

Review

Commercial Thermal Technologies for Desalination of Water from Renewable Energies: A State of the Art Review

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Abstract: Thermal desalination is yet a reliable technology in the treatment of brackish water and seawater; however, its demanding high energy requirements have lagged it compared to other non-thermal technologies such as reverse osmosis. This review provides an outline of the development and trends of the three most commercially used thermal or phase change technologies worldwide: Multi Effect Distillation (MED), Multi Stage Flash (MSF), and Vapor Compression Distillation (VCD). First, state of water stress suffered by regions with little fresh water availability and existing desalination technologies that could become an alternative solution are shown. The most recent studies published for each commercial thermal technology are presented, focusing on optimizing the desalination process, improving efficiencies, and reducing energy demands. Then, an overview of the use of renewable energy and its potential for integration into both commercial and non-commercial desalination systems is shown. Finally, research trends and their orientation towards hybridization of technologies and use of renewable energies as a relevant alternative to the current problems of brackish water desalination are discussed. This reflective and updated review will help researchers to have a detailed state of the art of the subject and to have a starting point for their research, since current advances and trends on thermal desalination are shown.

Keywords: Desalination; Multi Effect Distillation; Multi Stage Flash; Vapor Compression Distillation; Renewable Energies.

1. Introduction

Water on the planet is apparently abundant; however, most of it is salt water, represented as seawater in a high percentage. Seawater is not suitable for human consumption or for most man-made processes. Furthermore, distribution of fresh water throughout the world is not uniform. In some places, fresh surface or groundwater is abundant in sparsely populated places, such as northern Russia, Scandinavia, Canada, Alaska, and parts of southern South America. In contrast, there are densely populated areas with growing industrial areas, located in sites with a low fresh water availability; consequently, subjected to a high degree of water stress according to the relationship between demand for water and amount of water available [1]. According to the United Nations, more than 2 billion people live in countries that experience high water stress [2], an aggravated situation if UNESCO's projections for the period from 2017 to 2028 are considered, where it predicts a greater demand for water not only for agriculture, whose consumption is 70% of the demand worldwide, but also for energy production and generation [3]. Similarly, climate change, world population

growth, contamination of fresh water sources, accelerated urbanization in cities and expansion of public service networks also contribute to global water stress [4, 5]. The World Water Program (WWP) estimates that by 2030 only 60% of water demanded will be available. On the other hand, the Organization for Economic Cooperation and Development (OECD) has predicted that by 2050, availability will be reduced to 55% and by the end of the century, 40% of the world's population will live in areas with water stress [6].

Using seawater as a source of fresh water supply could be a solution to the increasing global water stress. Nonetheless, intensive energy requirements and prohibitive costs of desalination technologies restrain their massive use in many communities affected by water scarcity, even though having unlimited access to seawater [7, 8]. According to the International Desalination Association (IDA), total capacity of all operating desalination plants worldwide was of 92.5 million m³/d in 2017 [3]; however, the electrical or thermal energy used in the desalination process represents about 50% of the total cost of production [9]. Amount of energy required for a desalination process depends on the feed water quality, level of water treatment, treatment technology used by the facility and the capacity of the treatment plant [7, 10, 11]. As a substitute or replacement for electrical energy, desalination systems powered by renewable energies represent a real alternative to reduce operating costs in conventional desalination systems [14, 15]. Table 1 shows the energy required to produce 1 m³ of fresh water from distinct types of water sources.

Table 1. Energy requirements for different water sources. Source: Reproduced from Ref. [7, 12, 13]

Water source	Energy (kWh/m ³)
Surface water (lake or river)	0.37
Groundwater	0.48
Wastewater treatment	0.62 – 0.87
Wastewater reuse	1.0 – 2.5
Seawater	2.58 – 8.5

Generally, water desalination processes can be classified into phase change or thermal processes, and processes without phase change or by membranes [1, 4, 7, 16-20]. The phase or thermal change process involves evaporation of salt water by contact with a heating surface (evaporation surface) leaving the salts in it; then, the fresh water vapor condenses in cooling pipes producing high-pressure water with quality and without salts [21].

The phase change or thermal technologies, available and of great commercial use, are Multi Effect Distillation (MED), Multi Stage Flash Distillation (MSF), Mechanical Vapor Compression (MVC), and Thermal Vapor Compression (TVC) [1, 17, 22, 23]. Similarly, there are technologies that directly use solar radiation as an energy supplier, such as Solar Still (SS), Solar Chimney (SC), and Humidification/Dehumidification (HDH) [24], although they are not currently commercially available on a large scale. Desalination process without phase change consists of the use of membranes or any other element or material to directly separate the dissolved salts in the water, applying high doses of energy or pressure. Membrane techniques include Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), Membrane Bioreactor (MB), Membrane Distillation (MD), Electrodialysis (ED), and Reverse Osmosis (RO) [25]. These are pressure-driven processes to remove particles, bacteria, and salts from water by size exclusion through membranes with different pore sizes [26, 27]. A diagram of the different technologies available for desalination of seawater or brackish water is shown in Figure 1.

