Sustainably integrating desalination with solar power to overcome future freshwater scarcity in China

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Abstract: Freshwater resources and energy are the two material foundations of human survival and the two challenges for human sustainable development. China’s huge population needs a large amount of freshwater for basic necessities. Desalination is an intelligent and promising technology for increasing water resources to realize a sustainable supply of freshwater. However, high levels of energy consumption and greenhouse gas emissions have restricted the development of desalination. Solar energy has the unique advantage that it can be harnessed in different forms. This paper discusses the water resources and solar energy utilization status in China and presents a comprehensive review on a possible solution: coupling desalination technologies with sustainable energy. China’s desalination market is reviewed, and the energy consumption for several desalination processes is summarized to present a brief outlook of desalination techniques in China. Potential coupled methods for solar-powered desalination are compared. This study will facilitate understanding of the latent water crisis in China and help China’s desalination market transition from conventional energy sources to choose an appropriate solar-powered desalination process.

Keywords: Desalination, Solar energy.

1 Introduction

Water plays an important role in our daily lives and is an important foundation for human economic and social development. Approximately 97.5% of the water on earth is seawater with an average salinity of 35,000 mg/L and cannot be used. Only 0.5% of the remaining 2.5% freshwater (salinity < 500 mg/L) is in easily accessible places such as lakes and rivers. Thus, the shortage of freshwater resources is a major challenge facing global development [1-3]. The demand for freshwater is exponentially escalating because of urbanization, industrialization, and raised living standards. Thus, the increased use of desalinated seawater is necessary to ensure a sustainable water supply.

There are two main desalination processes: thermal-based and membrane-based [4]. Thermal energy can be obtained from the combustion of conventional fossil fuels, which can be substituted with sustainable energy sources such as solar, geothermal, and nuclear. In a thermal-based process, seawater is evaporated into water vapor with a thermal energy source, and the vapor is condensed...
to produce potable water. Some common desalination technologies that use thermal energy are multi-stage flash (MSF), multi-effect distillation (MED), humidification–dehumidification (HDH), and vapor compression (VC) [5,6]. Membrane-based processes allow water to pass through a membrane without a phase change. Representative membrane-based technologies include electrodialysis (ED) and reverse osmosis (RO) [7,8]. At present, RO is commonly used for desalination worldwide because of its low specific energy consumption, low environmental impact, and flexible capacity; it accounts for more than 60% of the installed capacity [9].

In 2018, approximately 18,000 desalination plants with a total capacity of approximately 38 billion m³/yr were installed worldwide. Seawater desalination has been studied in China since 1958, and medium- and large-scale seawater desalination plants have been developed since 1975. Currently, the freshwater output can reach approximately 1.2 million tons/d. Desalination is highly energy-intensive because of the high salinity of the source. The desalination of seawater based on fossil fuels is neither economically feasible nor environmentally friendly from a long-term perspective as fuel becomes increasingly expensive and scarce. The desalination industry is additionally threatened by CO₂ emissions and severe environment impacts. Excessive exploitation of freshwater resources, fossil fuel depletion, and climate change all highlight the need for desalination powered by sustainable energy. Desalination can be made sustainable if it is integrated with a sustainable energy source to decrease conflicts at the water–energy nexus. Sustainable energy sources generally include solar, wind, and geothermal. Among these, solar energy is the most environmentally friendly and makes up nearly 57% of the sustainable energy consumption by the desalination market [10].

This paper presents a comprehensive review of the developments made in solar-powered desalination and its key technologies with a focus on feasibility in China. Improvements in solar collectors and PV panels are conducive to the evolution of new seawater desalination industry. The strengths and weaknesses of various solar-powered seawater desalination technologies and current research advances are discussed.

