input. Scarce cleaning water, limited maintenance capacity, scaling caused by highly mineralized feedwater, and the need for environmentally acceptable concentrate management can further restrict deployment.

Overall, MD is a technically promising but not yet universally commercial alternative to mature processes such as RO and MED. Its strongest applications are likely to be those in which low-cost thermal energy is continuously available, feedwater salinity is too high for efficient RO operation, or brine concentration and resource recovery are required. Future research should prioritize long-duration field testing, standardized reporting of thermal and electrical energy demand, durable wetting-resistant membranes, effective heat recovery, and techno-economic validation under representative arid-region conditions.

2.4. Humidification–Dehumidification Desalination

Humidification–dehumidification (HDH) desalination is a thermally driven freshwater production technology that mimics the natural hydrological cycle through successive evaporation and condensation processes. In a typical HDH system, heated saline water transfers moisture to a stream of air inside a humidifier, producing warm, humid air that subsequently enters a dehumidifier where water vapor condenses into high-quality freshwater. Since the process operates at relatively low temperatures (typically below 90 °C), HDH systems can effectively utilize low-grade thermal energy supplied by solar collectors, geothermal resources, industrial waste heat, or hybrid renewable energy systems. Consequently, HDH has attracted considerable interest as a sustainable desalination technology for decentralized water production in remote and arid regions where conventional infrastructure is limited [33–37].

Unlike conventional thermal desalination technologies, HDH systems operate under atmospheric or near-atmospheric pressure and require relatively simple mechanical equipment, resulting in lower operational complexity and reduced maintenance requirements. The process is particularly attractive for small-scale applications because it combines operational simplicity with flexibility in renewable energy integration. However, freshwater productivity is strongly influenced by the effectiveness of heat and mass transfer within the humidifier and dehumidifier, making component design one of the most critical factors affecting overall system performance [34–37].

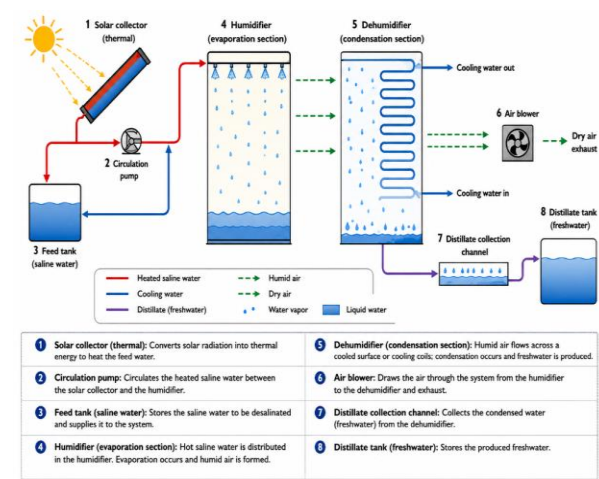


Figure 6. Schematic diagram of a solar-assisted humidification–dehumidification desalination system.

Figure 6 illustrates the operating principle of a solar-assisted HDH desalination system.

Saline feedwater is first heated using renewable thermal energy and introduced into the humidifier, where evaporation enriches the air stream with water vapor. The humid air subsequently passes through a dehumidifier, where cooling promotes condensation and freshwater recovery. Depending on airflow arrangement and system configuration, HDH units are generally classified into open-air and closed-air cycles. Open-cycle systems continuously exchange air with the surrounding environment, whereas closed-cycle configurations recirculate the carrier air to improve thermal efficiency and water recovery. The selection of an appropriate configuration depends on climatic conditions, freshwater demand, system capacity, and the availability of renewable heat sources [34–37].

Recent research has focused on improving the thermodynamic performance of HDH systems through enhanced heat recovery, optimized humidifier and dehumidifier geometries, ultrasonic atomization, packed-bed humidifiers, and advanced heat exchanger designs. These modifications increase the contact area between air and saline water, thereby improving evaporation efficiency while reducing specific energy consumption. In addition, mathematical modeling, exergy analysis, and computational fluid dynamics have significantly enhanced the understanding of heat and mass transfer mechanisms, enabling more effective optimization of operating parameters such as feedwater temperature, airflow rate, water-to-air ratio, and humidity distribution [35–38].

Renewable energy integration is one of the principal advantages of HDH technology. Solar thermal collectors provide a reliable source of low-temperature heat for evaporation, while photovoltaic systems can supply electricity for circulation pumps, fans, and automatic control systems. Hybrid renewable configurations combining solar thermal collectors, photovoltaic modules, thermal energy storage, and waste-heat recovery have demonstrated improved operational stability and higher freshwater productivity compared with standalone systems. Thermal energy storage using phase-change materials further extends freshwater production during periods of low solar irradiance, increasing daily system utilization and improving overall energy efficiency [36–39].

Despite these advantages, HDH desalination still faces several technical and economic challenges that restrict large-scale commercialization. Freshwater productivity generally remains lower than that of reverse osmosis and multi-effect distillation, while overall

thermal efficiency is highly dependent on heat exchanger effectiveness and humidifier performance. Furthermore, scaling, corrosion, heat losses, and insufficient heat recovery reduce long-term operational efficiency and increase maintenance requirements. Many published studies report improvements under laboratory conditions; however, long-term field validation under realistic environmental conditions remains limited. Consequently, comparisons among different HDH configurations should be based on standardized performance indicators such as specific thermal energy consumption, gained output ratio (GOR), water productivity, exergy efficiency, and levelized cost of water rather than solely on freshwater production [35–39].

HDH technology is particularly suitable for arid and semi-arid regions because abundant solar radiation can provide the low-grade thermal energy required for evaporation while decentralized system configurations minimize dependence on centralized water and electricity infrastructure. Nevertheless, harsh environmental conditions—including high ambient temperatures, dust accumulation on solar collectors, elevated feedwater salinity, and limited maintenance capacity—may significantly reduce long-term system performance if appropriate design strategies are not implemented. Therefore, future HDH development should emphasize robust heat exchanger materials, anti-scaling technologies, intelligent process control, hybrid renewable energy integration, and comprehensive techno-economic assessments under representative field conditions.

Overall, humidification–dehumidification desalination represents a promising renewable-energy-driven technology for decentralized freshwater production. Although its commercial deployment is currently limited by relatively low productivity and moderate thermal efficiency, continued advances in heat recovery, component design, thermal energy storage, and intelligent operational control are expected to substantially improve its technical and economic competitiveness. These developments position HDH as an attractive solution for sustainable freshwater production in remote, off-grid, and water-scarce regions.

2.5. Multi-Effect Distillation Technology

Multi-effect distillation (MED) is a mature thermal desalination technology designed to improve energy utilization through the repeated reuse of latent heat. The process consists of a series of

evaporator stages, referred to as effects that operate at progressively lower pressures and temperatures. Vapor produced in one effect condenses on the heat-transfer surface of the next effect, releasing latent heat that drives further evaporation. This cascading arrangement allows MED to achieve higher thermal efficiency and lower energy demand than single-stage thermal desalination processes [16, 38–40].

In a conventional MED system, preheated saline feedwater is distributed across heat-transfer surfaces in the first effect, where an external thermal source initiates evaporation. The generated vapor then passes to the subsequent effect, which operates at a lower pressure and boiling temperature. The process continues through multiple effects until the remaining vapor is condensed in the final condenser. Distillate streams from the individual effects are collected as freshwater, while the concentrated brine is discharged or transferred for further treatment. System performance depends on the number of effects, top-brine temperature, heat-transfer area, feed arrangement, vapor losses, condenser performance, and the effectiveness of thermal recovery.