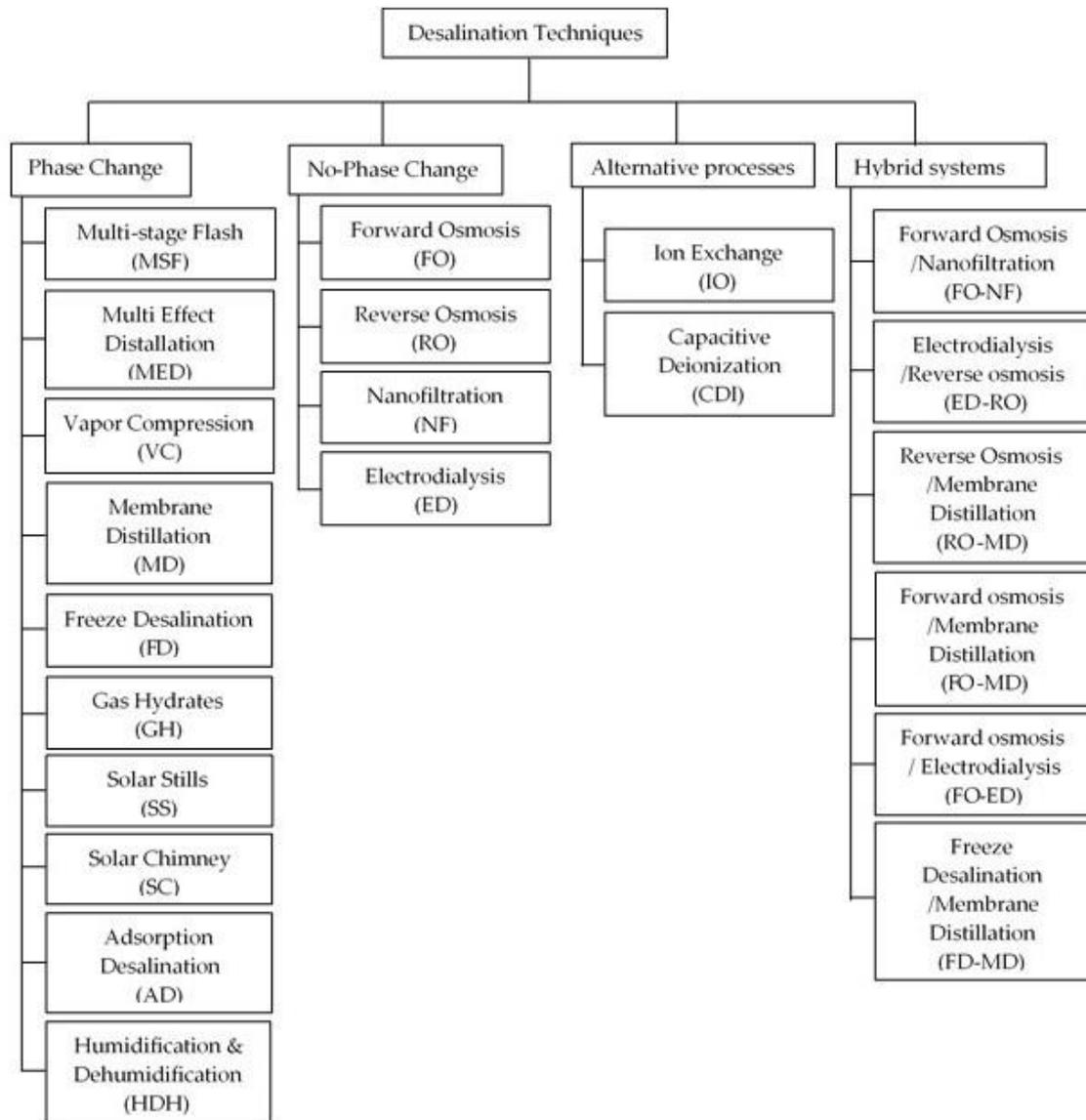


Figure 1. Available desalination technologies. Source: Adapted from Ref. [4, 17, 19, 24]

This paper aims to provide a review of the state of the art of the different commercial phase-change (thermal) desalination technologies that currently exist and present an overview of the use of renewable energy in water desalination systems and their future perspectives as a contribution to the sustainability of the water resource.

2. Phase Change Technologies

The main thermal desalination processes of great commercial use are: Multi Stage Flash Distillers (MSF), Multiple Effects Distillation (MED), and Mechanical Vapor Compression (MVC), with a market share of commercial desalination plants of 87.3%, 12.5%, and 0.2%, respectively. Other types of thermal desalination processes such as solar stills, humidification-dehumidification, and freezing are not found commercially and are limited to experimental prototypes or conceptual designs [28]. The characteristics of the main commercial use thermal desalination techniques and the development of the different optimization strategies for each of these technologies are shown below.

2.1 Multi Effect Distillation

Multi Effect Distillation (MED) was the first thermal process used in commercial desalination of seawater. Small MED plants with capacities less than 500 m³/day were introduced to the desalination

industry in the 1960s [28, 29]. MED systems have a series of stages or effects, with a decreasing pressure gradient. A heat source is used to increase the feed water temperature to 110°C for the first effect. This heat can come from a boiler running on fossil fuels, waste heat, or renewable resources. Water vapor is produced in a serial pattern and, in the first stage, it is transferred through a tube to subsequent stages to further boil seawater [30]. This is a medium to high capacity desalination method, where the created vapors are condensed, to give the necessary enthalpy of condensation to the seawater that feeds the system [31]. A scheme of the MED desalination process is shown in Figure 2.

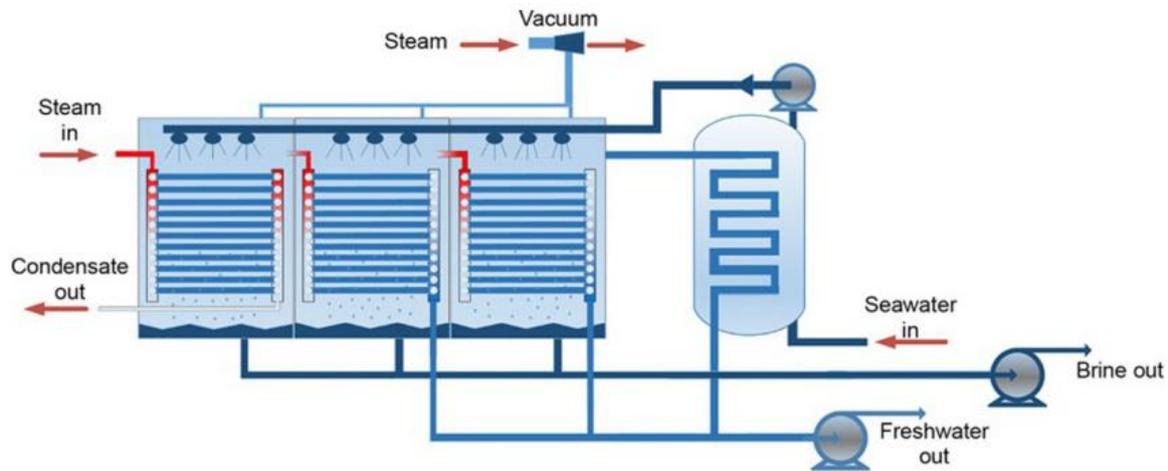


Figure 2. Schematic representation of the Multi Effect Distillation process, MED. Source: Reproduced from Ref. [30]

Industrial MED systems include up to 12 evaporation effects, giving them a water production capacity from 600 to 30,000 m³/day. The evaporation in the first effect is driven by the vapor extracted from the cogeneration boilers. The vapor formed in the first effect is used to drive evaporation in the second effect. This process continues with subsequent effects until the vapor temperature drops to around 30-40°C. Most industrial MED systems are designed to operate in autonomous mode, where part of the vapor formed in the last effect is compressed to the desired temperature and is used to drive evaporation in the first effect [28].

Among the desalination processes, the MED thermal process is a promising process due to low electrical energy consumption, low operating cost, and high thermal efficiency [11, 32]. Based on the energy consumption and obtained heat transfer, MED has been found to be more efficient than Multi Stage Flash Distillation (MSF) [21, 33, 34]. Table 2 shows the most recent technical literature published on this topic.

Table 2. Summary of literature reviews of optimization MED

Authors (Ref., Year)	Optimization methodology	Main Reported Results
Liponi et al, 2020 [35]	Mathematical modeling from different MED configurations.	Configurations that implemented seawater preheating increased the performance ratio by up to 10%.
Al hotmani et al., 2020 [36]	Mathematical modeling of the MED process and production cost model.	This study showed that the lowest freshwater production cost can be achieved with an optimal number of effects of 17 for certain operating conditions.