2 Water resources and future challenges

2.1 Water resources in China

Fig. 1 and Fig. 2 describe the amount and distribution of water resources (total and per capita) in China. In 2016, China’s total annual water resources was 3,246.64 billion m³. Although China has a large amount of water
resources, the per capita water consumption is low because of its large population, and the drinkable water resources are limited. The uneven distribution of precipitation has caused an imbalance in the water supply. The cultivated land in the Yangtze River Basin and south of the Yangtze River accounts for 36% of the country but 80% of the water resources. Meanwhile, northern China has only 8% of the water resources but 40% of the cultivated land. Water shortages and an imbalanced water distribution have become controlling factors hindering economic growth and sustainable development [11].

2.2 Desalination in China

Seawater desalination has been studied in China since 1958, and medium- and large-scale seawater desalination plants have been developed since 1975. In recent years, the overall scale of desalination projects in China has grown steadily. By the end of 2017, 136 seawater desalination projects were completed nationwide with a project scale of 1,189,105 tons/d. Five new desalination projects were completed nationwide in 2017, and the scale of the new desalination projects was 1040 tons/d [12]. According to the In-depth Research and Investment Strategic Planning Analysis Report on China’s Desalination Industry in 2018–2023, RO accounted for 65% of the total freshwater production, followed by MED at 34% and MSF and ED at 1%. RO technology occupies the leading position in China’s desalination industry.

At the end of 2017, national desalination projects were distributed in nine coastal provinces and cities, as shown in Fig. 3, where water resources were seriously drained. The north is dominated by large-scale industrial desalination projects that are mainly for high-water consumption industries such as electricity and steel in Tianjin, Shandong, Hebei, etc. The southern desalination projects, which are mainly 100 and 1000 tons, were mostly established on islands in Zhejiang and other places.

China’s desalination capacity does not rank highly globally; hence, developmental changes are essential to compare favorably with the global level. Most desalination plants in China mainly use RO technology in small-scale industries to obtain freshwater from seawater.

3 Solar energy in China

Fig. 4 shows the annual sunshine hours in China in 2016. The map clearly shows a sufficient supply of solar energy. In Liaoning, Hebei, Tianjin, and Shandong, which have well-developed large-scale desalination projects, the sunshine hours are enough to drive desalination process. Other coastal provinces such as Jiangsu, Zhejiang, Fujian, Guangdong, Hainan, and Taiwan have sufficient sunshine hours for 100- and 1000-ton desalination projects. Therefore, China receives sufficient solar energy to drive the desalination process.
4 Solar desalination

Sustainable energy is an alternative solution to the decreasing reserves of fossil fuels. Solar energy is an inexhaustible resource that can be used to drive seawater desalination, mainly due to its thermal and optical effects [13]. Conventionally, there are two main methods of using solar energy: solar photovoltaics (PV) directly converts sunlight into electricity, while concentrated solar power (CSP) or concentrated photovoltaics (CPV) uses mirrors to reflect sunlight and focus it in a receiver to be transformed into thermal energy. Steam is produced to impulse a turbine engine and drive the generator to produce electric power [14].

The technologies of using solar energy have improved, which had led to the development of energy–desalination coupling schemes. These can be divided into indirect and direct processes according to whether the solar energy collection and desalination are carried out with the same device, as shown in Fig. 5. Direct processes mainly include solar distillation (SD), solar HDH, and solar chimney (SC); solar power is collected and utilized as thermal energy, and the desalination process is carried out by the same device.

In an indirect process, solar collection is separate from desalination. Solar power can be converted into heat by a solar collector or into electricity by PV power generation [15]. Indirect processes include thermally driven MSF desalination, MED, VC desalination, membrane distillation (MD), freeze desalination (FD), and adsorption desalination (AD) as well as electrically driven RO and ED.

