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Solar desalination: A review of recent developments in environmental, regulatory and economic issues

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ABSTRACT

The aim of the current study was to provide a review of recent developments in solar desalination from the viewpoint of environmental, regulatory, and economic aspects. The analysis attempted to give better insight into the larger question of why more solar desalination plants are not being established by reviewing different technologies, drivers, barriers, and markets. Critical barriers which were dependent on the level of regional development were found to be uncertainty of government subsidies and a lack of regulatory policies. A new tool called a Pareto frontier may be utilized to generate optimal points in complex scenarios with a high number of variables. This all-inclusive method should be employed in any major decision-making process. Furthermore, in exciting innovative research studies, a sustainable Janus wood evaporator was developed that overcame many of the current solar desalination problems. While subsidies were crucial in the growth of renewable energy programs, barriers in deployment of solar desalination systems still exist such as low electricity tariff structures and fragmented energy policies. The overall trend was towards integration of renewable energy with conventional sources and energy storage systems.

1. Introduction

Rapid industrialization especially in developing countries and the need for better protection of the environment has resulted in an increased demand for clean non-polluting renewable energy (RE) sources such as wind and solar for producing freshwater and electricity [1]. The growth of technology such as solar photovoltaic (PV) panels has required innovation and often government subsidies. Combining diverse technologies in creative ways has become a vital element in reducing the costs of solar desalination systems by making them economically competitive with conventional schemes. Al-Obaidi et al. [2] for example integrated two RE technologies, concentrated solar power (CSP) and PV, to operate thermal and membrane seawater desalination processes to make them more cost-effective. The economic advantages of integrating RE and desalination systems were also demonstrated by Choi et al. [3].

Financial aspects in establishing solar desalination plants were highly country or region dependent. The economic challenges will be less in richer developed countries compared with poorer developing nations. de Doile et al. [4] examined the economic feasibility and regulatory issues of hybrid wind and solar PV energy generation with energy storage systems. Their results indicated that most scientific studies focused on only one of the RE technologies. There were only a few hybrid studies, according to the authors. These centered on wind, solar PV, and energy storage system technologies. Even fewer looked at regulatory or legal aspects. The sustainable commercialization of RE technologies for solar desalination is a complex process involving not only environmental and economic considerations but also an understanding of the local markets, government regulations and the level of a country's economic development [5].

In the creation, application and commercial distribution of new technologies, government subsidies, policies and regulations have played key roles. For example, subsidies were crucial in the evolution of RE systems such as solar panels which were quite expensive several decades ago, but which are now more affordable. However, policies have also sometimes acted as barriers. It is crucial that decision makers understand the level of development or maturity of regulatory policies in a region. To aid in this process, the United Nations sustainable development goals (SDGs) now form an essential part of all aspects of our society, from education, to innovation, to gender equality, and health care.

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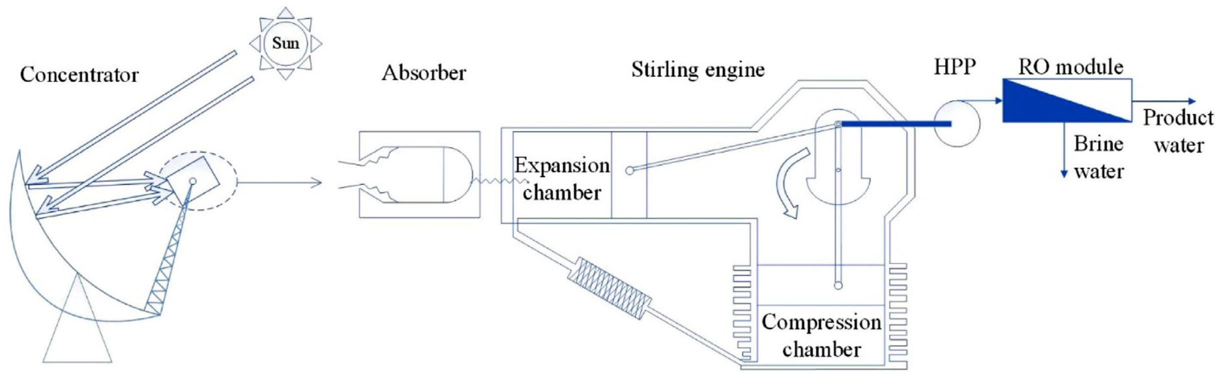

Fig. 1. Schematic illustration of a parabolic dish solar collector providing direct heat through an absorber to a-Stirling (DS) engine powering a high-pressure pump (HPP) which drives a Reverse Osmosis (RO) membrane module for producing potable (i.e., drinking) water [9].

Wydra et al. [6] in a case study from Egypt noted that in application of RE for generating electricity, it is not enough to consider just the technical aspects. All policy barriers need to be considered to ensure that they are overcome or at least minimized so that the quality of life of the local communities is improved.

Effective protection of the environment including water, air and soil, is a key challenge when dealing with desalination plants. For example, what should be done with the brine solution? Is there any air pollution occurring from the energy generated to run the plant? From an environmental perspective a solar energy based zero-liquid discharge (ZLD) desalination system is the ideal goal in terms of protecting the ecosystem while at the same time providing potable drinking water for society. It can be argued here that the challenge in this case is to generate useful commercial products from the salts recovered from the brine water. With the ZLD approach potable or fresh water is a side product. As an example, Onishi et al. [7] analyzed a solar-driven ZLD system for shale gas wastewater desalination.

The aim of the current study was to provide a review of recent developments in solar desalination from the perspective of environmental, regulatory, and economic aspects. The analysis attempted to give better insight into the larger question of why more solar desalination plants are not being established by reviewing different technologies, drivers, barriers, and markets.

2. Influence of different technologies, drivers, barriers, and markets in the search for sustainable solar desalination plants

The sustainable commercialization of renewable energy (RE) technologies for solar desalination is a complex process involving not only environmental and economic considerations but also an understanding of the local markets and government regulations which could push (i.e., be a driver) or hinder (i.e., be a barrier) its marketplace development. While clean energy strategies, for example, have been initiated in the gulf cooperation council (GCC) countries, significant barriers still exist. Farag and Bansal [8] reported that the effective integration of solar energy into the electrical energy grid has yet to be fully realized within the GCC region. Some of the difficulties observed included the effects of dust and high temperatures which decreased the effectiveness of photovoltaic (PV) panels for electricity production (i.e., heat has a detrimental effect on semiconductors present in PV modules). It can be argued, for example, that this would decrease the efficiency of electrically driven reverse osmosis desalination powered by PV panels. Suggested solutions included PV panel cooling by active and passive techniques. This would improve electrical conversion efficiencies. The authors noted that one of the drivers was the abundant financial resources available to fund large scale renewable energy projects. Markets were also plentiful due to a heightened regional business and manufacturing culture. The authors concluded that better strategic visions or goals were needed for a successful integration of renewables with the existing electrical energy grids. This is a key barrier or challenge in the commercial application of solar energy in large-scale desalination.

There is a consensus that most solar-reverse osmosis (RO) plants utilize PV systems to generate the electricity to run the high-pressure pumps for the membrane RO units. However, an important alternative or option is to utilize solar thermal energy directly in organic Rankine cycle and Stirling cycle engines to generate mechanical work to operate a high-pressure pump in the RO process (Fig. 1) [9]. It can be argued that an advantage of such a setup is its relative simplicity. A parabolic dish collector is automatically oriented towards the sun to provide optimum solar heat to the working fluid (i.e., absorber) at the focal point of the mirror. The absorbed heat is stored in the working fluid which cyclically moves between the expansion and compression chambers. The cyclical pressure variation of the working fluid is transformed into mechanical power via a crank mechanism. This shaft work can generate electricity which drives the high-pressure pump which in turn provides the pressure difference across the RO membrane resulting in product water (i.e., potable drinking water).