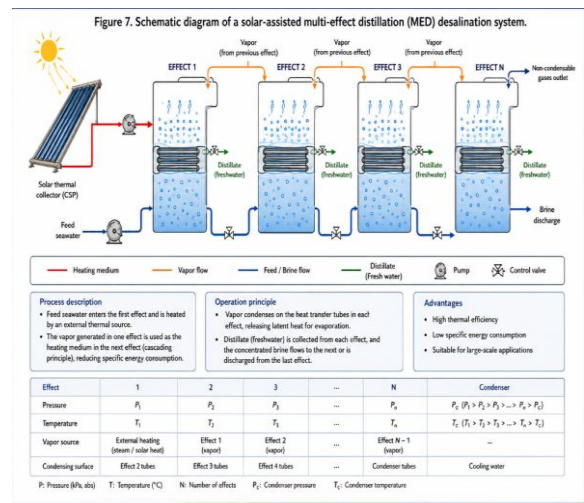


Figure 7. Schematic configuration of a solar-assisted multi-effect distillation system, showing the solar thermal source, sequential effects operating at decreasing pressure and temperature, vapor reuse, freshwater collection, condenser, and brine discharge.

MED can be coupled with low- and medium-temperature heat sources, making it compatible with solar thermal collectors, concentrated solar power (CSP), geothermal energy, industrial waste heat, and hybrid cogeneration systems. Among these options, CSP is particularly attractive because it can provide dispatchable thermal energy when combined with thermal-energy storage. Solar-assisted MED

systems can therefore maintain operation beyond daylight hours and reduce dependence on fossil-fuel-based steam generation [17,38–40].

The performance of MED should be assessed using quantitative indicators such as specific thermal energy consumption, specific electrical consumption, gained output ratio, freshwater recovery ratio, distillate production rate, and levelized cost of water. Although MED is generally more thermally efficient than multi-stage flash desalination, its actual energy performance varies significantly with plant design, heat-source temperature, number of effects, and degree of heat recovery. Consequently, comparisons across studies should distinguish between stand-alone MED, thermal-vapor-compression MED, and solar-assisted configurations rather than treating MED as a single uniform technology.

Recent research has focused on increasing heat-transfer coefficients, reducing irreversible losses, improving feed distribution, integrating thermal storage, and optimizing operating conditions. Falling-film evaporators, enhanced heat-transfer surfaces, advanced process control, and improved condenser design can increase freshwater productivity while reducing the required heat-transfer area. Thermodynamic, exergy, and techno-economic optimization have also been used to determine the most favorable number of effects, operating temperatures, storage capacity, and solar-field size.

Renewable-energy integration nevertheless introduces system-level trade-offs. Solar-assisted MED requires a sufficiently large collector or CSP field, thermal-storage capacity, heat exchangers, and control systems, all of which increase capital costs and land requirements. Intermittent solar input may reduce operating stability if thermal storage is inadequate, while repeated start-up and shutdown can increase thermal stress and scaling risk. Therefore, lower operational emissions do not necessarily guarantee lower water costs unless the solar-resource quality, capacity factor, financing conditions, and system scale are favorable.

Scaling, corrosion, and non-condensable gas accumulation remain major operational limitations. Scale formation on evaporator surfaces reduces heat-transfer efficiency and may require chemical dosing, periodic cleaning, or operation at controlled top-brine temperatures. Corrosion is particularly important because MED equipment is continuously exposed to hot saline water and chloride-rich environments. Material selection, feed pretreatment, antiscalant use, deaeration, and appropriate temperature control are therefore

essential for long-term reliability. These measures improve performance but also increase chemical consumption and maintenance costs.

MED has several advantages for arid and semi-arid regions. High solar irradiance can support solar thermal or CSP integration, while the technology can provide stable large-scale freshwater production for municipalities, industry, and coastal infrastructure. However, arid environments also present challenges, including dust accumulation on solar collectors, high ambient temperatures that may reduce condenser effectiveness, limited cooling-water availability, and difficulties associated with concentrated brine disposal. Inland deployment may be especially constrained because conventional marine discharge is unavailable and alternative brine-management options can be costly.

Life-cycle environmental assessments indicate that renewable-driven MED can reduce greenhouse-gas emissions relative to fossil-fuel-powered thermal desalination, but the full environmental burden depends on collector manufacture, thermal-storage materials, chemical use, land occupation, intake impacts, and concentrate management [39]. Accordingly, environmental claims should be based on life-cycle indicators rather than operational energy consumption alone.

Overall, MED is best suited to medium- and large-scale applications where a reliable thermal resource, appropriate maintenance capacity, and effective brine-management infrastructure are available. Its principal strengths are stable water production, high product-water quality, and compatibility with renewable or waste heat. Its main limitations are high capital intensity, system complexity, scaling and corrosion, and the substantial thermal infrastructure required. Future research should prioritize long-duration field validation of solar-assisted systems, improved thermal storage, corrosion-resistant materials, standardized economic reporting, and integrated water-energy-brine optimization under representative arid-region conditions.

2.6. Comparative Analysis of Renewable Energy-Based Desalination Technologies

Renewable energy-based desalination technologies differ substantially in terms of energy demand, freshwater productivity, water production cost, operational complexity, environmental impact, technological maturity, and suitability for different climatic and geographical conditions. Consequently, selecting an appropriate desalination technology requires a comprehensive

evaluation of both technical and socio-economic factors rather than relying on a single performance indicator. For applications in arid and semi-arid regions, additional considerations—including renewable energy availability, feedwater salinity, infrastructure limitations, operation and maintenance requirements, and brine management—must also be incorporated into the decision-making process.

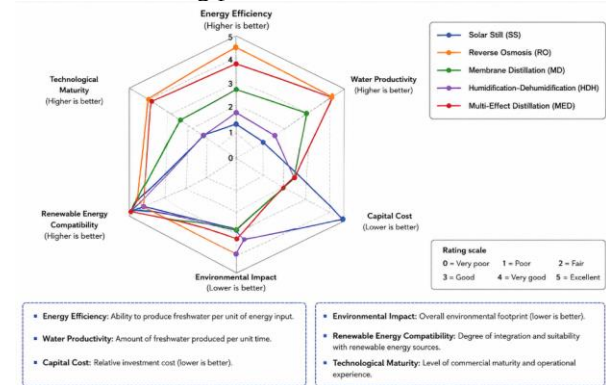


Figure 8. Comparative performance of renewable energy-based desalination technologies

Figure 8 summarizes the comparative characteristics of the five renewable energy-based desalination technologies evaluated in this review, while Table 1 presents a quantitative comparison using representative performance indicators reported in the recent literature. Because operating conditions, feedwater characteristics, plant capacity, and system configuration vary considerably among published studies, the reported values should be interpreted as typical ranges rather than absolute performance limits.

Reverse osmosis (RO) remains the benchmark technology for large-scale desalination because of its high technological maturity, modular design, and comparatively low specific energy consumption. Modern seawater RO plants equipped with energy recovery devices typically require approximately $3\text{--}6 \text{ kWh m}^{-3}$ of electrical energy while achieving water recovery ratios of $35\text{--}50\%$ for seawater and considerably higher values for brackish water. Furthermore, the levelized cost of water generally ranges from 0.5 to $1.5 \text{ US\$ m}^{-3}$, depending on plant capacity, feedwater quality, local electricity prices, and membrane replacement costs. Nevertheless, membrane fouling, concentrate disposal, and dependence on stable electricity supply remain the principal challenges limiting sustainable operation in remote locations [10–13].