![Fig. 5 Schematic of solar power coupled with desalination](image)

### 4.1 Direct desalination processes

#### 4.1.1 Solar chimney

The SC power station (SCPP) is an important method for realizing the large-scale development and utilization of solar energy. The main components of a SC are large-diameter solar collectors, a turbine, a generator, and a long chimney [18], as shown in Fig. 6. The bottom layer of the heat-collecting shed and the seawater layer absorb most of the solar radiation energy, which increases the temperature of the seawater layer and intensifies the evaporation process. This generates a large amount of steam in the upper space of the heat collecting shed and produces moist air that rotates a turbine at the bottom of the chimney as it rises to generate electricity. The temperature drops, and liquid water condenses on the outer surface of the bundle when the wet air is exothermic [19,20]. The mass flow rate was given by

\[
\dot{m} = \rho_{air} V_{ch} A_{ch}
\]

![Fig. 6 Schematic diagram of a desalination system integrated with a solar chimney](image)
The possible power output of the SCPP [21] is given by

\[ P = 0.385 \eta_0 \Delta P \frac{\dot{m}}{\rho} \]  

(2)

The collector efficiency was studied by Koonsrisuk et al. [22] with mathematical models and is defined as

\[ \eta_{\text{col}} = \frac{\dot{m} c_p \Delta T}{\dot{q} A} \]  

(3)

Table 1 compares SC desalination systems. The infrastructure cost of the SC desalination system was analyzed by [23] and includes a collector (€9/m²), chimney (€250/m²), wind turbine generator (€0.5 million), and distillation pond (€18/m²). These costs include materials, transportation, and construction. In Northwest China, which has abundant solar energy resources, the average annual sunshine time is 2800–3300 h. The large amounts of barren land, such as the Gobi Desert, are suitable for building large-scale SCPPs.

| Main characteristics                  | Plant components                  | Comments                                                                 | Outcome                        |
|---------------------------------------|-----------------------------------|--------------------------------------------------------------------------|--------------------------------|
| CSCSPD and CSCS (model simulation)    | Solar collector, chimney, turbine  | Solar radiation: 1000 W/m²                                               | \( P_{\text{CSCSPD,freshwater}} = 3807.1 \text{ L/s} \) |
|                                       | generators, condenser              |                                                                          | \( P_{\text{CSCSPD,power}} = 39.2 \text{ MW} \) |
| SCPP, SCPPCSD and WSSCPPSCD           | Solar collector, ventilator blade, | Solar radiation: 800 W/m²                                               | \( P_{\text{SCPPCSD,freshwater}} = 30 \text{ g/h} \) |
| (numerical simulation) [25]            | chimney, turbine generators, condenser |                                                                          | \( P_{\text{SCPPCSD,power}} = 14.7 \text{ kW} \) |
| SCPP combined with desalination pond  | Solar collector, chimney, turbine  | Solar radiation: 1000 W/m²                                               | \( P_{\text{SCPP,power}} = 128.8 \text{ MW} \) |
| (numerical simulation) [26]            | generators, condenser, desalination pond |                                                                          |                                                                      |
| SCPWDP (numerical simulation) [27]     | Solar collector, chimney, turbine  | Solar radiation: 800 W/m²                                               | \( P_{\text{SCPWDP,freshwater}} = 6.5 \text{ L/s} \) |
|                                       | generators, condenser, water pool  |                                                                          | \( P_{\text{SCPWDP,power}} = 18.5 \text{ kW} \) |
| CSCSPD (numerical simulation) [28]     | Solar collector, chimney, turbine, energy storage layer, basin still | Solar radiation: 800 W/m²                                               | \( P_{\text{CSCSPD,freshwater}} = 31.7 \text{ L/h} \) |
|                                       |                                    |                                                                          | \( P_{\text{CSCSPD,power}} = 129 \text{ kWh/h} \) |

CSCSPD: Combined solar chimney system for power generation and seawater desalination; CSCS: Classical solar chimney power system; SCPP: Solar chimney power plant; SCPPCSD: Solar chimney power plant combined with seawater desalination; WSSCPPSCD: Wind supercharged solar chimney power plant combined with seawater desalination; SCPWDP: Solar chimney power-water distillation plant.