Results of their investigation showed that freshwater production increased with higher absorber fluid temperature. The optimum temperature for maximum efficiency was found to be in the range 1100 to 1300 K. The authors concluded there was a need to improve the effectiveness of the expansion and compression chambers (i.e., regenerator) in the Sterling engine. They noted that reducing the heat leak coefficient would at the same time improve the energy and exergy efficiencies. The latter refers to the ratio of the thermal or heat efficiency of a real system equated to a perfect or reversible version. In practical terms this means that by improving the regenerator, heat leakage would be reduced, and the system would perform better.

Looking at market conditions in the European region, Aprà et al. [10] analyzed the reasons why concentrated solar power (CSP) is not as widespread as it could be. The authors examined the opportunities and the enablers or drivers for a better distribution of this technology. They concluded that CSP can improve its access in the European electricity grid by employing the generated heat for industrial activities including desalination for fresh water production. The latter is particularly relevant to sunny and semi-arid regions such as in Spain, Sicily and Greece. However according to Aprà et al. [10], CSP has difficulties in the technological, political, and economic areas. Table 1 offers a synopsis of the primary enablers (i.e., a driver that makes something possible) and obstacles for a wider development of CSP in Europe. One barrier, for example, was the high levelized cost of electricity (LCOE) compared to other renewable energies The LCOE determines the average net present cost of electricity production for a generator throughout its lifetime. It has been employed for venture capital planning and to evaluate various methods of electricity generation on a constant basis. On the positive side, one enabler or driver of CSP technology was its low environ-

Table 1
Enablers & barriers for wider deployment of CSP in Europe (adapted from Aprà et al. [10]).

Enabler or Driver	Barrier
Wider promotion of CSP as clean technology	High amounts water required for cooling and cleaning
Enhanced storage capacity	Need for high solar radiation and large land areas
Low environmental impact	High levelized cost of electricity (LCOE) compared to other renewable energies
New policies and subsidies for CSP	Effective disposal of concentrated brine from solar desalination plants

mental impact. Aprà et al. [10] suggested that additional investigations should be concentrated on analyzing the political, environmental, and economic limitations of all CSP power plants. This could give decision makers including investors a broader insight into the trends and opportunities of this technology. One barrier to wider application of CSP in desalination is what to do with the concentrated brine solution after recovery of potable water.

According to El-Agouz et al. [11], high energy consumption is a major barrier to the effective large-scale implementation of membrane distillation (MD), an emerging thermally driven membrane process having numerous advantages, such as ability in treating challenging feed streams with moderate fouling [12]. A possible solution to the high energy consumption barrier, according to the authors, lies in applying solar thermal heating methods for the feed water in MD systems. This would allow for sustainable freshwater production. Energy usage would also be reduced. In their review El-Agouz et al. [11] reported on the newest advances in solar-powered MD expertise and in particular hybridization arrangements, energy performance assessment, and financial analyses. The authors recommended multi-objective price optimization studies to reduce the water production cost. The aim was to increase the commercialization of MD desalination. This was like the Pareto frontier approach described by Assareh et al. [13]. Pareto efficiency is a situation where no action is available that will make one individual better off without making another worse off. This is analogous to an equilibrium state. The idea was named after Vilfredo Pareto an Italian civil engineer and economist from the last century who used the concept in his studies of economic efficiency and income distribution. If researchers and decision makers are faced with a high number of variables due to a complex problem, then a Pareto frontier can be employed to create a set of best possible points.

Onishi et al. [7] utilized a Pareto approach in the thermo-economic and environmental optimization of solar-driven zero liquid discharge (ZLD) systems, which were employed for desalinating high-salinity wastewaters from shale gas operations. In their investigation, a set of trade-off Pareto solutions were obtained revealing a reduction of 95 % in the total annualized cost (TAC) at the expense of increased environmental impacts of 246 %, when comparing minimum economic and environmental optimal solutions. The Pareto curve also showed that intermediate optimal solutions provided significant reductions in environmental impacts at small increases in the total costs. The environmental impacts were mainly decreased by enlarging the area of the solar parabolic trough collectors, which reduced natural gas consumption and led to savings in operating expenses. The authors concluded that the use of solar thermal collectors to operate the ZLD desalination system was not only an eco-friendly alternative but also a cost-effective solution. Thus, the comprehensive multi objective approach represented a useful tool for decision makers to identify the best alternatives that simultaneous balanced both environmental and economic criteria.

Delgado-Torres and Gacia-Rodrigues [14] reviewed the latest designs in solar desalination driven by organic Rankine cycles (ORC) and supercritical CO_2 power cycles as power conversion units. The latter utilizes high and low temperature fluids to recover heat in a process to increase cycle efficiency. Desalination with both cycle systems occurred because of conversion of heat or thermal energy into mechanical energy with the aid of a crank shaft mechanism thus allowing the use of electricity and/or heat to drive desalination processes. The chief goal of the paper by Delgado-Torres and Gacia-Rodrigues [14] was the review of the literature and then to give design suggestions. The authors reported that in the medium-temperature range, there were many studies in which the heat rejected by the cycle was employed to drive processes in thermal desalination as well as absorption cooling. For solar supercritical CO_2 power cycles, the most common option was the use of rejected heat in multi effect distillation (MED) units or integration with a solar-driven adsorption cycle to maximize the energy efficacy of the whole system [15]. With regards to recommendations, the authors argued that designs should consider the extra costs associated with cooling flow. In a related study, the obstacles to implementation of solar water desalination in the community were reviewed by Kusumadewi et al. [16] using Indonesia as a case study. Critical barriers which had the most influence included uncertainty of government subsidies, poor solar energy data and a lack of regulatory frameworks or policies.

Dursun [17] performed a comparative study using a mathematical model describing the solar energy potential in the Horn of Africa (i.e., east central region of Africa consisting of primarily Ethiopia and Somalia). The author remarked that despite the huge solar energy availability for generating electricity, more than well over 100 million people in this impoverished region do not have access to electricity. One can speculate that this could also be a key barrier in implementation of small-scale electrically driven reverse osmosis desalination units for providing fresh water to local remote communities. The analysis by Dursun [17] presented an overview of the potential of solar energy in the region. The authors also reviewed the present solar energy standing and policies related to it. However, it was not clear from the manuscript what those polices were. The mathematical simulation model that was developed analyzed the solar radiation graphically based on photovoltaic units and electricity production. For example, Ethiopia-Addis Ababa received the highest annual solar radiation at 2915 kWh/m^2-year while Eritrea-Asmara had the lowest annual solar radiation at 2198 kWh/m^2-year. The annual electrical output of the photovoltaic modules in Ethiopia-Addis Ababa was the highest with 287 kWh/year and Eritrea-Asmara had the lowest at 216 kWh/year. One criticism of this paper was that no clear recommendations were put forth in terms of possible policies or actions to help alleviate the problem of the lack of access to electricity for the millions of people living in this territory. For example, what about providing subsidies to small towns and villages for off-grid solar powered electricity generation for brackish water desalination? Funding could come from either local governments or perhaps from international organizations such as the UN. In a related study, Mambwe et al. [18] reported on the mini grid RE market in Africa. One of their primary conclusions was the need for regulations to control grid encroachment due to subsidized electricity generated from the main electricity grid. For arid and poor areas of the world such as north-west Africa it is important to remember that the need for low-cost electricity production and small-scale desalination units for providing potable water for local remote communities are equally vital.

Elamine et al. [19] showed that desalination technologies can be combined with various RE schemes such as having a MD set up united with a humidification-dehumidification greenhouse desalination unit (Fig. 2). A case study was presented from Algeria. The authors argued that an all-inclusive method must be utilized when scaling up hybrid systems. Ecological concerns, markets, and government must all be considered in the decision-making process.

