Solar Desalination

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Desalination is a capital-intensive process that requires a significant amount of energy, and since it is now mostly powered by fossil fuels across the globe, it has the potential to leave a significant carbon footprint.

Keywords: greenhouse desalination ; humidification–dehumidification of air ; renewable energy

1. Introduction

Water is essential to the beginning and continued existence of humanity. Because it covers almost three-quarters of the earth's surface, water is one of the most abundant resources on the planet. The oceans contain approximately 97% of the water on Earth, which is salt water. The remaining 3% of the water on Earth is fresh water, which can be found at the poles (in the form of ice), in ground water, lakes, and rivers. Fresh water supplies the majority of the water that is needed by humans and animals. Glaciers, areas with permanent snow cover, ice, and permafrost are home to over 70% of the world's tiny 3% fresh water supply, respectively. Thirty per cent of the world's fresh water is found underground, most of which is located in very deep aquifers and difficult to access. Rivers, lakes, and underground water reserves have traditionally served as man's primary sources of water for domestic, agricultural, and industrial uses. Around 70% of the world's fresh water is used for agricultural purposes, whereas only 20% is used for industrial purposes and only 10% for residential uses [1].

According to the UN-Water Annual Report 2021, published in June 2022, 2 billion people in underdeveloped nations lack access to clean drinking water. Additionally, 3.6 billion people (46% of the world population) lack access to appropriate sanitation [2]. According to some recent forecasts, about half of the world's population will experience genuine water supply problems [3]. Around 3 billion of the world's population lack access to adequate quality and/or quantity of fresh water, and 107 countries are not on track to have sustainability-managed water resources by 2030 [2]. Currently, one-fifth of the world's population lives in places with insufficient fresh water supply. In many developing nations, 80% of the population lives in rural areas with much poorer access to fresh water than in metropolitan areas [4]. By 2025, it is anticipated that up to two-thirds of the world's population will live in nations with water scarcity [5].

However, increased industrialisation and the global population boom have significantly increased the need for fresh water for home use and crops to generate sufficient food. Additionally, there is the issue of river and lake contamination caused by industrial pollutants and vast volumes of sewage released. Water demand doubles every 20 years on average, making the water problem all the more alarming [1][2]. The seas are the only essentially limitless supply of water. Their primary disadvantage is their excessive salinity. As a result, it would be desirable to address the water scarcity issue by desalination this water. Salinity in water is limited to 500 parts per million (ppm) and up to 1000 ppm in rare instances, but most of the accessible water on Earth has a salinity of up to 10,000 ppm and salt water typically has a salinity of 35,000–45,000 ppm in the form of total dissolved salts [1][6].

Excessive water salinity results in a loss of flavour, gastrointestinal discomfort, and laxative effects. A desalination system's objective is to clean or purify brackish or salt water and deliver drinkable and irrigation water with TDS of less than 500 ppm or from 500–1500 ppm for irrigation [7]. This is performed via a variety of desalination procedures that will be investigated; as a result, desalination operations use a large amount of energy to separate salts from salt water. Renewable energy systems produce energy from renewable sources such as geothermal energy, solar energy, low-grade energy sources, photovoltaic thermal (PV/T) panels, and power plant waste heat. Their primary feature is that they are environmentally friendly. The production of fresh water using desalination technology powered by renewable energy systems is considered a possible solution to the problem of water scarcity in distant places that lack access to potable water and traditional energy sources such as heat and electricity. Numerous renewable energy desalination pilot plants have been erected worldwide, with the majority operating effectively for several years. Almost the majority of them are custom-designed for particular locales and generate fresh water by solar or geothermal energy [8]. Although renewable energy-powered desalination systems cannot compete with traditional desalination systems in terms of the cost of water produced, they are appropriate in specific places and are projected to shortly become more broadly practicable. El-Ghonemy [9] analysed water desalination systems driven by renewable energy sources, highlighting current advances in the area of renewable energy-based desalination, with a concentration on technology and economics. Some broad recommendations for the selection of desalination and renewable energy systems, as well as the factors for examination, were provided.

