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A techno-economic review of solar-driven multi-effect distillation

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ABSTRACT

The provision of clean drinking water is one of the greatest challenges in our time. Global population increase puts a lot of stress on current water desalination plants to meet the rising demand for freshwater and requires an increase in capacity. Conventional desalination plants are powered by fossil fuels and hence are a major cause of climate change as well as being unsustainable in the long term. There is a need to develop a sustainable desalination process, which does not contribute to climate change and is also economically competitive. Coupling solar thermal energy with the multi-effect distillation (MED) process is one of the most promising alternatives. This paper reviews extensively research on coupling solar thermal energy with MED from a technical and economic point of view. The MED process is discussed, the most suitable solar collectors are presented and various plant configurations are critically analyzed. The review highlighted the advances in knowledge obtained from experimental and modeling research studies. In addition, the main challenges in solar-driven MED such as storage, adaptability issues and cost are discussed. The review also provides general remarks about the literature and research gaps that should be addressed in the future.

Keywords: Solar thermal; Multi-effect distillation; Techno-economic; Desalination

1. Introduction

The provision of drinking water is one of the greatest challenges in our time. In many parts of the world, desalination is the only viable and economic solution to the problem of freshwater shortage. This is particularly applicable to the Gulf Cooperation Council (GCC) region which has the largest installed capacity of desalination plants in the world: 38% of the global capacity [1]. The majority of desalination plants in the GCC region operate using the multi-stage flash (MSF) and the multi-effect distillation (MED) with thermal vapor compression (TVC). The reverse osmosis process (RO), however, is gaining increasing popularity and currently has a 29% market share in the GCC region [2]. By 2013, the GCC region had 3,732 online plants that produced 29,503 Mm^3 of freshwater per day [3]. On average, 80% of drinking water in the GCC region comes from desalination [4]. Water desalination is an energy-intensive process and hence requires large amounts of fuel. It was estimated that in 2012, desalination plants in the GCC region consumed 3.49 MGJ of fuel per day [5]. Furthermore, in 2014, the GCC countries spent $15.9 billion in fuel costs for desalination [6]. At a global scale, due to population increase and increased demand for food, demand for freshwater will continue to rise. This will put a lot of pressure on current desalination plants and require more plants to be built which in turn means an escalating energy and fuel demand. The current desalination technologies are all reliant on fossil fuels and hence have high greenhouse gas (GHG) emissions that are a major cause of climate change.

Solar-driven desalination is identified as the most promising alternative for fossil fuels driven desalination. The abundance

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of solar resources in the many water-scarce regions make solar-driven desalination ideally suited to replace conventional desalination. Solar energy is the most abundant renewable energy source and is highly suitable for powering both thermal and membrane desalination processes. A number of studies have highlighted the importance and suitability of solar desalination for the Middle East and North Africa (MENA) region and can be found in references [7–9]. Moreover, the use of solar energy means minimizing the environmental impact of the desalination process in terms of GHG emissions. Solar desalination should be considered as a real alternative for fossil fuel powered desalination by policy makers.

Among the currently developed solar desalination technologies, the solar-driven MED is possibly the most suitable for large-scale implementation due to its superior thermodynamic and heat transfer characteristics, low pumping energy (compared with the MSF process) and lower levelized cost of water (LCOW) [10,11]. Building on this, we believe that solar-driven MED is the most suitable thermal desalination technology for large-scale seawater desalination as highlighted also by Bataineh et al. [12]. In this paper, we define solar-driven as any system driven entirely or partially by solar energy.

On a global scale, 7% of global desalination capacity is based on the MED process, 21% is based on MSF, 65% is based on RO and 7% by other processes according to the International Desalination Association (IDA) [13]. Most thermal desalination plants are found in the GCC region. Interest in the RO has been rising due to its minimal total energy requirements although it requires complex feed water pretreatment. However, the feed water pretreatment requirements are very minimal for all thermal desalination processes. The MED process can easily be integrated to current power plants whether powered by fossil fuels or concentrated solar power (CSP). This means dual production of desalted water (DW) and electric power (EP). The possibility of integrating MED to CSP plants provides great research opportunities and also poses many technical challenges such as the large water requirements for CSP plants and the necessity of storage to increase plant capacity factor. Sustainability of CSP plants maybe increased by integrating them with thermal desalination plants [14]. This is one of the main motivations for carrying this review.

This paper reviews extensively research works on solar-driven MED with a focus on process innovations and strategies that reduce the LCOW. Section 2 is the literature review that includes the MED process, the types of solar collectors used in solar-driven MED, different plant configurations with their advantages and disadvantages and the assumptions and limitations of modeling studies. Section 3 reviews critically the economics of solar-driven MED, costs associated and calculation methods in reference to the LCOW specifically. Section 4 addresses key challenges in solar-driven MED, namely, storage, adaptability issues and LCOW. Section 5 concludes the review and provides a number of key takeaway messages and recommendations.

2. Literature review

2.1. The MED process

MED is a thermal desalination process wherein seawater is desalted by boiling at successive effects. Latent heat of an external heat source is used to boil a fraction of the feed water in the first effect. This generates freshwater vapor and brine at the effect's pressure. The brine is circulated by a pump to the next effect and partially boils due to the latent heat from the previous effect's condensing vapor and this subsequently generates more distillate. Each effect in the MED system is kept a pressure and temperature lower than the previous effect. This ensures that the brine will boil at a lower temperature each time. Efficiency in thermal desalination processes is measured by the gain ratio (GR), which is the mass flow rate of the distillate divided by the heating steam mass flow rate. The GR is always equal to or less than the number of effects. The MED process has a number of advantages over the MSF process that make it more suitable for integration with solar collectors. MED can be carried at a low top brine temperature (TBT) and hence, this means low-grade process steam can be used to power the process. This means that even under low solar intensity, the solar collectors can still supply enough thermal power to the MED unit. A low TBT also means that the likelihood of scaling is minimized. Furthermore, the MED system is more flexible than the MSF system in terms of configuration. For example, an eight-effect MED plant with a GR of 7.5 and a capacity of 1 million imperial gallons per day (MIGD) can be rearranged to work as four effects with double the capacity (2 MIGD) but at a lower GR [15]. Moreover, the MED process is more responsive to the enthalpy of the heating system than the MSF and can change its distillate capacity accordingly. It is a common practice in large MED plants to also incorporate a TVC. The TVC is a device that extracts entrained vapor from the last effect and mixes it with motive steam from the steam generation source (e.g., back-pressure turbine) to produce the heating steam that enters the first effect. This helps in reducing the heating steam requirement and hence increases the GR. In addition, MED has a higher recovery fraction than MSF and also lower operating costs. Fig. 1 shows a six-effect forward feed (FF) horizontal tube MED/TVC unit. All these points give great preference for MED over other thermal desalination processes for large-scale seawater desalination.