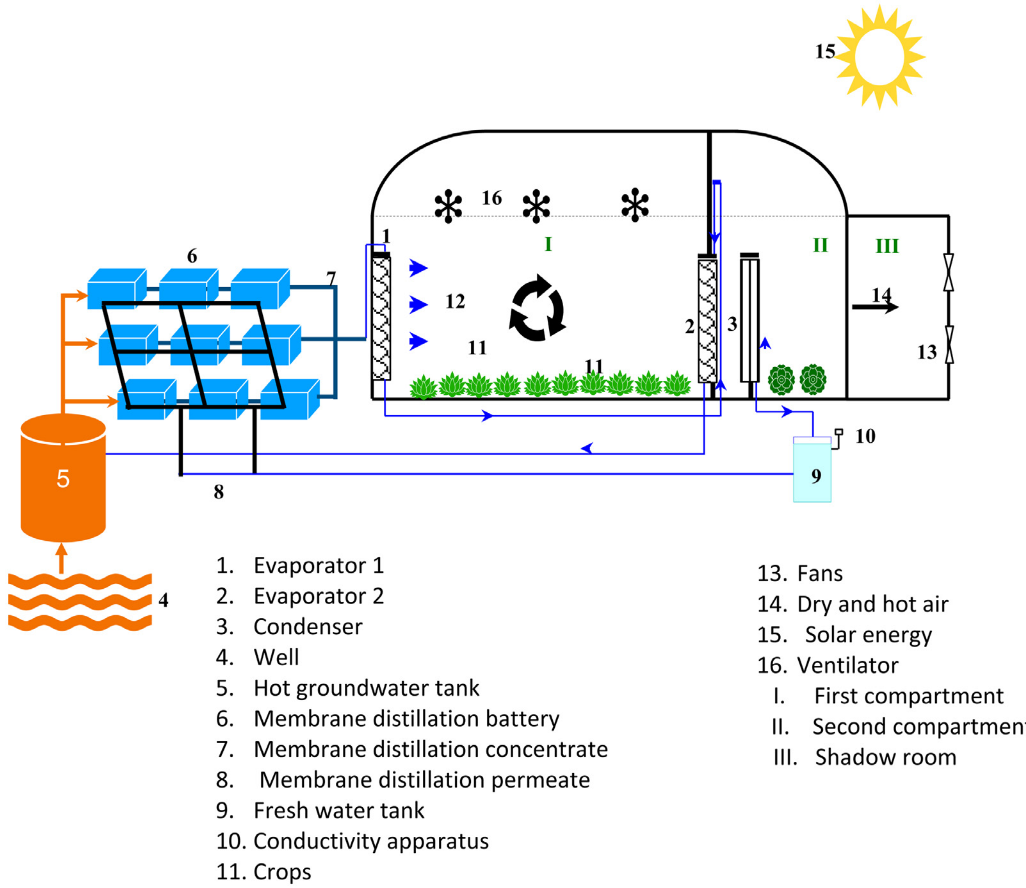

Fig. 2. Process schematic for membrane distillation units coupled with humidification–dehumidification brackish water greenhouse [19].

Elsheikh et al. [20] through a literature search examined the importance of the heat exchanger for enhancing the freshwater production in solar desalination. Results indicated that by combining flat plate solar collectors with a heat exchanger the water production rate could be increased. The same results were achieved when the solar desalination system with a parabolic trough collector was employed along with the exchanger. Some of the challenges identified by the authors included corrosion of the heat exchanger tubes due to contact with salt water, surface fouling like what is seen with membrane fouling, and the need to find cheaper materials from which to make the exchanger tubes.

Lim et al. [21] in an excellent paper reviewed in detail eight types of vertical multiple-effect diffusion solar distillers (VMED). Four of the recommended configurations are shown in Fig. 3). The manuscript contained 41 Figures of different multiple-effect solar stills going back four decades. A total of 46 VMED's were assessed and divided into eight types or categories of VMED (Table 2). The authors concluded that the VMEDs with a basin and reflector (Figs. 3B & C respectively) had the highest output in terms of freshwater production at a maximum of 23 and 38 Kg/(m^2 d), respectively. However, it can be argued that based the results found in the comparison summary Table 2, a VMED with an external heat source had a maximum potable water output of 317 Kg/(m^2 d). This was about ten times greater than the basin and reflector systems. In their recommendations, Lim et al. [21] noted that there is need for optimization studies, including economic feasibility. The total real cost of a process, for example, consists of the amortization rate (i.e., price of borrowing money to build a desalination system), the maintenance and operating costs, and the price of energy. This is a highly recommended paper for scientists and decision makers who are interested in solar desalination systems that are relatively simple and small structurally but that also have a relatively high freshwater production rate.

Selimefendigil et al. [25] investigated two new types of thermal storage units based on a phase change material and a dolomite powder integrated with or imbedded in a phase change material. The authors concluded that the inclusion of a natural mineral powder improved the thermal energy storage properties of system. In a related report, Tiwari et al. [26] reviewed solar desalination systems and noted that significant barriers still exit. Challenges included high capital (i.e., equipment) costs, the need to improve water production as well as system efficiency, salt deposition and scaling inside the units, and overheating of glass covers in solar stills in summer. Likewise, Zhang et al. [27] noted that three factors determine the commercial feasibility or success of a solar desalination system: the rate of water production, the lifetime of the device or plant, and the capital costs of the system. All three issues need to be addressed or optimized.

3. Ecofriendly sustainable desalination technologies & environmental protection

The advent of an increasing number of major incidents associated with climate change (e.g., floods, storms, fires, rises in air and ocean temperatures, melting of the polar ice caps) has signaled that mankind must urgently address environmental and sustainability concerns. This requires looking at specific problems involving multiple stakeholders holistically. AlHashmi, et al. [1] for example proposed a partnership between a community and a government with the goal of creating low-carbon energy use residential buildings. Two approaches were outlined: structure intercession for the municipality and a clean energy application for the government. The authors concluded that a partnership between communities and the government was best for meeting pollution emissions reduction targets. In a related study, Alhaj, et al. [28] exam-