4.1.2 Solar distillation

SD is gradually becoming the most widely used direct process; it has a simple structure, easy and flexible operation, and low consumption of conventional energy. It boasts technical and economic competitiveness and is accessible for remote coastal areas with high solar irradiance and limited primary energy supply. Its application started in 1872, when Wilson designed the first conventional solar still in Chile [29]. SD can be divided into passive and active modes depending on whether or not a solar power collector is used [30]. By coupling solar stills with auxiliary equipment such as sponge cubes [31], condensers, concave and convex surfaces, sun tracking, flat plates, evacuated tube collectors, phase change materials (PCMs) and reflectors [32], the heat and mass transfer process inside the system can be effectively improved. In addition, the recovery and utilization (i.e., reuse) of the internal latent heat of condensation and distillate yield can be increased.

SD is the subject of great interest. The improved performance of solar stills has led to the development of different designs of solar stills: double, triple, and multi-effect solar stills; vertical stills; tubular-type solar stills; finned and crinkled stills; and stepped-type solar stills [33-38]. Fig. 7 shows some types of solar stills. Table 2 presents SD technologies.
Additives can effectively increase the overall performance of the system. The performance of a single basin SD system was evaluated with different energy absorber materials, and the experimental results showed that the addition of potassium dichromate (K₂Cr₂O₇) to the basin effectively enhanced the solar radiation flux and basin temperature [39]. Furthermore, adding nano-Al₂O₃ to the PCM increased the running time; the distillate yield increased by 60.53% compared to that of the simple distiller [40]. The impact of the structure of the condensing surface on the distillate output has been studied. Experiments were carried out to examine the difference in productivity between single-slope and double-slope solar stills, and the results were 2.34 and 3.07 (L/m²/day), respectively [41,42]. The operating principle of the inverted absorber solar still, wick-type solar still, and solar still incorporating compound parabolic concentrator (CPC) systems were identified.

4.2 Indirect desalination processes

The desalination process has a very high energy requirement. The minimum energy required for the desalination process is much greater than the theoretical value that could be acquired with the second law of thermodynamics. If RO technology is taken as an example, the minimum theoretical required energy for desalinating seawater with a salinity of 45,000 mg/L is around 1 kWh/m³ [3,51]. Table 3 compares the energy consumptions of various desalination processes. There is much room for further desalination technologies that are environmentally friendly and energy-efficient.

RO desalination has increased in popularity because of advances in membrane technology and its high recovery ratio (RR) and low specific energy consumption. In terms of solar-powered desalination, Solar-RO comprises 52% of indirect solar desalination plants with Solar-MED and Solar-MSF making up 13% and 9%, respectively, around the world. Solar-ED represents 16% of the total and has seen promising developments [15]. RO accounts for 65% of the total water production, MED accounts for 34%, and MSF and ED account for 1%, as shown in Fig. 8. RO technology has a leading role

