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# Solar-Driven Water Treatment: New Technologies, Challenges, and Futures

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## Abstract

In this review, the new solar water treatment technologies, including solar water desalination in two direct and indirect methods, are comprehensively presented. Recent advances and applications of five major solar desalination technologies include solar-powered humidification–dehumidification, multi-stage flash desalination, multi-effect desalination, RO, and solar stills. Each technology's productivity, energy consumption, and water production costs are presented. Also, common methods of solar water disinfection have been reviewed as one of the common and low-cost methods of water treatment, especially in areas with no access to drinking water. However, although desalination technologies have many social, economic, and public health benefits, they are energy-intensive and negatively affect the environment. In addition, the disposal of brine from the desalination processes is one of the most challenging and costly issues. In this regard, the environmental effects of desalination technologies are presented and discussed. Among direct solar water desalination technologies, solar still technology is a low-cost, low-tech, and low-investment method suitable for remote areas, especially in developing countries with low financial support and access to skilled workers. Indirect solar-driven water desalination technologies, including thermal and membrane technologies, are more reliable and technically more mature. Recently, RO technology has received particular attention thanks to its lower energy demand, lower cost, and available solutions to increase membrane durability. Disposal of brines can account for much of the water cost and potentially negatively affect the environment. Therefore, in addition to efforts to improve the efficiency and reduce the cost of solar technologies and water treatment processes, future research studies should consider developing new solutions to this issue.

**Keywords**

Renewable Energy (RE), Solar-Driven Desalination, Solar Water Disinfection (SODIS), Brine, Greenhouse Gases (GHGs), Reverse Osmosis (RO)

## 1. Introduction

Besides population increase and economic expansion, growing water demand, which is worsened by polluting water resources and global warming, aggravates water scarcity throughout the World [1]. Around half of the World's population severely lacks water [1]. Such difficult circumstances show that traditional water resources (e.g., rain, snowmelt, rivers, and aquifers) cannot satisfy the water necessities. As a procedure to augment water supply, desalination technology has attracted growing interest and is progressively employed [2]. Such technology is founded on removing salt from seawater (SW) or brackish water (BW) to produce fresh water [3]. Throughout the globe, about 16,000 desalination units are making 97 million $m^3$/day to more than 300 million people worldwide [1] [4]. Half of the planet's desalination potential is noted in the Middle East and North Africa [2].

Desalination engineering needs energy [1]. Renewable energy sources are required to decrease carbon emissions, as 25 kg of carbon dioxide ($CO_2$) is emitted to process 1 $m^3$ of freshwater. This is why renewable energy seems to be an indispensable mohair to traditional energy sources. There is a growing trend to employ renewable energy in desalination engineering [5]. In distant regions, the absence of electricity worsens the lack of potable water. In such areas, it is crucial to carry out small-scale, autonomous, and decentralized renewable energy-founded desalination methodologies [6].

In this review, the second generation of solar water treatment technologies, including solar water desalination in two direct and indirect methods, is comprehensively presented. Recent advances and applications of five major solar desalination technologies such as solar-powered humidification–dehumidification (HDH), multi-stage flash desalination (MSF), multi-effect desalination (MED), reverse osmosis (RO), and solar stills have been comprehensively reviewed. In particular, solar stills have been described in detail as one of the oldest yet simplest methods of direct solar water desalination. Each technology's productivity, energy consumption, and water production costs are presented. Also, common methods of solar water disinfection have been reviewed as one of the common and low-cost methods of water treatment, especially in areas with no access to drinking water. Although desalination technologies have many social, economic, and public health benefits, they are energy-intensive and negatively affect the environment. In addition, the disposal of waste from desalination processes is one of the most challenging and costly issues. In this regard, the environmental effects of desalination technologies are presented and discussed.

## 2. Desalination Beginning

Desalt was noted as a term from 1909, and the beginning of desalination (removal of salt) returns to 1943; also, desalinate is from 1949 [7]. Even if the first aim of desalination was not the generation of freshwater, it was the extraction and utilization of salt from salty water via natural evaporation [1] [8]. Researchers affirmed that historically desalination returns to the 4th century BCE [9].

Prematurely desalination applications were known on naval ships from the 17th to 19th century [1]. The earliest desalination plants were engineered for ships to provide fresh boiler water [9]. In 1872, the first distillation plant was built with a production capacity of 22.70 $m^3$/day in Chile [10]. In 1912, a desalination unit with a potential of 75 $m^3$/day was proposed in Egypt [11], and in 1938 a bigger one was in Saudi Arabia [1]. Throughout the 1930s, the capability of water desalination augmented due to the dawn of the oil industries [11].

During the 1960s, the familiarity with desalination significantly progressed thanks to the fast population expansion and water shortage [1]. Advanced desalination techniques employed fossil sources, as numerous oil-producing countries in the Middle East and North African region encountered water lacks. Thus, they assigned some energy resources (oil or gas) to water desalination [9].

In 1960, the earliest desalination plants were built in Kuwait and Channel Island [11]; in the late 1960s, desalination units with a production capability of $8 \times 10^3$ $m^3$/day were used in various regions throughout the globe [1]. Most of the built units were founded on thermal methods, even if such practices were costly and needed massive energy [12], so they were appropriate for oil-rich countries in the Middle East [9]. During the last half-century, membrane processes have become increasingly used [11].

## 3. Desalination Methods

Desalination engineering is classified into two sets (**Figure 1**): thermal and membrane-based [1]. In the first one, heat is employed to distill feedwater and generate freshwater by taking as a model the natural cycle of evaporation and condensation [1]. Among the thermal techniques, solar still desalination [13], humidification-dehumidification (HDH) desalination [14], multi-effect distillation (MED) [15], multi-stage flash (MSF) distillation [16], vapor compression distillation (where steam is formed mechanically [17] or thermally [18]), freezing desalination [19], and hydrate formation [20]. Membrane-founded methods are reverse osmosis (RO), run via hydraulic power (pressure difference) [21], electrodialysis (ED), run via a potential difference (direct current, DC) [22] and membrane distillation (MD), run via temperature difference [1]. Different techniques comprise adsorption desalination [23], hydrogel desalination [24], and ionic exchange desalination [25].

RO remains the most industrially famous among the aforementioned membrane-founded processes as it could be employed for SW; also, the ED process remains appropriate for BW desalination [26]. In addition, MED and MSF remain

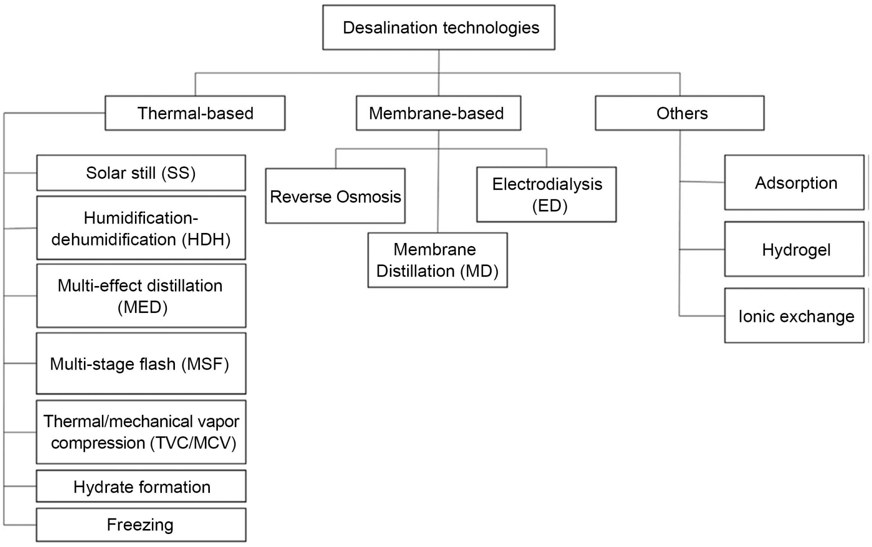

**Figure 1.** Categorization of desalination engineering [1].

the most common thermal techniques [11]. Twenty years ago, the volume of freshwater produced thermally (mainly MSF) and by RO was $11.6 \times 10^6$ and $11.4 \times 10^6$ m$^3$/day, constituting 93% of the total freshwater. During the last two decades, RO units increased exponentially, and thermal techniques increased slightly [1] [27]. Currently, the RO production potential is $65.5 \times 10^6$ m$^3$/day (*i.e.*, 69% of the volume of freshwater produced) [2]. In contrast to MED and MSF, RO is not apt to combine with a power plant to employ the plant's by-product heat, as a merit that low-grade heat is ready for use and inexpensive [5]. Selecting a convenient technique remains linked to several elements, such as the economy, the physical circumstance of the site, the quality of feedwater and desalinated water, local capability, and engineering [5].

## 4. Renewable Energy (RE)-Founded Desalination

Current desalination plants are frequently large-scale and need a lot of materials and energy [1]. Further, such plants remain dedicated to developed nations and stay inconvenient for developing countries and distant regions. Numerous desalination units consume vast quantities of fossil fuels to generate thermal and electrical energy in the thermal units and electrical power requested for membrane units [28]. For thermal methods (particularly MSF and MED), total energy demand is between 14 and 30 kWh/m$^3$ [29]. On the other hand, the energy consumption of membrane methods (particularly RO) remains more minor and between 2 and 5 kWh/m$^3$ of electrical energy [30].

Nevertheless, desalination units liberate greenhouse gases (GHGs, mainly $CO_2$) that possess ecological sequels. Decarbonizing desalination techniques seem vital to reduce $CO_2$ emissions simultaneously with satisfying water demand [31]. Renewable resources have lately attracted more and more interest as they request little maintenance, are a free and durable energy source, and lessen ecological contamination [32].

Employing renewable energy-founded desalination engineering emerges as an appropriate solution for generating freshwater. Besides, it is convenient for distant areas where access to potable water and electricity is hard [33]. Furthermore, renewable resources (e.g., solar, wind, hydroelectric, biomass, and geothermal could be combined with desalination processes [32]. As solar energy is the most plentiful sustainable energy source on the planet (**Figure 2**), it has attracted much interest [1] [34]. Earth collects 1.361 kW/m$^2$ of solar radiation per year at the top of the atmosphere [1]; around 30% of it is dispersed, and the remaining part is utilized [35]. Therefore, approximately 70% of renewable energy-founded desalination plants throughout the globe depend on solar energy, thanks to their potential to generate both thermal and electrical energies [1] [36]. **Figure 3** depicts the portion of renewable energy utilized in different desalination techniques. The following sections will review the photovoltaic-RO (PV-RO), solar MED, and solar MSF techniques.

## 4.1. Solar-Driven Desalination Techniques

Solar-founded desalination techniques are classified into two categories: direct and indirect methods (**Figure 4**). In the first one, the solar energy received by the solar collector is employed directly to generate freshwater (like what happens in solar stills) [1]. In the second one, the solar energy is collected by solar thermal collectors and/or PV modules, transformed into thermal and/or electrical power, and used in desalination techniques like MED, MSF, MD, and RO. **Table 1** sums up the merits and drawbacks of solar desalination techniques.

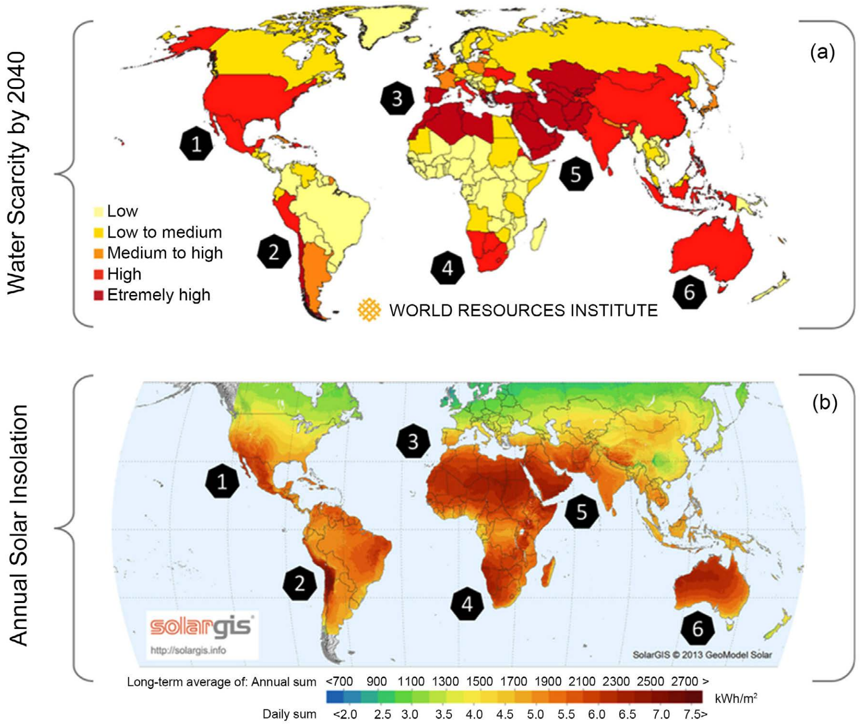

**Figure 2.** Global solar insolation alignment with water-scarce regions. (a) Potentially water-scarce regions by 2040; (b) Global solar insolation/irradiance as the annual sum [4].