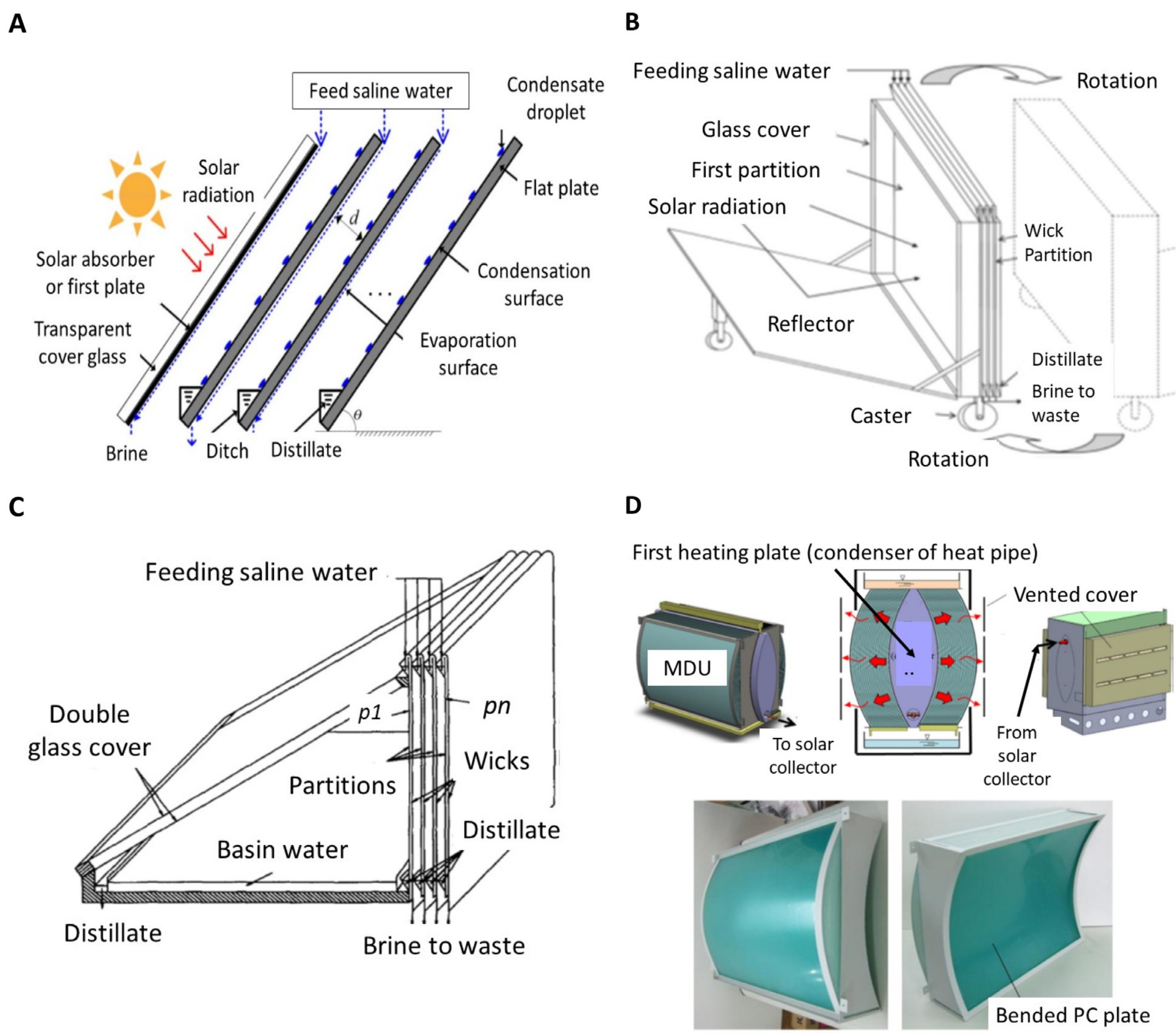

Fig. 3. Examples of four types of vertical multiple-effect diffusion solar distillers (VMED): A Classical [21], B With reflector [22], C With basin [23], and D with bent plates [24] (adapted from Lim et al. [21]).

Table 2
Comparison of freshwater production according to the type of vertical multiple-effect diffusion solar distillers (VMED) and heat source. Adapted from Lim et al. [21].

Type of VMED	Years covered by references	Heat Source	Fresh water production Kg/(m^2 d)
Classical	1964–2020	Solar energy Electrical heater Artificial radiation	2 to 36
With a solar collector	1961–2020	Solar energy Electrical heater Artificial radiation	2 to 36
With an external heat source	1984–2016	Electrical heater Hot water Hot steam Waste heat Thermal energy from biomass	7 to 317
With a reflector	2005–2007	Solar energy	4 to 38
With a basin	2000–2019	Solar energy Waste heat Electric heater	6 to 23
With a curved plate	2014–2020	Solar energy	6 to 35
With a tilted wick still	2016–2017	Solar energy	1 to 40
Horizontal	2004	Solar energy	15

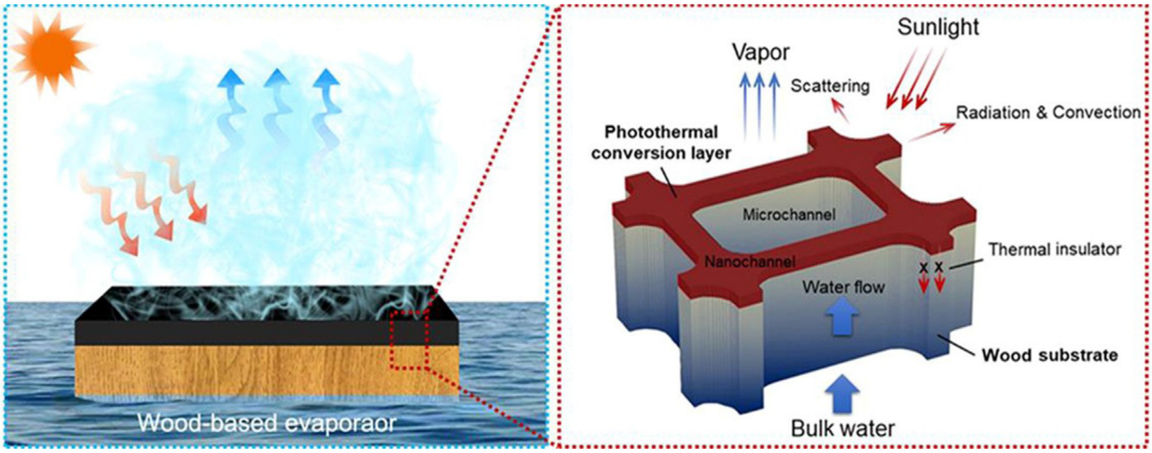

Fig. 4. Schematic of a Janus wood evaporator and its working principle. The photothermal transformation coating is responsible for the light absorption and photothermal conversion. The wood substrate provides physical support and transports water to the surface. The wood also acts as a thermal insulator which reduces heat loss in the system. (from Dong et al. [31]).

ined how the environmental life cycle of a solar driven conventional multi-effect desalination (MED) plant can be minimized through integration and optimization. Their life-cycle assessment (LCA) results indicated that most of the impact occurred due to electric pumping energy. The authors reported that a linear Fresnel collector (i.e., a linear concentrating solar thermal collector) had a better LCA rating than a parabolic trough collector. It was recommended that environmental scientists and decision makers need to define the challenges more clearly in directing LCA for desalination studies. Likewise, Siefan et al. [29] performed an LCA of a solar-powered MD plant in Jordan. They concluded that the best power was provided by Silicon PV panels since this combination had the lowest environmental impact.

Desalination of seawater and brackish water is a challenging process due to high energy demands, the need for brine (i.e., concentrated salt solution) disposal and the high capital and operating costs. The utilization of solar-thermal energy in the desalination provides a possible partial solution by for example reducing the costs and carbon footprint since RE is used. However, there is still the issues of salt accumulation and disposal, performance degradation due to erosion of materials such as metal fittings caused by salt solutions. While solar-thermal evaporation is a promising technology for reducing environmental pollution, there is still the problem, for example, of salt accumulation on solar absorbers. System durability is also a concern due to erosion. These drawbacks hinder its widespread application.

In an exciting new development, as far as the current authors are aware, Chen et al. [30] reported on a sustainable Janus wood evaporator that overcomes many of the current solar desalination problems. For instance, very-high evaporation efficiencies were achieved for very saline (e.g., brackish water) solutions. The Janus wood evaporator has asymmetric surface wettability, where the top layer acts as a hydrophobic solar absorber with water blockage and salt resistance, while the bottom hydrophilic wood layer allows for rapid water replenishment and superior thermal insulation (Fig. 4) [31]. According to the authors there was a higher evaporator efficiency and a greater resistance to salt erosion. To assess whether there was a better environmental impact of this type of evaporator (i.e., more ecofriendly), a LCA was conducted to compare this evaporator with other similar Janus evaporators. It was not clear from their report exactly how this version was better (i.e., more sustainable) for desalination compared to existing versions. As shown in Fig. 4, the wood substrate consisted of micro-nano channels that pumped water through by capillary action or force. The authors highlighted the challenges or barriers including the need to select high-efficient photothermal materials. The heat and mass transfer mechanisms in wood-based evaporators need to be better understood to help in optimization. This would aid in large-scale production at hopefully a reduced cost. In an interesting comment Dong et al. [31] argued that the use of wood or other natural materials does not automatically make a process environmentally friendly. Aside from environmental impacts, other aspects, such as cost, scalability, stability, adaptability, and evaporation efficiency, need to be considered. Different photothermal materials, such as the use of MXene, have been proposed to enhance the evaporation rate but their scalability in an efficient module remains a big challenge [32].