Alsehli et al., 2020 [37]	MED process optimization with thermal storage tanks + solar collector.	An average of 21 Kg/day of water distillate was produced, with an average daily yield ratio of 2.5 and an average specific thermal energy consumption of 831 kJ/Kg.
Andrés et al., 2020 [38]	Mathematical modeling and experimental evaluation MED	The simulated volume of distilled water annually generated ranged from 41.7 to 70.5 m ³ .
Aroussy et al., 2020 [39]	MED with parallel cross feed and MED + TVC with parallel cross feed + solar power	The MED process coupled to the TVC can operate with solar energy and provide interesting results especially for countries that do not have oil resources (such as Morocco.)
Guo et al., 2020 [40]	MED + Spray Evaporation (SE)	Results indicate that a high evaporation efficiency of 99.86% can be achieved with use of a modified Spray Evaporation Tank (SET).
Birney et al., 2019 [41]	MED + Geo-thermal Energy	This research concludes that the MED-binary cycle plant can operate in a self-sufficient way, producing fresh water and electricity in Texas, USA.
Cui et al., 2019 [42]	Mathematical modeling with different MED settings.	Results show that MED can generally save about 50% energy and up to 30% operating costs compared to a conventional distillation column.
Cunha et al., 2019 [43]	Steady-state mathematical modeling of the parameters controlling the MED process	The model was useful to optimize the MED process in investment and operating costs and to facilitate access to drinking water in arid regions with high solar incidence.
Cueviella et al., 2019 [44]	Heat recovery from an industrial furnace to apply it to a MED system.	Obtained results show the optimal configuration based on the thermal variables that could reach up to almost 92% of the water required compared to conventional technology.
Goodarzi et al., 2019 [45]	Recovery of waste heat from combustion gases to apply it to a MED system.	The economic analysis showed that the optimal number of effects in MED is 16 and that the waste heat recovery system is better economically than the conventional system.
Hu et al., 2019 [46]	Mathematical modeling of exergy for reverse electro dialysis heat engine + MED	Results showed that increasing the concentration of the initial brackish solution or the number of effects in the MED was useful to improve the exergy performance of the heat engine.
Naserbegi et al., 2019 [47]	Mathematical modeling with different coupling configurations of a nuclear plant + MED.	The exergy analysis showed that the maximum exergy destructions (1,292.9 MWh) were related to the reactor core, which is considered the main irreversible component.

Mohammadi et al., 2019 [48]	Technical and economic review hybrid systems + Concentrated solar energy	This study showed that there are many potential ways to hybridize concentrated solar energy with desalination systems.
Saldivia et al., 2019 [49]	Mathematical modeling of parameters that control the MED process.	A powerful computational tool was developed that can be useful for the design, optimization and evaluation of the technical feasibility of installation of future MED solar plants.
Khorshidi et al., 2019 [50]	MED + TVC mathematical modeling with parallel cross feed + solar power	The system optimization with the genetic algorithm makes the distillate production increase by 16.62% and the total exergy destruction rate decreases by 3.58%.
Leiva et al., 2019 [51]	Mathematical modeling with different configurations of solar thermal generation, coupled to MED	Multi-generation solar schemes are more profitable than autonomous systems. Main components increasing electricity costs are the solar collectors, the evaporator, and the re-heater.
Tarpani et al., 2019 [52]	Environmental impact assessment in operational MED plant	Results show that coupling solar fields and the electric grid dramatically reduces environmental impact in most categories.
Alhaj et al., 2019 [53] Alhaj et al., 2018 [54]	Mathematical modeling of mass and energy balance of an integrated MED + solar linear Fresnel collector system	Under Qatari operating conditions, simulation results showed that 1 m ² of linear Fresnel-type solar collector produces 8.6 m ³ of fresh water per year.
Sharan et al., 2019 [55] Sharan et al., 2018 [56]	Mathematical modeling of the solar field, energy cycle, MED and economic analysis.	The optimal design of a thermal storage tank reduces the cost of distillate by 19% and increases the MED capacity factor from 46.4% to 75%.
Chorak et al. 2018 [57]	Waste heat recovery with heat absorption pump + MED	In direct mode, the increase in the latent vapor flow rate increases the production of the distillate, and in indirect mode, the highest performance is achieved by increasing the temperature of the water entering the MED.
Khalilzadeh et al., 2018 [58]	Mathematical modeling MED + Waste heat of a high-capacity wind turbine (Pilot Plant)	The steam produced at 100°C and 101.3 kPa is enough to produce 45,069 m ³ /day of drinking water. Using waste heat from wind turbines increases the exergetic efficiency of the integrated system by 7.34%.
Kosmadakis et al., 2018 [59]	Steady-state mathematical modeling of the parameters that control the MED process	A new correlation of the specific MED cost has been developed based on the plant capacity considering the actual plants for municipal water supply.
Palenzuela et al., 2018 [60]	MED Pilot Plant + Solar Power	In Chile, cost of distilled water produced by the MED plant ranged

		from 15.0 USD/m ³ for the production capacity of 10 m ³ /day to 1.25 USD/ m ³ , when this variable is increased to 5000 m ³ /day.
Xue et al., 2018 [61]	Mathematical physical modeling of MED thermodynamics	Results of the economic analysis showed that reducing the amount of extraction steam from the steam turbine can significantly reduce the cost of water production.
Alhaj et al., 2017 [62]	MED technical and economic review	The review highlighted advances in knowledge gained from modeling and experimental research studies.
Chorak et al. 2017 [63]	Pilot Plant MED + Static Solar Test Field	The solar field can produce much more thermal energy than required by the MED unit, especially at 65°C.
Bamufleh et al., 2017 [64]	MED Pilot Plant + Membrane Distillation + process heat integration	A superstructure-based optimization formulation was developed to determine the key design and operational variables.
Wang et al., 2017 [65]	Mathematical modeling MED + TVC + Adaptive Nozzle Exit Position (ANXP) ejector	In a MED-TVC desalination system, use of an ANXP improves the performance of the system.
Abadi et al, 2016 [66]	Mathematical modeling MED + Thermo-compressor (TVC and MVC)	Based on numerical simulations, a correlation is proposed for calculating the mixing efficiency of the motive and entrained flows within the thermo-compressors.
Azimibavil, 2016 [67]	Physical-Mathematical modeling of tube-bundle of a MED plant	Results showed that during the start and feed of the main steam to the process, quality of the steam almost fell linearly within the model tubes.
Guo et al., 2016 [68]	Simplified unbalanced vaporization mathematical modeling for water spray in MED	It presents the relationship of the water droplet size and distance of fall with the temperature of the warm air vapor and the required injection/spray parameters.
Ortega et al., 2016 [69]	MED + TVC coupled to parabolic trough solar power plants	Use of low pressure steam to power the MED-TVC plant reduces electricity consumption compared to the use of high pressure steam, but it also decreases the fresh water production.
Hamed et al., 2016 [70] Askari et al., 2016 [71]	Mathematical modeling and experimental evaluation in MED + solar linear Fresnel collector pilot plant	It was found that to produce thermal energy of 13.6 MWh to the power plant, a solar field area of 55,737 m ² was required.
Palenzuela et al. 2016 [72] Palenzuela et al. 2014 [73]	Steady-state mathematical modeling of the parameters that control the MED process	Thermal consumption and increase in water production were characterized with the increase in the hot water inlet