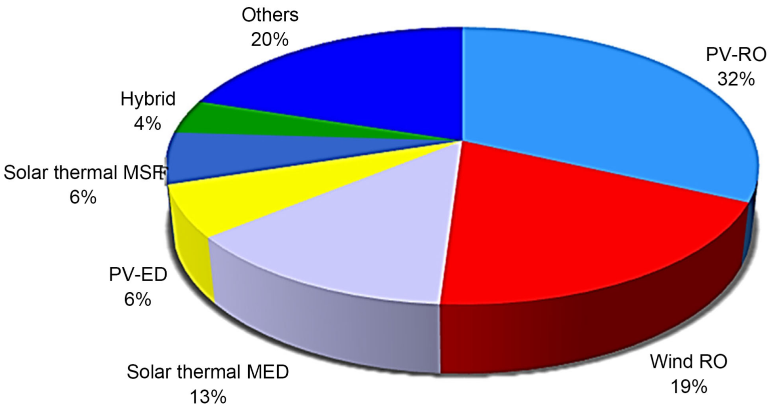

**Figure 3.** Desalination techniques combined with renewable resources at plants throughout the globe (MED: multi-effect distillation, MSF: multi-stage flash, PV-ED: photovoltaic-electrodialysis, PV-RO: photovoltaic-reverse osmosis, RO: reverse osmosis) [1].

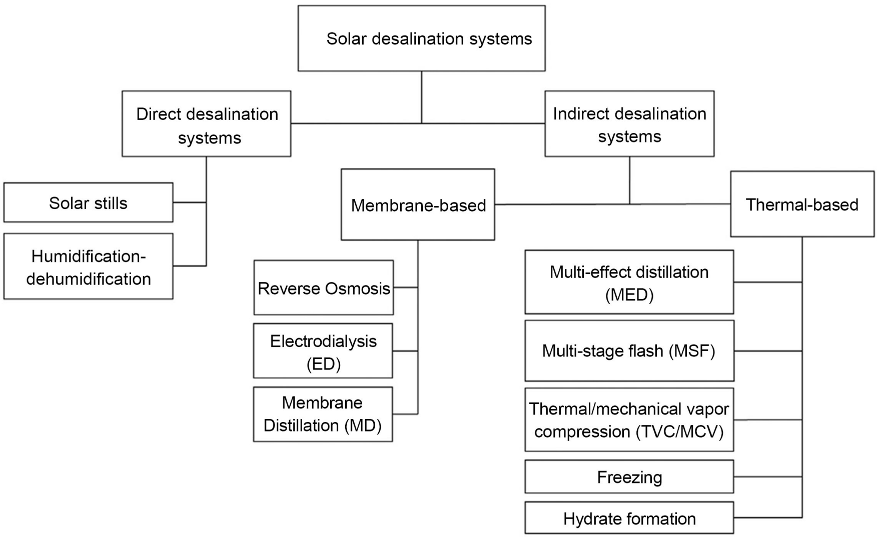

**Figure 4.** Classification of direct and indirect solar desalination processes [1].

**Table 1.** Merits and drawbacks of different solar desalination techniques [1].

| Desalination kind | Merits | Drawbacks |
|---|---|---|
| Solar stills | • Environmentally-friendly.<br>• Low operation and maintenance (O&M) cost.<br>• Generated water possesses high quality.<br>• High construction material availability.<br>• Appropriate for households and communities living on islands.<br>• Elimination of fluoride, arsenic, bacteria, etc., from the water. | • Large area occupation.<br>• Low efficiency.<br>• Is not appropriate for high capacities of water production. |

**Continued**

| | | |
|---|---|---|
| Humidification-dehumidification (HDH) | • Low installation and O&M costs.<br>• High flexibility.<br>• Appropriate for decentralized operation.<br>• Simpler brine pretreatment.<br>• Works with any energy.<br>• Requires availability. | • High capital investment cost.<br>• High overall costs of produced water. |
| Multi-stage flash (MSF) | • Generating high-quality distilled water.<br>• Reliable device operation.<br>• Appropriate for large-scale distillation plants.<br>• Water of any quality can be treated.<br>• Minimum or no feedwater pretreatment is needed. | • High energy consumption rates.<br>• High operation temperature causes corrosion in devices.<br>• Heavy structure.<br>• High capital cost. |
| Multi-effect distillation (MED) | • Lower thermal energy consumption levels.<br>• Reliable device operation.<br>• Producing high-quality distilled water.<br>• High operation temperature is not required.<br>• No feedwater pretreatment is required.<br>• Lower $CO_2$ emission compared to the MSF desalination. | • Costly and heavy structure.<br>• Electricity consumption for vacuum pump. |
| Solar photovoltaic (PV)-powered reverse osmosis (RO) | • Smooth operation.<br>• Operation at ambient temperature.<br>• Flexibility in capacity expansion.<br>• Can be constructed as a compact or portable device.<br>• Low energy consumption.<br>• Highly suitable for the treatment of groundwater and BW. | • Membranes have a short lifetime.<br>• A high-pressure pump (HPP) is required.<br>• Possibility of biological fouling of membranes.<br>• Requires pretreatment of feedwater.<br>• Using a battery is not recommended owing to the high capital cost and the need for battery replacement. |
| Solar thermal-powered reverse osmosis (RO) | • Device is safe.<br>• Flexible operation.<br>• Environmentally-friendly.<br>• Batteries are not required.<br>• A low-temperature source is sufficient.<br>• Solar collectors could cover a wide temperature range.<br>• No efficiency losses.<br>• Low O&M cost.<br>• Nonskilled labor would suffice.<br>• Suitable for large-capacity operation.<br>• Consumes less energy for posttreatment. | |

As aforesaid, in solar desalination techniques, solar energy is utilized in both direct and indirect procedures [1]. In the indirect ones, where solar energy is first collected and then exploited, the solar desalination system comprises two subsystems: the solar collector and the desalination unit. Solar energy is transformed into electricity and heat in the solar collector by PV-based systems or thermal collectors like concentrator solar power (CSP) systems [37]. **Figure 5** displays the integration of solar systems with desalination units to supply electricity or heat. This Section examines PV and solar heating systems employed in desalination techniques.

## 4.2. Solar Photovoltaic (PV)-Founded Desalination

PV power production setups stay appropriate, especially for distant regions where power demand remains comparatively low [1]. PV cells are semiconductors that generate direct current (DC). The collection of cells constitutes a PV module with a clear glass cover on the surface and a waterproof substrate on the back surface. The group of modules as well comprises strings and arrays. PV modules have two significant configurations: on-grid and off-grid. The first does not inject generating power into the network; the second transmits the output power from the PV modules to an inverter and then to the distribution network. PV-founded desalination technique is an outstanding choice for small- to medium-sized communities in distant areas with elevated access to solar energy and saline water [37].

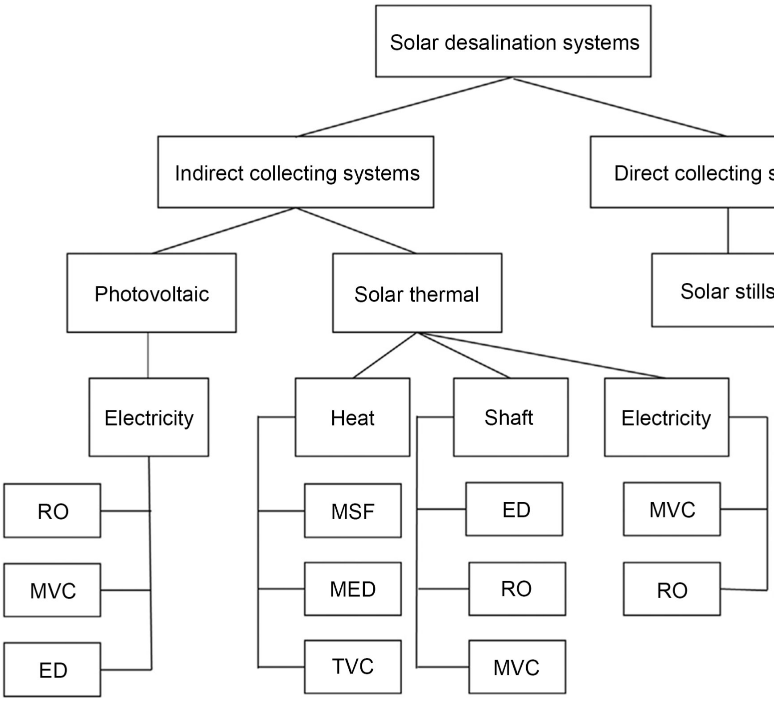

**Figure 5.** Integration of solar power systems with traditional desalination techniques (ED: electrodialysis, MED: multi-effect distillation, MSF: multi-stage flash, MVC: mechanical vapor compression, RO: reverse osmosis, TVC: thermal vapor compression) [1].

Lately, solar PV has become a cheap renewable technique juxtaposed to hydropower and wind energy sources [38]. Quick expansion in engineering has reduced the price of PV modules by 80% during the last decade [1]. Juxtaposed to 2015, PV prices could be decreased by 59% more, diminishing the global average from 0.05 to 0.06 $/kWh [1]. During the next three decades, PV is anticipated to constitute 20% of the worldwide energy supply, with a 50% reduction in $CO_2$ emissions at the beginning of the next century [39]. One of the desalination techniques integrated with solar PV, the PV-RO technique, emerges as a promising one, especially in terms of commercial expansion [40].

### 4.3. Solar Thermal-Founded Desalination

Solar thermal setups employ the thermal energy of solar radiation [1]. Solar collectors remain the most straightforward solar thermal device as they can absorb sunlight and move its heat to a fluid. The most accepted sorts of collectors remain flat plate collectors and evacuated tubes. The first ones contain a black absorber plate in which the heat the plate receives is transferred to the fluid in the tube. The second ones are composed of double-walled borosilicate glass tubes under vacuum. The black coating on the inner tube can absorb solar heat and transfer it to the tube's liquid; the void between the two pipes also reduces heat loss. Water, air, and oil can be used in solar collectors as operating fluids [32].

CSP systems are one more kind of solar thermal collector running at more important temperatures and are frequently utilized to produce electricity [1]. This collector uses mirror(s) to concentrate solar radiation and produce heat. The two principal types of CSP collectors are power towers and parabolic trough collectors (PTC). The PTC comprises curved reflective material and a receiving tube in the parabolic focal line. Concentrated radiation is received by the heat exchange fluid in the receiver tube and transformed into heat. In the PTC, the fluid temperature attains 350˚C - 400˚C. Such a critical temperature is juxtaposed with the liquid temperature in the flat plate and evacuated collectors. In solar thermal units, the collectors' efficiency depends on the technology adopted, the working temperature of the running fluid, the ambient temperature, and the solar radiation. Solar collectors could improve thermal efficiency from 60% to 75% [32].

In desalination devices with photovoltaic-thermal (PV-T) or concentrated photovoltaic thermal (CPV-T), the produced electricity and heat energy wasted in PV panels are employed simultaneously in the desalination technique [1]. Therefore, HDH-PVT, MED-PVT, solar still/-PVT, and RO-PVT methods stay among the chosen integrated desalination devices in the published works [41].

### 4.4. Direct Solar Desalination

Solar still and HDH process could be viewed as direct solar water desalination techniques [1]. In such processes, freshwater is constantly generated throughout the evaporation/condensation cycle. Therefore, solar energy promptly causes saline water to evaporate and form steam. After that, freshwater is generated because of the condensation of the resulting vapors. In this Section, such two techniques are examined.

### 4.4.1. Solar Stills

Using direct solar energy, a solar distiller could transform saline water into freshwater [1]. The principle of the method is identical to the rain formation cycle in nature. Solar energy gives rise to moisture evaporating from the surface of the ocean, lakes, and reservoirs on the globe's surface. The vapors formed in the atmosphere stay until they condense and turn into water droplets. The vapors are in the form of clouds and are distributed by the wind all over the planet. As water droplets integrate into the shadows and get bigger, they fall from the sky as rain. Identically, solar stills run. Through solar energy, the saline water is evaporated in the distillation basin. The resulting vapors move upward toward the surface of the condenser glass cover, like the generation and movement of clouds. On the glass surface, vapors condense, and the formed water droplets flow under the effect of gravity and are stored in the collection chamber [42].

### 4.4.2. Solar-Powered Humidification-Dehumidification (HDH) Technique

As one of the decentralizing water desalination techniques on a small scale, the HDH technique possesses numerous economic and environmental advantages comprising the potential to combine with sustainable energy sources, low working temperature, low maintenance, and easy structure [28]. Several attempts have been made to integrate the HDH desalination method with renewable energy sources to satisfy all the system's energy requirements from the local renewable energy source [1]. Thanks to obtainable solar energy, even in remote regions encountering a lack of drinking water, the phenomenon of diffusion and condensation of saline water and air will happen productively [43]. Considering its ecological questions, energy, and economic aspects, such solar HDH method is the most preferable and credible process for local freshwater production. Dehghan *et al.* [1] described the HDH method, its varieties, and the solar techniques employed in the solar HDH system.

## 4.5. Indirect Solar Desalination

As aforementioned, indirect solar desalination techniques are classified: as thermal and membrane processes [1]. This Section discusses thermal methods (like diffusion-driven desalination (DDD), MSF desalination, and MED) and the RO membrane process. In thermal ways, desalination is founded on the evaporation-condensation cycle and with phase alteration. On the other hand, in membrane processes, freshwater is generated via saline water through the membrane without modifying the phase. Here, a brief discussion is accorded to the introduced methods, their integration with solar energy, and the solar equipment utilized in such desalination units.