Desalination methods available today are mostly classified into two categories: thermal and membrane approaches. The former is prohibitively expensive, has corrosion issues, and requires large, difficult-to-maintain installations (e.g., multi-stage flash (MSF)), while the latter suffers from membrane fouling and demands water pre-treatment before being delivered into the desalination modules, as well as post-treatment. Other less prevalent desalination systems are less established, and each has its own set of advantages and disadvantages.

Desalination is characterised by fast technological advancements. Each year, several new desalination facilities are tested and implemented globally. Desalination methods have matured technologically and economically, enabling them to play a larger part in the future water supply. These installations may be built using a variety of different technological approaches and provide a great deal of versatility in terms of size and energy use (a function of energy resources and the situation). MSF is the most often thermal-based utilised method. This approach is used in about 50% of all installations worldwide. On the other hand, when production scales down, the efficiency of conventional distillers falls due to the difficulty of implementing a given number of effects in small installations. For these smaller installations (in rural areas, for example), conventional distillers are unsuitable: the installation costs, energy usage, and hence water costs, are too expensive.

Several well-established desalination techniques exist, including reverse osmosis (RO), MSF, and multi-effect distillation (MED); however, these technologies are often inappropriate for developing countries because of their high infrastructure requirements, reliance on fossil fuels as a source of energy, and cost-effectiveness on very large scales.

Greenhouses (GHs) are a critical component of the food supply chain as they increase crop yield [10]. The productivity of GHs is commonly known to be 7–10 times that of an open field. Furthermore, it only uses 10% of the water required for open field agriculture [11]. They protect the plants while conserving resources such as electricity and water [12]. GHs are utilised to chill or heat the air within the GH depending on their geographical location and season [13]. The grown crop's production is heavily reliant on the GH environment, namely, the GH temperature and relative humidity (RH) [14]. Plant photosynthesis has a diverse spectral profile; however, in vitro, most photosynthesis chemicals exhibit narrow spectral absorbance maxima in the blue (400–500 nm) and red (600–700 nm) wavelength bands, which account for less than 30% of the incoming solar spectrum [15]. The remaining 70% of solar energy is in the near-infrared (NIR) band (700–2500 nm), where photons do not drive photosynthesis but do raise the ambient temperature within a GH. Temperature is recognised to have a crucial role in regulating plant development [16]. However, the transfer of NIR radiation into greenhouses often leads to excessive solar heating and increased water demand for evaporative cooling, particularly in hot and dry locations. Heat stress occurs when plants are exposed to high temperatures for an extended length of time, resulting in decreased output [17]. Similarly, high RH promotes the growth of pathogens such as fungi, whereas low RH causes plants to lose too much water to the GH air, resulting in wilting [18]. As a result, it is critical to maintaining an optimal temperature and relative humidity within the GH for growing high-quality produce. Additionally, year-round crop production is required to make the GH commercially viable in dry locations. However, in desert areas, high temperatures and a scarcity of water restrict crop production to a few months, making agriculture economically unviable and difficult. Due to the paucity of fresh water, farmers are sometimes obliged to utilise salty ground water for agriculture to satisfy irrigation needs [19]. Additionally, the cooling burden rises dramatically during the summer, resulting in temperatures that exceed the optimal range, which is harmful to plant growth. As a result, numerous methods have been developed to control the GH microclimate and meet irrigation needs in dry places [20][21]. However, the microclimate of the greenhouse is reliant on dynamic, non-linear, and uncertain parameters such as solar irradiation, outside temperature, air speed, and inside conditions [22].