		temperature and decrease in the vapor temperature of the last effect.
Palenzuela et al. 2015 [74]	MED coupled to concentrating solar power with Parabolic Trough (PT-CSP)	Under certain conditions this technology is more efficient to produce fresh water and energy than an RO unit connected to a PT-CSP plant.
Touati et al., 2015 [75]	Energy recovery through salinity differences	It was shown that it is possible to recover, as hydraulic pressure, a significant part of the osmotic energy of the MED brine, and simultaneously, reduce the discharge salinity.
Christ et al., 2015 [76]	Mathematical modeling of Boosted MED technology	Boosted MED system offers both thermodynamic and economical superior performance, especially when low temperatures of the heating medium prevail.
Frantz et al., 2015 [77]	Thermal Steady State Mathematical Modeling of MED + Solar Tower Plant	Annual production can be doubled if a heating steam temperature of 90°C is used instead of 65°C.
De la Calle et al., 2015 [78] De la Calle et al., 2014 [79]	Dynamic mathematical modeling of a MED + Solar power	The mathematical formulation based on physical principles describes the main phenomena of heat and mass transfer in this type of installation.
Thu et al., 2013 [80]	Mathematical modeling of a hybrid MED + Adsorption cycle (AD) system	In the 8-stage MED + AD cycles operating at temperatures between 65–90°C, production rate increases from 60% to 100% compared to MED.

In the MED process optimization, numerical algorithms have been used, through computational mathematical models in steady state [43, 59, 72, 73, 77] and dynamic state [61, 67, 76, 78, 79], to simulate distinct stages. Similarly, different configurations of thermal generation have been modeled as power supplies to the MED process [35, 36, 42, 47, 49, 51, 53-56, 63, 69-71, 74] and hybridization of technologies [40, 64-69]. On the other hand, several authors suggest increasing the number of stages or effects in MED plants between 16 and 17 to optimize the process [36, 39, 45] and other investigations recommended preheating the seawater before feeding the MED [35, 37, 81]. Several investigations have been carried out in the Solar Platform of Almeria, attached to the Center for Energy, Environmental and Technological Research (CIEMAT) of Spain, focused on the optimization of MED processes, through mathematical modeling with data from experimental prototypes [43, 72-74, 78, 79], heat recovery and exergy [44, 50, 51, 57, 63, 75]; and by hybridization with thermal vapor compression technologies [69].

2.2 Multi Stage Flash Distillation (MSF)

The basic principle of the MSF distillation technique is flash evaporation. The MSF process distills seawater by vaporizing part of the water in various stages under vacuum, arranged in series [82]. In this process, the evaporation of seawater takes place by reducing the pressure rather than increasing the temperature. To get the maximum output and maintain MSF economies, regenerative heating is generally performed. Therefore, this process needs distinct stages for its completion and it is necessary to gradually raise the temperature of the incoming seawater at each stage [83]. In modern MSF plants, multi-stage evaporators in which there are between 19 and 28 stages, are used [84]; although other authors report the number of stages between 4 and 40, which allows the systems of

MSF to produce volumes of water in the order of 10,000 to 40,000 m³/day [85]. The operating temperature of the MSF plant is in the range of 90 to 120°C.

The first MSF plant was built in the 1950s, however, despite the fact that multi stage flash desalination is an energy-intensive distillation process requiring both thermal and electrical energy [30], it was only in 1974 that the Federal Republic of Germany and Mexico developed in Mexican territory, a MSF plant powered by solar energy with a capacity of 10 m³/d with brine recirculation. It had parabolic trough collectors, a double tube flat plate collector, storage tanks and a desalination unit in the plant [85]. MSF's largest desalination plants are in the Persian Gulf. The Saline Water Conversion Corporation's Al-Jubail plant in Saudi Arabia is the largest plant in the world, with a capacity of around 815,120 m³/day [84], while MSF's largest unit located in the United Arab Emirates, is the Shuweihat plant with a capacity of 75,700 m³/day [3].

Among the advantages of the MSF system for seawater desalination, there is the reliability for large-scale production of distilled water, tolerance to the quality of the supply seawater, and the high quality of the distilled water. However, this technology has the disadvantages of high energy consumption and that the plant is heavy and expensive [86]. A schematic of MSF is shown in Figure 3.

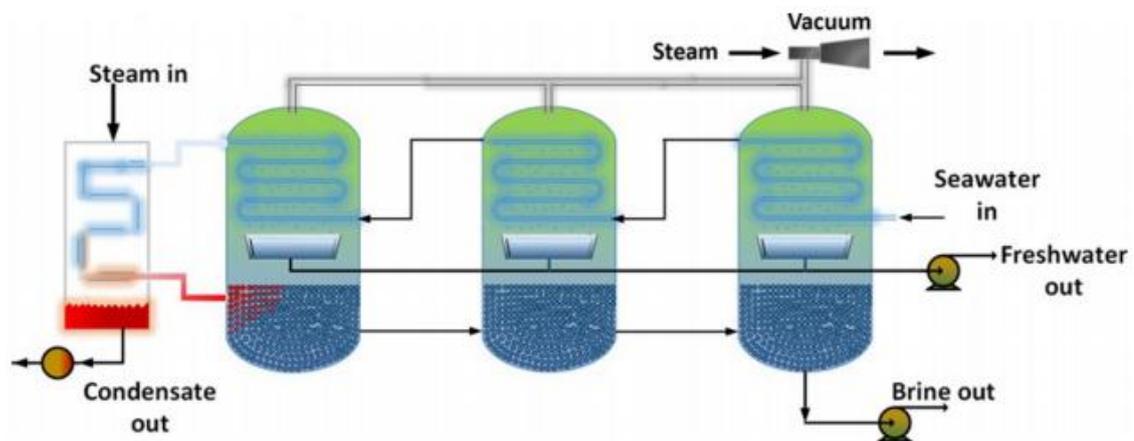


Figure 3. Schematic representation of the Multi-Stage Flash Distillation process, MSF. Source: Reproduced from Ref. [30]

At MSF, the seawater feed is pressurized and heated to the maximum allowable plant temperature. When heated liquid is discharged into a chamber held slightly below the saturation vapor pressure of water, a fraction of its water content is converted to vapor. Flash vapor is removed from suspended brine droplets as it passes through a mist eliminator and condenses on the outer surface of the heat transfer pipe. The condensed liquid drips into trays as hot fresh water [87].

The investigations developed for the optimization of the MSF units have focused on 4 main aspects: exergy, energy saving, environmental management, and economy [88]. Table 3 shows the most recent publications on SPS.

Table 3. Summary of literature reviews about optimization MSF

Authors (Ref., Year)	Optimization Methodology	Main Reported Results
Wuryanti, 2020 [89]	Heat recovery with brine recirculation.	With brine recirculation, MSF can work with a recycled water temperature of 30 to 45 °C and with a coefficient of performance of 4.4.