| Table 2 | Technologies of solar distillation |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Main characteristics** | **Structures of system** | **Absorber material** | **Comments** | **Results** |
| Shape of basin surface [44] | Stepped | Convex and concave | 20° inclination | Water yield increased by 56.60% and 29.24% respectively compared with original |
| Shape of basin surface [45] | Stepped | Mini pond and Flat plate with fins | 9°55’ inclination | Addition of fins and sponge increased the yield by 85% compared to conventional SSSS |
| Internal and external reflectors [32] | Stepped | Galvanized steel sheets with black paint | 20° inclination | Lower unit production cost (0.031 $/L and 0.049 $/L) than conventional SSSS |
| Tracking system [46] | Single slope | Flat plate collector | Single-axis tracking systems | Increased productivity by 22% compared with fixed one |
| Additive in PCM [40] | Single slope | PCM with nano-Al₂O₃ | 30° inclination | Longer running time and distillate yield increased by 60.53% |
| Life cycle cost analysis [47] | Single slope | Flat plate collector | Passive and hybrid (PV/T) active solar distill | Energy payback times assessed as 2.9 and 4.7 years, respectively |
| CFD simulations [43] | Single slope | Flat plate collector | 45° inclination | CFD can be a tool for solar still design and parameter analysis |
| Floating absorbers with bubble wrap (BW) [48] | Single slope | Carbon impregnated foam (CIF) | Size: 0.50 m² | Productivity of the SSSS-CIF hybrid BW insulation was 3.1 L/m²/day with lower costs than previous works |
| Galvanized iron sheet [41] | Double slope | Flat plate collector | 11° inclination | Maximum distillate output of 3.07 L/m²/d with 0.01 m water depth |
| Wick materials [49] | Double slope | Aluminum fin covered with black cloth | 30° inclination | Light black cotton cloth was the most effective with increased production per day |
| Fin configuration [50] | Single slope | Flat plate with fins | 15° inclination | Productivity of 5.377 L/m²/day (fins n = 7, fin height Hf = 0.04 m, fin thickness xf = 0.001 m, and mw = 40 kg) |
in desalination in China. In recent years, indirect solar-powered desalination technologies have been studied. A comprehensive review of indirect solar desalination is presented below.

4.2.1 Solar powered multi–effect distillation

The origins of MED can be traced back to the 1830s. However, in the early stages of MED, it was constrained by a proneness to scaling on the heat transfer surface; it was not until the 1960s that the development of low-temperature MED (LT-MED) technology eased the problems of scaling and corrosion. The MED process [52] is based on using the latent heat of steam in the first cell as a dynamic source to drive seawater evaporation and provide a heat source in the next cell; this is repeated in the following cells until the minimum temperature is reached. Horizontal-tube falling film evaporators are used to eliminate the influence of static pressure on the evaporation surface and increase the total heat transfer coefficient. This allows operation at low temperatures (top brine temperature (TBT) is 65–70 °C) and limits scale formation on the walls [53,54]. Frantz et al. [55] performed numerical simulations to systematically study the correlation of parameters in a solar-MED system. The results showed that the freshwater yield can be doubled when the steam is heated from 65 °C to 90 °C, and the yield can be increased by 50% if the surface area is augmented by 30%. Table 4 shows the technologies of solar-MED.

Table 3 Comparison of different desalination technologies

| Process   | MSF | MED  | TVC     | MVC  | RO   | ED   |
|-----------|-----|------|---------|------|------|------|
| Typical unit size (m³/day) | 50000–70000 | 5000–15000 | 10000–30000 | 100–2500 | 98000–128000 | 2–145000 |
| Electrical consumption (kWh/m³) | 4–6 | 1.5–2.5 | 1.8–1.6 | 7–12 | 1.5–5.5 | 0.7–5.5 |
| Equivalent electrical of thermal consumption (kWh/m³) | 15.83–21.5 | 12–19 | 14 | 0 | 0 | 0 |
| Total consumption (kWh/m³) | 19.83–27.5 | 13.5–21.35 | 16–18 | 7–12 | 1.5–5.5 | 0.7–2.5 | 2.64–5.5 |
| Feed water quality (mg/L) | 10000–100000 | 10000–100000 | 10000–100000 | 10000–100000 | 100–50000 | <2500 | 2500–5000 |
| Product water quality (mg/L) | 10 | 10 | 10 | 10 | 400–500 | 150–500 |

Table 4 Technologies of solar MED

| Main characteristics | Location (solar radiation) | No. of stages | Solar Collector | Operating temperature (°C) | Outcome |
|----------------------|-----------------------------|---------------|----------------|----------------------------|---------|
| MED-thermal [15]     | Southern Mediterranean (1000 W/m²) | NA | ETC | 60–80 | $P_{\text{footprint}} = 1000$ |
| MED-DEAHP [56]       | Almería, Spain              | 14 | PTC | 60–70 | 50% reduction of the required solar field area compared to the solar-MED system |
4.2.2 Solar-powered reverse osmosis