From an environmental perspective a solar energy based zero-liquid discharge (ZLD) desalination system is an ideal goal in terms of protecting the ecosystem while at the same time providing potable drinking water for society. It can be argued here that the challenge in this case is to find useful commercial products from the salts recovered from the brine water. As an example of this type of approach, Onishi et al, [7] analyzed a solar-driven ZLD system for shale gas wastewater desalination. Their integrated set-up consisted of three main units: a solar field for collecting energy, a Rankine engine for converting heat into mechanical work (via a turbine) and thus electricity, and finally a multiple effect evaporator with mechanical vapor recompression. According to the authors their integrated system significantly lowered the cost and environmental impact of the industrial wastewater operation. It was important to note here that the authors employed a multi-objective model in their economic and environmental optimization. This was like the Pareto frontier approach described by Assareh et al. [13]. Due to the high number of variables, a Pareto frontier can be utilized to generate a set of optimal points. Onishi et al, [7] also generated a Pareto set of best possible trade-off solutions (Fig. 5). The Figure which shows the total cost per year in the Y axis versus time indicated that the minimum environmental impact occurred at point A (i.e., low annual cost).

In a very interesting and extensive review paper with over 200 references, Selvam et al. [33] examined photothermal desalination as an eco-friendly means of achieving potable drinking water using Janus wood type architecture like what was reported by Chen et al. [30] and Dong et al. [31]. The manuscript had many very useful descriptive Figures. The authors concluded that photochemical desalination is a new and encouraging area for production of potable drinking water using environmentally friendly Janus wood architecture nanotechnology. In another recent review, Soukane et al. [34] emphasized the role of different advanced materials integrated with localized heating in MD. An extensive energy analysis showed a significant improvement in photothermal and localized heating using solar energy. However, the authors emphasized the difficulty in achieving large scale modules that comply with proper material integration and energy routes.

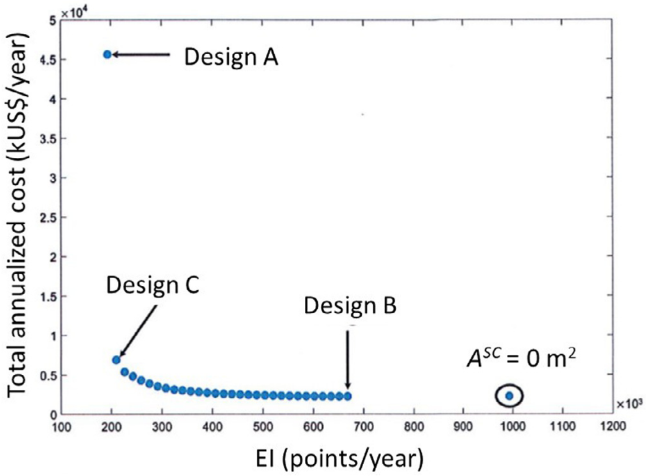

Fig. 5. Pareto curves for optimal trade=off solutions. Design A indicates the minimum environmental impact solution, while Design B represents the minimum total annualized cost solution (from Onishi et al. [7]).

The United Nations Sustainable Development Goals (SDGs) now form an essential part of all aspects of our society, from education, to innovation, to gender equality, and health care. Wydra et al. [6] in a case study from Egypt noted that in application of RE for generating electricity, it is not enough to consider just the technical aspects. All barriers need to be considered to ensure that they are overcome or at least minimized so that the quality of life of the local communities are improved as per the SDGs. This approach has widened the scope for scientists and the community to include sociopolitical, geographical, ecological (i.e., environmental) and economic issues in any decision-making process. There is also a need for good governance both at the corporate level as well as at the community level. This will provide stability, sustainability, and a good climate for economic development.

New types of more sustainable and environmentally friendly technologies are routinely being created. Lorfing et al. [35] for example described a new type of solar boiler (SB) with what the authors called a "beam down" optical system that boiled seawater directly to produce steam which was passed through a MED unit and condensed to give potable drinking water. A combined SB-MED integrated system was more efficient than a standalone SB unit with the former requiring 10 times less energy, according to the authors. It was claimed based on life cycle assessment (LCA) and modelling studies that the environmental performance of the SB-MED system was equivalent to slightly better than a standard reverse osmosis (RO) set-up with emissions of the former process at 2.4 kg CO_2/m^3 of potable drinking water produced compared with 3.8 kg CO_2/m^3 for the latter. It was recommended that pilot scale assessment, optimization as well as economic evaluation was required to further determine the commercialization potential of this new technology. In a related investigation, simulation modelling was employed by Sonawane et al. [36,37] to analyze or assess the environmental and economic issues associated with using various absorber materials (i.e., black ink, black dye, and black toner) in solar stills. Black toner was found to be the most eco-friendly in terms of reducing CO_2 production. The highest water production rate was also obtained with the same absorber material.

Future researchers according to Zheng et al. [38] must consider all the challenges associated with solar desalination from a holistic or overall general point of view. For example, energy, economics, and environmental considerations must be considered at the same time. With so many variables a Pareto frontier style approach will be needed as explained in a report from Assareh et al. [13]. Due to the high number of variables, a Pareto frontier was utilized by the authors to generate a set of optimal points. The essence or paradox (i.e., irony) of this type of approach is that if there is an economic benefit by optimizing one part of a complex system then another part of the system will suffer. For example, decreasing taxes on desalination equipment will make good sense for scale-up and commercialization. However, the negative side of this is that less funds (i.e., fewer tax dollars) will go to the government which will limit its ability to finance new strategic R&D projects. A Pareto frontier is widely used in engineering when no economic changes can make one individual or process better off without making someone else or some other process worse off.

On another topic but which has indirect insight into the road ahead, the application of nuclear energy for electricity generation is considered by many to be a controversial subject. It can be argued that this type of energy falls between renewable and non-renewable. However, it is important that this issue is briefly considered here in the context of desalination. Khan and Orfi [39] performed a review of the economic, environmental, and social issues associated with the use of nuclear energy in electrical power generation freshwater production (i.e., desalination). Results of the economic assessment indicated that either membrane or hybrid membrane with thermal energy may be the best choice for nuclear reactors integrated with desalination plants. The authors also noted that the environmental impact was least if a nuclear desalination plant was located along the coastline. It can be argued that the nuclear energy issue can be considered as a type of Pareto frontier.

4. Influence of regional regulations & policies on solar desalination

In the creation, application and commercial distribution of new technologies, government subsidies, policies and regulations have played key roles. For example, subsidies were crucial in the evolution of renewable energy systems such as solar panels which were quite expensive several decades ago, but which are now more affordable. However, policies have also sometimes acted as barriers. Al-Sarihi & Mansouri [5] identified the barriers that hindered the application of renewable energy (RE) technologies in the gulf cooperation council countries (GCC) of the Arabian Gulf. They made recommendations for policies that they argued would bring down barriers and promote successful implementation of RE. While previous studies indicated technical and economic feasibility issues as the main barriers, Al-Sarihi & Mansouri [5] in a more holistic (i.e., all inclusive) approach revealed that hydrocarbon subsidies, a low electricity tariff structure, a fragmented energy policy, the absence of dedicated RE regulators and regulatory frameworks, and a highly controlled power market were also major market barriers (Fig. 6). For example, one market obstacle was economics owing to RE not being cheaper than conventional fossil fuel electricity pricing. Due to subsidies consumers were not charged the real cost electricity. Their paper concluded with recommended policy options such as ensuring that customers paid for the actual costs of energy so that, for instance, an electricity bill would reflect the genuine cost of production (i.e., without subsidies). The authors argued that this would not only increase the competitiveness of RE sources but also encourage efficient use and thus lessen stress on a country's budget.