Luqman et al., 2020 [90]	Polygeneration of solar energy as a supply source	With 100,000 m ² of total area of parabolic trough collectors (PTC), the system produces 583.3 kW of electricity, approximately 4,284 kW of cooling and 1,140 m ³ of fresh water per day.
Gao et al., 2020 [91]	Mathematical modeling in steady state.	Steam temperature is the only factor that has a significant and positive effect on the distillate flow rate and the production/profit ratio.
Manesh et al., 2020 [92]	Exergy and exergo-economic modeling	Production of fresh water in the MED plant is significantly higher than that of the MSF plant (1,000 vs. 1,521 kg/s).
Snoussi et al., 2020 [93]	Entropy analysis for various MSF configurations	With more than 10 stages, the impact on the required area is negligible. Heat transfer was shown to be responsible for 65-85% of the total irreversibility per stage.
Lv et al., 2019 [94]	A mathematical model of a multi stage flash camera (MSF) was proposed	The simulation results showed that flash efficiency can be significantly increased by adding the deflector and/or changing the angle of the vertical deflector.
Thabit et al., 2019 [95]	Hybridization with direct osmosis and MSF.	The study showed the promising application of the direct osmosis process for seawater pretreatment at the MSF plant.
Kalendar et al., 2019 [96]	MSF Component Optimization	Amount of fresh water produced by an MSF system is increased by using improved pipes instead of common smooth pipes in the desalination process.
Darawsheh et al., 2019 [97]	Experimental parametric study to optimize process performance	By reducing atmospheric pressure by 20% in one of the instant vacuum chambers, the distillation-evaporation ratio was improved by 53% and specific energy consumption was reduced by 35%.
Hassanean et al., 2019 [98]	Steady-state mathematical modeling to evaluate MSF performance with brine recirculation (MSF-BC).	The developed model can be used to analyze the desalination process of MSF-BC under steady state operating conditions.
Hamed et al., 2019 [99]	Experimental study of exergy in configurations of condensing steam turbines + MSF	Specific energy consumption of water in cogeneration systems with turbines ranges from 58.8 to 69.8 kWh/m ³ .
Deymi et al., 2019 [100]	Recovery of waste heat for MSF and exergy analysis.	An exergy destruction rate of 71% was reported in the 25-stage MSF unit. It is possible to produce 9,000 m ³ /day of

		distilled water with 30,000 m ³ /day of brine.
Al-Othman et al., 2018 [101]	Mathematical modeling using parabolic through collectors (PTC) and a solar pond for MSF.	Results showed that two PTCs in an area of 3,160 m ² can provide approximately 76% of MSF's energy requirements.
El-Ghonemy, 2018 [102]	Case study. Experimental monitoring.	Operating the MSF large-scale thermal desalination plant in cold regions is more economical than in warm regions for reasons of saving pumping energy.
Ezzeghni et al., 2018 [103]	Recovery of waste heat for MSF and exergy analysis.	The exergy shows that in an MSF, the pumps and motors are the main sites of the greatest destruction of exergy.
Demir et al., 2017 [104]	Mathematical modeling use of solar tower, volumetric solar receiver, solar thermal damper and MSF.	An integrated system to produce electricity and fresh water was thermodynamically analyzed using energy and exergetic approaches.
Azhar et al., 2017 [105]	Mathematical modeling of exergy and energy of multiple systems of generation of renewable energies and MSF.	It was reported that energy and exergetic efficiencies of the modeled system, in general, are 13.93% and 17.97% respectively.
Khoshrou et al., 2017 [106]	Mathematical modeling for optimization of MSF processes.	Solutions are provided for two MSF problems: required heat supply, especially in remote areas, and high feedwater rejection rate.
Harandi et al., 2017 [107]	Mathematical modeling for process optimization MSF + TVC.	The economic parameters put a limit on the maximum performance ratio in the design of an MSF-BR-TVC.
Roy et al., 2017 [108]	Mathematical modeling for MSF process optimization.	The impact of Top Brine Temperature (TBT) up to 160°C is shown on both the design and performance characteristics of MSF systems.
Alsehli et al., 2017 [109]	Optimization in the MSF design powered by solar energy.	The resulting system used a solar catchment area of 42,552 m ² and generated an average daily production of 2,230 m ³ of fresh water with a total water price of 2.72 dollars per cubic meter.
Lappalainen et al., 2017 [110]	One-dimensional mathematical modeling and dynamic simulation of MSF.	The model combined the simultaneous solution of mass, momentum, and energy, the local phase equilibrium and the rigorous calculation of the properties of seawater as a function of temperature, pressure, and salinity.

Qi et al., 2017 [111]	Mathematical modeling for process optimization MSF + TVC.	This model can provide a reliable tool for the method of approximation and determination of key technical parameters of the MED-TVC device on a large scale.
Khoshrou et al., 2017 [112]	Mathematical modeling of exergy for optimization of MSF.	It was shown that exergy destruction can be reduced by more than 39% in pumps, about 29% in the distillate stream, and 30% in the blowdown.
Bandi et al., 2016 [113]	Steady-state mathematical modeling to evaluate MSF performance with recirculation of brine.	Optimization of the MSF one-time, single-mix (MSF-M), and brine recycle process setups was evaluated.
Ali et al., 2016 [114]	Steady-state mathematical modeling to evaluate MSF performance with recirculation of brine.	Optimization of the operational parameters of a plant with recirculation of brine (MSF-BR), considering the fouling factor of the brine heater and the seasonal variation of the temperature of the sea water.
Al-Hamahmy et al., 2016 [115]	Mathematical modeling to evaluate MSF performance with brine recirculation.	It is proposed to extract a part of the cooling brine from the water boxes and inject this extracted brine directly into the evaporation chambers.
Tenno et al., 2016 [116]	Mathematical modeling to evaluate MSF performance.	An MSF process was modeled with non-linear systems considering the pressure head, salinity, and changes in spatial and temporal temperature of the brine.
Darwish et al., 2016 [117]	Hybridization with Forward Osmosis (FO) and MSF.	A suggested arrangement for using FO as an MSF feed pretreatment is presented.
Okazaki et al., 2016 [118]	MSF optimization with microbubbles.	Introduction of micro bubbles into the spray jet as nucleation sites was proposed to increase the rate of spray flash evaporation.

In summary, optimization of the MSF processes has been developed from mathematical modeling to improve yield rates [91-94, 98, 99, 101, 104-108, 110-116], hybridization with forward osmosis used as pretreatment [95, 117], brine recirculation to recover residual heat [89, 100, 103], and optimization of components of MSF systems [96, 97, 109, 118].

2.3 Vapor Compression Distillation

Vapor Compression Distillation (VCD) is a process used for the evaporation of contaminated saline water, in which the compressed vapors release latent heat. In the vapor compression distillation process, the function of the compressor is to compress the vapors, to increase both their temperature and pressure. Therefore, the latent heat released during the condensation process can be reused to create more vapor [119]. In vapor compression desalination systems, the feed saltwater is heated from the uncondensed vapor, which is mechanically or thermally compressed. The resulting vapor during evaporation overheats due to the increase in the brine boiling point at a pressure lower than the saturation pressure of clean water. If this vapor is compressed to a higher pressure, its temperature increases due to the input of supplementary energy. By increasing its pressure and

temperature to the desired level, it can be used as a heat source for the evaporation of brackish water or seawater [31].