In dry areas, natural ventilation alone is inadequate to manage the temperature within the GH during the summer season, when solar gains and outside temperatures are high [23]. While coupling natural ventilation with shade screens may help reduce cooling loads, restricting solar irradiance entering the GH canopy affects plant growth since sunlight is necessary for photosynthesis [24]. Evaporative or fan and pad cooling is another way of lowering the temperature of the air passing through the GH and converting it to latent heat. However, evaporative cooling is temperature and relative humidity dependent; in dry climates, when temperature and relative humidity rise, the air's wet-bulb temperature increases as well, resulting in inefficient cooling within the GH [25]. As a result of these considerations, active mechanical heating, ventilation, and air conditioning (HVAC) systems scheduling and decision-making may be improved by anticipating factors many hours in advance. In addition, the link between the GH's cooling load and water demand in an environment with high temperatures and a scarcity of fresh water is evaluated. Crops yield and output are greatly reliant on the microclimate created by the HVAC system in the GH. Maintaining optimal conditions in the greenhouse necessitates monitoring and managing temperature and relative humidity, as well as identifying potential scenarios/techniques to decrease energy and water usage. In the summer, when sun irradiance and temperature reach 1000 W/m^2 and 45 °C, respectively, it is difficult to maintain optimum growth conditions while minimising energy and water use. In order to operate a GH efficiently, it is required to calculate the cooling and water requirements under various climatic conditions/seasons [26]. HVAC systems are the most effective technique for controlling the GH microclimate, but they use a significant amount of energy. The majority of energy is generated by fossil fuels, which contribute to damaging greenhouse gas (GHG) emissions. As a result, GHs powered by renewable energy and equipped with active mechanical cooling systems provide a viable option for sustainable agriculture in comparison to traditional food production systems fuelled by fossil fuels.

The sun, the sea, and the environment are used to generate fresh water and cool air in a seawater greenhouse. Within a controlled setting, the procedure recreates the natural hydrological cycle. The building's front wall is a salt water evaporator. It is made of a honeycomb lattice and confronts the wind. Air movement is controlled by fans. Seawater drips down the lattice, cooling and humidifying the air that passes through into the planting area. The sun is diffused by a specifically designed roof. The roof absorbs infrared heat while allowing visible light to pass through to encourage photosynthesis. This results in ideal growing conditions, which are cold and humid with high light intensity. Seawater heated in the roof goes through a second evaporator, producing hot, saturated air that flows through a condenser. Incoming salt water cools the condenser. Because of the temperature differential, fresh water condenses out of the air stream. Air temperature, relative humidity, solar radiation, and airflow rate all influence the amount of fresh water. With adequate meteorological data, these circumstances may be modelled, allowing the design and procedure to be optimised for any acceptable site [27][28][29].

In a salt water greenhouse, substantially more water evaporates than condenses back into fresh water. Because of the high rates of ventilation used to keep the crops cool and supplied with CO_2, this humid air is 'lost.' The greater humidity of the exhaust air aids in the development of more hardy crops downwind of the greenhouse. This phenomenon may allow biofuel crops to be grown in the region around the seawater greenhouse.

A seawater GH is a GH structure that permits the cultivation of crops and the generation of fresh water in approximately one-third of the planet's dry areas. This is in reaction to the worldwide water shortage, peak water, and soil salinisation. The system is powered by solar energy. It employs a construction similar to the pad-and-fan GH, but with added evaporators and condensers. The salt water is pumped into the GH to generate the best circumstances for the development of temperate crops: a chilly and damp atmosphere. [30] Using the idea of solar desalination, which eliminates salt and contaminants, fresh water is generated in a concentrated form. The residual humidified air is then removed from the GH and utilised to enhance outside plant growth conditions.

2. Solar Desalination Technologies

As previously stated, the majority of desalination procedures use a significant quantity of energy. The bulk of desalination facilities now operating on a global scale is powered by fossil fuels. However, the majority of places that face increased fresh water demand also obtain significant quantities of solar energy. Thus, solar energy might be an excellent source for this purpose since it is plentiful and emits few pollutants. Solar desalination methods are divided into direct and indirect categories across the literature. In this context, if solar radiation is absorbed directly by the desalination plant's input feed water, the plant is regarded to be of the direct kind. Solar energy is collected by solar thermal collectors and then transmitted to the salty water in indirect plants, or it is converted to electricity and then utilised to power the plant. In both scenarios, solar energy might be utilised to power the plant using a heat engine. Adapted from [31], **Figure 1** displays this categorisation of solar desalination modules. However, this reference classifies HD as a straight drive. This is because, in an HD system, saline water may absorb sun energy directly or via solar thermal collectors. It might be either direct or indirect in this sense.