Regulatory aspects can be very regional/country specific. One can speculate for example that mature developed countries such as Europe, Japan and the USA will have well established guidelines in place, while GCC countries such as the UAE and Saudi Arabia are still going through a process of optimizing policies related to the use of RE for desalination. Oman, for instance, adopted policies to support the adoption of renewable energy technologies both at a large scale and small scale [5]. At the small-scale level, for example, the Authority for Public Services Regulation issued the first policy to incentivize the installation of renewable energy technologies in rural areas aimed at integrating renewable energy into existing diesel-based energy systems. This policy drove or triggered the establishment of other rural area projects, such as the wind-based pilot project in the rural island of Masirah. Likewise, in Indonesia, which is developed but not as rich as Oman, the government

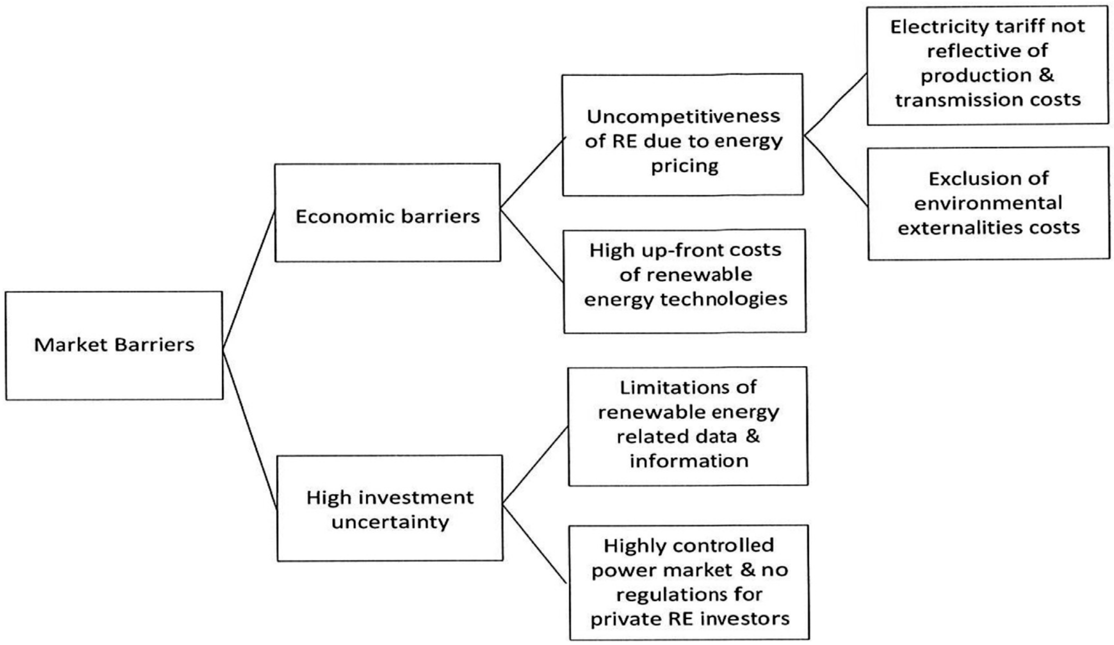

Fig. 6. Market barriers for renewable energy adoption in the GCC. (adapted from Al-Sarihi, [40]).

authorized the sale of solar energy generated back to the grid by issuing a Ministerial Decree. This new legislation resulted in an increase in the number of solar photovoltaic installations in the country. Furthermore, Singapore, which is highly developed, and a regional leader in RE research and development, authorized the country's public housing authority, to establish a Solar Capability Building Program to investigate the viability of large-scale solar PV for both new and old housing projects. As a final example, in the small but densely populated country of Brunei Darussalam, government rules and regulations were enacted to force homeowners and industry to install rooftop PV-based lighting systems. These were then connected (i.e., integrated) with the existing electrical power grid. Batteries were employed for electric power storage for lighting in the absence of solar radiation.

According to the policy recommendations put forth by Al-Sarihi & Mansouri [5] financial incentives for investors are required, especially for small private stakeholders. Direct cash grants or soft loans could be a policy method for lowering the high upfront financing cost. Likewise, subsidies to support medium to large-scale RE asset investments might be an attractive mechanism for establishing competitive environments for RE energy projects and conventional energy supply technologies. Finally, the authors suggested rooftop PV module installations (solar panels), as well as net metering The latter is a billing mechanism that credits solar energy system owners for the electricity they generate. For example, if a home RE system generates excess electricity, the excess can go back into the grid. In this case the electricity meter runs backwards, giving a net saving to the homeowner. Likewise, Pandey et al. [41] looked at government policies as related to energy storage and barriers in implementation of RE technology in the Association of Southeast Asian Nations (ASEAN). The authors found a significant gap exists between energy supply and demand. It was recommended that the governments in the region need to set specific targets to raise the percentage of RE by a specific date (e.g., 2025). Many policies need to be not only implemented but also enforced within each country. The key is to make regulations compulsory. As an analogy, for example, what is the purpose of having speeding rules on roads if drivers are not fined for speeding. de Doile et al. [4] examined the economic feasibility and regulatory aspects of hybrid wind and solar PV energy generation with energy storage systems. Their results indicated that most scientific studies focused on only one of the RE technologies. There were only a few hybrid studies, according to the authors. These centered on wind, solar PV, and energy storage system technologies. Even fewer looked at regulatory or legal aspects. In the case of Brazil, the authors noted that even the regulators of the electricity sector did not encourage the installation of energy storage systems. It can be said that these observations can be applied not only to Brazil but also to other countries that do not currently have regulations or policies for encouraging the use of energy storage systems. In a related investigation Subiela-Ortin et al. [42] recommended technical and economic guidelines and policies to help improve the implementation RE (solar and wind) driven RO desalination systems. The authors contended that regulations should be put in place to ensure that for each plant site operating and maintenance studies should be performed in particular when the venue for a desalination plant is a country with very limited resources. To reduce costs energy recovery and energy storage system should be incorporated. Hybrid systems such a solar and wind are also preferred to reduce the problem of intermittency in electrical energy production.

In a final example, Tarazona-Romero et al. [43] noted that renewable energy offers local communities a sustainable solution to their energy needs by empowering them so that they do not need to rely on the main electricity grid. The authors commented that careful studies must be done for each community to consider social, economic, and technical constraints regarding what is available locally. For example, a small-scale renewable energy desalination can be built in a poor remote region. However, if the community does not have sufficient financial resources for operating and maintenance then that plant will eventually stop producing fresh water and electricity.

5. Importance of system integration in reducing costs of solar desalination

Combining diverse technologies in creative ways has become a vital element in reducing the costs of solar desalination systems by making them economically competitive with conventional schemes. Al-Obaidi et al. [2] for example integrated two renewable energy (RE) technologies, concentrated solar power (CSP) and photovoltaic (PV), to operate thermal and membrane seawater desalination processes to make them more cost-effective. Specifically, they assessed multistage flash (MSF), multi effect distillation (MED), and reverse osmosis (RO). Economic fac-

Table 3
Specific energy consumption and water production cost associated with integration of solar energy systems (CSP & PV) with thermal (MED) and membrane (RO) desalination (adapted from Al-Obaidi et al. [2]).