A number of design considerations must be noted in MED plants. The TBT is usually kept at a low value: 65°C at 0.3 bar since this helps in reducing the probability of scale formation. MED plants operating at low TBT are sometimes referred as low temperature MED (LT-MED). The number of effects in MED systems is also lower than MSF plants (around 6–8 effects). Since the final brine temperature is usually set at 40°C and the TBT is usually 65°C, the temperature difference in each effect has to be 2–4°C which results in 6–8 effects in total. The value of ΔT has to be designed carefully to avoid having a high heat specific heat transfer area (A/D). The smaller ΔT is, the higher the specific heat transfer area. A high A/D value will result in a higher LCOW. Furthermore, to make the MED system competitive to the MSF, A/D has to be around 200–300 $m^2/kg/s$ [5]. Adding feed preheaters in the MED system can increase the GR but at the expense of higher pumping energy and more capital costs. The electrical energy requirements or specific power consumption (SPC) for MED systems is between 1.5 and 2.5 kWh/m^3 of distillate, whereas the thermal energy consumption is around 80 kWh/m^3 [16]. Darwish et al. [17] presented a critical analysis of some MED plants and discussed in details their performance and characteristics. The implications of these design considerations on solar-driven MED are discussed in the further sections.

2.2. Coupling of MED with solar thermal systems

An MED plant powered by solar energy has the same overall plant design as a conventional MED one. There are two major blocks: the solar field block and the MED unit block. A storage medium maybe used to link both blocks and a heat exchanger is employed to transfer the solar thermal energy to the first effect of the MED chamber. Fig. 2 shows a simplified block diagram of a solar-driven MED plant. The most commonly used solar collectors in solar-driven MED are parabolic trough collectors (PTCs), linear Fresnel collectors (LFCs) and flat plate collectors (FPCs). Some research studies also considered using compound parabolic collectors (CPCs) and solar power towers. The solar field absorbs solar thermal energy by using a heat transfer fluid (HTF) and then transfers this energy to the MED chamber via a heat exchanger (which will effectively be a steam generator). Thermal energy storage (TES) may be used to compensate any drop in solar intensity.

It was found from the literature that most research studies used CSP collectors such as the PTC and LFC. Table 1 shows the choice of solar collectors in various studies found in the literature. As the table shows, there is a high interest and focus on using PTC followed by FPC for solar-driven MED. Solar collectors such as CPC, LFC and power tower have been given very little attention. To understand this further, we need to highlight the parameters affecting the choice of the solar collector in an MED system.

The choice of the solar collector depends on the required heating steam temperature, design plant capacity, capital costs and whether the plant also produces EP. In LT-MED, as mentioned earlier, the heating steam temperature is usually 70°C at 0.3 bar and hence the HTF should be heated by the solar collector to 5°C–7°C above 70°C. This results in a lower temperature difference in the heat exchanger and hence, lower thermal stresses, which is important from a maintenance point of view. FPC and non-concentrating collectors in general are very suitable for small systems and experimental units. Such collectors can easily heat water to temperatures

Table 1
Summary of solar collectors used in solar-driven MED in the literature

Solar collector	References
Used an FPC or vacuum tabular solar collectors	[18–23]
Used CPC	[24]
Used LFC	[25,26]
Used PTC	[12,27–35]
Used solar power tower	[36]

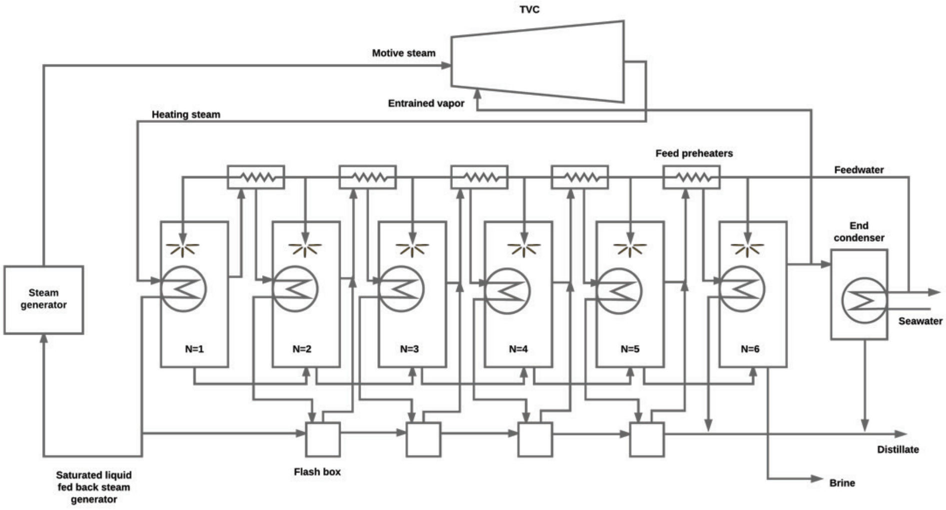

Fig. 1. Six effect forward feed horizontal tube MED/TVC unit.

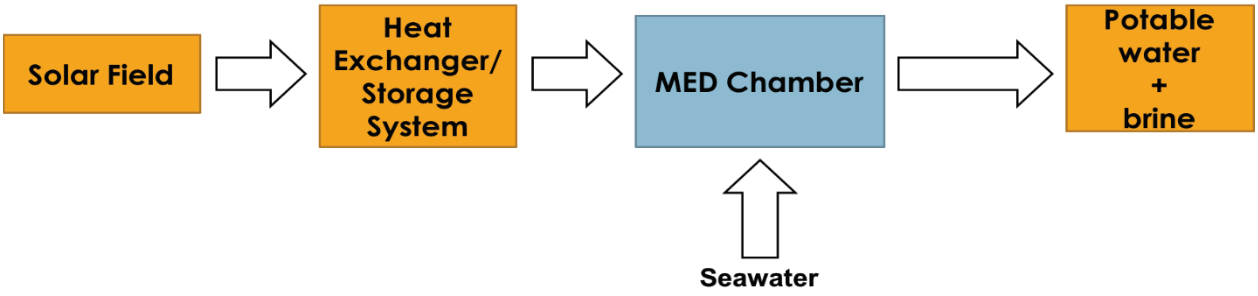

Fig. 2. Block diagram of a solar-driven MED plant.