Multi-effect distillation (MED) is recognized as one of the most efficient thermal desalination technologies because latent heat is repeatedly reused throughout successive evaporation stages. Although MED requires a substantially higher thermal energy input than RO, its electrical energy demand is relatively low, and the process provides highly stable freshwater production with excellent reliability. MED is particularly attractive when integrated with concentrated solar power, geothermal resources, or industrial waste heat, where renewable thermal energy can significantly reduce fossil fuel consumption. However, high capital investment, scaling, corrosion, and extensive heat-transfer infrastructure continue to limit widespread deployment [16, 38–40].

Membrane distillation (MD) occupies an intermediate position between conventional membrane and thermal desalination technologies. Operating temperatures below 90 °C enable effective utilization of solar thermal collectors, geothermal resources, and industrial waste heat. MD also demonstrates excellent salt rejection and can efficiently treat highly concentrated brines that are difficult to process using RO. However, conductive heat loss, membrane wetting, temperature polarization, and relatively low permeate flux continue to restrict commercial implementation. Consequently, MD currently appears most promising for niche applications involving high-salinity feedwater, brine concentration, and hybrid renewable-energy systems rather than conventional municipal desalination [19, 22, 23, 29–32].

Solar stills represent the simplest renewable-energy-driven desalination technology and require neither high operating pressure nor sophisticated mechanical equipment. Their minimal maintenance requirements, environmental compatibility, and independence from external electricity make them particularly attractive for isolated households, small communities, emergency water supply, and remote agricultural applications. Nevertheless, daily freshwater production generally remains below $6 \text{ L m}^{-2} \text{ day}^{-1}$, substantially lower than membrane-based or thermal desalination systems. Numerous enhancement techniques—including nanomaterials, phase-change materials, wick structures, external reflectors, and photovoltaic-thermal integration—have increased productivity under experimental conditions, but economic competitiveness at larger scales remains limited [14,24–29].

Humidification–dehumidification (HDH) systems also utilize low-grade thermal energy and can be effectively integrated with solar thermal collectors. Their relatively simple construction and atmospheric-pressure operation make them suitable for decentralized freshwater production in off-grid locations. However, freshwater productivity strongly depends on humidifier performance, heat recovery efficiency, airflow management, and climatic conditions. Compared with RO and MED, HDH generally exhibits lower water production rates and moderate thermal efficiency, restricting its application primarily to small- and medium-scale systems [33–39].

For arid-region deployment, renewable energy availability plays a decisive role in technology selection. Solar photovoltaic-powered RO is generally the preferred option where reliable electrical infrastructure or battery storage is available, whereas solar thermal-driven MED and HDH systems become attractive when abundant low-grade heat can be economically supplied. Membrane distillation offers significant advantages for treating highly saline groundwater and industrial brines because of its compatibility with renewable heat and high salt rejection. Solar stills remain valuable for isolated communities with very low freshwater demand and limited technical capacity. Therefore, no single technology can satisfy the diverse requirements of all water-scarce environments.

Environmental sustainability extends beyond operational energy consumption. Although renewable-energy-powered desalination substantially reduces greenhouse-gas emissions compared with fossil-fuel-driven systems, environmental performance also depends on concentrate disposal, land occupation, material consumption, membrane replacement, chemical pretreatment, and life-cycle impacts associated with renewable energy infrastructure. Consequently, future comparative assessments should combine technical performance with life-cycle assessment, water–energy nexus analysis, and comprehensive techno-economic evaluation to identify the most sustainable desalination pathway under site-specific conditions.

Overall, reverse osmosis currently offers the best balance between energy efficiency, technological maturity, and economic feasibility for large-scale freshwater production. MED remains the preferred thermal technology where renewable heat or waste heat is readily available. Membrane distillation

exhibits considerable long-term potential for high-salinity applications, while HDH and solar still technologies are particularly suitable for decentralized freshwater production in remote arid regions. Future advances in renewable energy integration, thermal energy storage, advanced membrane materials, digital monitoring, and

artificial intelligence-based process optimization are expected to further improve the efficiency, reliability, and sustainability of all renewable energy-based desalination technologies.

Table 1. Comparison of major renewable energy-based desalination technologies..

Technology	Specific Energy Consumption	Water Productivity / Recovery	LCOW (US\$/m ³)	Technology Readiness	Renewable Energy Compatibility	Suitable Scale	Suitability for Arid Regions
Solar Still (SS)	Solar thermal	2–6 L m ⁻² day ⁻¹	2–10	High	Excellent	Household–Small	Excellent
Reverse Osmosis (RO)	3–6 kWh m ⁻³	35–50% (SW), 60–85% (BW)	0.5–1.5	Commercial	Excellent (PV/Wind)	Medium–Large	Excellent
Membrane Distillation (MD)	50–120 kWh□□ m ⁻³ + 1–3 kWh _e m ⁻³	5–30 kg m ⁻² h ⁻¹	1.5–5.0	Pilot–Early commercial	Excellent (Solar thermal, Waste heat)	Small–Medium	Very High
Humidification–Dehumidification (HDH)	80–200 kWh□□ m ⁻³	5–25 kg h ⁻¹ (system dependent)	2–6	Pilot	Excellent (Solar thermal)	Small–Medium	Excellent
Multi-Effect Distillation (MED)	40–80 kWh□□ m ⁻³ + 1.5–2.5 kWh _e m ⁻³	30–45% recovery	0.8–2.0	Commercial	Excellent (CSP/Solar thermal)	Large	Excellent

3. Recent Technological Advances in Renewable Energy-Based Desalination Systems

Renewable energy-based desalination has progressed from simple coupling between a desalination unit and a single renewable source toward integrated systems that combine advanced materials, energy recovery, thermal or electrical storage, hybrid power supply, and intelligent monitoring. These developments aim to improve water productivity, reduce specific energy consumption, increase operational stability under fluctuating renewable-energy input, and lower the life-cycle environmental burden of freshwater production [11–14, 18–23].

Recent advances can be grouped into four main areas. The first concerns membrane and interfacial materials. Fouling-resistant thin-film composites, nanocomposite membranes,

superhydrophobic surfaces, photothermal absorbers, and selective coatings have been investigated to improve permeability, salt rejection, vapor transport, solar absorption, and resistance to scaling or wetting. In membrane distillation and reverse osmosis, these materials may increase flux and extend membrane service life, while in solar stills they can localize heat at the evaporation interface and reduce bulk-water heating requirements [11, 12, 14, 24–32]. Nevertheless, many reported improvements are based on short-duration laboratory experiments, and long-term stability, fabrication cost, material leaching, and large-scale manufacturability remain important uncertainties.

The second area involves hybrid renewable-energy and energy-storage configurations. Photovoltaic, solar thermal, wind,

geothermal, and waste-heat resources are increasingly combined to reduce the intermittency associated with a single renewable source. Battery storage can stabilize electrically driven systems such as reverse osmosis, whereas sensible-heat and phase-change storage can support thermal processes such as membrane distillation, humidification–dehumidification, and multi-effect distillation. Hybrid photovoltaic–thermal systems are especially attractive because they can simultaneously supply electricity for pumps and controls and heat for evaporation-based processes [18–23, 28, 38–40]. However, additional storage, power-conditioning, and control equipment may increase capital cost and system complexity, requiring site-specific techno-economic optimization.

The third area is process intensification and heat or energy recovery. Modern reverse-osmosis systems employ high-efficiency pumps and pressure-energy recovery devices, while thermal systems increasingly incorporate heat exchangers, cascading evaporation stages, vapor reuse, and optimized feed arrangements. In solar stills and HDH systems, fins, wicks, packed humidifiers, condensers, and improved heat-transfer surfaces have been used to increase evaporation and condensation rates. These measures can reduce energy losses and improve productivity, although their benefits depend strongly on operating scale, feedwater quality, and local climatic conditions [11, 12, 24–28, 33–40].