#### 4.5.1. Solar-Powered Diffusion-Driven Desalination (SDDD)

Diffusion-driven desalination (DDD) may be considered a low-cost and low-energy technology that needs little maintenance [1]. Thus, solar energy could operate entirely [44]. Such technology uses direct contact evaporation and condensation to desalinate SW and BW [45]. The evaporation and condensation phenomena are linked to the inlet water and air temperature, humidity, and water-to-airflow ratio [46].

The solar-powered diffusion-driven desalination (SDDD) technique comprises a direct contact evaporator, condenser, and solar collector [1]. At first, saline water circulation occurs in a flat plate solar collector to heat it. The packed bed material is employed to fill direct contact between the evaporator and condenser; thus, a direct connection between air and water could be provided. Heated saline water is sprayed through a nozzle to the top of the packed bed. The airflow is forced as a counter-current stream from below by a fan into the evaporator and is in direct contact with the falling liquid film. The airflow is evaporated and humidified by the heated water. Humidified air in a completely saturated state exits the top of the evaporator. It is blown into the condenser, where it is in direct contact with the falling liquid layer of freshwater. The air stream dehumidifies and returns to the evaporator. The heat exchanger is bypassed when the system is operated with a solar heater. The saline water discharged from the evaporator is returned to the water storage tank for recirculation. Identically, freshwater is released from the condenser into the freshwater tank to be recirculated in the condenser (**Figure 6**). Because the system runs securely, except for heat lost by the system components, no heat discharge happens throughout operation [44] [46].

The quantity of water generated in the SDDD technique is three times that of solar still [1]. Because solar stills do not employ electricity comparatively with SDDD or any other method, a larger surface area and volume per unit liter of distilled water are needed [44]. The water generation price in SDDD in low-cost collectors is around 4 $\$/m^3$ [44]. Following simulations, for the specific production of 100 L/day of freshwater by SDDD process and employing eight flat plate collectors with an area of 2 $m^2$, specific energy consumption (SEC) is estimated to be 3.6 $kWh/m^3$. Considering the low SEC of such technology and the low construction cost, it could be affirmed that the SDDD method is competitive with different desalination techniques with small scales [44].

#### 4.5.2. Solar-Powered Multi-Stage Flash (SMSF) Desalination

Multi-stage flash (MSF) desalination was the earliest large-scale commercial desalination technique and came to prominence in the 1970s [1]. Since then, it has possessed a considerable part of the market in the Middle East [16]. MSF accounts for 21% of the World's installation capacity for desalination, second only to RO [30]. The generation capacity of MSF can change considerably, varying from units that could generate 23,000 $m^3$/day to massive units that could generate 528,000 $m^3$/day. The generation price changes (0.52 - 1.75 $\$/m^3$) [29].

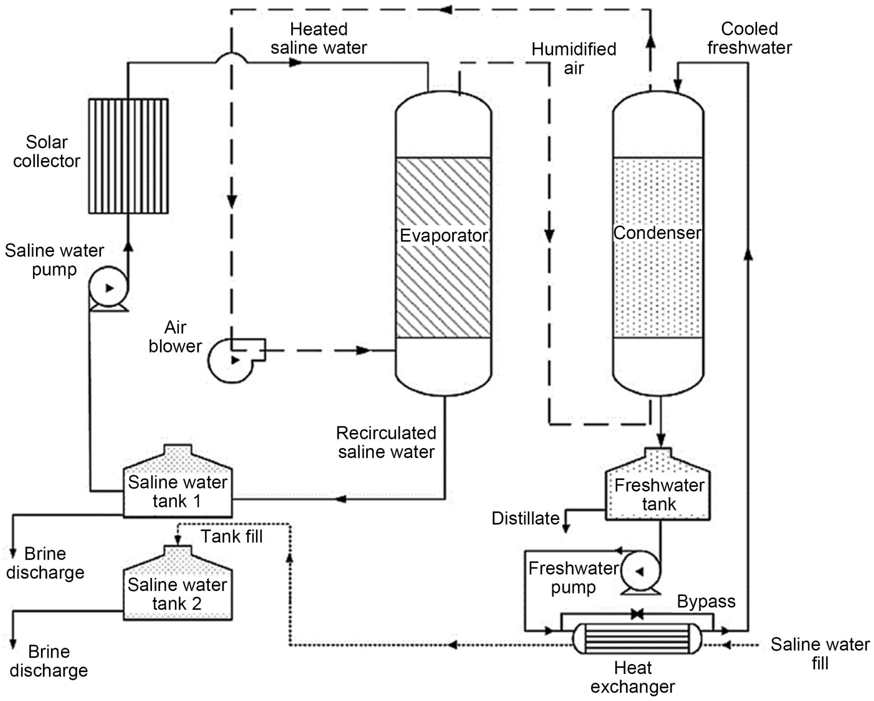

**Figure 6.** Process flow diagram of solar-powered diffusion-driven desalination (SDDD) [46].

The energy demand of the MSF process is elevated and changes between 13.5 and 25.5 kWh/m$^3$. Therefore, most MSF units are built next to an existing power plant [1]. Such a thermal desalination process is founded on a flash distillation of heated brine at decreased temperature and pressure. SW/BW feed into such a technique, where the flow goes through successive heating stages. After flashing, some heat exchangers (on the shell side) condense the freshwater, recycling latent and sensible heat. Usually, the SW is preheated by an external heat source before entering the first stage. The brine temperature then augments to 90˚C - 110˚C. After that, the heated brine flows continuously in stages; a small quantity of water is vaporized at each step. The resulting steam condenses at each location, and freshwater is formed. Finally, concentrated brine and freshwater are drained from the last stage (**Figure 7**). MSF units typically comprise 4 - 40 steps. Each stage runs at a lower temperature and pressure than the previous stage. As a result, the boiling point of the feedwater is decreased throughout successive stages, and owing to the continuous boiling of the brine; there is no requirement for an additional heat source in addition to the SW preheating heat source [1]. The performance and gained output ratio (GOR) of the MSF method are improved by boosting the top brine temperature (TBT), the brine temperature in the first flashing stage, reducing the intake saline water temperature, boosting the steps, and augmenting the specific heat exchange area [47].

In solar-powered multi-stage flash (SMSF) setups, different solar techniques (comprising parabolic collectors, flat plate collectors, central tower receivers, linear Fresnel reflectors, evacuated tubes, solar ponds, and PV panels) are utilized to integrate into MSF desalination system [48]. To combine MSF with solar energy, the TBT (90˚C - 110˚C) should be regulated to avoid unstable operation [48]. **Figure 8** depicts the MSF unit combined with a solar collector [47]. Since the 1980s, numerous SMSF units with a 10 - 20 $m^3$/day capacity have been launched [49]. For example, in Kuwait, an SMSF plant employing PTC collectors was installed four decades ago with a 10 $m^3$/day capacity and an SEC of 81 - 106 kWh/$m^3$ [50].

During the last two decades, several investigations have been dedicated to solar-powered MSF units juxtaposed to the solar-powered MED method, most of which have focused on pilot- and small-scale units [1]. This manifests that solar MSF is less technologically and economically competitive than solar MED due to many causes [47]: 1) The necessity for a comparatively elevated TBT in such a technique has made it inconvenient to merge with solar energy. 2) More elevated TBT implies higher fouling and scaling rates. 3) MSF is less effective thermodynamically as contrasted with MED.

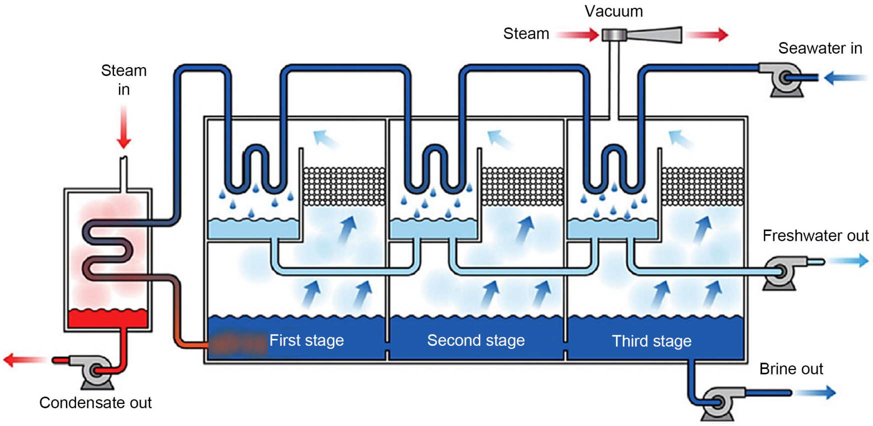

**Figure 7.** Schematic of multi-stage flash (MSF) technique [29].

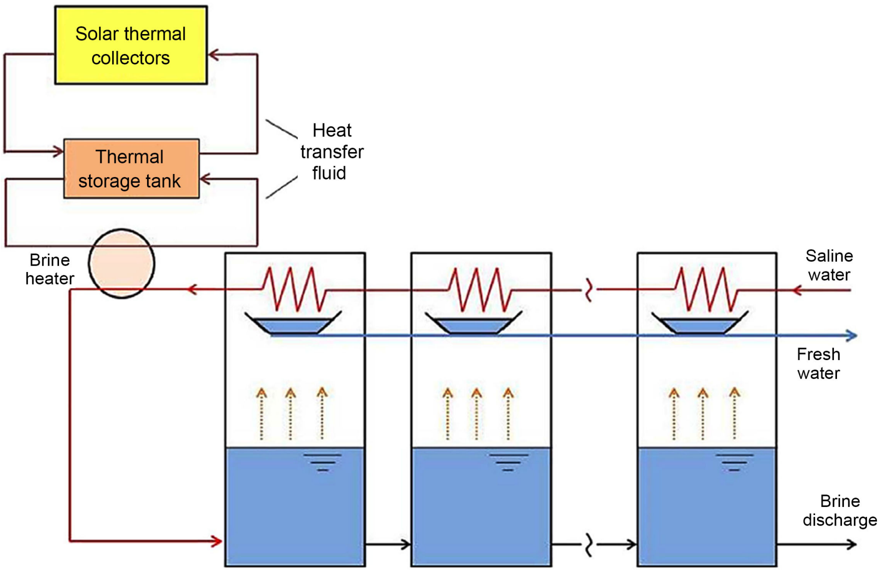

**Figure 8.** A solar-powered multi-stage flash (SMSF) desalination system [47].

#### 4.5.3. Solar-Powered Multi-Effect (SMED) Desalination

It is rare even if the multi-effect desalination (MED) technique stays thermodynamically more functional than the MSF technique [1] [51]. The MED technique constitutes 7% of global installed capacity and expends two to three times as much energy as the RO method [51]. MED units can treat 600 - 91,000 m$^3$/day. Nonetheless, these units' investment and energy consumption costs stay elevated [51]. The MED desalination technique comprises a series of cells (*i.e.*, effects), generally between 2 and 16 effects, which run at decreased pressure [1].

Hot steam enters the first effect from an external heat source through the tube. As a consequence of spraying SW on the tube, heat is transferred from vapor to water, and thus the SW evaporates. The steam from the evaporation of water and the boiling of the brine enters the second effect, and the evaporation/condensation process is carried out, and freshwater is formed. The steam and brine move between the effects at decreased temperature and pressure, which persists until the last effect. There are three primary arrangements of the MED system: forward feed (FF), backward feed (BF), and parallel cross feed (PCF) [52]. In the first arrangement, SW and steam enter the first effect, and the output brine from each effect is utilized to condense the steam into the following effect. In such conditions, the steam and brine stream move in the same direction and forward. In the second arrangement, brine and steam move in opposite directions; thus, SW enters the last effect, and steam enters the first effect. In the third arrangement, SW enters all effects, and steam enters the first effect; hence, the brine enters each effect in parallel with the steam [1]. Such arrangement possesses the most significant efficiency and lowest SEC relative to the two former ones; besides, it is the most frequent arrangement in industrial MED units [52]. A schematic of the PCF-MED method is depicted in **Figure 9**. The GOR of a MED unit is a function of the evaporator temperature at the last effect. It is not substantially affected by the feed stream temperature [1].

#### 4.5.4. Solar-Powered Reverse Osmosis (RO)

As a technique applied in desalination, RO is expanding at an incredible rate and is anticipated to override a market part of 9 billion US dollars by 2022 [1] [32]. Furthermore, RO stays one of the most performant desalination techniques thanks to its low SEC (2 × 5 kWh/m$^3$) and elevated averages of acceptance (*i.e.*, dominating 65% of parts of the installed desalination capacity throughout the globe [30]). **Table 2** lists the main reasons RO is better than other techniques [53].

As a pressure-driven technique, salt is separated from water by a semipermeable membrane in the RO process through a solution-diffusion pathway [32]. Saline water is directed to the membrane with high pressure to overcome the osmotic pressure. Freshwater is collected from the permeate side, and concentrated brine is rejected [47]. The operating pressure in SWRO is between 77 and 55 bar, and in BW, RO is between 15 and 30 bar [1]. The RO process consists of three stages [55], as listed in **Table 3**.