above 100°C. However, when considering larger desalination systems and those using a TVC, using concentrating collectors is more suitable as they can produce superheated steam. This superheated steam (at temperatures around 150°C and 5–20 bar) will effectively be the motive steam entering the steam ejector. CSP collectors are also required when the desalination plant operates in cogeneration mode. In this case, superheated steam is needed to drive a turbine and as it is de-superheated, a fraction of it will be directed to the MED/TVC unit from the back-pressure turbine. Another consideration factor for the solar collector choice is capital costs. Non-concentrating collectors (like the FPC) are cheaper than CSP collectors and are stationery; hence, do not require tracking. Almost all experimental studies on solar-driven MED that had a working prototype used FPC or evacuated tube collectors. Very few experimental studies used PTC or LFC for MED simply because of the large investment costs required. Examples of these include the MED plant in Plataforma Solar de Almeria (PSA) in Spain [27] and a small pilot plant for agricultural drainage water desalination in the United States [30]. The economics of solar-driven MED are discussed later in depth in this paper.

From the literature, it was noticed that few papers gave justifications of the choice of the solar collector. Yılmaz et al. [19] used an FPC in a hybrid solar-driven MED system and justified the choice of the FPC by stating that FPC can absorb both direct and diffuse solar radiation which is an advantage over CSP collectors. Other studies seemed to choose the FPC due to system simplicity and low cost. Studies that investigated cogeneration of DW and EP such as [28,29] used the PTC because it can easily generate superheated steam at temperatures above 300°C and a pressure of 100 bar. There seems to be an agreement that among CSP collectors, the PTC is the most suitable for cogeneration of DW and EP in a solar thermal-driven desalination plant as highlighted by other studies [29,37,38]. These studies asserted that the PTC is the most commercially mature CSP collector and hence has good reliability and is suitable for large-scale desalination. We can conclude from this that if the PTC is to be integrated to an MED plant, then it might be suitable to consider a cogeneration plant. In this way, there will be less exergy destruction since superheated steam is expanded in a high pressure turbine. Another advantage of using PTC is the possibility of powering hybrid desalination plants such as RO+MED.

The design capacity of the MED plant also plays a key role in determining the optimum solar collector from a theoretical point of view. Currently, almost all solar-driven MED systems are either small demonstration units or have been implemented in a computer model only. Demonstration units and small solar-driven MED plants currently have a maximum capacity of 3 m^3/h. The two largest solar-driven MED experimental systems are the Abu Dhabi solar desalination plant [18] and the solar MED plant in PSA in Spain [24]. The plant in PSA was using CPC. On the other hand, solar-driven MED systems implemented in computer models had design capacities reaching 1 MIDG and sometimes the study would assume a distillate production rate of an actual MED plant. It was noticed from the literature that there is no relation between the solar collector choice and the plant capacity (the distillate production rate) in experimental-based studies. Few systems like the one developed by Stuber [30] tested a PTC coupled to an MED unit with a heat pump for agricultural sub-surface drainage water treatment and had a product flow rate of merely 0.46 m^3/h. This was despite the fact that this study used one of the highest quality PTC in the market. Other studies like the Abu Dhabi solar desalination plant obtained a distillate production rate of 3.3 m^3/h although using FPC and in fact this plant was operational for 13 years. To develop sound understanding of solar-driven MED, more data from experimental studies are required. However, we can highlight the following design considerations for the solar field selection:

- Large-scale solar-driven MED should be based on the MED/TVC configuration that is very efficient and has a high GR. This means only CSP collectors should be used since they can supply superheated steam. It should be noted, however, that the TVC can operate using saturated steam.
- Investigation of the FPC and CPC should focus mainly on MED units suitable for remote areas. In such cases, the feasibility of the system should be based on the LCOW.
- It is important to use solar collectors with high efficiency so that total surface area is minimized and as a result the water cost too.
- The plant location must be considered in the selection of the solar collector. In locations with high DNI, CSP collectors should be used.

Table 2 summarizes this section by showing the most suitable solar collectors for MED and their respective advantage and disadvantages:

2.2.1. Thermal energy storage

Intermittency of solar resources means that solar-driven MED plants cannot operate continuously and hence, distillate production is reduced. The solution is either to start and shut them down every day or to use a storage system and/or a backup boiler. Continuous start-up and shut down jeopardizes the reliability of the equipment and increases maintenance costs. Nevertheless, carrying computer simulations of a solar-only MED plant could help researchers understand the boundary limits of these systems.

Incorporating a storage system (energy or water storage) is a good solution. In the context of solar-driven MED, energy storage systems (also called TES) are ones which store either sensible or latent heat. A number of materials can be used for TES such as water, sand-rock and synthetic oils. Materials for TES can be either phase-change materials (PCMs) or thermochemical materials (TCM). Fig. 3 shows the storage capacity and temperature range for a number of PCM and TCM. The use of the TES can extend the operating hours of the plants, reduce the LCOW, reduce environmental impact and manage resources in a better way [39]. Detailed information about incorporating TES in solar-driven MED can be found in other studies [12,18,24–27,29,36]. However, using a large TES means increasing the solar field size significantly that has a high influence on the LCOW. Hamed et al. [25] found that powering an 1 MIGD MED plant by an LFC solar field is more cost efficient if no TES is incorporated.

Table 2
Comparison of solar collectors suitable for solar-driven MED

Solar collector	Temperature range	Suitable MED process	Advantages	Disadvantages
FPC	80°C–120°C	LT-MED	Low cost No tracking required Absorbs DNI and DHI High reliability Has been experimentally tested in many desalination systems	Small plant capacity Cogeneration not possible
PTC	350°C–500°C	MED/TVC	Commercially mature Can be used for cogeneration Can drive MED+RO	High capital cost : 300–350 €/m^2 [1] Land requirements are high High maintenance requirements
LFC	100°C–450°C	MED/TVC and LT-MED	Smaller mass per unit area than PTC Low specific investment costs: 200–250 €/m^2 [1] Low land requirements	Moderate commercial maturity (as compared with the PTC) Very little data available from research studies

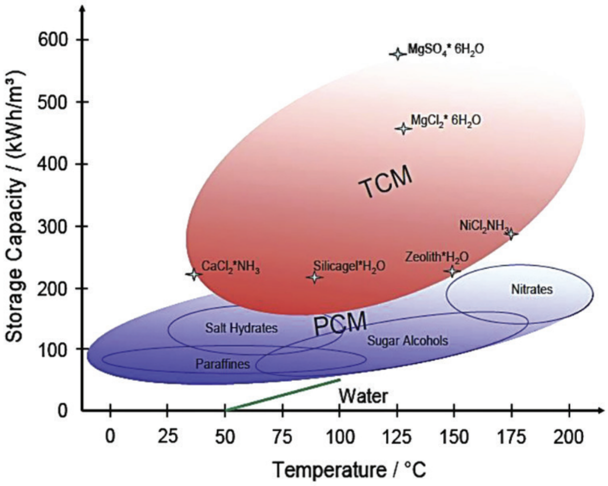

Fig. 3. Storage capacity and temperature range for TES systems based on PCM and TCM [39].