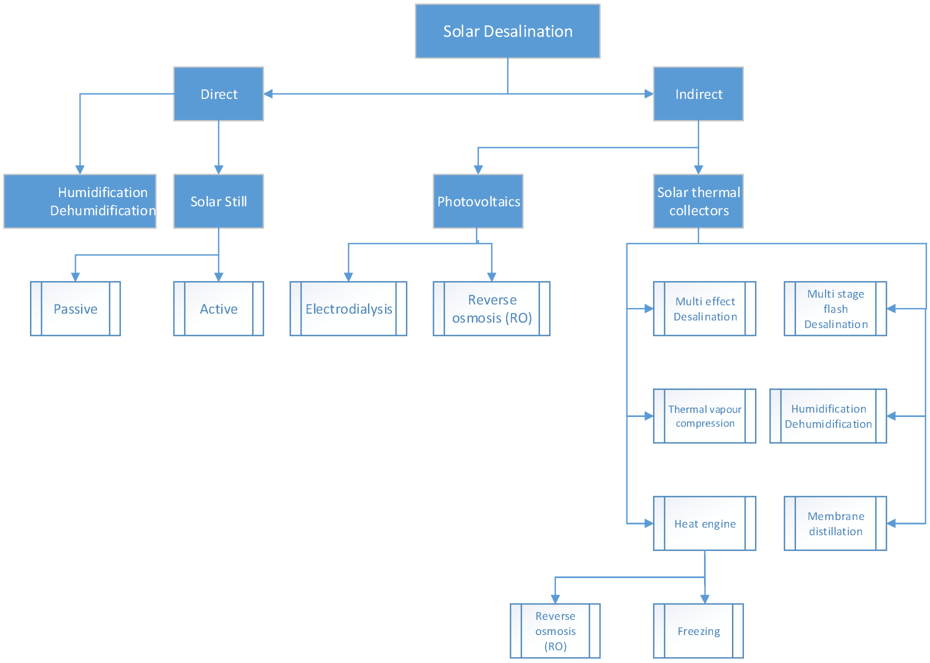

Figure 1. Classification of desalination processes based on solar energy.

Numerous aspects must be considered while selecting technology for a desalination project. It is highly dependent on the demand side, available resources, economic considerations, maintenance concerns, and the projected lifespan of the project, among other factors. For example, the simultaneous need for fresh water and energy may necessitate the use of poly-generation plant technology. Additionally, surplus heat generated by solar thermal collectors in the desalination plant might be used to meet heating needs. The magnitude of the demand sector may have a significant impact on the design process since certain technologies are incapable of meeting large demand levels. The operation and maintenance sectors are also important to examine since certain technologies are capable of working for an extended period without requiring significant upkeep. Another factor to consider is the amount of available land and the potential market. Additionally, environmental concerns should not be overlooked since they may be addressed in economic calculations. The benefits and disadvantages of various methods of solar desalination are listed in **Table 1** in terms of environmental, economic, energy consumption, construction, material availability, efficiency, and distilled water quality, among other aspects. This table may provide relevant information on the comparison of several desalination systems.

Table 1. Merits and demerits of various solar desalination technologies.