Although the principle of compression distillation was known before the 1970s, due to limitation of compressor technology, compression distillation in the seawater desalination field developed slowly. After 1970, with the high-efficiency centrifuge, some difficult problems of the compressors were overcome, such as overweight, slow speed, large size, and especially, compressor shaft sealing technology. Today, compression distillation technology is quite mature and has become the chosen technology to be combined with other desalination technologies to save energy and improve the economic performance of the system. For instance, it is possible to obtain high values of the GOR performance index (Gain Output Ratio) in multiple effect stills (MED) when a vapor compressor is coupled to the system, thus improving the unit thermal performance. [82, 86].

According to the use of devices and energy in the compression process, the compression distillation process is divided into mechanical compression (MVC) and thermal compression (TVC), where the mechanical compressor works with electricity and the thermal compressor uses an ejector of steam jet to create vacuum [31]. Normally, the production rate of distilled water from MVC (100 to 3000 m³/day) is lower than that of TVC (10,000 to 30,000 m³/day) [30]. Figure 4 shows the schematics of the MVC and TVC processes, respectively.

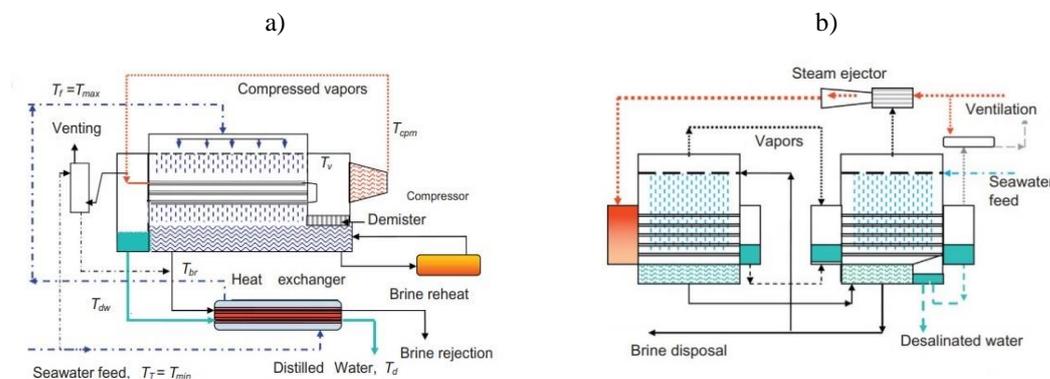


Figure 4. Schematic representation of the process: a) Mechanical Vapor Compression (MVC) and b) Thermal Vapor Compression (TVC). Source: Reproduced from Ref. [31]

Among the advantages that vapor compression distillation (VC) systems have are the high efficiency of converting heat into work, the reduced volume compared to other distillation systems, they do not require large-scale heat sources and that the compressor works with electricity or with diesel engines, so they are suitable for implementation on ships, islands, and maritime bases, i.e., on a reduced scale. Nonetheless, disadvantages are the delicate boiler design and that the scale of water production is limited by the capacity of the compressor [120]. Table 4 shows the most recent publications on vapor compression distillation technology.

Table 4. Summary of literature reviews on Vapor Compression Distillation

Authors (Ref., Year)	Optimization Methodology	Main Results Reported
Panagopoulos, 2020 [121]	Process simulation and technical-economic evaluation MED + TVC	The high quality of fresh water produced with MED + TVC can be profitable due to the income from the sale of fresh water.
Randon et al., 2020 [122]	Thermodynamic and economical modeling of a single effect mechanical	The MVC system is a very suitable technology to treat high hardness water, economically and efficiently.

	vapor compression system (SE-MVC)	
Wen et al., 2020 [123]	Performance evaluation of a steam ejector for a MED + TVC system	The developed model showed that disequilibrium condensations play a crucial role in the performance analysis of steam ejectors for MED-TVC.
Xue et al., 2020 [124]	Design and research of a two-stage vacuum ejector to improve performance of the MED + TVC desalination system	The two-stage vacuum ejector design for the MED-TVC system achieved a degree of vacuum of approximately 5.3 kPa.
Chen et al., 2019 [125]	Thermodynamic modeling for spray assisted low temperature desalination system (SLTD) + TVC	Integration of TVC into the SLTD process improves the overall production rate by 10-35%. The integration of TVC makes the system economically viable.
Dong et al., 2019 [126]	Dynamic modeling of a nuclear desalination plant based on the MED + TVC process	Proper control of operational parameters can provide high performance of MED + TVC.
Elsayed et al., 2019 [127]	Exergy and economic modeling of a MED + MVC system	Configuring the power layout to the MED + MVC system can reduce total fixed costs by up to 30%.
Gu et al., 2019 [128]	Performance evaluation of a self-adjusting steam ejector for a MED + TVC system	The simulation results show that by using the self-adjusting ejector, relatively higher Entrainment ratios (E_r) can be achieved with distinct types of motive steam.
Wang et al., 2019 [129]	Optimization of the steam ejector design for the MED-TVC desalination system	The proposed design method can improve the overall ejector efficiency by 14.41% compared to conventional methods.
Zhou et al., 2019 [130]	Mathematical modeling of MED and MED + TVC	Results show that designs can be improved when the compression ratio of the thermal vapor compressor is 2.1 to 2.6.
Cao et al., 2018 [131]	Hybridization of Thermal Vapor Compression (TVC) + Reverse Osmosis (RO)	Results indicate that better system performance can be achieved by the proposed serial TVC-RO than the independent parallel system.
Dong et al., 2018 [132]	Experimental evaluation of a steam ejector for a single-acting (S) TVC system	Results showed that the steam ejector can work well in S-TVC driven by a low temperature heat source below 100 °C.
Elsayed et al., 2018a [133]	Dynamic modeling of MED + TVC operating parameters	Results show that intensity variation of the disturbances has a significant role in the behavior of the desalination plant.
Elsayed et al., 2018b [134]	Exergetic and thermoeconomic modeling of a MED + TVC system	The model results indicate that the Parallel Cross Feed (PCF) configuration has better performance