The fourth area concerns digital monitoring, data-driven prediction, and intelligent control. Artificial intelligence and machine-learning methods are being explored for forecasting water production, detecting fouling, optimizing operating parameters, scheduling maintenance, and coordinating renewable generation with desalination demand. Internet-of-Things sensors can provide real-time information on pressure, temperature, salinity, permeate flux, membrane condition, and energy availability. These tools may be particularly useful in hybrid systems exposed to variable solar or wind input. However, their practical value depends on the availability of reliable field data, sensor calibration, cybersecurity, interpretability, and validation under long-term operating conditions. Accordingly, AI should be treated as an enabling tool rather than as a substitute for sound process design and physical understanding.

Concentrated solar desalination represents another important development, particularly for arid regions with high direct normal irradiance. Concentrated solar power can provide medium- or

high-temperature heat for MED and other thermal desalination processes, while thermal-energy storage can extend operation after sunset. The principal limitations are high capital investment, land requirements, optical losses, dust accumulation, and the need for efficient cooling and brine management [17, 18, 38–40].

These advances are especially relevant to arid and semi-arid regions, where abundant solar resources coincide with severe water scarcity. Nevertheless, harsh field conditions—including high ambient temperature, dust deposition, variable feedwater salinity, weak grid infrastructure, and limited maintenance capacity—can reduce the performance of advanced systems. Future development should therefore prioritize long-duration field trials, standardized performance reporting, modular designs, durable materials, low-cost storage, and integrated assessment of energy use, water cost, carbon emissions, and concentrate management.

Overall, recent technological progress has improved the technical feasibility of renewable-energy-based desalination, but commercialization remains uneven across technologies. Reverse osmosis and MED are commercially mature, whereas membrane distillation, HDH, advanced solar stills, and AI-enabled hybrid systems remain mainly at pilot or early deployment stages. Figure 9 summarizes the principal innovation pathways and their relationships with the major technical challenges and research priorities.

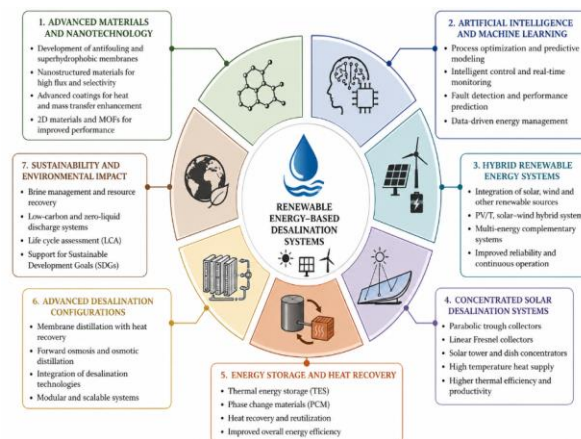


Figure 9. Major technological advances and emerging research directions in renewable energy-based desalination systems, including advanced membranes and photothermal materials, hybrid renewable-energy integration, electrical and thermal energy storage, heat and pressure recovery, digital monitoring, artificial intelligence-assisted control, concentrated solar desalination, and brine-resource recovery.

3.1. Advanced Materials and Nanotechnology

Advances in materials science and nanotechnology have created new opportunities to improve the efficiency, durability, and environmental performance of renewable energy-based desalination systems. Research has focused on advanced membrane materials, nanostructured absorber surfaces, thermal-energy-storage media, and multifunctional coatings that can enhance water transport, solar-energy absorption, heat transfer, and resistance to fouling, scaling, and membrane wetting [11, 14, 24–32]. However, many reported improvements have been demonstrated under controlled laboratory conditions, and their long-term stability, manufacturing cost, environmental safety, and scalability remain important barriers to practical deployment.

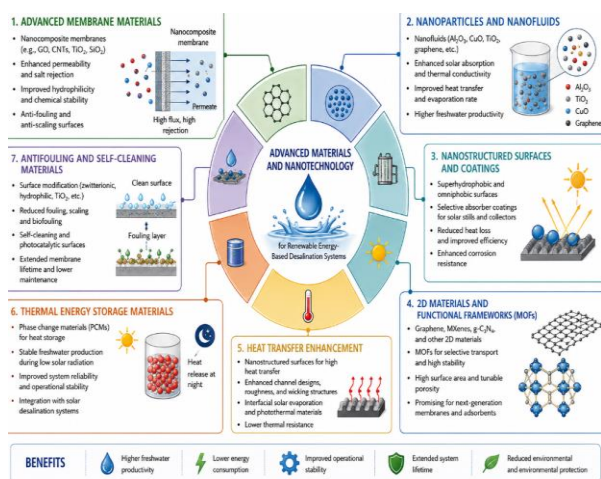


Figure 10. Major applications of advanced materials and nanotechnology in renewable energy-based desalination systems.

In pressure-driven and thermally driven membrane processes, nanocomposite and surface-modified membranes have been developed to improve permeability, salt rejection, hydrophobicity, and resistance to contamination. Graphene oxide, carbon nanotubes, silica nanoparticles, metal-organic frameworks, and other two-dimensional or porous materials have been incorporated into polymeric membranes or applied as surface coatings. These additives can increase water or vapor transport, modify surface charge and roughness, and reduce the adhesion of organic matter, microorganisms, and inorganic salts [11,29–32]. In membrane distillation, superhydrophobic and omniphobic surfaces are particularly important because they increase liquid-entry pressure and delay pore wetting. In reverse osmosis, hydrophilic and anti-fouling modifications can reduce flux decline and cleaning frequency.

Despite these benefits, the incorporation of nanomaterials also creates technical and environmental concerns. Poorly dispersed particles may block membrane pores or form defects that reduce salt rejection. Surface coatings may delaminate during cleaning or long-term operation, while nanoparticles may leach into the feed, permeate, or concentrate stream. Additionally, the fabrication of high-performance nanocomposite membranes may require costly materials, toxic solvents, or complex manufacturing methods. Therefore, membrane development should be evaluated not only in terms of initial flux and rejection but also through long-duration testing, chemical resistance, cleanability, material retention, life-cycle impact, and cost per unit of treated water.

Nanotechnology has also been applied to solar desalination through nanofluids, selective absorber coatings, porous photothermal materials, and interfacial evaporation structures. Nanoparticles such as Al₂O₃, CuO, TiO₂, carbon nanotubes, and graphene-based materials can improve solar absorption and thermal conductivity, thereby increasing evaporation rates in solar stills and solar-thermal desalination systems [14,24–28]. Interfacial photothermal materials offer an additional advantage by concentrating heat near the evaporation surface instead of heating the entire water volume. This can reduce bulk thermal losses and improve solar-to-vapor conversion under favorable operating conditions.

However, productivity gains obtained with nanofluids and photothermal absorbers vary considerably among studies because of differences in particle concentration, optical properties, water depth, solar irradiance, system geometry, and experimental duration. High nanoparticle concentrations may increase viscosity, pumping demand, sedimentation, or fouling. Photothermal materials may also suffer from salt accumulation, oxidation, mechanical degradation, or reduced optical performance during prolonged outdoor use. Consequently, reported percentage improvements should be interpreted cautiously unless they are supported by standardized testing and long-term field validation.