A number of studies on solar-driven MED did not consider adding a TES [19,20,28,30,31,40]. On the other hand, water storage systems simply require oversizing the MED plant (adding more effects) that has a relatively lower impact on LCOW. It is because of this that some studies, such as Weiner et al. [41], proposed that water storage is more cost-effective than energy storage (for a hybrid configuration using CSP to power an MED and RO desalination process) and calculated a critical cut-off cost for energy storage which was \$0.0125/kWh$_{th}$. It can be identified that the storage issue is one of the major areas of disagreement in the literature and requires extensive studying especially from an economic point of view. Advanced plant design for solar-driven MED must consider the temperature range for each TES system and its suitability with the chosen solar collector and the required distillate production. This requires sophisticated optimization simulations. It would be of interest to also calculate and analyze the equivalent economic value of a TES with regards to its environmental benefits. Furthermore, one of the key questions to address is as follows: does a solar-driven MED plant with TES has a higher reliability than another plant without TES but with a backup boiler? These are research questions yet to be answered.

2.2.2. Adapting solar technologies to MED

One of the fundamental challenges of coupling solar thermal collectors (especially CSP collectors) to MED systems is the collector performance. CSP collectors have originally been designed for power generation that requires generating high pressure steam to do work. In desalination systems, the thermal energy of steam at a critical temperature (top steam temperature or TST) is the key requirement. This TST is usually 70°C–75°C at 0.3 bar. If the TST increases a lot, the probability of scale formation increases significantly in horizontal tube falling film MED. There should be a strong focus on developing new solar collectors whose average thermal power output is in the range required by MED plants. In addition, the fact that most CSP collectors will produce excess thermal energy means that investing in reducing the cost of TES is one of the key areas of research. Furthermore, it is necessary to consider hybrid configurations when powering an MED plant entirely on solar energy. An example is to use PV for the electrical energy requirements, LFC for generating heating steam and a TES for increasing capacity factor. Such a configuration implies the need for developing sophisticated control systems that can process numerous inputs and suggest the optimum operation strategy. A good paper to refer to in this regard is by González et al. [42], which developed an economic optimal control algorithm that regulates the mass flow rate in the solar field to achieve maximum freshwater production. Improving the adaptability of solar technologies to MED also means limiting or even eliminating the use of backup boilers as much as possible.

2.3. Plant configurations

There are several plant configurations for a solar-driven MED system. The core components of the plant are the solar field, the steam generator and the MED unit. Additional components that may be incorporated include the TVC, MVC, TES, electrical generation system and a heat pump. In modeling based studies, it was noticed that the plant structure was much more complex than in experimental studies. This is naturally due to the flexibility of modeling software.

The Abu Dhabi solar desalination plant [18], as an example, was based on a simplified configuration which is shown as a block diagram in Fig. 4. The plant was operating for 24 h due to the use of the TES. It had a maximum capacity of 120 m^3/d and a water cost in the range \$7–\$10/m^3 [43]. Further its MED chamber was made of 14 effects which is a considerably large number. Having a large number of effects implies a smaller ΔT in each effect and hence larger specific heat transfer area (A/D). In addition, a large number of effects will add further costs to the plant although it does increase distillate production.

Some experimental studies like the PSA plant had a complex plant configuration. Fig. 5 shows the plant configuration for the PSA solar-driven MED plant. This plant utilized a double-effect absorption heat pump (DEAHP) which was used to increase the energy efficiency of the process by utilizing thermal energy from the saturated steam produced in the last effect. When there is little or no solar radiation, the DEAHP absorbs heat from the saturated steam from the last effect plus thermal energy from the gas boiler. As a result, the DEAHP can increase the temperature of the water exiting the first effect from 63.5°C back to 66.5°C. A study on the performance of the DEAHP in this plant by Alarcón-Padilla et al. [44] investigated two possible methods to connect the DEAHP to the existing solar MED plant using CPCs. The study argued that integrating the DEAHP with the MED unit optimizes the overall heat consumption of the system. For this study, energy contribution from the solar field was not included. The aim of the study was to determine which connection method yields a steadier operation and higher thermal performance. The connection of the DEAHP to the MED was first done in a direct manner. This means that water leaving the first effect was fed directly to the DEAHP absorber and condenser without first passing through the storage tanks. It was found that the direct connection does not provide a steady operation for the system. However, when the DEAHP was connected indirectly through the use of two auxiliary water tanks, steady operation was achieved. Furthermore, the PR was increased from 9 to 20 and the thermal power produced by the DEAHP rose from 150 to 200 kW. The drawback of this method, however, was that the external heat input had to increase from 70 C to 180 C. Furthermore,

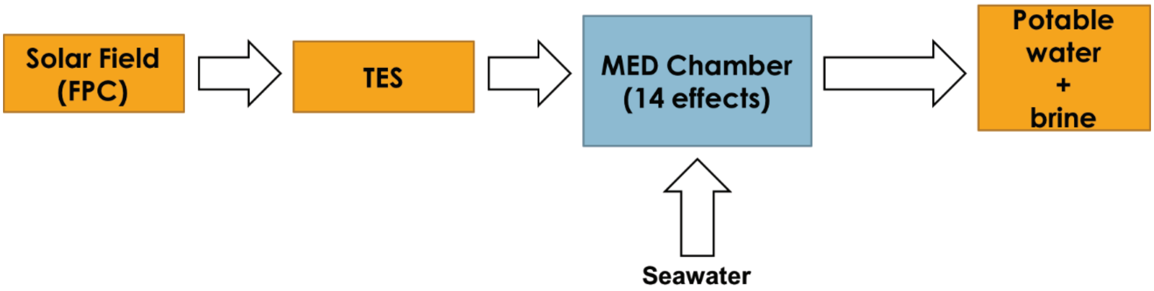

Fig. 4. Plant schematic for the Abu Dhabi solar desalination plant.