		characteristics than the other feed configurations.
Ghaebi et al., 2018a [135] Ghaebi et al., 2018b [136]	Thermodynamic modeling of MED + TVC coupled to a combined cooling, heating and power (CCHP) system	Results show that the efficiency of the integrated system reached 84% and efficiency of the gas turbine cycle was 32%.
He et al., 2018 [137]	MVC Evaluation with a Rankine Cycle (CRC) Driven Steam Compressor	The calculated results are enough to demonstrate the feasibility and availability of the combined desalination system to produce fresh water.
Khalid et al., 2018 [138]	Mathematical modeling to identify the optimal location of the thermal vapor compressor (TVC or ejector) coupled to MED	The lowest specific cooling water flow rate was obtained by setting the ejector (TVC) at $N/2$, where N is the number of effects.
Ghazi et al., 2017 [139]	Hybridization of Wind-Photovoltaic System + Thermal Vapor Compression (TVC)	Results show that using only the photovoltaic system is the most suitable configuration, however, using between 35% - 40% as photovoltaic contribution in the renewable hybrid system is the best combination.
Han et al., 2017 [140]	Mathematical modeling of MVC for zero emissions (ZEDS), based on exergy and energy analysis	The MVC based desalination system is found to be available to achieve the zero-emission target.
Jamil et al., 2017 [141]	Thermo-economic analysis of MVC effect with and without recirculation of brine.	The input parameters of the simulations have a notable influence on the final value of the cubic meter of distilled water.
Onishi et al., 2017 [142]	Optimization model for the design of Single and Multiple Effect Evaporation systems (SEE/MEE)	Results highlight the potential of the model to cost-effectively optimize SEE/MEE systems by producing fresh water and reducing brine discharges and associated environmental impacts.
Sadri et al., 2017 [143]	Mathematical modeling for MED + TVC + Reverse osmosis (RO)	Results showed that if the hybrid system is used instead of the individual system, energy loss can be significantly reduced.
Askalany, 2016 [144]	Hybridization of MVC + Adsorption System (AD)	Results show that daily desalinated water, per ton of silica gel, has increased in a range of 10-45% depending on the conduction temperature.
Swaminathan et al., 2016 [145]	Hybridization of MVC System + Membrane distillation (MD)	The hybrid MVC-MD system can generate an approximately 6% reduction in the water cost, compared to a standalone MVC system.

Generally, the most recent publications are oriented to the development of mathematical models for the optimization of TVC distillation processes coupled to MED [39, 50, 65, 66, 69, 121, 126, 129,

130], development and optimization of the ejectors of the TVC thermal compressors [123, 124, 128, 129, 132, 138], mathematical modeling of MVC coupled with MED [127, 137, 141], and hybridization systems of MVC [144, 145] and TVC [131, 139] with other desalination technologies.

3. Use of Renewable Energies in Water Desalination

Conventional fossil fuel-powered desalination techniques consume substantial amounts of energy to produce fresh water and have a very damaging impact on the environment [7, 18]. Table 5 shows the specific energy requirements to produce one cubic meter of fresh water from currently available technologies for commercial seawater desalination.

Table 5. Typical total electrical energy consumptions in different desalination technologies.

Source: Reproduced from Ref. [18, 146]

Desalination Technology	Specific Energy Requirements
Multi-Effect Distillation (MED)	14 – 21 kWh/m ³
Multi-Stage Flash (MSF)	20 – 27 kWh/m ³
Mechanical Vapor Compression (MVC)	7 – 12 kWh/m ³
Thermal Vapor Compression (TVC)	16.26 kWh/m ³
Seawater Reverse Osmosis (RO)	4 – 6 kWh/m ³

In general, thermal-based desalination techniques consume significantly more energy compared to membrane techniques [11, 146], and only 131 desalination plants worldwide, representing approximately 1% of the world's water desalination capacity work with energy from renewable sources [10]. However, use of renewable energy for seawater desalination has increased from 2% in 1998 to 19.3% in 2015 [18].

The main conventional renewable energy sources of interest for water desalination are solar, geothermal, wind, and tidal energy. Solar and wind energy contribute predominantly to the general renewable energy capacity, and to a lesser extent, geothermal and tidal energy [147]. Figure 5 shows the evolution of the use of renewable energies worldwide.

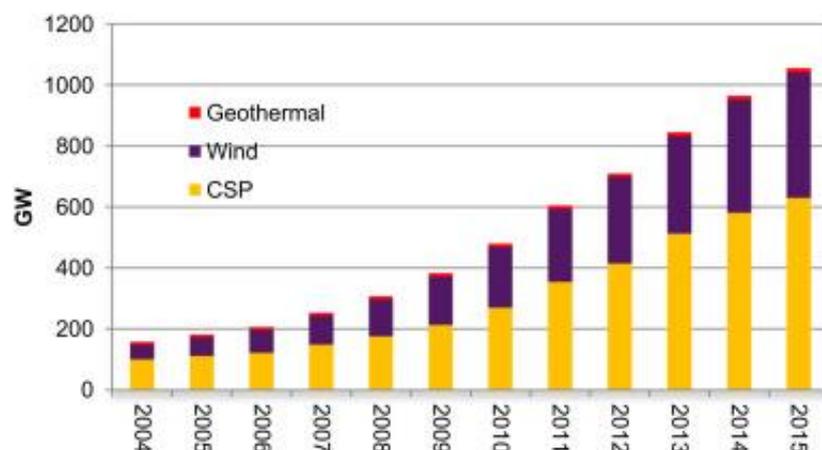


Figure 5. Global evolution of the use of renewable energies. Source: Reproduced from Ref. [147]

Selecting a suitable solar system requires many considerations, such as locally available solar radiation, plant location, energy storage method, operating temperature range, plant configuration, type of solar collector, fluid power (working fluids), among others. Most solar desalination systems have not been developed as a single system, but are integrations of independently developed components, although some systems require minor changes for better integration [148]. On the other

hand, wind turbines represent a mature technology that has been present in many countries for a long time and represents a viable option as a source of energy for desalination systems; however, problems such as public acceptance, correct location of turbines, visual impact, audible noise, interference in communications, and various impacts on the natural habitat and wildlife, have hampered their full development [147]. Use of hybrid renewable solar-wind energy systems has recently been reported with excellent results in isolated islands, and thanks to these integrated generation systems, it is possible to have continuous energy, even if there is no permanent solar radiation [149, 150].

Concentrated Solar Power (CSP) plants have gained great interest due to the possible simultaneous cogeneration of water and electricity. The coupling of CSP to MED and RO desalination systems has been the one with the best technical and economic performance; therefore, it is the one with the greatest technological development, although commercially integrated on a small scale [146]. This is mainly because promoting thermal desalination with CSP is not economically feasible on a large scale, since the costs associated with the production of 1 m³ of fresh water range between US \$0.94 and US \$4.31, where cost is mainly affected due to the capital expenditure in the solar field and the operating expense of the desalination plant [151]. Consequently, desalination is a costly process if compared with the USD \$0.53 price of 1 m³ of fresh water when it is produced through a conventional process [69, 87]. Although thermal desalination technologies require higher energy demands and have high maintenance costs compared to RO [152], both thermal and membrane-based processes are key to fresh water supply. Thus, reducing their energy demands through advances in research is equally important for both [7]. As a response, mathematical models and algorithms have emerged to allow simulating the costs of freshwater production with desalination systems, both thermal and membrane, coupled to diverse sources of renewable and non-renewable energy, allowing them to be compared with each other, to optimize decision-making in the selection [153]. Currently, in any case, the only desalination systems coupled with solar energy, with market opportunities and capable of producing up to 20,000 m³/d of fresh water, are based on reverse osmosis driven by parabolic or linear trough concentrators, or with concentrators of plate coupled to micro gas turbines [154].