Phase-change materials and other thermal-energy-storage media represent another important materials-based strategy. These materials absorb excess heat during periods of high solar irradiance and release it when solar input decreases, extending operation into evening hours and reducing thermal fluctuations. In solar stills, HDH, MD, and MED

systems, thermal storage can improve daily freshwater production and operating stability [28,38–40]. Nevertheless, storage effectiveness depends on phase-transition temperature, latent heat capacity, thermal conductivity, cycling stability, containment design, and heat-transfer integration. Some PCMs also require encapsulation or conductivity enhancement, which increases system complexity and cost.

Anti-scaling, anti-fouling, and self-cleaning surfaces are particularly relevant to arid-region desalination because feedwaters may contain high concentrations of dissolved salts and suspended solids, while dust deposition can impair solar collectors and exposed surfaces. Hydrophilic, zwitterionic, photocatalytic, and low-surface-energy coatings have been investigated to reduce contaminant adhesion and facilitate cleaning. Yet, their long-term performance under high temperature, intense ultraviolet exposure, abrasive dust, chemical cleaning, and saline conditions remains insufficiently demonstrated.

For practical deployment, the most promising materials should combine high performance with durability, low toxicity, simple fabrication, and compatibility with existing desalination equipment. Future research should therefore prioritize pilot-scale manufacturing, standardized accelerated-aging tests, multi-cycle cleaning studies, field operation under realistic feedwater conditions, and life-cycle assessment. Particular attention should also be given to recovery or safe disposal of nanomaterials and to preventing their release into freshwater or brine streams.

Overall, advanced materials and nanotechnology can improve membrane selectivity, heat and mass transfer, solar-energy utilization, thermal storage, and resistance to fouling or wetting. Their contribution to sustainable desalination will depend, however, on whether laboratory-scale performance gains can be translated into stable, affordable, and environmentally responsible operation. In this regard, durability, manufacturability, material safety, and whole-system techno-economic performance are as important as peak productivity or membrane flux.

3.2. Artificial Intelligence and Machine Learning Applications

Artificial intelligence (AI), machine learning (ML), and digital technologies are increasingly important in renewable energy-based desalination because they enable data-driven process optimization, predictive maintenance, intelligent

energy management, and autonomous system control. Unlike conventional control strategies that rely on predefined operating conditions, AI-based approaches continuously analyze operational data to improve freshwater production, reduce energy consumption, enhance equipment reliability, and support decision-making under variable renewable energy availability. These capabilities are particularly valuable for renewable-powered desalination systems, where fluctuations in solar irradiance, wind speed, feedwater quality, and water demand require adaptive operational strategies.

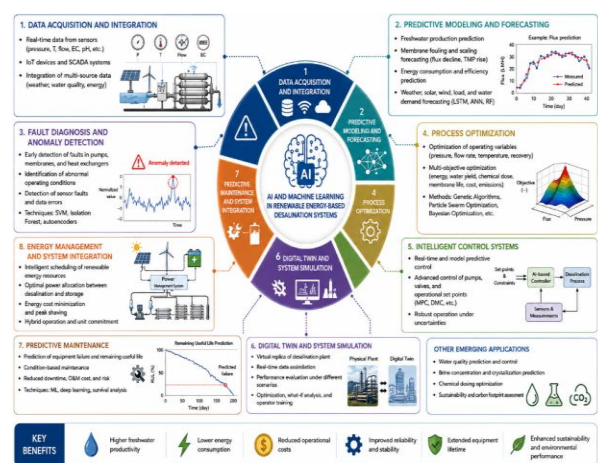


Figure 11. Applications of artificial intelligence and machine learning in renewable energy-based desalination systems.

Machine-learning algorithms have been widely applied to predict key performance indicators such as permeate flux, freshwater production, specific energy consumption, membrane fouling, thermal efficiency, recovery ratio, and water quality. Artificial neural networks (ANNs), support vector machines (SVMs), random forest (RF), extreme gradient boosting (XGBoost), Gaussian process regression (GPR), and deep-learning architectures have demonstrated superior predictive accuracy compared with conventional empirical models when sufficient operational data are available. These models enable rapid estimation of system performance without repeatedly solving complex thermodynamic or transport equations, thereby reducing computational time for design optimization and operational planning.

One of the most significant applications of AI in desalination is membrane fouling prediction and mitigation. Fouling remains one of the primary causes of increased energy consumption, reduced permeate flux, frequent chemical cleaning, and shortened membrane lifetime in reverse osmosis and membrane distillation systems. Machine-

learning models trained using operational variables—including feedwater salinity, temperature, pressure, flow rate, pH, turbidity, and membrane age—can identify early fouling trends and recommend optimal cleaning schedules before severe performance deterioration occurs. Predictive maintenance thus reduces operational interruptions, extends membrane lifetime, and lowers maintenance costs.

Artificial intelligence also supports intelligent control of renewable-energy-driven desalination systems. Photovoltaic-powered reverse osmosis, solar-assisted membrane distillation, HDH, and MED systems experience continuous variations in available energy because of changing weather conditions. AI-based optimization algorithms can dynamically regulate pump speed, operating pressure, feed flow rate, thermal input, storage utilization, and water production according to renewable energy availability. Such adaptive control improves operational stability while reducing unnecessary energy consumption and increasing freshwater productivity.

The rapid development of Internet of Things (IoT) technologies has further accelerated the digital transformation of desalination systems. Distributed sensors continuously monitor operating parameters including pressure, temperature, salinity, permeate conductivity, solar irradiance, wind speed, membrane performance, and equipment condition. These real-time data streams are transmitted to cloud-based platforms where AI algorithms analyze system behavior, detect abnormal operating conditions, and support remote decision-making. Digital twins, which combine physical process models with real-time operational data, are emerging as powerful tools for simulating plant performance, evaluating alternative operating strategies, and predicting long-term system behavior under varying climatic conditions.

Although AI offers considerable opportunities, several challenges remain before widespread industrial implementation can be achieved. Most published machine-learning studies rely on relatively small laboratory datasets collected under controlled operating conditions, limiting their generalization to commercial desalination plants. Data quality, sensor reliability, missing measurements, model interpretability, cybersecurity, computational requirements, and the availability of standardized datasets continue to restrict practical deployment. Furthermore, highly accurate prediction models do not necessarily guarantee improved system performance unless

they are integrated into robust operational control strategies.

For renewable energy-based desalination systems operating in arid regions, AI provides additional advantages because it can optimize system performance under highly variable environmental conditions. Intelligent forecasting of solar radiation, ambient temperature, electricity generation, and water demand allows more efficient scheduling of energy storage, freshwater production, and system maintenance. These capabilities are particularly valuable for off-grid and decentralized desalination systems where both water availability and renewable energy resources fluctuate throughout the day.

Future research should focus on developing explainable artificial intelligence (XAI), federated learning, reinforcement learning, digital twins, and autonomous optimization frameworks capable of combining physical process knowledge with real-time operational data. Greater emphasis should also be placed on establishing publicly available benchmark datasets, validating AI algorithms under long-term field conditions, and integrating techno-economic and life-cycle assessment into digital optimization frameworks. Such developments will improve confidence in AI-assisted desalination and accelerate commercial deployment.

Overall, artificial intelligence should be regarded as an enabling technology rather than an independent desalination process. Its greatest value lies in enhancing the efficiency, reliability, sustainability, and operational flexibility of renewable energy-powered desalination systems through intelligent monitoring, predictive analytics, adaptive process control, and data-driven decision support. As digital technologies continue to mature, AI is expected to become an essential component of next-generation smart desalination systems capable of delivering reliable freshwater production under increasingly complex environmental and energy conditions.