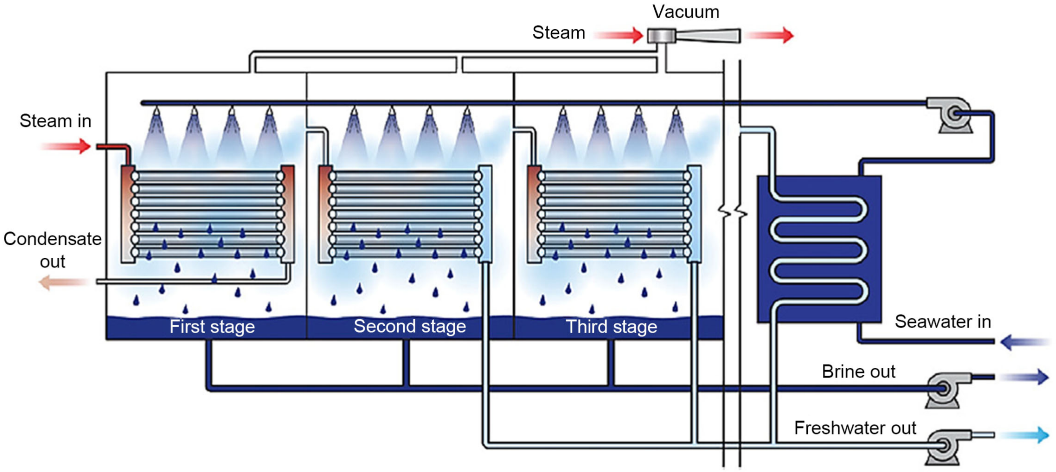

**Figure 9.** Schematic of parallel cross-feed-multi-effect distillation (PCF-MED) unit [29].

**Table 2.** Arguments for RO domination on different processes applied in desalination [53].

| Reason | Description |
|---|---|
| *Reason #1* | RO generation potential changes from standalone units (with a production potential < 1 $m^3$/day) to units with larger scales (a production potential > 53,105 $m^3$/day). |
| *Reason #2* | RO functions in a large span of feedwater salinity (*i.e.*, from BW to SW). |
| *Reason #3* | RO units work constantly and indeed without enlarged shutdown times. |
| *Reason #4* | RO units with low SEC function in the domain of 2 - 4 kWh/$m^3$, close to the thermodynamic limit of 1 kWh/$m^3$ for SW. |
| *Reason #5* | $C0_2$ emissions from seawater reverse osmosis (SWRO) units are in the interval 1.7 - 2.8 kg$CO_2$/$m^3$, which is the smallest quantity relative to other desalination techniques, even if the amount of $CO_2$ emissions from MSF distillation units is in the span 15.6 - 25 kg$CO_2$/$m^3$ and from MED units is in the span 7 - 17.6 kg$CO_2$/$m^3$. |
| *Reason #6* | The RO technique stays cost-effective thanks to constantly lowering water treatment costs. For example, five years ago, for RO units with a larger scale and a production potential of >43104 $m^3$/day, production costs were in the interval of 0.8 - 1.2 \$/$m^3$, which is anticipated to diminish by more than 60% during the following two decades to attain 0.3 - 0.5 \$/$m^3$ [54]. |

**Table 3.** Four RO process stages [55].

| Stage | Description |
|---|---|
| *Stage #1*<br>*Pretreatment* | Using valuable chemical agents that may comprise percolation and sterilization to reduce scaling and fouling. |
| *Part #2*<br>*Treatment* | HPP to furnish the pressure difference necessary to force water along the semipermeable membrane to separate freshwater from saline water. |
| *Part #3*<br>*Posttreatment* | Injecting chemical products to generate high-quality freshwater. |

Thanks to its low SEC, the RO process juxtaposed with different desalination technologies, RO-founded renewable energy has attracted more interest [1]. The SEC is composed of two parts [53]: 1) The energy required for the RO process itself, which is a function of water quality, membrane efficiency, pump efficiency, recovery rate, and energy recovery device (ERD) utilized, varies between 1.7 and 2.5 kWh/m$^3$. 2) Energy required for secondary methods, comprising feedwater pumping, pretreatment, and unit electrical services, varies from 0.3 to 1.5 kWh/m$^3$. Decreasing SEC is attained by innovating membrane material valleys, ERDs, and pumps [56]. Currently, commercialized membranes are capable of 99.8% desalination with a flow rate of 0.16 - 1.2 m$^3$/m$^2$/day over more than 30 years [1]. ERDs employ the energy remaining in the brine to pressurize the feed [1]. Augmenting 2% in the pump efficiency leads to a considerable decrease in SEC, particularly for feedwater with high salinity (e.g., SW) [56]. Operational indicators, such as feed salinity, permeate quality, recovery rate, and feed temperature, influence the needed pressure and energy consumption [57]. Electric and mechanical pumps may furnish the required pressure [32]. To provide electrical and mechanical power in RO units, PV and solar thermal methods are appropriate, even if, in the case of thermal techniques, a thermal energy unit or thermal energy-driven pumps are requested for pressurizing the feed [32].

1) *Photovoltaic-reverse osmosis* (*PV-RO*)

**Figure 10** shows a schematic of a PV-powered RO desalination system. The PV-driven RO desalination system was introduced in the 1980s and has become a market leader among solar desalination technologies [58]. Solar PV is proper as a driver for RO units owing to the following reasons [53]: 1) the modularity of PV modules makes it possible to run them with the RO system at various scales, and the capacity of these modules can be boosted after initial installation. 2) PV modules need little maintenance and have a lifespan longer than 20 years. 3) Areas that require a lot of water consumption generally have a lot of solar radiation that makes PVs adapt to the intended use. 4) The predictability of the daily/monthly/yearly solar energy facilitates planning for unit performance during any period. 5) Water storage capacity means mitigating the need for energy storage (e.g., during the night or solar lulls) [1].

The SEC of PV-RO prototypes changes between 1.1 and 16.3 kWh/m$^3$, related to the system size, battery life, feed source, pretreatment, and ERD type [59]. The water cost of a PV-RO system is around 15.6$/m$^3$ when the membrane life is five years [47]. Decreasing PV costs (following solar insolation, type of source water utilized, system size, and government policies) makes PV-RO systems more practical [1]. Several investigators focused on the PV-RO systems' feasibility and suggested numerous configurations augmenting them. Employing PV with batteries in the RO system was unsuitable due to high costs [59]. In battery-less PV mode, diverse techniques can be employed, comprising a direct connection between the PV and the DC motor to start the high-pressure RO pump and using a supercapacitor as an electrical regulator or a controlled DC/DC

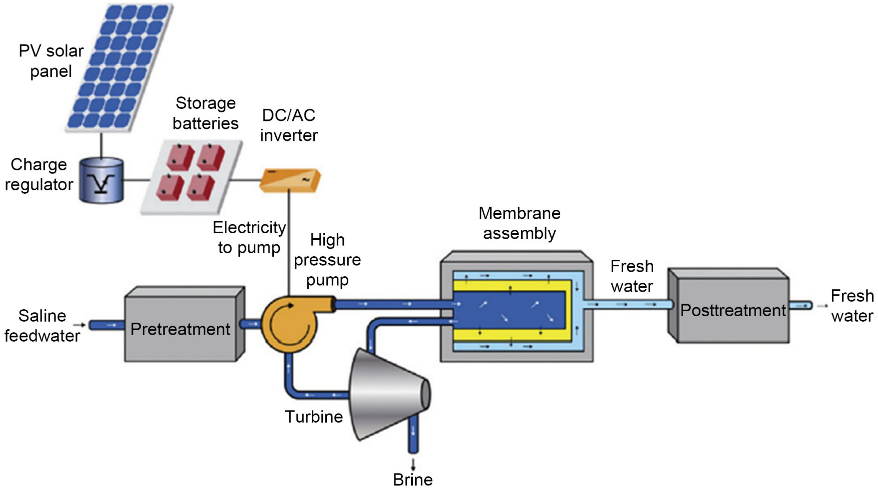

**Figure 10.** A picture of photovoltaic-reverse osmosis (PV-RO) desalination unit [29].

converter. The efficiency of a PV-RO unit in two modes, namely using the battery as an energy storage system and connecting directly to the PV array, showed that in the case of no need to charge the battery or charge controller in direct connection mode, the system is less complex [1] [60] [61].

Techno-economic analyses for diverse configurations of PV-RO systems (e.g., RO unit that is alternately driven by diesel engine, RO unit that is directly connected to PV array, and RO unit that works by combining PV and diesel engine) depict that PV-RO systems are more economically feasible than diesel-equipped systems, provided that there would be sufficient solar insolation [1]. Even with this, the extensive implementation of PV-RO on both small and large scales usually is restricted due to high energy costs that can be overcome by boosting the energy efficiency of PV-RO systems. In the case of the PV system, the trouble of the variability of the solar energy source should be solved by developing energy storage devices or batteries. In the case of RO systems, energy efficiency should also be increased through better-performing membranes, ERDs, and more efficient pumps [32]. Upgraded process design enhanced RO systems' efficiency [32].

2) *Solar thermal-driven reverse osmosis* (*ST-RO*) *system*

In a solar thermal reverse osmosis (ST-RO) system, heat can be received by the collector and transferred to the power conversion unit (PCU) or/and heat storage module [32]. The PCU consists of a power cycle that provides electrical or mechanical energy to the RO system [1]. One of the most considered power cycles is the organic Rankine cycle (ORC). When ORC is combined with RO, the ORC can employ cold feedwater as a heat sink that heats the feedwater and improves the membrane flux [1]. Other power cycles, such as steam Rankine cycles, Stirling engines, and Brayton cycles, are employed in solar heating systems. However, the Rankine cycle stays a good choice for ST-RO systems owing to its simplicity and the most prominent power cycle for ST-RO [32].

An ORC is a thermodynamic power cycle that can convert heat into mechanical energy using organic working fluid [47]. An ORC has pumps, evaporators, turbines, and condensers [61]. An ORC-based ST-RO system has a solar field, the Rankine cycle, and RO unit(s) [61]. In the solar field, a flat plate, evacuated tube, and/or PTC are employed to supply the thermal energy of the Rankine cycle [61]. The organic operating fluid can be pressurized and injected into the evaporator. It is heated inside the evaporator to evaporate through heat exchange with a high-temperature fluid. After that, the generated steam is expanded inside the turbine, and the necessary mechanical power is provided to start the HPP of the RO unit. Meanwhile, to increase the membrane's permeability, saline water can be preheated in the condenser [47]. This process is shown in **Figure 11** [1].

Optimizing solar-driven ORCs to increase efficiency is vital in creating a vision for scaling ST-RO systems [32]. In addition, advances in the design and efficiency of solar thermal power cycles also make the prospect for ST-RO scaling up [62] [63].

3) *Comparison between photovoltaic-reverse osmosis* (*PV-RO*) *and solar thermal-driven reverse osmosis* (*ST-RO*)

Unlike the PV-RO system, which is relatively mature and can be found at many scales, ST-RO systems are in the preliminary stages [1]. Recently, PV-RO units have been reported from small to medium scale with a capacity of 0.2 - 200 $m^3$/day for SW and BW desalination [1]. In contrast, ST-RO units have been tested for larger-scale desalination systems, with a capacity of $1.186 \times 10^3$ - $5 \times 10^4$ $m^3$/day. Nonetheless, power plants have yet to be reported to be serviced [1]. Analyses show that the PV-RO system's water production cost is 8.855$/$m^3$, while the solar-driven ORC-RO system is 13.78$/$m^3$ [64]. The cost of the solar-driven ORC system is expected to decrease by 30% after maturing and

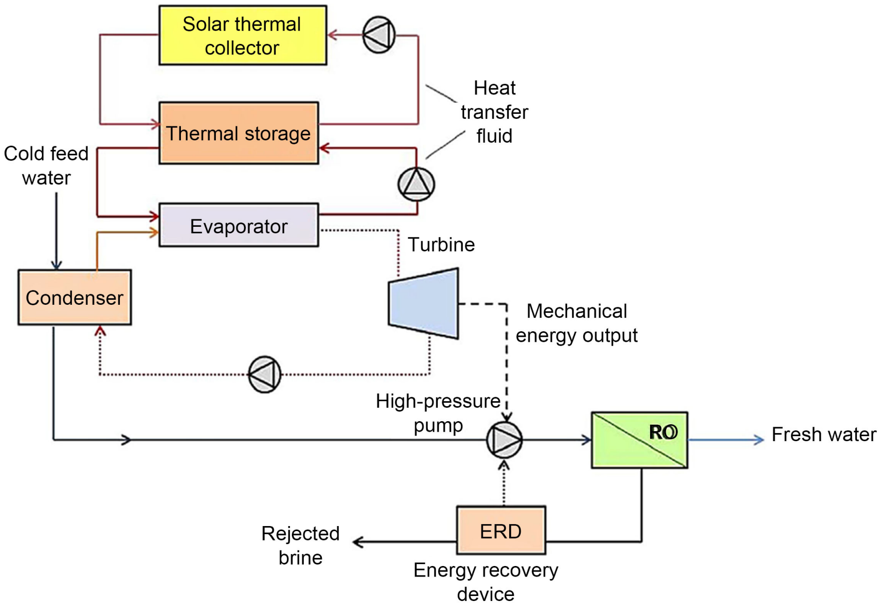

**Figure 11.** Solar organic Rankine cycle (ORC)-driven reverse osmosis (RO) system [47].

commercialization [64]. The levelized cost of electricity for ORC is 27% lower than that of a PV-powered system with energy storage [65]. **Table 4** lists the RO-based solar power plants with the capacity and type of solar technology used. Al Khafji is the World's first solar-powered plant with a large scale based on PV-RO. Water production capacity in Al Khafji varies between 16 and 60,000 $m^3$/day [32].