RO is the most common desalination technique owing to its low energy cost and installed capacity. It is a pressure-driven desalination process where feed water is forced across a semi-permeable membrane module; freshwater is collected, and the brine is drained [60-62]. The required seawater RO (SWRO) desalination productivity to meet the global water demand in 2030 is estimated to be approximately 2374 million m$^3$/day [63]. The common energy consumption of a SWRO desalination plant is approximately 2–4 kWh/m$^3$ and depends on the feed water salinity, RR, pretreatment, brine discharge, and electric power used within the plant [64].

Combining solar energy and RO will effectively reduce the consumption of conventional energy sources and promote the sustainable development of seawater desalination. At present, this approach can be divided into two types: PV-powered and solar thermal-powered RO desalination [65,66]. Fig. 10 shows schematic representations of these systems.

PV powered RO desalination relies on PV modules to convert heat generated by solar radiation into electricity to drive a water pump [67]. The heat can also be converted into mechanical energy through an organic Rankine cycle (ORC) to drive the high-pressure pump in the RO system; this is known as solar thermal-powered RO desalination. Waste heat can increase the temperature of the feed liquid, which helps increase the membrane permeate flux [68,69]. This is a cost-effective way to realize a commercial application of sustainable energy to small-scale RO desalination systems.

Some researchers have used small-scale PV-RO desalination systems in remote areas that can produce 0.51 m$^3$/h while consuming 1.1 kWh/m$^3$. Compared with diesel-powered RO system, a PV-powered RO system can produce water at a lower cost [70,71].

The mass flux that is transported across the RO membrane is given by [72]

$$N_A = L(\Delta P - \Delta \pi) \quad (4)$$

Many places still need the construction of freshwater production plants, especially in remote areas. In [73], it was pointed out that PV-powered RO is theoretically feasible for the majority of remote locations with large solar resources based on Geographic Information System (GIS) data. Table 5 compares different solar-RO technologies. RO is a mainstream desalination technology; the energy recovery system occupies a vital role. The maximum system recovery

| Main characteristics | Location (solar radiation) | No. of stages | Solar Collector | Operating temperature (°C) | Outcome |
|----------------------|-----------------------------|---------------|----------------|----------------------------|---------|
| MED-ORC [57]         | Suez Gulf region, Egypt (503 W/m$^2$) | 16–20         | PTC            | 70–75                      | $P_{	ext{freshwater}} = 100$ m$^3$/d |
| MED-TC [58]          | Aqaba, Jordan (500–1000 W/m$^2$) | NA            | PTC            | 70                         | $P_{	ext{freshwater}} = 50000$ m$^3$/d |
| MED-TVC RC [59]      | Trapani, Italy               | 12            | CPC            | 70                         | $P_{	ext{freshwater}} = 10000$ m$^3$/d |
| MED-CRC [55]         | Al-Kosseir, Egypt            | NA            | CPC            | 65                         | $P_{	ext{freshwater}} = 30000$ m$^3$/d |

ETC: Evacuated tube collector; PTC: Parabolic trough collector; CPC: compound parabolic collector; DEAHP: double-effect absorption heat pump; ORC: organic Rankine cycle; RC: Rankine cycle; CRC: Clausius-Rankine cycle.