3.3. Hybrid Renewable Energy Systems

Hybrid renewable energy systems combine two or more energy sources, storage technologies, or conversion pathways to provide a more stable supply of electricity and heat for desalination. Their principal advantage over single-source renewable systems is the ability to compensate for temporal variability in solar irradiance, wind speed, and thermal-energy availability. By coordinating complementary resources, hybrid configurations can reduce system downtime, improve desalination

capacity utilization, and limit dependence on fossil-fuel backup [13,18–23].

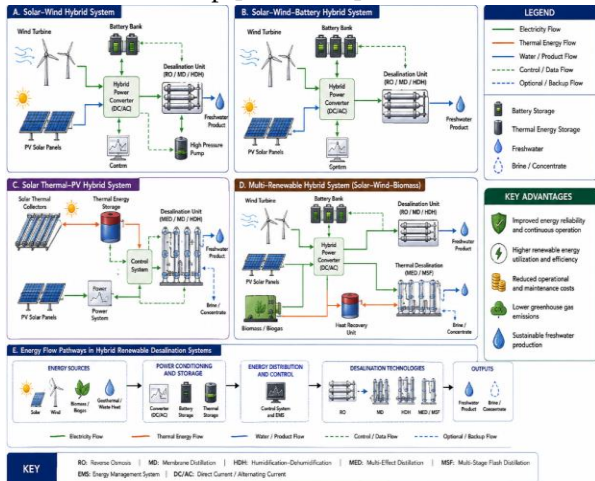


Figure 12. Typical configurations and energy flow pathways of hybrid renewable energy-based desalination systems.

Solar–wind systems are among the most widely investigated hybrid configurations because the two resources may exhibit complementary daily and seasonal generation profiles. Photovoltaic modules typically provide electricity during daylight hours, whereas wind turbines may continue operating during cloudy periods or at night where adequate wind resources are available. Coupling these sources with reverse osmosis can reduce fluctuations in electrical supply and improve the reliability of off-grid freshwater production. Nevertheless, the benefits are site-specific and depend on local solar and wind profiles, component sizing, water demand, and the selected storage strategy [13, 19, 20].

Hybrid photovoltaic–thermal systems offer an additional pathway by producing electricity and useful heat from the same collector area. The electrical output can operate pumps, fans, sensors, and control systems, while the recovered thermal energy can support membrane distillation, humidification–dehumidification, solar stills, or feedwater preheating. This combined use of electrical and thermal outputs can improve overall solar-energy utilization, particularly in systems requiring both forms of energy. However, PV/T integration also introduces thermal-management challenges because increasing collector temperature may improve heat recovery while reducing photovoltaic efficiency.

Energy storage is a central component of many hybrid desalination systems. Batteries can stabilize power supplied to electrically driven technologies such as RO, whereas sensible-heat storage, phase-change materials, and other

thermal-storage media can support MD, HDH, and MED during periods of reduced solar input. Storage improves continuity of operation but increases capital cost, maintenance requirements, conversion losses, and replacement needs. In some applications, storing produced water may be more economical than storing electricity or heat. Therefore, optimal design should compare energy storage, freshwater storage, and flexible desalination scheduling rather than assuming that maximum energy-storage capacity is always preferable.

Hybrid renewable systems have been integrated with several desalination technologies. PV–wind–RO systems are suitable for electrically driven, modular water production; solar thermal–MD and solar thermal–HDH systems can utilize low-grade heat; and CSP–MED configurations can provide dispatchable thermal energy when coupled with thermal storage. Geothermal or industrial waste heat may also be combined with solar resources to support more continuous thermal desalination. The preferred configuration depends on whether the process requires electricity, heat, or both, as well as on feedwater salinity, plant scale, resource availability, and local infrastructure [18, 19, 22, 23, 38–40].

Advanced energy-management systems are increasingly used to coordinate renewable generation, storage, desalination load, and freshwater demand. Model-predictive control, multi-objective optimization, and AI-assisted scheduling can adjust pump operation, thermal input, storage charging, and production timing according to weather forecasts and operating constraints. These approaches may reduce energy curtailment and operating costs, but their effectiveness depends on accurate forecasting, reliable sensors, robust control architecture, and field validation. Complex digital control should therefore complement, rather than replace, resilient physical system design.

Despite their potential, hybrid systems involve important trade-offs. Additional generators, storage devices, converters, heat exchangers, and control equipment increase capital investment and system complexity. Oversized systems may produce excessive curtailed energy, whereas undersized systems may fail to meet water demand during unfavorable weather conditions. Battery degradation, thermal-storage losses, component mismatch, and maintenance requirements can further affect long-term

economic performance. Consequently, hybrid-system assessment should include leveled cost of water, renewable fraction, loss-of-water-supply probability, capacity factor, storage cycling, component replacement, and life-cycle environmental impacts.

These considerations are especially important in arid and off-grid regions. High solar availability creates favorable conditions for photovoltaic and solar-thermal generation, but dust accumulation can reduce collector output and increase cleaning demand. High ambient temperatures may accelerate battery degradation and lower photovoltaic efficiency, while limited technical capacity can complicate maintenance of multi-component systems. Water scarcity may also restrict panel-cleaning options. Designs for these environments should therefore emphasize modular components, dry or low-water cleaning methods, thermal protection, remote monitoring, simple maintenance, and sufficient freshwater-storage capacity.

Overall, hybrid renewable energy systems can improve the reliability and flexibility of renewable-powered desalination, but they are not automatically more economical or sustainable than well-designed single-source systems. Their value depends on resource complementarity, appropriate component sizing, effective storage, operational control, and local maintenance capacity. Future research should prioritize long-term field demonstrations, standardized techno-economic comparisons, degradation-aware optimization, and integrated planning of energy generation, desalination, storage, and water demand under representative arid-region conditions.

3.4. Concentrated Solar Desalination Systems

Concentrated solar desalination (CSD) has emerged as one of the most promising approaches for large-scale sustainable freshwater production because it combines high-temperature solar thermal energy with mature thermal desalination technologies. Unlike conventional solar desalination systems, concentrated solar technologies employ reflective optical components to focus direct solar radiation onto a receiver, producing medium- or high-temperature heat that can efficiently drive thermal desalination processes. Consequently, CSD systems are particularly attractive for regions characterized by high direct normal irradiance (DNI), where abundant solar resources coincide with severe freshwater scarcity [17, 38–40].

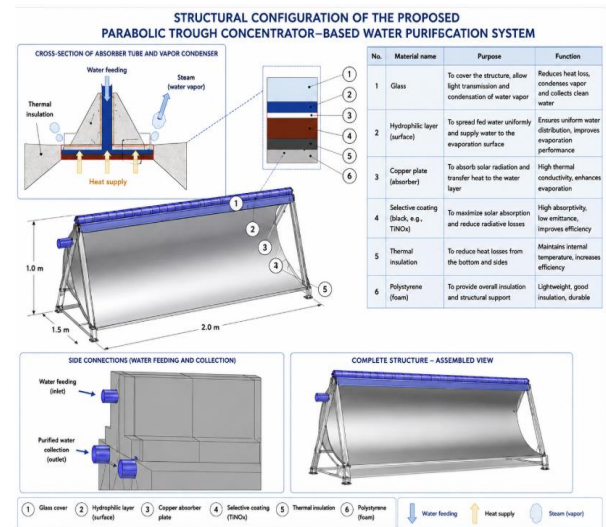


Figure 13. Schematic configuration of a concentrated solar desalination system integrating solar concentrators, thermal energy storage, heat-transfer fluid circulation, thermal desalination units, freshwater production, and brine management

Several concentrated solar technologies have been investigated for desalination applications, including parabolic trough collectors (PTCs), linear Fresnel reflectors (LFRs), central receiver (solar tower) systems, and parabolic dish concentrators. Each technology provides different operating temperatures, optical efficiencies, and economic characteristics. Parabolic trough collectors remain the most mature and widely investigated option because they provide stable thermal energy at moderate temperatures suitable for multi-effect distillation (MED), membrane distillation (MD), and humidification–dehumidification (HDH) systems. In contrast, solar tower systems achieve significantly higher temperatures and are more suitable for large-scale centralized desalination, although their higher capital cost and operational complexity currently limit widespread deployment [38–40].