**Table 4.** Specification of installed or under installation solar-powered reverse osmosis (RO) plants (BW, brackish water; SW, seawater; WW, wastewater) [32].

| Location/online year | Capacity ($m^3$/day) | Feedwater | Solar system | Collector type |
|---|---|---|---|---|
| United States (Genesis Solar)/2013 | 3168 | BW (3000 - 20,000 ppm) | Concentrator solar power (CSP) | Parabolic trough |
| Tunisia (Ben Guerdene solar-powered BWRO)/2013 | 1800 | BW | Photovoltaic (PV) | - |
| Saudi Arabia (Al Khafji solar-powered SWRO)/- | 60,000 | SW (20,000 - 50,000) | PV | - |
| Mexico (Centro Morelos Solar Power Plant)/2014 | 840 | BW | PV | - |
| Mexico (Baja California Sur IV Solar Power Plant)/2014 | 48 | BW | PV | - |
| Madagascar (Beheloke Brackish Solar)/2012 | 16 | BW | - | - |
| Spain (Arenales Solar Power Plant)/2013 | 480 | BW | CSP | Parabolic trough |
| Spain (Olivenza Solar Power Plant)/2013 | 720 | BW | CSP | Parabolic trough |
| Brazil (Solar, Fortaleza)/2014 | 3600 | BW | PV | - |
| Algeria (Hassi R'Mel Solar Thermal Plant)/2011 | 1577 | WW | Solar thermal | Parabolic trough |
| United States (California Valley Solar Ranch Water System)/2012 | 75 | BW | PV | - |
| Qatar (Qatar Solar Technologies Polysilicon Project, Ras Laffan)/2013 | 12,000 | SW | PV | - |
| Vanuatu (Solar-powered SWRO plant, Aniwa Island)/2013 | 96 | SW | PV | - |

## 5. Solar Disinfection

Approximately 2 billion people in the World consume fecal-contaminated drinking water, and 2.3 billion people lack adequate sanitation. Such circumstances conduct to water-borne diseases [1]. With more than 2.2 million deaths annually, it is the leading cause, mostly in developing countries. Cholera, typhoid fever, dysentery, and hepatitis A virus remain the most frequent water-borne diseases. In developing countries, most wastewater (WW) is discharged into the environment without treatment, contaminating surface waters and transmitting water-borne diseases. Also, the diffusion of pathogens and the prevalence of water-borne diseases depend on environmental and climatic conditions. With the increase in the frequency and severity of tropical storms, droughts, and floods caused by climate change in the future, the health problems related to drinking water are expected to escalate [66] [67].

Several disinfection techniques have been suggested and employed to supply secured potable water [1]. Disinfection aims to eliminate pathogens that engender water-borne disease. Two usual processes perform disinfection: 1) physical techniques, comprising sedimentation, filtration, ultraviolet (UV) radiation, and pasteurization, and 2) chemical techniques, involving coagulation, chlorination, chloramination, chlorine dioxide treatment, and ozonation. Such techniques are energy-intensive and need considerable capital, expertise, and infrastructure. Water treatment methods are employed on large and medium scales and have successfully maintained public health against water-borne diseases [66]. Energy and water remain two vital and correlative sources, without which the other cannot be produced or supplied. The energy-water nexus has attracted considerable awareness about the increasing energy demand in the water sector, especially the water disinfection process. Traditional disinfection methods consume 0.25 - 1 kWh/m$^3$ of energy, accounting for around 2% - 3% of the World's energy consumption [68]. Nonetheless, as demand for high-quality drinking water increases, energy consumption in the water treatment sector will increase. Consequently, high energy consumption in water treatment plants, besides the energy crisis following the global increase in energy consumption and increasing GHGs emissions, highlights the need to use sustainable technologies in water treatment processes. Meanwhile, solar energy is one of the most efficient sustainable energy sources for disinfection.

Solar disinfection is not a new technique. In the late 1870s, Downes and Bluent [1] first suggested the bacterial effect of sunlight and the relationship between parameters, including solar radiation intensity, solar exposure duration, and wavelength, with the inactivation of bacteria. In numerous developing countries where potable water supply is not possible because of a lack of local electricity network, high electricity costs, and lack of access, and the high price of chemicals for treatment, solar disinfection could be utilized as a low-cost, electricity- and chemical-independent solution [66]. Nevertheless, its most widespread use is in rural and remote areas with low access to safe drinking water and high access to solar radiation [1].

### 5.1. Solar Water Disinfection (SODIS)

Solar water disinfection (SODIS) is an easy, stable, and low-cost water treatment method that kills pathogens by utilizing the germicidal effect of UV rays and heat production [66] [69]. More than 5 million people in more than 50 countries in Asia, Latin America, and Africa use this method daily for drinking water treatment. In this method, water is exposed to sunlight in a transparent glass or plastic container (usually 2 L PET bottles). Exposure time varies from 6 to 48 h according to the radiation intensity and pathogens' resistance [70] [71] [72]. Unlike the conventional UV method in WW treatment, where UVC rays penetrate directly into the DNA of pathogens and destroy DNA strands, in the SODIS process, UVA rays first form reactive oxygen species (ROSs) in water; then, these species destroy the DNA of pathogens and inactivate microbes [73] [74] [75]. **Figure 12** shows a simple schematic of the SODIS process [70], **Figure 13** illustrates a schematic diagram of general mechanisms of action of sunlight for water photocatalytic disinfection [76], and **Figure 14** depicts scanning electron microscopy (SEM) images of *Enterococcus* sp. (a-c), *Staphylococcus aureus* (d-f), *Escherichia coli* (g-i) and *Salmonella* (j-l) during photocatalytic disinfection process by P/Ag/$Ag_2O$/$Ag_3PO_4$/$TiO_2$ (PAgT) composite under visible light irradiation [77].

It is recommended that disinfected water be used within 24 h to prevent post-exposure regrowth. However, disinfection efficiency in this basic system can be increased through the following strategies [70]: 1) Putting filled bottles on reflective plates: to increase the absorption of solar energy; 2) Blackening the bottom surface of the SODIS reactor: to increase solar heat; 3) Shaking a two-thirds filled bottle before exposing it to the sun: to increase the level of dissolved oxygen for solar-induced oxidative inactivation processes, and 4) Filter water before filling the reactor [1].

Although conventional plastic bottles are cost-effective, the main drawback is the limited capacity (less than 2 L) of this type of reactor. Glass bottles are one of the best alternatives to plastic. Ordinary glass bottles can transmit 90% of solar radiation, especially wavelengths in the UVA range [78]. The heaviness of the bottle after filling and the possibility of injury to people after breaking the bottle are problems of this type of reactor. Another option is PET bottles. Undamaged PET bottles pass about 85% - 90% of the UVA wavelength and block the UVB wavelength [1]. Under conditions of long-time exposure, the release of chemical compounds in plastic and reaction with water is a significant problem for using these reactors [70]. The PET bag is also used as a SODIS reactor. The exposure area is maximized in these bags, made of low-density polyethylene [79], and the path length for light penetration into water is minimized [70]. To improve the performance, the bag is placed on a black screen [70]. In remote areas with a shortage of PET bottles, using SODIS bags with the possibility of easy transportation and storage in large numbers would be a good option [70] [80].

### 5.2. Solutions to Boost Solar Disinfection

In SODIS bottles, sunlight shines only on the upper surface so that most radiation does not reach the water. To increase the radiation the bottle receives, efforts have been made to concentrate sunlight, including reflective surfaces and low-cost concentrating equipment [81]. Other practical solutions to increase the efficiency of solar disinfection include using chemical additives such as photocatalysts, sodium percarbonate, lemon juice or pulp, and riboflavin [66]. **Table 5** lists two methods of using reflective surfaces and concentrating equipment and adding photocatalysts to improve the efficiency of solar disinfection [1].

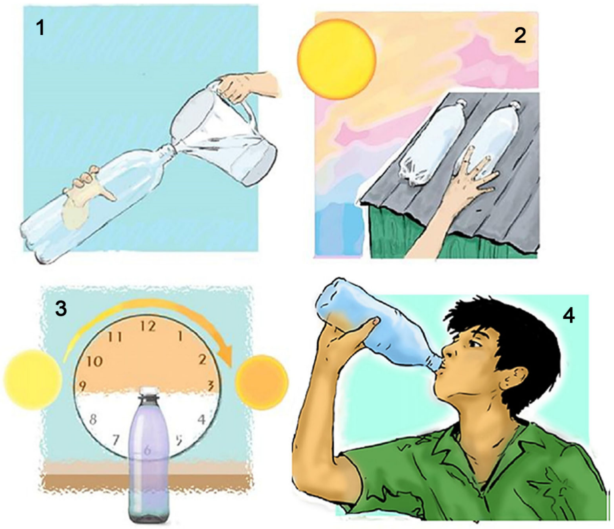

**Figure 12.** Graphical descriptions for Solar water disinfection (SODIS) household water treatment process [70].

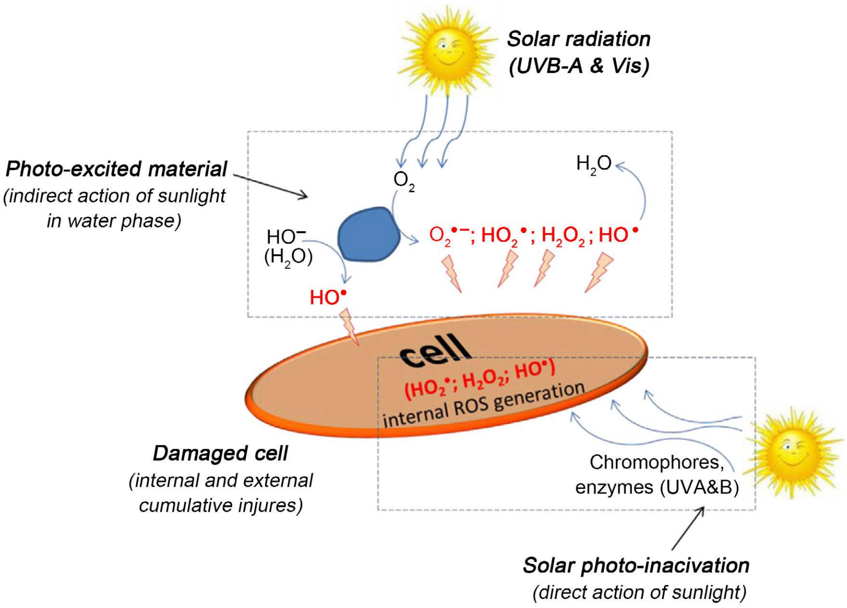

**Figure 13.** Schematic diagram of general mechanisms of action of sunlight for water photocatalytic disinfection [76].

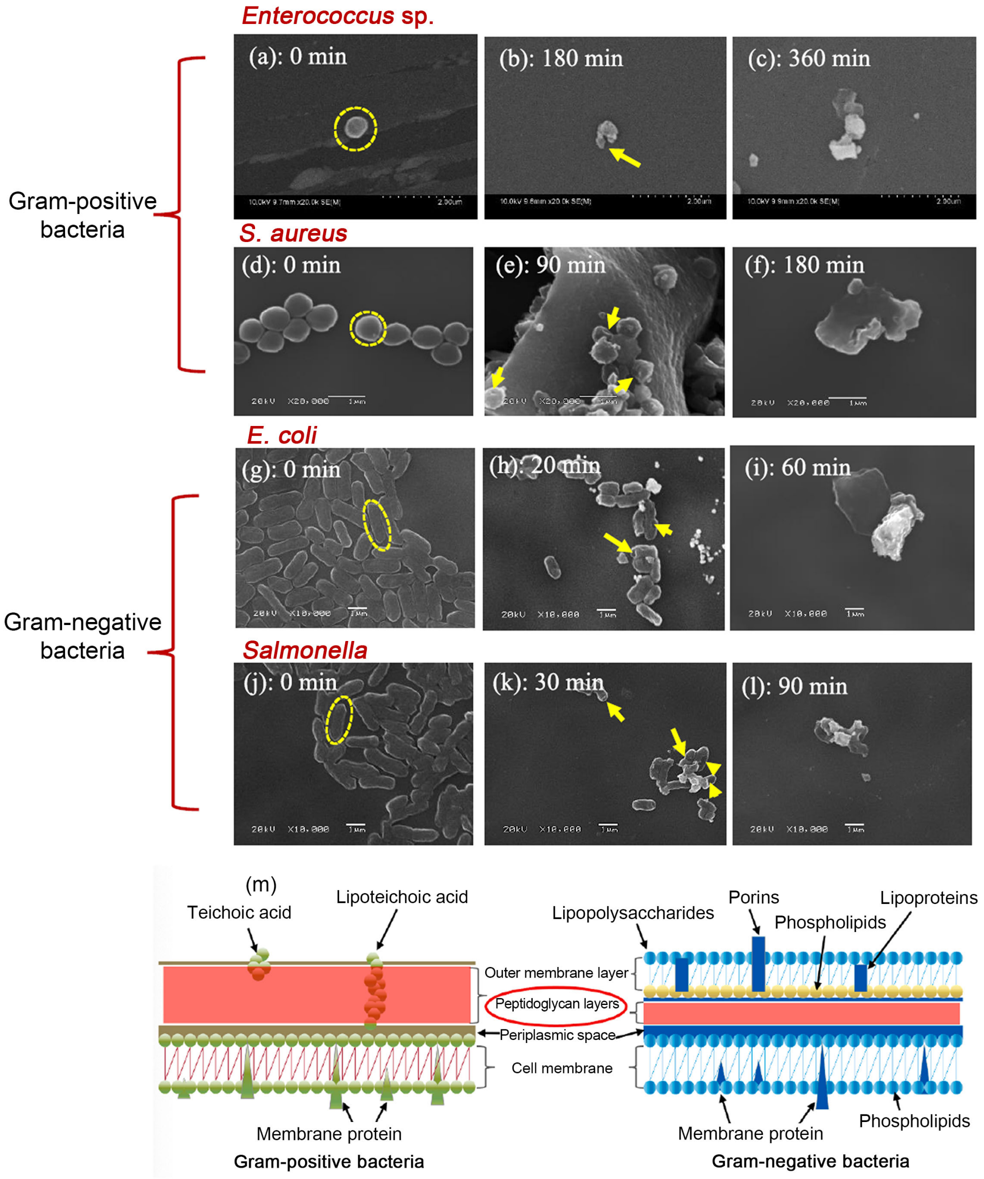

**Figure 14.** Scanning electron microscopy (SEM) images of *Enterococcus* sp. (a)-(c), *S. aureus* (d)-(f), *E. coli* (g)-(i), and *Salmonella* (j)-(l) during photocatalytic disinfection process by PAgT composite under visible light irradiation and (m) schematic of the cell wall structure of Gram-positive bacteria and Gram-negative bacteria [77].