Water Desalination Method	Total Capacity (m^3/day)	Specific Energy Consumption (kWh/m^3)	Water Production Cost (\$/m^3)	References
MSF	50,000–70,000	14–25	0.8–1.6	[44]
MED	5000–35,000	7–28	1.2–1.6	[44]
CSP + MED	>5000		2.5–3.0	[44]
RO	15,000–320,000	3–8	0.7	[44]
PV + RO	100	4–5	12–16	[45]
PV +RO	1000	2.4	1.7–2.6	[46]
PV + RO	50,000–190,000	3–7	0.9–1.8	[47]

tors associated with possible upgrades were analyzed to see if they were feasible. The main conclusion reached by the authors in a financial evaluation was that the water production cost using RE was not as good as compared to the using fossil fuels (Table 3). For example, while the water production cost for fossil fuel powered MED was 1.2–1.6 \$/m^3, for solar powered CSP-MED the cost was double at 2.5–3.0 \$/m^3. On the other hand, the highest specific energy consumption, 14–25 kWh/m^3, was seen for MSF, powered by fossil fuels, and the lowest, 2.4 kWh/m^3, for PV-RO. The authors suggested that a carbon tax on fossil fuels, to help reduce the carbon footprint (i.e., pollution) may encourage desalination industries to increase the adoption of RE technology to power seawater and brackish water desalination systems.

For solar energy-powered seawater desalination plants, Al-Obaidi et al. [2] reported that the main capital equipment cost was the solar collectors. The authors went on to argue that the price of electrical power generation from solar energy systems could be offset by employing higher efficiency solar panels. They suggested a mixture of PV units with batteries for energy storage, fossil fuels as a conventional back-up, and wind turbines as an additional renewable source. Such an integrated system, while relatively a complex combination, would provide consistent energy at possibly a more modest cost. It is important to note here that the general trend is towards integration of RE, conventional, external heat sources (e.g., waste heat from industrial processes) and energy storage systems. The key question is to be able to decide on which integrated system has the best economics for scale-up. This is the challenge facing decision makers.

As another example of the importance of integration on the overall economics of a system a comprehensive review was performed by Askari & Ameri [48] of the technical and economic aspects of integrating different MED configurations with various types of solar thermal sources. The authors reported that the integration of MED with low, medium, and high temperature solar collectors led to water production costs of ranging from 1.4\$/m^3 to 3.6\$/m^3 with a payback period of 4 to 16 years. These results were very similar to that reported by Al-Obaidi et al. [2] at 2.5\$/m^3 – 3.0\$/m^3 for CSP + MED (Table 3). It can be argued that this type of analysis provides useful information for decision makers to aid them in choosing the best integrated solar/MED technology for either small or large-scale applications. Similar efforts have shown in the past the importance of real integration of solar energy with MED at medium scale (4 effects) by comparing its robustness under severe conditions to solar PV-RO using real seawater [49].

Assareh et al. [13] examined a combined energy system consisting of a CSP plant, steam Rankine, and organic Rankine cycles, RO unit, and a thermoelectric generator. With Rankine cycle a fuel is employed to generate heat such as, for example, a water liquid in a boiler turning to steam. The produced steam is then expanded through a mechanical turbine producing useful work such as electricity. The relatively complex system analyzed by Assareh et al. [13] was subjected to optimization by minimization of annual operating and maintenance costs and maximization of efficiency (i.e., exergy or the amount of work a system can perform). The additional uniqueness of the study was that the physical location was in an area which faced water shortages and had environmental concerns, presumably due to possible pollution of air, soil, or water. However, at the same time the area had a great potential for solar radiation.

The most critical parameters influencing system operation were found to be the intensity of direct solar energy (i.e., normal irradiance), the number of heliostats (i.e., devices that continually tilt mirrors to track the sun's movement), the mechanical turbine efficiency and the steam Rankine cycle pump inlet temperature. Due to the high number of variables, a Pareto frontier was utilized to generate a set of optimal points by Assareh et al. [13]. The essence or concept behind this type of approach is that if there is an economic benefit by optimizing one part of a complex system then another part of the system will suffer. For example, decreasing taxes on desalination equipment will make good sense for scale-up and commercialization. However, the negative side of this is that less funds go to the government which will limit its ability to finance new strategic R&D projects. A Pareto frontier is widely used in engineering when no economic changes can make one individual or process better off without making someone else or some other process worse off. In a related study, Makkiabadi et al. [50] reported on a techno-economic assessment of a hybrid solar desalination system consisting of concentrating solar collector (CSP) to heat saline water and an electric heater integrated with a solar still. They concluded that compared to a conventional solar still, the hybrid system was preferred from a techno-economic perspective (i.e., favored for the commercial market).

The economics of integrating a solar parabolic collector (PDC) with small-scale MSF desalination plant was examined by Babaeebazaz et al. [51] (Fig. 7). The technical part was optimized by varying feedwater flow rates and utilizing vacuum pressure. The aim here was to obtain the ideal exergy (i.e., amount of work a system can perform). The price of the produced water was also determined for the best economics. Results indicated that the scale-up from 8 to 8000 L/day made for a 96 % reduction in distillate production costs. This showed that scale-up can have a significant beneficial effect on the economics of operating a plant. The importance of scale-up in reducing water production costs was also demonstrated by Al-Obaidi et al. [2] using an integrated PV-RO system. For water production of 100, 1000 and 50,000 m^3/day, the associated costs were 12, 1.7, and 0.9 \$/m^3. This was a 93% reduction because of scaling up and was like that reported by Babaeebazaz et al. [51].

The economic advantages of integrating RE and desalination systems were also demonstrated by Choi et al. [3]. They examined a small-scale pilot solar MD plant from an economic perspective by varying the operating conditions. Various renewable energies such as solar, geothermal, and even waste heat from industry, were employed to reduce the overall cost of thermal energy. Integration strategies included direct contact MD (DCMD) and air gap MD (AGMD). According to the authors a 30% decrease in the specific energy consumption (SEC) was observed. This translated into a significant operating cost saving. These results confirmed that combining MD with solar energy can improve its performance during long-term operation.

In a related investigation using Iran as a case study, Esmaeilion et al. [52] examined the possibility of utilizing RE for desalination in arid and semi-arid regions. They assessed solar, wind, geothermal and ocean wave energies for their potential. The authors reported that on the eco-

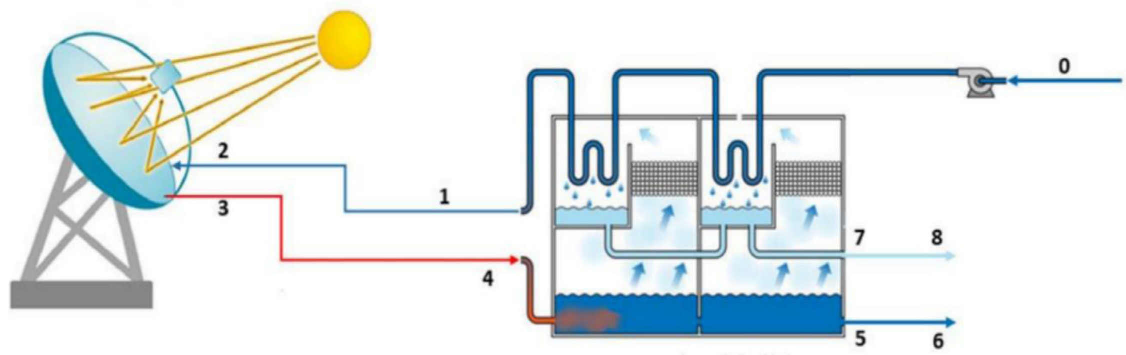

Fig. 7. Stream flows throughout the MSF desalination unit (0: Feedwater, 1–2: Preheated feedwater, 3–4: Hot water at TBT, 5–6: Discharged brine, 7–8: Produced distillate water). (adapted from Babaeebazaz et al. [51]).