One of the principal advantages of concentrated solar desalination is its compatibility with thermal energy storage. Sensible heat storage, molten-salt systems, and phase-change materials enable excess solar energy collected during peak irradiation periods to be stored and utilized after sunset or during transient weather conditions. This substantially improves capacity utilization, stabilizes freshwater production, and reduces the intermittency commonly associated with conventional solar-powered desalination systems. Consequently, concentrated solar systems can achieve higher operational continuity than direct solar desalination technologies that rely exclusively on instantaneous solar radiation.

Recent technological developments have focused on improving optical efficiency, heat-transfer performance, and system integration. Advanced selective absorber coatings, low-emissivity receiver tubes, improved solar tracking algorithms, high-performance heat-transfer fluids, nanofluids, and compact heat exchangers have contributed to reducing thermal losses and increasing solar-to-thermal conversion efficiency. Furthermore, hybrid concentrated solar systems combining photovoltaic generation, thermal energy storage, waste-heat recovery, and intelligent energy management have demonstrated improved operational flexibility and greater renewable energy utilization compared with standalone configurations.

Concentrated solar technologies have also expanded the application potential of several desalination processes. Solar-assisted MED systems can efficiently utilize medium-temperature thermal energy while maintaining stable freshwater production at relatively large capacities. Membrane distillation benefits from concentrated solar heat because feedwater temperatures can be maintained within the optimal operating range without excessive electrical energy consumption. HDH systems similarly benefit from stable low- to medium-temperature heat supplied by concentrated solar collectors. These integrated configurations enable higher renewable energy penetration while reducing greenhouse-gas emissions associated with fossil-fuel-powered desalination [17,38–40].

Despite these advantages, several technical and economic challenges continue to restrict large-scale implementation. High initial capital investment, extensive land requirements, solar tracking systems, receiver degradation, optical losses, and cleaning requirements significantly increase system costs. In arid environments, dust deposition on reflective mirrors and receiver surfaces may substantially reduce optical efficiency unless regular cleaning is performed. Water availability for mirror cleaning, therefore, becomes an additional operational challenge in regions already experiencing severe water scarcity. High ambient temperatures, wind loading, thermal stresses, and degradation of selective coatings further influence long-term system performance and maintenance requirements.

Environmental considerations extend beyond carbon-emission reduction. Large concentrated solar installations require considerable land area and substantial material inputs, while thermal

desalination continues to generate concentrated brine requiring environmentally responsible disposal or resource recovery. Therefore, comprehensive environmental evaluation should include life-cycle assessment, land-use analysis, water consumption for mirror cleaning, embodied carbon of solar collectors, and concentrate management rather than considering operational emissions alone.

From an economic perspective, the competitiveness of concentrated solar desalination strongly depends on local solar resources, plant capacity, financing conditions, storage configuration, and integration with existing energy infrastructure. Although capital investment remains relatively high compared with photovoltaic-powered reverse osmosis, the ability to provide dispatchable renewable thermal energy may improve long-term economic performance in locations with excellent direct normal irradiance and high freshwater demand.

Future research should prioritize advanced optical materials with reduced dust sensitivity, high-temperature thermal storage technologies, corrosion-resistant receiver materials, intelligent solar tracking, hybrid photovoltaic–thermal integration, digital process optimization, and resource recovery from concentrated brine streams. Equally important is the need for long-term pilot-scale demonstrations and standardized techno-economic comparisons under representative arid-region operating conditions.

Overall, concentrated solar desalination represents one of the most promising renewable-energy pathways for medium- and large-scale freshwater production in arid and semi-arid regions. Its ability to provide stable renewable thermal energy, achieve high thermal efficiency, and integrate effectively with MED, MD, and HDH technologies makes it an attractive option for future sustainable desalination. Nevertheless, broader commercial deployment will depend on continued reductions in capital cost, improvements in thermal-energy storage, enhanced resistance to harsh desert environments, and comprehensive life-cycle economic validation.

4. Challenges, Future Perspectives, and Research Opportunities

Despite substantial progress, renewable energy-based desalination technologies continue to face interconnected technical, economic, environmental, and operational barriers that restrict their large-scale and long-term deployment.

Membrane fouling, inorganic scaling, biofouling, pore wetting, corrosion, heat losses, and limited component durability remain among the principal causes of performance deterioration. In reverse osmosis, fouling and scaling increase transmembrane pressure, reduce permeate flux, increase cleaning frequency, and shorten membrane lifetime. In membrane distillation, pore wetting, temperature polarization, and conductive heat transfer reduce salt rejection and thermal efficiency, whereas thermal systems such as multi-effect distillation and humidification–dehumidification are affected by scale deposition, corrosion, non-condensable gases, and insufficient heat recovery [11, 12, 29–32, 38–40].

The intermittent nature of solar and wind resources introduces an additional operational challenge. Variations in solar irradiance and wind speed can cause fluctuations in feed pressure, flow rate, operating temperature, recovery ratio, and freshwater production. Repeated start–stop operation may reduce pump efficiency, accelerate membrane fouling, and create thermal stress in collectors, evaporators, and heat exchangers. Reliable operation therefore requires flexible control strategies, variable-speed drives, thermal or electrical energy storage, water-storage buffers, and improved forecasting of renewable-energy availability. However, these measures increase system complexity and capital cost, and their benefits depend on plant scale, local energy resources, and water-demand patterns.

Economic feasibility remains a major barrier, particularly for concentrated solar desalination, multi-effect distillation, membrane distillation, and hybrid systems incorporating battery or thermal storage. The costs of collectors, photovoltaic modules, pumps, membranes, tracking systems, heat exchangers, power-conditioning equipment, land, storage, and control infrastructure can outweigh operational energy savings if the system is poorly sized or operates at a low capacity factor. Many published studies report improvements in productivity or efficiency without adequately accounting for component replacement, chemical use, maintenance, storage degradation, financing conditions, system downtime, and brine-management costs. Future techno-economic studies should therefore report standardized indicators such as levelized cost of water, capital and operating expenditure, renewable-energy fraction, capacity factor, replacement intervals, and sensitivity to financing and energy-price assumptions.

Brine management is another critical environmental challenge. Concentrate streams may

contain elevated salt concentrations, residual antiscalants, cleaning chemicals, metals, and other treatment by-products. Poorly controlled marine discharge can increase local salinity and affect aquatic ecosystems, while inland plants face limited disposal options. Evaporation ponds require substantial land, whereas deep-well injection, crystallization, and zero-liquid-discharge systems can be energy intensive and expensive. Renewable-energy integration reduces operational greenhouse-gas emissions but does not eliminate environmental burdens associated with land occupation, material production, membrane disposal, battery replacement, chemical consumption, and cooling-water use. Consequently, life-cycle assessment should accompany technical and economic evaluation rather than treating reduced fossil-fuel consumption as the sole indicator of sustainability.

Resource recovery from brine presents a promising research direction, especially through selective salt separation, mineral extraction, membrane distillation–crystallization, and near-zero-liquid-discharge configurations. Nevertheless, the economic value of recovered products depends on purity, market demand, processing energy, transport requirements, and local industrial conditions. Resource recovery should therefore be evaluated as part of an integrated water–energy–materials system rather than assumed to be economically beneficial in all cases.