### 5.3. Photovoltaic-Solar Water Disinfection (SOLWAT)

PV-solar water disinfection (SOLWAT), a hybrid system for disinfection and electricity generation, has been developed according to the use of solar energy. In this system, several conversion mechanisms occur for two final applications (PV to generate electricity and heat and UV to disinfect). As a result, this system has low energy consumption and good performance. Therefore, it is suitable for industrial water treatment systems or remote rural regions that do not have access to drinking water and electricity [98]. The schematic of the SOLWAT system is displayed in **Figure 16**.

**Table 5.** Two methods of using reflective surfaces and concentrating equipment and adding photocatalysts to improve the efficiency of solar disinfection [1].

| Method | Description |
|---|---|
| *Thermal enhancement* | Since there is a high synergy between optical and thermal inactivation at temperatures above 45˚C, many strategies are developed to improve thermal inactivation [1]. In general, the thermal enhancement solutions of the SODIS reactor are [70]: blackening the bottle, circulating water on a black surface as a solar energy absorber, and using a collector and solar reflector. Blackened bottles have the lowest efficiency in converting solar energy into heat [1]. Unlike blackened surfaces, reflectors reflect UVA rays even on cloudy days. Thus, even on cloudy days, optical inactivation and an increase in water temperature for disinfection occur [70]. Using solar mirrors as reflectors reduces disinfection time to 3 - 4 h [82]. Combining the SODIS process with concentrating parabolic collectors in less than 6 h results in the complete disinfection of water [83] [84]. |
| *Photocatalysis* | Photocatalysis is one of the most effective technologies for mineralizing resistant organic compounds and inactivating water pathogens among advanced oxidation processes (AOPs) [85] [86]. Photocatalysts are divided into two categories: heterogeneous (semiconductor catalysts for water treatment) and homogeneous (photo-Fenton process) [87]. In the heterogeneous photocatalysis process, stubborn organic matter is degraded by the combined action of a semiconductor photocatalyst, an energy source, and high ROSs [88]. Among semiconductor photocatalysts, $TiO_2$ is one of the most widely used photocatalysts in water treatment applications [70]. For example, solar photocatalytic processes with $TiO_2$ photocatalysts are used to disinfect water, in which UVA-resistant microorganisms are inactivated by the $TiO_2$ photocatalyst [89] [90].<br>The photo-Fenton process is the most familiar homogeneous solar photocatalytic process in water treatment [91]. The Fenton oxidation process is an AOP process, which produces $^•OH$ radicals by the catalytic reaction of $H_2O_2$ with iron ions (see **Figure 15**). The photo-Fenton process ($Fe^{2+}/H_2O_2$/UV vis) has a higher oxidation rate, lower iron consumption, and less sludge production than the Fenton reaction [47] [92]. In this process, owing to light radiation in the range of near UV to visible and up to 600 nm wavelength, free radicals are formed and cause water disinfection [93]. The non-selectivity of this process has made it possible to remove a wide range of antimicrobial-resistant microorganisms [94] [95]. Parameters affecting the efficiency of this process are pH, temperature, the concentration of hydrogen peroxide ($H_2O_2$), iron and their ratio, and the intensity and wavelength of radiant light [96]. The type of light source has been shown to affect the disinfection of hydrogen peroxide significantly. As a result, the higher intensity of light radiation leads to a higher disinfection rate [1] [97]. |

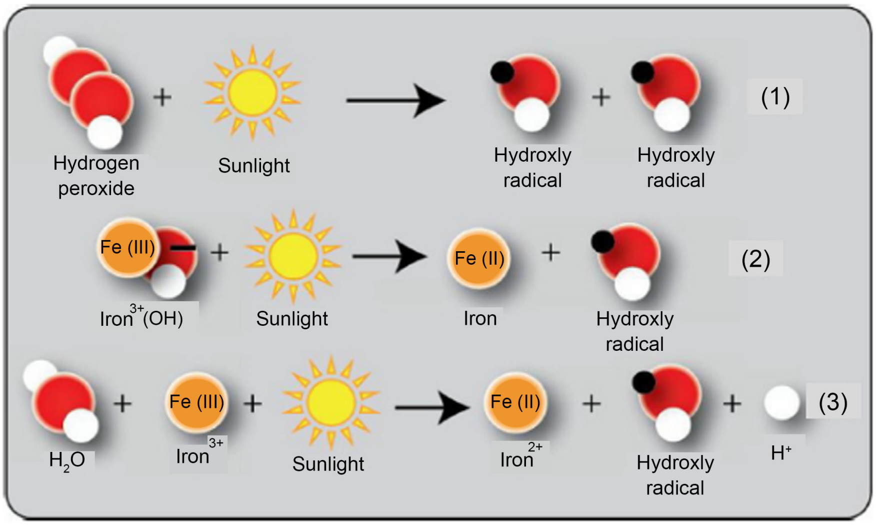

**Figure 15.** Photo-Fenton mechanism [96].

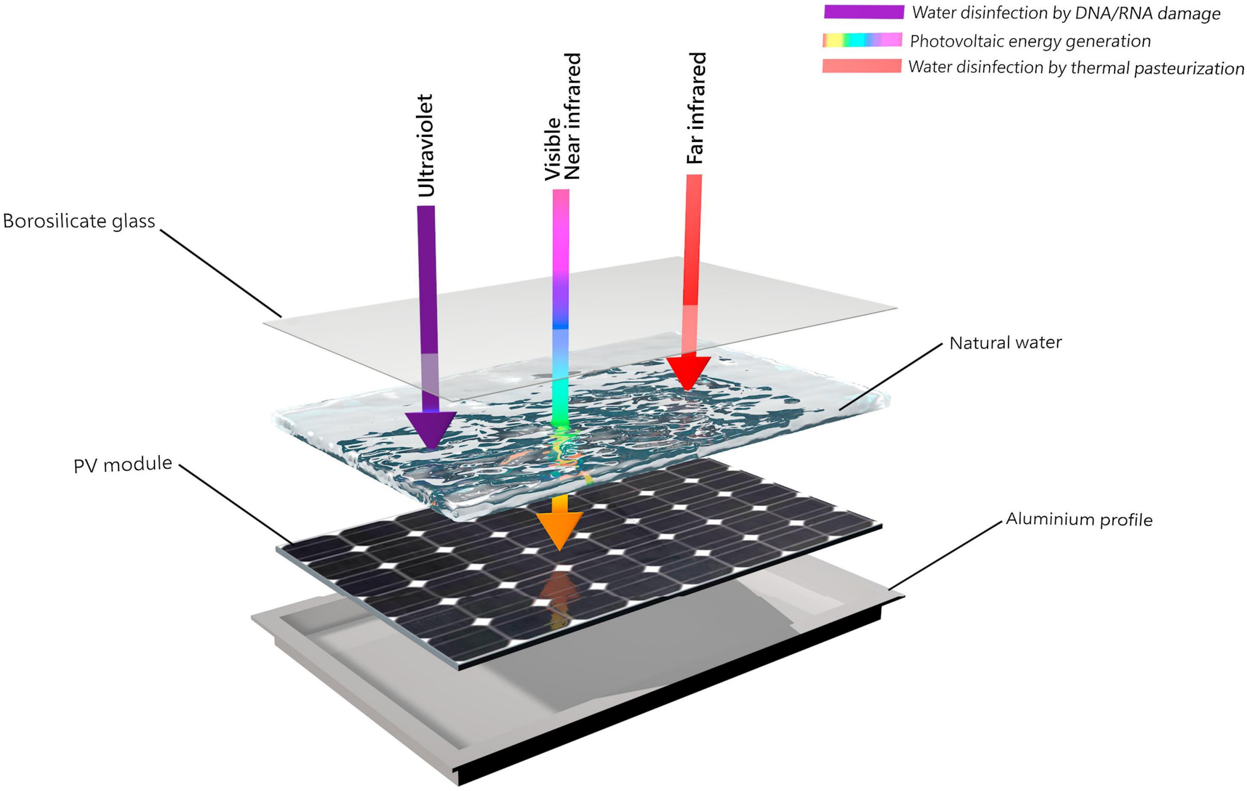

**Figure 16.** Photovoltaic-solar water disinfection (SOLWAT) system design and configuration, including the solar spectrum usage [98].

The SOLWAT system performs better than PET bottles in water disinfection owing to the difference in PET bottle configuration (PET, cylindrical, and 38 mm of water thickness) compared to the SOLWAT system (flat, borosilicate, and 18 mm of water thickness) that prevents the penetration of light and reduces the absorption of solar radiation in water. The SOLWAT system can reach a temperature of 45˚C and even 50˚C in 3 - 5 h, in which case the synergy between UV and temperature improves disinfection. On the other hand, in PET bottles, disinfection is performed at temperatures between 20˚C and 45˚C for 6 h. In SOLWAT systems, the water layer on the PV module has a cooling effect and therefore eliminates the adverse effects of temperature on the module efficiency [1] [98].

A V-trough concentrator and a low concentration of hydrogen peroxide (5 mg/L) can be used to enhance the SODIS process in the SOLWAT system [99]. According to the results, in concentrator + water mode, compared to non-concentrator + water mode, the complete disinfection time of 8 L of water was reduced to 1.25 and 2.5 h for *E. coli* and *Salmonella*, respectively. Regarding power generation efficiency, the module's output power in concentrator + water mode reached 43 W, the highest value compared to the reference mode (26.1 W) and non-concentrator + water mode (24.1 W).

A photocatalytic treatment system can be combined with a PV system [100]. This system absorbs the solar spectrum more effectively. The photocatalytic reaction absorbs the UV spectrum. The visible and near-infrared (IR) spectra are absorbed by solar cells [101] [102]. The far- and near-IR spectra are absorbed by water (see **Figure 17**). Since only the two visible and near-IR spectra reach close to the surface of the PV cell, there is no increase in heat owing to the loss of other solar spectra, and the efficiency of the module increases by up to 35%.

Despite SODIS effectiveness, the restrictions of long exposure and bacterial regrowth [103] risk need more practice refinement. Shekoohiyan *et al.* [104] produced an iron oxide film on the inner surface of PET bottles employed in SODIS to form more mechanisms of solar-mediated inactivation, *i.e.*, a semiconductor mode of action and controlled iron leaching in the system, which both have demonstrated bactericidal capacity. Indeed, the deposition process utilizing Fe salts has been scrutinized, assessing the use of various homogeneous Fe precursors ($FeCl_3$, $FeSO_4$, and $Fe_2(SO4)_3$), amounts of iron (0.5 - 20 g/L) and deposition time (1 - 8 h) to find the delicate balance among deposition layer thickness and light penetration. At the best situations (4 h deposition, one g/L $FeCl_3$), SODIS was enhanced, reducing 60% the exposure time; by a simple washing, step brought a further reduction (70%) while eliminating regrowth in volumes from 330 up to 1500 mL reactors. A robust process and reactor were attained, able to reuse its precursor solution almost ten times and the reactor in 5 consecutive tests without re-deposition. The modification was also an invaluable iron source to fuel the photo-Fenton process when $H_2O_2$ was added to the system as an electron acceptor. The improvement induced by the heterogeneous photo-Fenton process was around 80% compared to the SODIS/$H_2O_2$ process in plain PET bottles and exceeded 85% when compared to SODIS while being durable to the high oxidative conditions (**Figure 18**). Finally, given the application in drinking water treatment, the process performed well in the lightly acidic region due to the physicochemical implications of natural waters' pH in iron cycling [104].