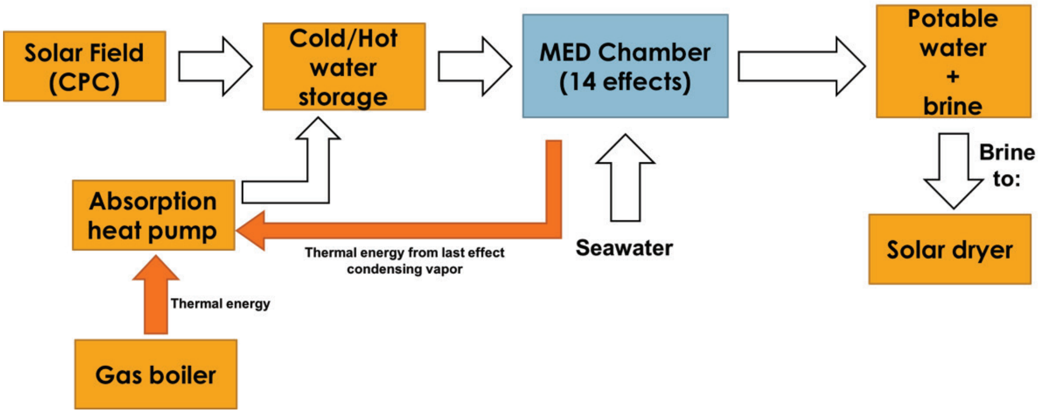

Fig. 5. Plant configuration for the PSA solar MED plant.

the use of the DEAHP poses health hazards because of the use of LiBr which is a poisonous material.

This plant was one of few which used sensible heat from the hot water entering the first effect. Another actual operating plant that uses hot water is the Ashdod plant [45]. The PSA project also considered the use of the PTC in a configuration similar to Fig. 4 and proposed a number of design recommendations for such systems [27]. The authors highlighted that based on experimental assessment of the system, it is recommended that MED should be supplied heat from hot water and not low pressure steam [27]. Using hot water has the advantage of the possibility of using low concentrating collectors which are cheaper generally than CSP collectors. However, when using water, the pumping energy increases and the specific heat transfer area in the first effect will increase because the overall heat transfer coefficient (U) is smaller for water than for steam. From the same study [27], the authors also made the following recommendations:

- Use of synthetic oil as a HTF is recommended due to the high temperature requirement of the DEAHP.
- The Euro-trough PTC is a suitable collector to power the DEAHP.
- MED unit should be an FF system operating at 68°C–70°C TBT.
- Cooling seawater for end condenser is not needed because the mass flow rate in the DEAHP is able to condense the distillate produced in the last effect.
- The vacuum system steam ejectors should use part of the steam generated in the solar boiler that drives the absorption heat pump. Successful operation of a prototype of the DEAHP supports this recommendation.

Overall, the PSA plant is possibly the best example of successful integration of solar power with MED and the plant provided valuable experimental data for researchers. The major concern related to this plant configuration is the use of the DEAHP, which is a very complex component and requires high safety measures.

There were few other studies that also investigated the heat pump in a solar-driven MED system. Among them is the experimental and modeling work by Stuber et al. [30]. In this work, a single effect absorption heat pump was used to reduce the thermal energy consumption. The aim of the study was to predict real system performance. The heat pump used here was using an alkaline nitrate mixture as the absorbent. Results showed that the heat pump reduces the thermal energy consumption by more than 49%. The experimental part in this study was carried for 50 d and hence we believe that the results of this study are close approximations of the real system performance. However, there were limitations in this study in terms of the modeling, which are discussed in the limitations section of this review.

Few studies compared more than one plant configuration with various flow arrangements such as Sharaf et al. [28]. This paper evaluated thermo-economically two configurations for coupling solar thermal energy with the MED process. The first configuration uses a PTC with a HTF to directly produce steam for the MED unit. This technique hence only produces DW. The second configuration utilizes exhaust steam from an organic Rankine cycle driven turbine to produce both EP and DW. This study focused on comparing four flow arrangements for each technique: FF, parallel feed (PF), backward feed (BF) and FF with preheaters (FFHs). This study was based on computer modeling using an in-house package: solar desalination systems (SDSs). The schematics for both configurations are shown in Figs. 6 and 7.

This study had numerous results but the key ones relating to flow arrangements are as follows:

- The MED-PF configuration showed the best overall results in terms of water cost and GR.
- MED-PF compared with FFH and BF requires less heat transfer area and hence this reduces costs and minimizes control requirements.
- Due to the low mass flow rate in the MED-PF, there is less exergy destruction per solar collector.
- The GR for PF was higher than FFH. This was because of the lower amount of steam needed.

The authors concluded from this study that the technical limitations of the MED process require increasing the number of effects (16–20) and reducing the TBT to 70°C–75°C. This increases the GR and reduces the SPC but increases the TWP. Furthermore, the MED-FF configuration is the least favorable since large amounts of energy are lost in preheating the feed to the required TBT. Producing DW only is more preferred than cogeneration of DW and EP in terms of TWP, solar field area and exergy destruction. The reduction in solar field area means less maintenance requirements. The last point here relates to the design consideration we mentioned earlier in this paper about using high efficiency solar collectors. The above research was further developed by coupling the MED system (in the computer model) to two types of vapor compression (VC) cycles: mechanical vapor compression (MVC) and TVC [40]. The major conclusions from the computer simulations were as follows:

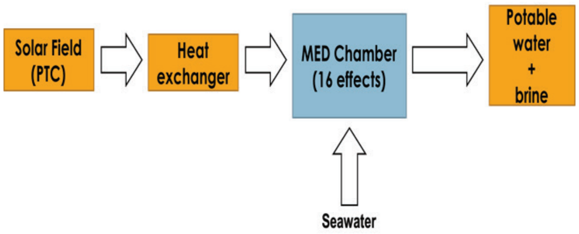

Fig. 6. Configuration 1 in the study by Sharaf et al. [28].