Arid and semi-arid regions present both favorable opportunities and severe operational constraints. High solar irradiance supports photovoltaic, solar-thermal, and concentrated solar systems, but dust and sand accumulation reduce optical efficiency and power output. High ambient temperatures can accelerate battery degradation, lower photovoltaic conversion efficiency, alter membrane selectivity, and reduce condensation performance in thermal systems. Highly saline groundwater increases osmotic pressure and scaling potential, while limited grid access, scarce technical personnel, restricted availability of spare parts, and water requirements for cleaning further complicate long-term operation. Future systems intended for arid environments should therefore emphasize dust-resistant coatings, dry or low-water cleaning, modular design, remote monitoring, thermal protection, simplified maintenance, and sufficient freshwater-storage capacity.

Advanced materials provide important opportunities for overcoming several of these limitations. Nanocomposite membranes, superhydrophobic surfaces, photothermal

absorbers, phase-change materials, nanofluids, and self-cleaning coatings may improve permeability, solar absorption, heat transfer, thermal storage, and resistance to fouling or wetting. However, many materials have been evaluated only in short-duration laboratory experiments. Their long-term stability, nanoparticle leaching, coating delamination, chemical resistance, ultraviolet degradation, manufacturability, toxicity, and end-of-life management remain insufficiently understood. Future work should prioritize pilot-scale fabrication, accelerated aging, repeated cleaning cycles, realistic feedwater testing, and life-cycle assessment instead of focusing only on peak flux or short-term productivity.

Energy storage and hybridization will also play central roles in future desalination systems. Batteries can stabilize electrically driven processes such as reverse osmosis, whereas sensible-heat storage and phase-change materials are more appropriate for membrane distillation, humidification–dehumidification, and multi-effect distillation. In some cases, storing produced water may be more economical than storing electricity or heat. Therefore, future optimization should jointly consider renewable generation, desalination demand, water storage, energy storage, component degradation, and loss-of-water-supply probability. Site-specific solar–wind, photovoltaic–thermal, solar–geothermal, and renewable–waste-heat systems should be designed using local resource data rather than generic assumptions.

Artificial intelligence, machine learning, digital twins, and Internet-of-Things monitoring offer additional opportunities for forecasting, fault detection, fouling prediction, predictive maintenance, and energy management. However, many existing studies rely on small laboratory datasets and have limited validation under long-term field conditions. Sensor drift, missing data, model transferability, cybersecurity, and limited interpretability remain important concerns. Future digital research should focus on physics-informed machine learning, explainable AI, standardized benchmark datasets, uncertainty quantification, and robust field deployment. AI should support engineering decisions rather than substitute for reliable process design and validated physical models.

The most urgent research priorities are therefore the establishment of standardized reporting for specific energy consumption, water productivity, recovery ratio, levelized cost of water, technology readiness, and life-cycle emissions; long-duration pilot testing under representative arid-region conditions; integrated

brine management and resource recovery; degradation-aware design of membranes, storage systems, and solar components; climate-resilient operation under dust, heat, high salinity, and weak-grid conditions; and site-specific selection of RO, MD, HDH, MED, and solar-still technologies. Whole-system assessments should combine techno-economic analysis, life-cycle assessment, water–energy nexus analysis, and social considerations.

Overall, the future of renewable energy-based desalination depends on shifting from isolated laboratory-scale improvements toward integrated, durable, economically validated, and environmentally responsible systems. Mature technologies such as RO and MED require more effective renewable integration and brine management, whereas MD, HDH, advanced solar stills, concentrated solar systems, and AI-enabled hybrids require stronger field evidence and scale-up validation. Progress will depend on coordinated research across membrane science, thermal engineering, renewable energy, materials science, environmental assessment, digital control, and local infrastructure planning.



Figure 14. Major technical, economic, environmental, and operational challenges, together with priority research opportunities for renewable energy-based desalination systems.

5. Conclusions

Renewable energy-based desalination can contribute significantly to water security in arid and semi-arid regions, but its suitability depends heavily on feedwater salinity, required production capacity, available renewable resources, infrastructure, maintenance capabilities, and brine disposal options. This review critically compared solar stills, reverse osmosis, membrane distillation, humidification–dehumidification, multi-effect distillation, and concentrated solar desalination using technical, economic, environmental, and deployment-related criteria.

Among the evaluated technologies, reverse osmosis currently offers the most favorable combination of commercial maturity, modularity, relatively low specific energy consumption, and compatibility with photovoltaic and wind power. It is therefore the most viable option for medium- and large-scale deployment where reliable pretreatment, pressure management, membrane maintenance, and responsible concentrate disposal are available. Multi-effect distillation remains attractive for large-scale and continuous freshwater production where solar thermal energy, concentrated solar power, geothermal heat, or industrial waste heat can be supplied economically. Its main limitations are high capital costs, thermal-system complexity, scaling, corrosion, and cooling requirements.

Solar stills and humidification–dehumidification systems are better suited to decentralized and small-scale applications because of their simple operation and compatibility with low-grade solar heat. Their wider use is restricted by comparatively low freshwater productivity and strong dependence on climatic and design conditions. Membrane distillation offers important advantages for high-salinity feedwater, brine concentration, and renewable-heat utilization, but membrane wetting, conductive heat loss, limited permeate flux, and insufficient long-term field validation continue to constrain commercialization.

The analysis also shows that renewable-energy integration does not eliminate the operational and environmental burdens of desalination. Intermittent power and heat supply can produce unstable pressure, temperature, and flow conditions, while dust accumulation, high ambient temperatures, weak infrastructure, and limited technical support are especially problematic in arid regions. Moreover, lower operational greenhouse-gas emissions must be evaluated alongside land use, chemical consumption, component replacement, membrane disposal, collector cleaning, and concentrate management.

Recent advances in nanocomposite membranes, anti-fouling and wetting-resistant surfaces, photothermal materials, thermal-energy storage, hybrid renewable systems, heat and pressure recovery, and digital monitoring have improved the technical potential of renewable-powered desalination. Artificial intelligence and machine learning may support forecasting, fouling detection, predictive maintenance, and energy management, but their practical contribution remains dependent on reliable sensors,

representative datasets, interpretable models, and long-term field validation.

Concentrated solar desalination is particularly relevant to high-DNI arid regions because it can provide medium- or high-temperature heat and can be combined with thermal storage to extend operation beyond daylight hours. However, high investment costs, optical losses, land requirements, mirror soiling, tracking-system maintenance, and water demand for cleaning must be addressed before broad commercial deployment. Parabolic trough, linear Fresnel, solar tower, and dish systems should therefore be selected according to required temperature, plant scale, local direct normal irradiance, storage requirements, and economic conditions.

The most important research priorities are long-duration pilot testing under representative arid-region conditions, standardized reporting of specific energy consumption and water-production costs, degradation-aware system optimization, durable and scalable membrane materials, low-cost storage, climate-resilient collector design, integrated brine resource recovery, and whole-system life-cycle assessment. Future technology selection should be site-specific rather than based on a universal ranking.

Overall, no single desalination technology is optimal for all applications. Reverse osmosis is presently the strongest general-purpose option for renewable-electricity-driven desalination; MED is preferable where reliable renewable heat is available; MD is promising for high-salinity and brine-concentration applications; and solar stills and HDH remain valuable for small, remote, and off-grid communities. The long-term contribution of renewable energy-based desalination will depend less on isolated improvements in peak efficiency and more on the development of integrated systems that are reliable, affordable, maintainable, environmentally responsible, and adapted to the practical constraints of arid regions.

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