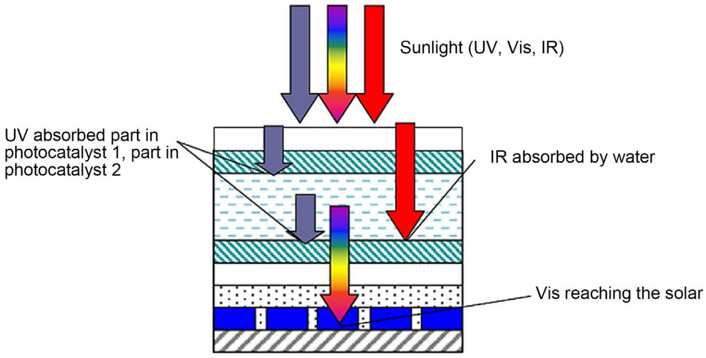

**Figure 17.** Spectral absorbance diagram of an integrated purified water and power system, ultraviolet (UV) is absorbed by each photocatalytic layer, far-infrared (IR) is absorbed by water, and visible and near-IR is absorbed by the photovoltaic solar cells [100].

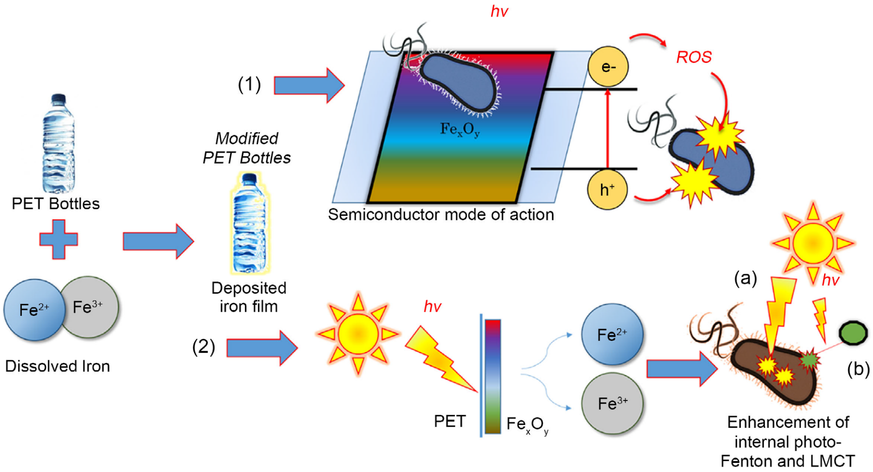

**Figure 18.** Suggested inactivation route attempted by modifying PET bottles with Fe salts [104].

Recently, García-Gil *et al.* [105] developed and validated a mechanistic kinetic model of SODIS *E. coli* inactivation, enhanced with $H_2O_2$. They suggested a mechanistic model involving *E. coli* cellular respiration, inactivation due to $^{\bullet}OH$ and $O_2^{\bullet-}$ radicals, and bacterial thermal inactivation using a series-event model based on the accumulation of damage and cell recovery corrected with the Arrhenius equation for inclusion of the thermal events. The contribution of external $H_2O_2$ was included in the internal $H_2O_2$ balance. In contrast, the balance of extracellular $H_2O_2$ is considered the consumption caused by its self-decomposition, interactions with cells' membranes, and organic matter from dead cells. Such a kinetic model helps to understand the intracellular mechanisms and the contributions of each source of inactivation, with the role of radicals' damage being most important at temperatures below 40˚C and the thermal inactivation for temperatures above this value [105].

McMichael *et al.* [106] designed and tried a photo-electrochemical reactor (PEC) with a compound parabolic collector (CPC) for the electrochemically assisted photocatalytic (EAP) disinfection of rainwater under actual sun conditions. The reactor consisted of a Ti mesh coated with aligned titania nanotubes with a carbon counter electrode in a concentric tubular configuration within a borosilicate glass tube with a CPC (**Figure 19**). Under real sun irradiation, EAP yielded a 5.5-$\log_{10}$ reduction for *E. coli* and a 5.8-$\log_{10}$ reduction for *Pseudomonas aeruginosa* for culture-based analysis. The EAP treatment also showed improved results by EMA-qPCR analysis with a 2.4-$\log_{10}$ reduction in gene copies for *E. coli* and 3.0-$\log_{10}$ for *P. aeruginosa*.

## 6. Ecological Influence of New Techniques

It is frequently adopted that desalination technology is clean in supplying potable water [1]. However, like any other industrial process, this method has inherent ecological impacts [107]. Indeed, even if desalination technology possesses numerous social, economic, and public health profits, it is energy-intensive and thus harms nature [108]. Currently, the energy needed by desalination plants is furnished from fossil fuels. Consuming fossil fuels leads to GHGs emissions and air pollution. A discharge stream called brine is also generated in desalination engineering, along with the freshwater stream. Brine is a hypersaline solution containing chemical compounds considered environmentally hazardous. Brine disposal occurs in the marine environment, exacerbating environmental concerns [107]. Further, the impingement and entrainment of SW through submerged pipelines or open intakes along the shoreline remove fish eggs and tiny marine organisms such as plankton and larvae from SW. Releasing nutrients, organic matter, and organisms with SW leads to aggressive water pretreatment through more chemical additives and more frequent cleaning of filters and membranes, ultimately affecting the brine flow [1].

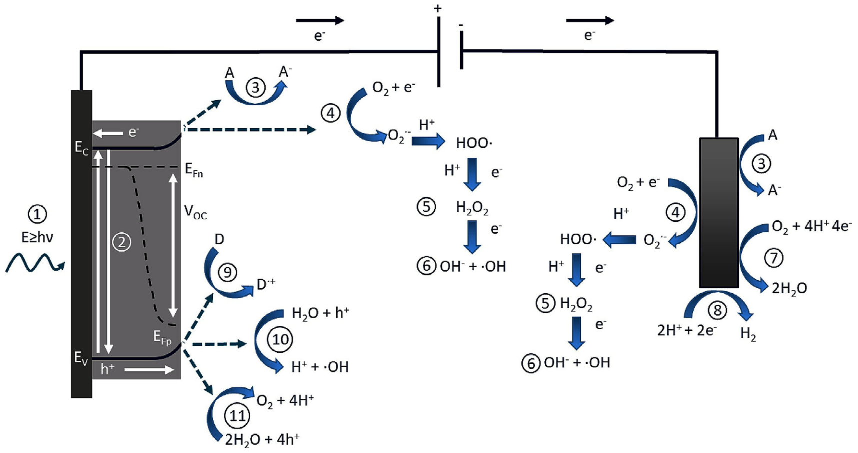

**Figure 19.** Diagram of the electrochemically assisted photocatalytic (EAP) process and pathways for radical production using a photoanode and a non-semiconducting counter electrode. 1) Photon absorption; 2) photo-excitation and recombination; 3) electron transfer to an electron acceptor; 4) oxygen reduction to superoxide; 5) formation of hydrogen peroxide; 6) formation of hydroxyl radical; 7) oxygen and proton reduction to water; 8) proton reduction to hydrogen; 9) donor electron transfer; 10) oxidation of water to form hydroxyl radical; 11) oxygen evolution reaction [106].

### 6.1. Brine Disposal

Brine (or concentrate or reject) is a highly concentrated by-product of desalination [109]. This liquid stream has many dissolved solids in the concentrated form [110]. The quality and quantity of brine depend on the quality of the feedwater, the pretreatment, the type of desalination process, and the water recovery rate. Besides high salinity, brine contains hazardous pretreatment chemicals (e.g., antiscalants, coagulants, and flocculants), organic matter [111] [112], and heavy metals. As a result, rejecting brine at sea harms the marine medium. Such unwanted impacts include eutrophication, pH fluctuation, and increasing concentrations of heavy metals in the aquatic medium [113].

Brine salinity is 1.6 - 2.1 times higher than SW (~35 g/L). Brine salinity for thermal processes (MSF and MED) is ranged from 55 to 65 g/L, and for the RO process, it goes from 60 to 85 g/L. This difference is owing to the higher water recovery rate (40% - 45%) of commercial and well-established RO units [107]. Researchers [1] found that even a marginal salinity increase upsets marine species' osmotic balance with the environment. It has a detrimental effect on marine life. Osmotic imbalance reduces turgor pressure and causes the extinction of marine species in the long-term run [1].

The temperature of the brine is related to the type of desalination process. Thus, the brine generated by membrane processes has a temperature equal to the temperature of SW (22˚C), and the brine temperature resulting from thermal processes is 1.37 - 1.82 times higher than the temperature of SW [113]. The higher temperature of brine than SW (30˚C - 40˚C) has destructive influences on marine life because the toxicity of metals and chemicals boosts with increasing temperature [1].

Heavy metals and chemical residues also have adverse effects on marine species. High temperatures in thermal processes cause corrosion of metal equipment. For example, the presence of Cu and Ni elements in brine is owing to the removal of Ni - Cu alloy because of wear in heat exchangers and pumps [1]. In membrane processes, owing to polymeric materials, the concentration of heavy metals is less than that to affect marine life [1].

The World currently produces $141.5 \times 10^6$ $m^3$/day of brine, 50% more than the total freshwater produced worldwide [1]. Seventy percent of the World's brine is made in the Middle East and North Africa (approximately 108 $m^3$/day) [4]. This is twice the amount of water produced in these areas. This fact shows that the desalination units work in these areas with a meager water recovery ratio of 0.25 [4]. Brine disposal techniques are surface water and sewer discharges, deep-well injection, evaporation ponds, and land application [113] [114]. Choosing the correct method depends on several factors, such as brine's quantity, quality, and composition, the geographical position of the disposal site, site accessibility, the permissibility of the option, social acceptability, costs, and facility potential [113] [114]. **Table 6** gives a brief description of each method.

**Table 6.** Summary of the brine disposal methods [113].

| Method | Concept | Cost ($/m$^3$ brine) | Ecological troubles |
|---|---|---|---|
| *Sewer discharge* | Brine rejection occurs in a sewage collection unit. | 0.32 - 0.66 | Bacterial growth is inhibited in WW treatment plants. |
| *Evaporation pond* | Brine evaporation occurs in a pond, and the remaining salt is gathered. | 3.28 - 10.04 | Groundwater is polluted, and soil can be salinized. |
| *Surface water discharge* | Brine rejects into surface water. | 0.05 - 0.30 | The marine environment can be polluted. |
| *Deep-well injection* | Brine rejection occurs in perforated subsurface rock formations. | 0.54 - 2.65 | Groundwater is polluted, and soil can be salinized. |
| *Land application* | Brine is employed in the irrigation of salt-tolerant crops and grasses. | 0.74 - 1.95 | Soil can be salinized. |

The zero liquid discharge (ZLD) approach, aiming at improving the water recovery rate by reducing brine production and thus reducing environmental impact, is a method of brine treatment [1]. The ZLD process recovers 90% - 95% of water. In addition, condensed solids are also disposed of in an environmentally friendly manner. ZLD consists of three stages: 1) preconcentration, 2) evaporation, and 3) crystallization. In the first step, membranes make water recovery and brine volume reduction. In the next two steps, thermal methods minimize the brine volume and solids production [113].

### 6.2. Energy Consumption and Greenhouse Gases (GHGs) Emission

Energy is a significant issue in the environmental assessment of desalination units. The energy can be used for desalination, freshwater and brine transportation, unit lighting, office equipment, etc. For industrial-scale desalination units, high energy consumption is considered the main obstacle [107]. The energy demand in desalination processes is related to the desalination technology (thermal or membrane), the type or quality of feedwater (SW, BW, and WW), and unit design (recovery system design, unit capacity, and energy recovery system efficiency) [115]. As a rule, membrane technologies (RO) require much electrical energy. On the other hand, the total energy required in thermal processes (MSF and MED), owing to the need for both thermal and electrical energies, is higher. In both cases, the required energy is easily supplied from fossil fuels [1].

Consuming fossil fuels is related to GHGs emitted [1]. **Figure 20** depicts the GHGs quantity emitted per cubic meter of freshwater generated when fossil fuels, renewable energy sources, and waste heat are employed. The emission rate of GHGs from thermal processes is at least ten times higher than the membrane process. Therefore, desalination has a critical role in air pollution [107].

One way to diminish the environmental consequences of high energy consumption in desalination processes is to power desalination units using renewable resources, including solar, geothermal, wind, tidal, or other alternative energy sources, including waste heat from industrial activities [1]. As illustrated in Figure 20, the emission rate of GHGs per cubic meter of freshwater is considerably decreased when utilizing renewable energy sources [56]. Scientists [116] employed life-cycle assessment (LCA) to evaluate the environmental impact of MSF desalination units in Qatar, wherein about 75% of the freshwater is supplied by MSF technology. They examined three MSF units with different GORs regarding climate change, freshwater eutrophication, ozone layer degradation, fossil fuel depletion, and human toxicity. The findings are illustrated in Figure 21 and Figure 22. In Figure 21, the numbers 1, 2, and 3 indicate the three MSF

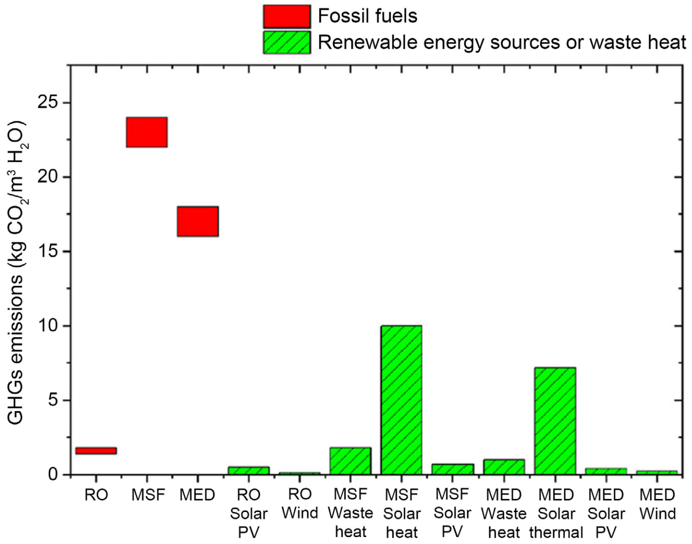

**Figure 20.** Greenhouse gases (GHGs) emissions per cubic meter of freshwater generated by the desalination methods [107].