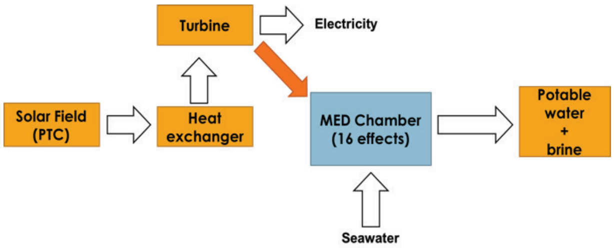

Fig. 7. Configuration 2 in the study by Sharaf et al. [28].

- The MED-TVC process provides better results compared with the MED-MVC in terms of GR, LCOW, SPC and thermo-economic product cost. The only parameter in which the MED-MVC is better is the solar field area.
- For the MED-TVC, it was proved that increasing the number of effects reduces the SPC. Similarly, increasing the compression ratio (CR) will increase the SPC hence it is important to keep the CR as low as possible.
- For the MED-MVC process, it was shown that reducing the top steam temperature (TST) from 80°C to 60°C and increasing the number of effects would decrease the SPC and thermo-economic product cost gradually. Similarly, the minimum value for solar field area and exergy destruction is achieved at minimum TST (60°C) and largest number of effects (16). However, increasing the number of effects would increase the CR. The steam temperature has more influence on the CR than the number of effects. On the other hand, the number of effects has more influence on the GR than the steam temperature.
- The study also concluded that reducing the CR to 2 may increase the cycle performance and reduce the SPC.
- The use of a steam ejector unit may reduce the need for more evaporators (and hence more effects) to increase the GR.

Although this study had a number of limitations in terms of the modeling assumptions, its outcomes are invaluable because the authors developed a complex model. Overall, it appears that use of the TVC is more preferred than MVC in an MED system in most modeling studies. Another interesting finding from this study is the relation between the number of effects and solar field area which was found to be inversely proportional. This point was hardly addressed in any other research paper.

However, it should be noted the number of effects in this study (16 effects) is very large even at a real plant scale and is rarely used. Some large MED plants like Sidem 2 [46] use 16 effects with a heating steam temperature of 110°C and a GR of 12.4. Another example is the Barge unit [47] which has a TBT of 99°C and 24 effects. Whenever a high TBT can be tolerated in the design then the number of effects can be increased. In practical cases, rarely does the MED have more than 6–8 effects because of the maximum brine temperature restriction in the last effect (usually 40°C). The last effect maximum brine temperature in many countries is regulated by the environmental authorities and hence plant design engineers must take this into consideration. Using a TBT of more than 110°C is very risky since most high temperature additives are only suitable for a TBT of up to 110°C [17]. Table 3 shows technical information about some large-scale MED plants.

Some studies focused on plant configurations that could be used for cogeneration of DW and EP.

An example is the work by Palenzuela et al. [29] that investigated four possible plant configurations for cogeneration based on a CSP plant supplying steam to the desalination plant. The CSP plant is based on the commercially operational Andasol-1 CSP plant in Spain. This study, however, also considered the use of TVC. The simulations done were based on 4 configurations: 3 using MED and 1 using RO. Since we are interested in the MED processes only, we will only present the results for MED here. The three configurations for MED are as follows:

- LT-MED coupled to a PTC CSP plant (turbine exhaust steam fed to first effect) – configuration 1
- LT-MED fed by steam from a TVC unit and coupled to PTC CSP plant (turbine exhaust steam fed as entrained vapor to steam ejector) – configuration 2
- MED-TVC coupled to a PTC CSP plant (entrained vapor to steam ejector fed from last effect) – configuration 3

The main features of configuration 1 are that there is no need for a condenser for the exhaust steam leaving the turbine. The LT-MED unit effectively acts as a heat sink for the low-pressure steam. However, this configuration requires the use of low-pressure steam which means a lower power cycle efficiency. Furthermore, the MED plant has to be situated very close to the steam turbine. This is because exhaust steam from the steam turbine has a high specific volume and hence will require large diameter pipes. The second configuration has the advantage of energy recovery and the exhaust steam condenser and hence can be used to power any thermal desalination process. Moreover, the presence of the condenser means that operation of the steam turbine is unaffected by any failure in the desalination unit. The third configuration has an advantage of a higher GR since less thermal energy is needed per unit distillate. In addition, refrigeration requirements are less than for configuration 2 because of the TVC is fed from the vapor generated in the last effect. This study focused on large-scale plant design and hence had a complex configuration. In fact, the power block was composed of 193 equations. Since this study had a numerous number of results and conclusions, we will only present here the most relevant results. The main findings from the simulations done were:

Table 3
Technical data of some MED plants

Location [ref.]	Ashdod [45]	Sidem 1 [48]	Eilat [45]	Barge unit [47]	Sidem 2 [46]
Number of effects	6	12	12	24	16
GR	5.7	9.8	10.1	22.3	12.4
TBT	50	64	70–74	99	106
Heat source	Hot water at 55.4°C–63 °C	Steam at 0.3 bar	N/A	Steam	Steam
Capacity	201 kg/s	139 kg/s	N/A	50 kg/s	290 kg/s

- Integrating the LT-MED with CSP as in configuration 1 is the best one thermodynamically.
- In terms of water cost, integrating RO with CSP yields a lower water cost compared with the MED process, due to lower investment costs.
- The study proposed the configuration 2 might be the most favorable for the industry because the condenser is included in the power block.

This study accelerates the research in solar-driven MED by modeling performance of large-scale systems. The findings also highlight that there is need to find ways to reduce the investment costs of MED systems by innovations in systems design and materials choice. Innovations in system design means addressing the following questions:

- What is the optimum capacity for a solar-driven MED plant? Is it necessary to focus currently on large-scale plant with capacities more than 1 MIGD?
- How do we enhance the safety of the absorption heat pump when integrated to an MED plant?
- What is the reliability of solar-driven MED plants?
- How is the choice of the solar collector related to the number of effects?
- What is the optimum method to feed the entrained vapor to the TVC?

Answering these questions thoroughly requires in depth comprehension of the operation of all plant components and complex modeling studies which use real plant data for validation.

2.4. Modeling studies: assumptions and limitations

Most studies that investigated solar-driven MED were based on computer models mostly using Modelica, MATLAB or EES. It is important to highlight the major assumptions used therein. The modeling assumptions can be divided into three types:

- Assumptions about the incident solar insolation.
- Assumptions on overall process operation.
- Assumptions on process losses.