Desalination Type	Merits	Demerits
Solar still (SS) [32]	• Environmentally friendly • Low operation and maintenance costs • High-quality produced water • Available building materials • Suitable for homes and communities living on islands • Removal of fluoride, arsenic, bacteria, and other contaminants from the water	• Occupies a large area • Is inefficient • Is not suitable for high-capacity water production

Desalination Type	Merits	Demerits
HD [33][34]	• High flexibility • Suitable for decentralised operation • Simpler brine pre-treatment • Operates with any form of energy • Low installation and operating costs	• High capital investment costs • High total expenses of generated water • Availability of requirements
Solar chimney [35][36]	• Long operating lifespan • Simple and robust construction • Low maintenance cost • Environmental friendliness • Production of by-products such as salt • Use of waste barren land • Low generated water prices • Generate electricity and fresh water at the same time	• Large area of occupation • Extremely expensive capital investment expenses
Multi-stage flash desalination (MSF) [37]	• Produces high-quality distilled water • Reliable device operation • Ideal for large-scale distillation operations • Water of any grade may be processed • Minimal or no pre-treatment of the feed water is necessary	• Excessive energy use • Excessive operating temperature results in device corrosion • Heavy structure • Excessive capital cost
Multi-effect distillation (MED) [37]	**Compared to multi-stage flash desalination, this process uses less thermal energy, produces better distilled water, and emits less CO_2 since it doesn’t need a high operating temperature or feed water pre-treatment.**	• Expensive and hefty construction. • Vacuum pump power consumption

Desalination Type	Merits	Demerits
Vapour compression desalination (VC) [37]	**There are several advantages to using this technology, including:** • Low energy consumption • High operational efficiency • Size depends on compressor size • High quality produced water • Appropriate for low-capacity operation • No additional cooling medium • Less pre-treatment of feed water • Low environmental impact	• High capital investment • Corrosion of the compressor • Water production costs
Natural vacuum desalination [38]	• Wastewater, seawater, and sewage may all be treated. **Low-temperature heat sources are adequate; water production costs are reduced; tall structures may be integrated; organic substance in the product is not destroyed because of the heat.**	• Removal of non-condensable gases created during water evaporation is necessary • High building heights beyond 10 m are required
Solar-powered RO [39][40][41][42][43][44]	**Several advantages include smooth operation, low energy consumption, flexibility in capacity expansion, and the ability to be built as a compact or portable device. However, the membranes can become fouled by biological organisms, so pre-treatment of the feed water is required. Using a battery is not recommended because of the high capital cost and the need for battery replacement.**	• It is not suggested to use a battery because of the high capital cost and the need for battery maintenance. • Membranes have a limited lifespan • High-pressure pump is necessary • Requires pre-treatment of feed water
Solar thermal powered RO [40][45][46][47]	**Minimal batteries are needed; a low-temperature source is adequate; solar collectors could cover a broad temperature range; no efficiency losses; low operation and maintenance costs; and non-skilled labour would suffice for large-capacity operation. Solar collectors, on the other hand, use less energy for post-treatment.**	• No potential demerits
Electrodialysis (ED) [45][48][49]	**Inverter-free DC operation means lower losses, longer membrane lifetimes, higher water recovery, and less fouling and scaling on the membrane. Less pre-treatment of the feed water is needed. Devices are easier to start and stop. Low efficiency since energy is required.**	• Every 20 min, the polarity must be reversed • The generated water is expensive and consumes a lot of energy

Desalination Type	Merits	Demerits
Membrane distillation (MD) [50][51][52][53][54][55][56]	• Reduced leakage compared to RO • Pre-treatment of feed water is not necessary • Pipelines are thinner • Reduced operation in low temperatures • High salt feed water may be treated	• Membrane wetting • High membrane prices • Due to low driving force, a large membrane surface is needed
Freezing [57][58]	• It takes just 420 kJ of energy to remove salt and create 1 kg of fresh water, which is six times less than what MSF needed • Due to the low working temperature, they are tolerant to corrosion issues and may function for a long period with minimum maintenance	• After the desalination process, ice handling is one of the most difficult tasks

To create a drinkable water product, three processes are required: pre-treatment, treatment, and post-treatment. Different desalination systems need varying degrees of pre-or post-treatment. In comparison to thermal desalination, membrane-based desalination techniques may be more susceptible to the presence of unwanted organic or inorganic chemicals or pathogens in the product water. Specifically, higher temperature desalination facilities with water temperatures more than 70 °C are considered to be rather safe in terms of the safety and quality of the generated water. This is because at high temperatures, any extant microbes are killed and dangerous inorganic compounds such as Boron products are eliminated by the distillation process, resulting in water with an acceptable purity. On the contrary, RO is unable to successfully remove Boron from seawater and other salty water sources. Additionally, ED cannot ensure pathogen elimination. In these circumstances, extensive post-treatment and water quality testing are necessary, increasing the plant's capital cost. However, further measures should be employed in thermal plants operating at temperatures below 50 °C, since this temperature is insufficient for reliable pathogen elimination. Additionally, it should be emphasised that water quality problems may be highly dependent on the quality and circumstances of the water supply.