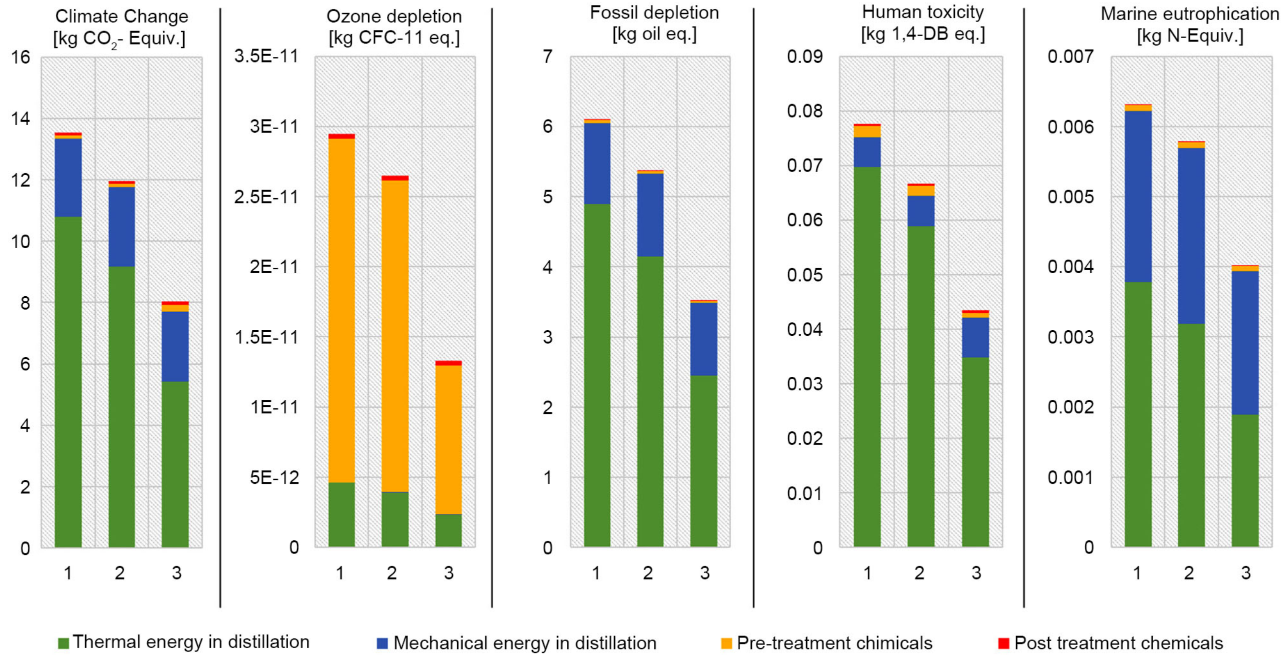

**Figure 21.** Findings of five categories for multi-stage flash (MSF) desalination unit [116].

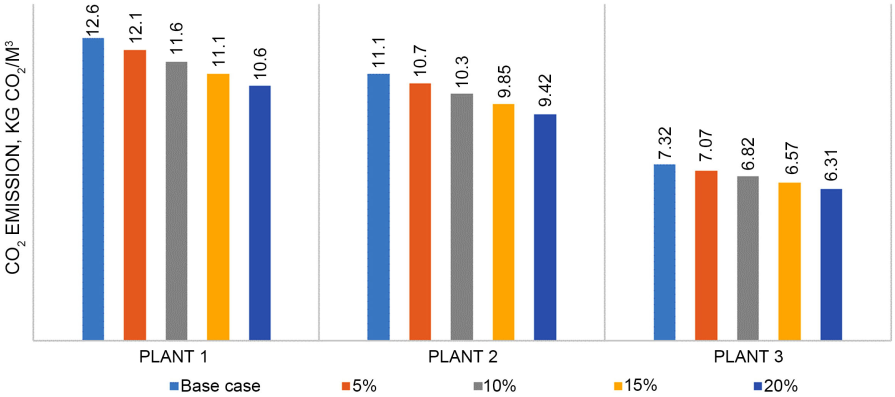

**Figure 22.** Decrease in $CO_2$ emission owing to integrating solar thermal energy for four various scenarios (coupling of 5%, 10%, 15%, and 20% of solar energy) together with the base case data for three multi-stage flash (MSF) units [116].

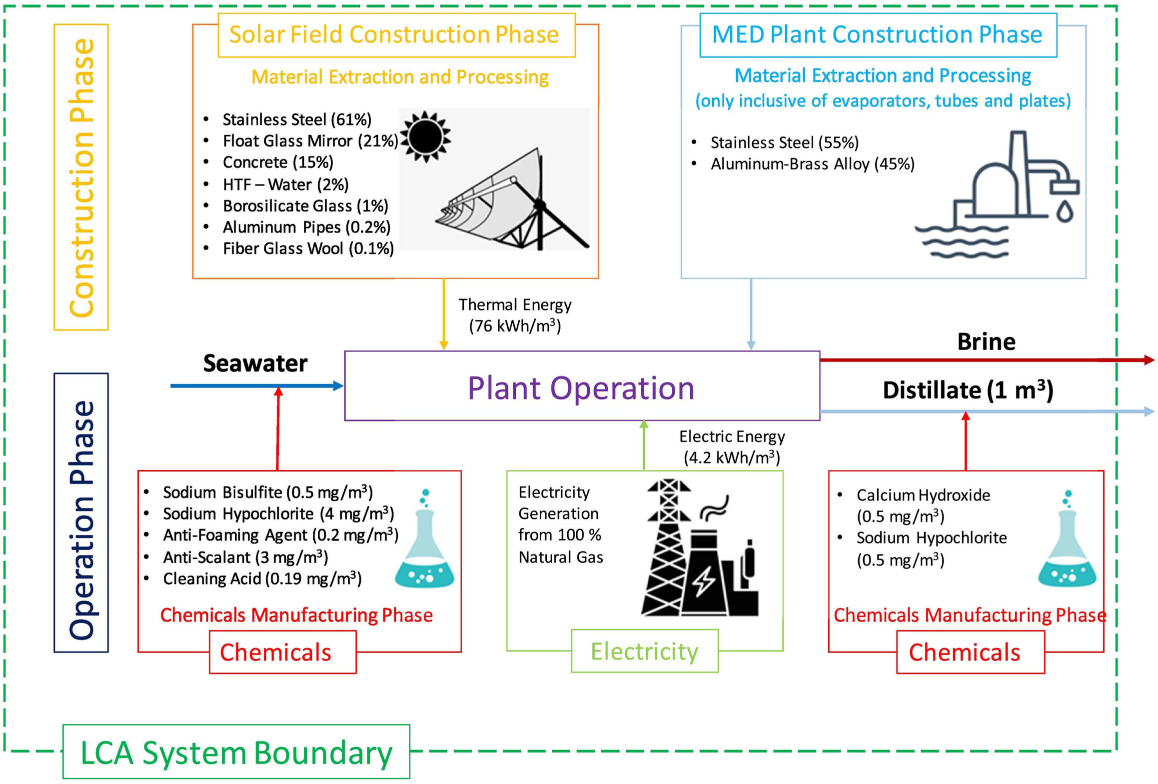

**Figure 23.** Life-cycle assessment (LCA) system boundary for a solar-integrated desalination plant. The proportionate mass contribution of each material to the total bill of materials is shown in the solar field and multi-effect distillation (MED) plant construction phases [4].

plants, including plants 1, 2, and 3, respectively. The GORs of plants 1, 2, and 3 are 8.21, 9.73, and 16.07, respectively. According to LCA results, desalination's most significant environmental impact is energy consumption. Increasing the GOR reduces the severity of ecological effects. Increasing the GOR reduces the severity of ecological effects. As a result, the amount of $CO_2$ emission from energy consumption is 7.32 kg in unit 3 (highest GOR) and 12.6 kg in unit 1 (lowest GOR). The same scientists [116] also investigated reducing $CO_2$ emissions by supplying the energy required by the MSF unit through 5%, 10%, 15%, and 20% solar thermal energy. They found that increasing the percentage use of solar thermal energy decreases the $CO_2$ emitted. For example, in unit 3, 20% of solar energy reduces $CO_2$ emissions by 13%.

Recently, Alhaj *et al.* [4] found that the solar-driven process decreases climate change impact by 10 kg-$CO_2$ eq., for every 1 $m^3$ of freshwater, compared to the conventional one, and the linear Fresnel collector has a better LCA rating than the parabolic trough collector (**Figure 23**).

## 7. Outlooks and Conclusions

Solar desalination technology is a growing field of research that has made significant progress in recent years. Increasing drinking water demands, limitations by decarbonization laws, and mitigating the side effects of global climate change have intensified researchers' efforts to combine desalination processes with renewable energy sources. Meanwhile, solar energy is a reliable and accessible source of energy. Choosing the appropriate solar-powered water treatment technology is site-specific and depends on the conditions. In this review, the new solar water treatment technologies and their ecological influences have been discussed, and the results can be summarized below [1]:

1) Among direct solar water desalination technologies, solar still technology is a low-cost, low-tech, and low-investment method suitable for remote areas, especially in developing countries with low financial support and access to skilled workers.

2) Indirect solar-driven water desalination technologies, including thermal and membrane technologies, are more reliable and technically more mature. Recently, reverse osmosis (RO) technology has received particular attention thanks to its lower energy demand, lower cost, and available solutions to increase membrane durability.

3) In many developing countries with the drinking water supply problem in rural and remote areas, solar disinfection can be used as a low-cost, energy-free solution. The solar water disinfection (SODIS) method is one of the most common methods in deprived areas thanks to its simplicity, chemical independence, availability, and cheapness.

4) The specific energy consumption (SEC) of conventional solar thermal (multi-stage flash, MSF, and multi-effect distillation, MED) and RO desalination plants exceeds the minimum energy required. For this reason, desalination is referred to as an energy-consuming process. In particular, SEC demand is higher in thermal processes due to thermal and electrical energy consumption. The SEC is equivalent to consuming more fossil fuels and thus exacerbating environmental pollution.

5) Compared with conventional fossil fuel-based desalination plants, the cost of producing water from solar desalination processes is still relatively high due to the high cost of solar equipment. For this reason, the commercialization speed of

solar desalination processes still needs to improve. However, in many cases, the environmental costs of using fossil fuels (including pollution in the preparation stage, greenhouse gas emissions, and air pollution) are largely ignored. In addition, the estimated costs of solar desalination plants indicate that they are becoming economically comparable to conventional power plants. However, most solar desalination plants are in the developing stages and need to be expanded in their actual application. Hence, there are still challenges in reducing solar equipment and cost through the development of solar energy technology.

6) One of the common techno-economic issues in most desalination technologies is the cost-effective and low environmental impact of waste (*i.e.*, brines) disposal. Disposal of brines can account for much of the water cost and potentially negatively affect the environment. Therefore, in addition to efforts to improve the efficiency and reduce the cost of solar technologies and water treatment processes, future research studies should consider developing new solutions to this issue.

7) Utilizing life-cycle assessment (LCA) as an indicator for environmental impacts is strongly recommended when choosing between various solar desalination technologies rather than looking only at specific energy consumption daily in desalination studies [4]. When operated in cogeneration mode, studying the life-cycle impact of solar-driven desalination systems is vital. Such systems can tap into a larger pool of users in remote coastal areas who require power and clean water. Exploring how expanding LCA system boundaries can help us understand the optimal conditions for sustainable desalination processes is crucial. Environmental scientists must address the methodological challenges in conducting in-depth LCA studies for desalination technologies. Among these issues is the definition of the functional unit and its relative value. For example, desalination systems produce freshwater with variable values in different parts of the World. This issue emphasizes the need to weigh and rank the LCA impact scores accordingly when comparing various scenarios. Furthermore, a quantitative uncertainty analysis must always be included to give policy-makers confidence about the outcomes of the LCA study [4].

8) Sunlight-driven semiconductor photocatalysis has emerged as a potential alternative strategy with considerable merits, high efficacy, and energy-efficient procedures for water disinfection. Based on the current research on disinfection control strategies, various long-term challenges and possible sustainable solutions concerning photocatalytic disinfection technology have been proposed. Although significant progress has been attained in exploring semiconductor photocatalysis-driven disinfection, designing highly efficient photocatalytic systems with scale-up applications is still challenging. Investigating fundamental disinfection reactions is crucial to understand the process deeply. To this end, the research on photocatalytic cell membrane peroxidation with mechanistic insights has yet to be explored. Moreover, most studies have yet to examine the kinetics of photocatalytically induced protein oxidation via radical generation.

Consequently, the synergistic relationship between the oxidation and death kinetics of the cell is still missing. Hence, future research in this area must explore the quantitative relationship between genetic core damage, protein oxidation, shape rupturing/distortion, and the fundamental parameters of the photocatalysis process, which substantially influence the disinfection process. Nevertheless, it is anticipated that by overcoming the inherent limitations of photocatalysis, its potential for disinfection control can be further explored to fill the existing research gaps [85].

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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