Regarding the incident solar insolation (in kWh/m^2 on W/m^2), usually it is assumed to be constant on an hourly, monthly or annual basis. The recommend practice is to use hourly data and then run the program for 8,760 h (assuming 24 h operation). The data availability and computational efficiency of the modeling software puts limitation of the type of solar radiation data that could be used. Nowadays, numerous online databases like NREL provide typical meteorological year (TMY) weather files which contain hourly values of direct normal irradiation (DNI), global horizontal irradiation (GHI) and diffuse horizontal irradiation (DHI) and temperature. Using data with a smaller resolution has the advantage of allowing system dynamic modeling. However, weather data should be based on actual ground measurements where possible since satellite-derived data can have discrepancies of more than 40% from real values. This can result in wrong assessment of the potential of solar energy to power thermal desalination processes.

Another important consideration relating to solar insolation data is computational power of the modeling tool. Due to this, some research works would evaluate the performance of the plant at one DNI value only for a 24 h period (as an example when CSP collectors are used) such as Sharaf et al. [28]. In this study, the monthly average DNI during winter months was used which is a good assumption. This is because the solar field is tested under worst-case scenarios and hence, during summer, the performance will likely be better. However, the major drawback of this assumption is that it does not allow for investigating the daily performance of the plant and the effect of transients cannot be captured. Furthermore, a constant solar insolation assumption does not allow for examining the start-up and shut down of the plant which may be needed for maintenance. Whenever the modeling software does not allow for a complete 24 h simulation, then it is recommended that a constant hourly value is used for the sunny hours in each day (usually 6–10 h). This is more realistic and feasible from a modeling viewpoint. Table 4 shows the solar radiation assumptions found in the literature.

The second major assumption is the overall process operation. Desalination plants are usually designed to operate continuously and hence, modeling should be based on steady-state operation. This was done in most research works [11,19,28,29,40]. However, it is also important to investigate the start-up and shut down of the plant and transient response. This can be done in a dynamic model that, although complex, is highly needed to develop a sound understanding of the performance of solar-driven MED plants and their reliability. Few studies considered developing a dynamic model for an entire plant. A dynamic model for the solar MED pilot plant in PSA was developed by De La Calle et al. [49]. This newly developed non-linear model focuses on the first effect only of a solar MED pilot plant. This model was developed in Modelica (an object-oriented modeling language). The aim of the model was to predict the thermal behavior of the first cell. The dynamic model developed was based on the specifications of the solar MED pilot plant at PSA in Southern Spain. The main assumptions adopted in this model are as follows:

- The falling film condenser was modeled using an algebraic relation (Newton's law of cooling).
- A built in library in the Modelica package was used to model the fluid flow in the preheater tube bundles.
- Inputs to the model were taken from experimental data which included: mass flow rate and inlet temperature of the hot water and feed seawater and pressure of the second effect.

Table 4
Solar insolation modeling assumptions

Assumption	References
Fixed value for solar radiation assumed in model	[18,25,28]
Hourly variable solar radiation data used in model	[19,26,29]
Monthly variable solar radiation data used in model	[12,36]

The authors also reported simulation errors, both absolute and average errors. Note that these results were for 18th October 2013. Overall, this study found that the model present results which are in very good agreement with actual test results. This model can be used to investigate the performance in different scenarios and suggests control strategies. The previous study was further developed by de la Calle et al. [50] whereby the same dynamic model was used to model the entire solar MED plant including the heater, all effects, the preheaters and the final condenser. The methodology used and the results obtained in this study were very similar to De La Calle et al. [49]. However, the new results reported included the condenser outlet temperature of the seawater and the mass flow rate of the distillate. The conclusions made from this study are the same as for the previous one since this was the same research work simply expanded.

The third major assumption is regarding the process losses. This means thermal losses in the solar field (collectors radiative and convective losses, pressure drops, optical losses etc), inefficiencies in the heat exchangers (expressed in terms of the effectiveness) and thermal losses in the MED section (thermal losses from the effects, pressure drops etc). As a general rule, it is required that the solar field be modeled including optical losses and receiver radiative losses. These are usually easily found from the manufacturer's datasheet. Optical losses may be found using the incidence angle modifier method [25,26]. Piping pressure drops may be neglected for small systems (less than 100 kW_{th}) but for larger industrial scale systems, pumping losses maybe larger and hence have to be accounted for. Most studies also assume an adiabatic process and hence neglect heat losses in the effects. This assumption serves to simplify the modeling procedures. Table 5 shows a list of major parameters in plant design and how they were accounted for in different research papers.

Table 5
Major modeling assumptions in the literature

Parameter	References
Steady-state process assumption	[11,19,28,29]
ΔT in all effects assumed constant	[30,31]
Adiabatic process assumption	[19,29,30]
Constant thermodynamic losses assumption	[11]
Calculated thermodynamic losses	[19]
Constant seawater inlet condition assumption	[28,36,40]
Constant U value (kW/m^2K) assumption	[12,19]
Top steam temperature fixed	[28,40]
Accounted for internal plant water consumption	[29]
Distillate by flashing not considered	[11]
Constant distillate density assumed	[30]

3. Economics of solar-driven MED

The aim of the economic analysis of SDSs is to find the LCOW and investigate how is it affected by other parameters. Particularly of interest is the effect of TES, back-up boilers, solar collector choice, environmental costs and location on the LCOW. Carrying a complete life cycle cost (LCC) analysis is also useful in investigating the economic competiveness of solar desalination plants. On the long term, scientific research on solar-driven desalination must be able to demonstrate the economic feasibility of this process. It should be noted that in this section, we are only interested in solar-driven MED plants that only produce DW and not cogeneration plants.

The general mathematical form of the LCOW is:

$$\text{LCOW} = \frac{\text{Capital costs} + \text{Operational costs}}{\text{Distillate production}} \tag{1}$$

where capital costs are the costs of the solar field, heat exchangers, back-up boilers (if any) and the MED plant. Capital costs also include the replacement costs of any component which may fail during the plant's life time. Furthermore, plant soft costs such as land and environmental permits are considered as part of the capital costs. Usually a lifetime of 20 years is assumed. Operational costs are the maintenance costs, electrical and fuel costs and the plant employee costs. Both capital and operational costs are evaluated in USD. Distillate production is the annual freshwater production in cubic meter. In order to evaluate the LCOW in current dollars, the capital costs component is multiplied by a discount ratio which is a function of the amortization rate (or interest rate). The interest rate is usually 5% or 6%. Some papers in the literature name the discount ratio: the capital recovery factor or CRF.

Few studies considered the environmental cost which is the cost of emissions of CO_2 that could be due to using electricity from the grid or using a back-up boiler. A study included the cost of CO_2 emissions in calculating the LCOW [51]. The cost was $40/ton of CO_2.