In comparison to other desalination systems, HD has a smaller capacity. However, it also takes very little care throughout the plant's life. While the generated water is more expensive than that produced by other technologies such as reverse osmosis, other aspects make solar HD a viable option for distant places with low-to-moderate demand levels. It is not dependent on electricity or other energy sources, and solar energy can generate the necessary thermal energy. Solar HD plants might be an excellent alternative for tiny locations that lack enough access to potable water networks. Additionally, as solar collector technology advances, the total cost of the generated water decreases, making it a viable choice for small-scale applications.

Global Water Intelligence (GWI DesalData) desalination and reuse markets [59] classified desalination technologies according to **Table 2**.

Table 2. Industrial solar desalination technologies classifications.

Established	Emerging
• Reverse osmosis (RO)	
• Nanofiltration (NF)	
• Multi-effect distillation (MED)	• Capacitive deionisation (CDI)
• Multi-stage flash distillation (MSF)	• Humidification–dehumidification (HD)
• Electrodialysis/electrodialysis reversal (ED/EDR)	• Membrane distillation (MD)
• Electrodeionisation (EDI)	• Forward osmosis (FO)
• Falling film evaporators	• Chemical solute extraction
• Direct contact evaporation	
• Forced circulation crystallises	

Figure 2 illustrates a technology’s path to commercialisation depicting the early enthusiasm around a new idea, followed by disappointment when practical challenges arise, and then the last push for commercialisation and widespread adoption.

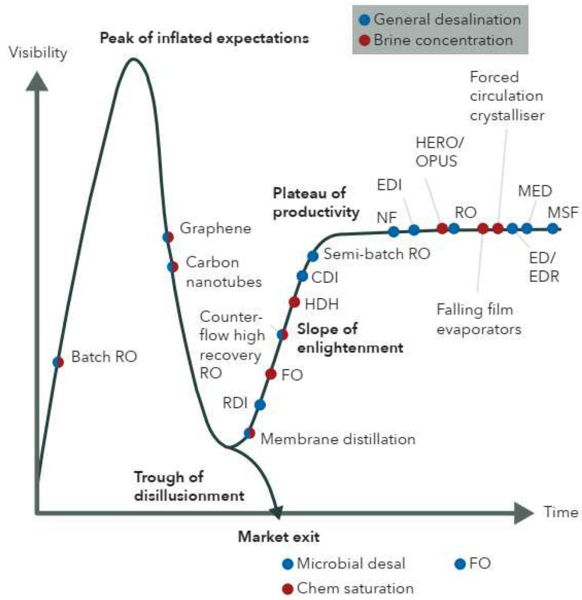

Figure 2. The commercialisation of innovative desalination and brine concentration technologies [59].

Management of brine is now a major driver of adoption. Except for semi-batch RO, almost all the methods undergoing the gradual march to widespread usage are largely utilised for brine concentration.

Materials such as graphene and carbon nanotubes are among the slowest-maturing technologies due to the time required to develop dependable and cost-effective production processes.

Operational R&D’ designs, such as semi-batch or counter-flow RO systems, are expected to gain traction considerably more swiftly.

Despite the capabilities of thermal desalination methods to use waste heat, research undertaken by MIT into primary energy usage demonstrates that even when waste heat is utilised, thermal procedures are less energy efficient than membrane processes. These primary energy values represent the value of the energy in the source, including generating losses and are based on the energy produced by a combined cycle gas turbine.

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