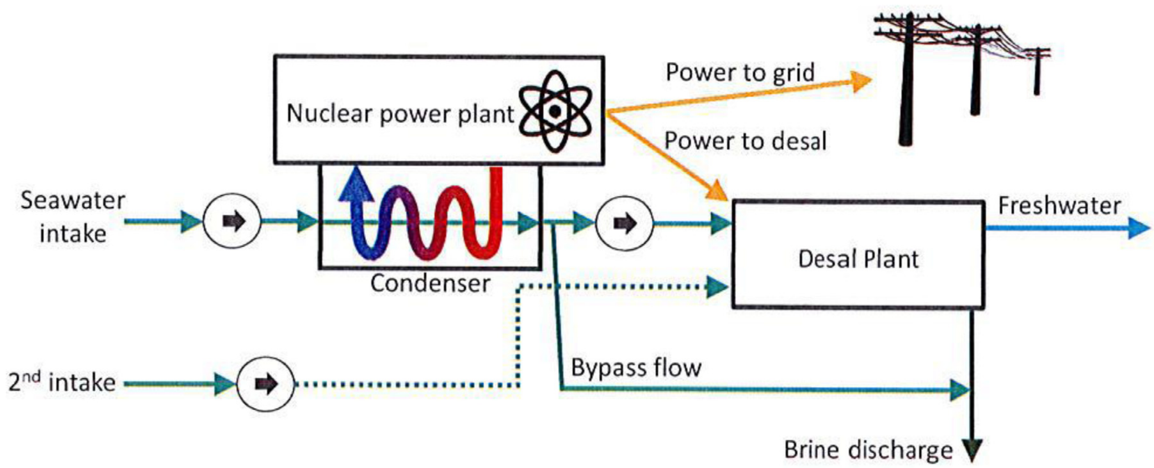

Fig. 8. Schematic of a cogeneration-desalination system integrated with a nuclear power plant (adapted from Bouma et al. [56]).

nomic side the difficulty in attracting suitable investments was considered a serious risk factor or barrier. Techno-economic optimization was considered crucial for effective utilization of any new technology. Esmaeilion et al. [52] concluded that for arid and semi-arid regions it was essential that all stakeholders including government, policymakers, the local community, and investors need to work together in establishing large-scale desalination plants powered by RE. Likewise, in a similar investigation Soliman et al. [53] compared several RE systems (i.e., PV and wind) for producing electricity for running a reverse osmosis unit. Based on a technical and economic analysis they found that the capital costs of PV panels were a key factor in reducing costs. A PV driven RO units had lower water production costs than a solar organic Ranking cycle RO system as well as a wind driven RO system. The authors cautioned that for large scale applications these conclusions may not hold. In this case thermal organic Ranking engines and wind farms may be more economic. In a similar study Al-Obaidi et al. [2] reported that the main capital equipment cost in a desalination process was the solar collectors. Based on these results it can be maintained that stakeholders need to be very careful when making decisions on the type and integration of equipment, as well as the scale (i.e., small, medium, large) when making major capital purchases for desalination plants. Likewise, economic aspects are highly regional/country specific when it comes to large-scale RE RO desalination systems. Iran for example is highly developed but it has difficulty in obtaining sufficient investments for establishing desalination plants [52]. This issue is less of a problem in countries such as the USA and the UAE.

In another important area, accurate and user-friendly mathematical modelling tools are crucial in helping to predict the technical and economic performance of integrated large-scale solar desalination plants. Fthenakis et al. [54] developed a user-friendly software analysis tool for the techno-economical evaluation of different solar desalination technologies as well as for selection of regions with the greatest solar potential. Large amounts of information from geographic information system (GIS) could be integrated into the calculations. What made this tool unique was that time dependent energy generation and water production was tied with plant performance. This would allow operators to make suggestions more easily for improvements. Likewise, Tuly et al. [55] in an investigation of a double slope solar still integrated with nanoparticles phase change material concluded that the increase in costs of a modified solar still was offset by a higher water production rate. The authors argued or claimed that while the lifetime of the still and the interest rate (i.e., amortization costs) of lending money from a bank to pay for the device will affect the water production price, the nanoparticle based solar still offered the most cost-effective solution.

In an outstanding report on the levelized cost of water (LCOW) Bouma et al. [56] also demonstrated the importance of integrating technologies. The authors evaluated the technical and economic viability of integrating an electrically driven large-scale seawater desalination plant (i.e., seawater reverse osmosis, SWRO) with an existing nuclear power plant on California's central coast (Fig. 8). Although solar energy was not involved, the study was an excellent example of the advantages of combining different technologies including waste heat recovery and shared infrastructure to help reduce water production costs and at the same time to better protect the environment. Seawater was utilized to cool the reactor. The shared or integrated infrastructure included common water intakes as well as outfalls (i.e., brine discharge) and utilizing the electricity generated by the nuclear plant. This resulted in significant savings in operating and maintenance costs for the SWRO plant. Advantages described by the authors included lower electricity costs, sharing the power plant's seawater intake and outfall, and having a zero-carbon footprint during operation.

According to Bouma et al. [56] electrically driven SWRO, in contrast to thermal desalination processes, was best for retrofitting current power plants because the mechanical turbines that generate electricity from steam and condensers that convert vapor to liquid water, would not need costly changes. There was a significant cost saving as shown by a levelized cost of water (LCOW) analysis which ranged from \$0.77 to \$0.98 per m^3 of fresh water. This compared favorably with California's largest desalination plant located in the USA which had an LCOW approximately double at US\$1.84 per m^3. This study showed that integrating SWRO and nuclear power had a significant economic advantage over conventional seawater desalination. However, it is important to acknowledge that the use of nuclear technology is still quite controversial with many scientists and decision makers around the world. Extra environmental care, not just economic analysis, needs to be taken by decision makers when dealing with integration of desalination plants with heat generated by nuclear technology. It can be argued that it is important to try and keep an open mind, to think outside the box, when trying to find the best solution to solve problems.

6. Concluding remarks

In complex scenarios with a high number of variables, a Pareto frontier, a relatively new concept, can be employed to generate a set of optimal points. The latter can be utilized in the decision-making process when scaling up and building integrated solar desalination systems. During this procedure there is also a need to analyze any political, environmental, and economic limitations in the construction desalination plants. Furthermore, an improved technique for electricity production was found to be integration of solar thermal energy units with organic Rankine and Stirling cycle engines to generate mechanical work to operate electric driven high-pressure reverse osmosis pumps. Additionally, new types of thermal storage units based on a phase change material enhanced energy storage properties. Critical barriers in commercialization of solar desalination plants were uncertainty of government subsidies, and a lack of regulatory policies.

In stimulating innovative research studies, a sustainable Janus wood evaporator was developed that overcame many of the current solar desalination problems. This photochemical desalination process produced potable drinking water at high efficiencies using environmentally friendly Janus wood architecture nanotechnology. Additionally, life-cycle assessment of solar desalination plants indicated that most of the environmental impact occurred due to electric pumping energy. Furthermore, the main capital equipment cost in a desalination process appeared to be the solar collectors. The trend was towards integration of renewable energy with conventional sources, and energy storage systems. Stakeholders therefore need to be very careful when making decisions on the type of equipment ordered, how to integrate them as well as the scale. Accurate and user-friendly mathematical modelling tools can be crucial in helping to predict the technical and economic performance of integrated large-scale solar desalination plants.

In closing, it is crucial for decision makers to keep in mind that the total real price of a new plant consists of the cost of borrowing money from the bank, the maintenance and operating costs, and the price of energy. A solar energy based zero-liquid discharge desalination plant is the ideal long-term goal in terms of protecting the ecosystem while at the same time providing potable drinking water for society and commercial products from the recovered salts. The implementation of cost effective, sustainable solar desalination plants will depend on a successful integration of key factors involving environmental, regulatory, and economic considerations. This is the challenge facing scientists, decision-makers, and society.

Declaration of Competing Interest

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