No paper, however, attempted to include the effect of carbon credits which are granted to renewable and clean energy projects under mechanisms like the clean development mechanism (CDM). These credits have the potential to reduce the LCOW from solar powered desalination plants. Among the novel analysis methods for the LCOW is to calculate it as a function of time in small resolution like seconds. Mokhtari et al. [52] calculated the LCOW in dollar per second using a genetic algorithm (GA) in a multi-objective optimization problem. Results showed that the GA can indeed predict which operational conditions of the solar-driven MED plant yield a lower LCOW.

The complexity variation between one research and another is in the number of components included under the capital and operational costs. As an example, Askari and Ameri [26] included 23 cost parameters in their calculation of the LCOW. The most difficult part in this analysis is to get realistic values that are used in desalination plants in the same country. When analyzing solar-driven MED plants, we propose that the economic analysis be focused on the distinguishing features of these plants such as the solar field and storage (thermal or water based). The effect of different solar field sizes, effect of DNI and location variation should be thoroughly investigated. Askari and Ameri [26] investigated the effect of plant scale and thermal storage cost on the LCOW for a hybrid solar MED plant. Results showed that the LCOW is reduced when the system capacity increases. Further, the sensitivity analysis showed high sensitivity to the solar field costs. However, this paper was based on a hybrid system with a back-up boiler which in some scenarios supplies more than 60% of the required thermal energy. Pugsley et al. [53] carried a comprehensive feasibility study on the global applicability of solar desalination and found that the LCOW is lower for location with high insolation levels. However, the relation between LCOW and DNI is not as simple as that. A high DNI level could result in excess thermal energy that is not needed by the MED unit and hence a large TES has to be employed. This may increase the LCOW. Furthermore, the above study did not include CSP collectors in the cost analysis.

Advancing research in solar-driven MED requires pushing the system design limits and working on maximum solar share. In addition, research should also consider environmental costs of brine disposal (or treatment) in a comprehensive life cycle assessment which is yet to be done. It was noticed from the literature that most papers attempt to compare the LCOW with that of conventional desalination plants [25,26,51]. We believe that this, although important and useful, should not be the major focus at this early stage of R&D in solar-driven MED. Renewable energies are still far more expensive than fossil fuels due to reasons like economies of scale, more maintenance requirements for some technologies and intermittency of the renewable resources. As a result, the LCOW from a solar desalination is almost always expected to be higher than conventional plants. Current price range for conventional desalination is less than \$1/m^3 while for solar-driven desalination processes in general, the range is \$0.7–\$2.26/m^{-3} [26]. Instead of comparing solar-driven MED with (and solar desalination in genera) conventional desalination, the comparison should be made with renewable energy desalination processes. Table 6 shows the water cost for different solar desalination technologies. It can be noticed that solar-driven MED (using CSP) has a relatively low water cost and a very high technical capacity. Furthermore, it is suggested that the economic analysis consider the water cost for remote plants whose economics differ from large-scale plants. It will also be of interest to investigate the suitable salinity levels for solar-driven MED that makes the plant more feasible. In most studies in the literature, it was found that the LCOW is primarily affected by the solar field costs. Reducing the solar field area effectively reduces the LCOW. This, however, requires building the plant in a location with a relatively high DNI which may not be the ideal location in terms of freshwater demand and distance to sea. As a result, it is necessary to carry more optimization studies on the relation between seawater salinity, DNI, plant capacity, size of storage and environmental costs on the LCOW. Costing externalities like CO$_2$ emissions are also keys in realizing the full economic advantage of solar desalination.

4. Conclusion

Solar-driven MED is a suitable and sustainable technology that can contribute to solving the problem of freshwater shortages globally. In this paper, we explained the MED process, its operation, process types (LT-MED, MED-TVC) and the key design considerations. The coupling of solar thermal collectors with MED was discussed by outlining possible collectors and the advantages and disadvantages of each. Furthermore, from the literature review, we critically analyzed the main plant configurations used and the features of each one along with some selected results. The results given were obtained from both experimental and modeling studies. The economics of solar-driven MED was explained by highlighting the main equations used, the cost parameters and the sensitivity of the LCOW to each. Finally, the review discussed three major challenges to solar-driven MED, namely: TES, adaptability issues and LCOW.

Our review highlighted a number of research gaps. These are as follows:

- Very little research work on using LFC in the solar field. This is an interesting area of research because the LFC inherently is more compact (smaller mass per unit area) than the PTC and less costly.
- Uncertainty over whether cogeneration is more cost efficient or not than producing DW only.
- Uncertainty over whether TES has more added benefits (e.g., increasing capacity factor) compared with its drawbacks (high capital costs). There were conflicting opinions in the literature regarding this issue.
- Using modeling assumptions that do not reflect annual plant performance (e.g., one DNI value).
- Economic analysis in the literature has neglected cost of CO$_2$ emissions in most papers and no paper considered

Table 6
Price range and capacities for solar desalination technologies [16,54]

Technology	Technical capacity (m^3/d)	Energy demand (kWh/m^3)	Water cost (USD/m^3)	Development stage
Solar stills	<0.1	Solar passive	1.3–6.5	Application
Solar multiple effect humidification	1–100	Thermal: 100 Electrical: 1.5	2.6–6.5	R&D, application
Solar membrane Distillation	0.15–10	Thermal: 150–200	10.4–19.5	R&D
Solar/CSP MED	>5,000	Thermal: 60–70 Electrical: 1.5–2	2.3–2.9 (possible cost)	R&D
PV-RO	<100	Electrical: Brackish water (BW): 0.5–1.5 Seawater (SW): 4–5	BW: 6.5–9.1 SW: 11.7–15.6	R&D, application

revenue generated by carbon credits (e.g., under the CDM).
- Developing new CSP collectors whose thermal power is close to the requirements of the MED process.
- Developing advanced control systems that can enhance plant optimal operation based on economic objectives.

By addressing these issues in details, the solar-driven MED can progress towards a lower cost per cubic meter (close to \$1/m^3). We can also explore the applications of solar-driven MED in brackish water desalting and agricultural drainage water treatment. These processes are relatively less energy-intensive and hence may have lower LCOW. The technical challenges of solar desalination must not be under-appreciated [55].

Symbols

d — Discount ratio
a — Amortization rate
n — Number of years
C_{CO2} — Cost of emissions
E — Emissions rate in tons/year
Z — Emissions unit cost in USD/ton

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