At the experimental level, membrane distillation (MD) is among the most promising desalination technologies from the potential use of sustainable energy sources. Fresh water production rates of 3 Kg/m²/h have been reported with an electrical and total efficiency of the experimental system of 18% and 71% respectively, based on the use of a concentrated photovoltaic/thermal system [155]. The University of Almerias in Spain proposes the integration of a solar thermal field based on static collectors coupled to a Vacuum Multi-Effect Membrane Distillation unit (V-MEMD), the experimental results show a rate of maximum fresh water production of 5.5 ± 1 L/m²/h [38]. However, the best application of solar-assisted MD for water desalination is for domestic use in single-family homes [156], where the main drawback is the cooling requirements, like any other heating distillation technology. Therefore, membrane distillation systems, when fully developed, will have market opportunities in seawater desalination systems, but with very small production capacities [154].

Another technique that has been presenting advances and improvements for the desalination of saline waters is Humidification-Dehumidification (HDH) coupled with different types of renewable energies and cooling and desalination technologies [157-159]. Recent studies reported an increase in the water production rate from 10.8 to 32.1 Kg/m²/day thanks to the use of hygroscopic solutions such as kaolin [160]. The design and operation of HDH processes coupled to solar photovoltaic thermal modules (PVT) for the simultaneous generation of clean water and electricity has been researched; however, the final cost of 1 m³ of water is expensive with this technology, but its high electricity production makes it the cheapest solution for places in critical environmental conditions [161]. In general, it has been shown that the integration of PVT systems with water desalination systems, ensures the polygeneration of products, improves the general efficiency of desalination, and improves the environmental sustainability of these systems [162].

Finally, on an experimental scale, another desalination technology that has aroused great interest among researchers is electrodialysis (ED) coupled to photovoltaic (PV) systems [163] and to hybrid

photovoltaic-wind systems [164]. In terms of renewable energy-driven desalination, ED is highly valued for its adaptability to varying power conditions, as ED could operate at a wide range of direct current voltages [165]. ED systems are more favorable for brackish water desalination with relatively low Total Dissolved Solids (TDS), as it is normally considered to be economically uncompetitive for seawater desalination due to expensive ion exchange membranes, expensive electrodes and relatively short lifespan when working in a high-density electric field [165, 166].

In short, the use of renewable energy sources for desalination is essential and decisive if we want to provide an adequate supply of clean water that meets our future needs, reduces harmful impacts on the environment, and is sustainable over time [10]. Therefore, the future of desalination with optimized energy requirements is projected to include ultra-high permeability membranes, scale resistant membranes, hybrid systems, and renewable energy-driven desalination [7].

4. Future Perspectives

Despite the evident advances that commercial thermal desalination systems have had in recent decades, which has allowed a considerable increase in the flows of desalinated water produced globally, it is necessary to mitigate the intensive energy requirements to lower the high production costs and make its massive use more accessible in regions in need of this technology and with low per capita income. Present and future research is aimed at significantly improving energy savings and optimizing processes and equipment, to reduce the current limitations of thermal desalination processes. Consequently, the hybridization of technologies and the use of renewable energies is the way to go, because the availability and coupling of emerging energies with hybrid systems is currently more relevant. Considering the limitations of solar radiation as the only energy provider, it is also recommended to hybridize renewable energies to take advantage of their full potential, such as a hybrid solar and wind energy system coupled to water desalination systems.

Today, the race for the next generation of seawater desalination systems has already started with reverse osmosis (RO) and low-temperature MED. Its low cost of energy consumption gives it more advantage compared to other systems such as MSF [39]. However, research on emerging desalination technologies have clear merits and environmental benefits over reverse osmosis (RO), for which the trend is the development of hybrid MED systems with this type of emerging technologies, where the most opted is Forward Osmosis (FO). Additionally, considering MED's low energy consumption, it can be operated with solar energy coupled to a MED + TVC system. However, it is necessary to deepen research on the configuration of this process, since it is still in the development stage, but with very good prospects on a commercial scale.

On the other hand, use of Waste Heat (WH) as an optimization strategy in conventional desalination technologies has demonstrated its technical viability, since it improves the productions and efficiencies in thermal desalination processes. Utilizing waste heat in desalination provides significant economic and environmental benefits by eliminating or reducing fuel and energy load. This, in turn, will result in reduced production cost of desalination and greenhouse gas (GHG) emissions associated with fuel consumption [167]; however, most waste heat driven systems are at pilot and laboratory scale, with a clear need for further development for large-scale plants. Future planning of a new desalination facility should consider the utilization of available waste heat sources associated with power plants or industrial parks [168].

Regarding the mathematical modeling of processes, energy and exergy analyzes should be used as key factors when applying solar energy systems to improve the energy and exergetic efficiency of the modeled systems [169]. Among the developments and research required to overcome the technological limitations that hinder the massive access of desalination technologies from renewable energies, the following can be mentioned [170]:

- Development of components, intelligent controls, and new materials that allow optimizing the coupling of desalination systems with renewable energy systems.
- Development of new types of desalination membranes that can easily and optimally hybridize with thermal desalination systems such as MED.

- Proper disposal of brine due to the high environmental impacts that its mismanagement represents.
- Deepening the coupling and extensive use of photovoltaic technology as an alternative energy supply in desalination systems.
- Optimization of solid-liquid phase separation processes in the thermal desalination of water.
- Improving the automatic management of energy loading and unloading, as they are necessary for the proper management of the maximum load of solar thermal and photovoltaic energy.
- Development of systems and equipment to improve the conversion efficiency of photovoltaic energy, because the currently available on the market is low.
- Innovation in materials for photovoltaic cells in such a way that they act independently of temperature and local climatic variables.
- It is necessary to develop prototypes and equipment where the desalination process is compact, portable, mobile, and simple in design and manufacturing to produce small-scale water from saline, brackish, and fluoridated water.
- In the thermal desalination system, scale formation in the pipes and tubes of the heat exchanger is the main problem due to the high salinity of the water. It is very difficult to remove scale and it also reduces the efficiency of the heat exchanger, therefore, coming up with technical solutions to these difficulties is a need that must be addressed promptly.
- All the limitations and challenges presented can be overcome with innovative ideas and research, which beat knowledge barriers and give development opportunities to experimental research, modeling, and computational simulation. Therefore, collaboration in the field of R&D between academia and industry is essential to transform these future technological developments into commercial products, capable of responding to the needs and problems of society.

5. Conclusions

Conditions of water stress that currently exist in many populated areas of the planet, and which are expected to increase in the short term, have led to the optimization of commercial thermal desalination systems and development of new alternative systems that, although still in the experimental stage and on a pilot scale, they represent the best alternative to face this problem. Optimization of thermal desalination systems has been oriented towards hybridization with commercial (VCD and RO) and non-commercial (HDH, ED, MD, AD) technologies and the reduction or replacement of electrical and combustion energy by renewable energies, especially by solar and wind, proposing alternation or simultaneity between them. The above, due to the need to reduce the costs of the equipment used in desalination technologies and the automation required for this type of process.

Recent research in the development of commercial thermal technologies revolves around reducing production costs, reducing impact on the environment and reducing greenhouse gas emissions; therefore, the focus is on increasing desalination efficiencies, recovering heat residual and exergy, mathematically modeling hybridization alternatives, and finally, the best is on integration with renewable energies. In this way and in the future, research will be directed towards the development of desalination technologies that allow to find inexpensive equipment, with low energy consumption and with high performance and efficiency.

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