Fig. 9 Schematic diagram of solar-MED components for desalination and power generation: solar field, boiler heat exchanger, pump, turbine, recuperator, and MED [110]

Fig. 10 Operating principle of the solar-powered reverse osmosis (RO) system [111]
Table 5 Solar-RO technologies

| Main characteristics                  | Location/Solar radiation                               | System recovery (%) | Membrane module                  | Energy source               | SEC (kWh/m²) | Outcome |
|---------------------------------------|--------------------------------------------------------|---------------------|----------------------------------|-----------------------------|--------------|---------|
| [15]                                  | Alexandria University, Egypt                           | NA                  | NA                               | PV-Wind-diesel              | NA           | P_{freshwater} = 30 m³/d |
| PV-RO with RO-Solar Rankine [74]      | Agricultural University of Athens, Greece              | NA                  | Sprial wound thin film composite | PV                          | 4.3–4.6      | P_{freshwater} = 0.8–0.9 m³/d |
| Two-stage pressure vessels [75]       | Djerba region, Southern Tunisia (1000 W/m²)            | 50                  | Spiral modules                   | PV (400 m³) + Wind          | NA           | P_{freshwater} = 57–111 m³/d |
| Two-stage PV-BWRO [70]                | Mersing, Johor, West Malaysia (600 W/m²)               | <50                 | NA                               | PV                          | 1.1          | P_{freshwater} = 5.1 m³/d   |
| Concentrating mirrors with PV-RO [76] | Cambridge, MA (1500 W/m²)                              | 9                   | NA                               | PV                          | NA           | P_{freshwater} = 0.3–0.45 m³/d |
| Tracking PV panel-RO [77]             | Dhahran, Saudi Arabia (650–1020 W/m²)                  | 80                  | Sprial wound membranes            | PV                          | NA           | P_{freshwater} = 0.65–0.925 m³/d |
| Hybrid power-RO [78]                  | Bozcaada Island, Turkey (1000 W/m²)                   | 30                  | NA                               | Wind-PV-PV-diesel-battery   | 4.38         | P_{cost} = $2.20/m³ |

SEC: specific energy consumption; BWRO: brackish water reverse osmosis.

4.3 Solar pond

The solar pond is an energy device that acts as a large-scale solar collector to absorb and store solar irradiation as low-grade heat, which can minimize current alarming environmental impacts and energy scarcity [79,80].

A solar pond with three different zones having various densities of saltwater can operate as large thermal batteries. The three zones are called the upper convective zone (UCZ), non-convective middle zone (NCZ), and lower convective zone (LCZ) [81,82]. The UCZ is the topmost layer of the solar pond and commonly consists of freshwater close to the ambient temperature; it has the functions of heat insulation and preventing the disturbance of the underlying solution. The NCZ is just below the UCZ with a gradually increasing salt concentration with increasing depth. This layer effectively prevents natural convection in the vertical direction caused by the rising temperature of the water in the lower pool, which minimizes heat losses from the highly saline bottom layer. The LCZ comprises a saturated salt solution with the highest saline density and no concentration gradient. This layer provides heat absorption and storage, and the maximum temperature can reach around 100 °C [83-86].

Solar ponds are mainly divided into two categories: convective and non-convective. A shallow solar pond is a convective solar pond; the salinity gradient solar pond (SGSP), equilibrium solar pond (ESP), solar membrane pond, and solar gel pond are non-convective [87,88]. The solar gel pond is generally more costly than the SGSP [89].

The solar pond is an energy storage technology with significant advantages; it eliminates the matching gap between intermittent sustainable energy sources and continuously operating desalination plants. The relation between energy storage and sustainable energy-driven seawater desalination technology was systematically illustrated in [90], which pointed out that the storage media, containers, and thermal insulation should be the focus of future research. Different desalination technologies have been integrated with a solar pond to increase the performance. Solar ponds can be used as thermal batteries for most desalination processes, such as solar pond-driven MSF, MED, distillation, SC, MD, and other thermal desalination technologies. It can also be used as a heat resource for draw solution recovery in FO. Table 6 presents coupling systems. The solar pond-driven MSF system is relatively mature and suitable for mass production.
### Table 6 Selected studies on solar pond assisted desalination technologies

| Main characteristics | Location/irradiation (kWh/m²/d) | Pond size (m²) | Top brine temp. (°C) | Capacity (m³/d) | Cost ($/m³) | No. of stages |
|----------------------|---------------------------------|----------------|---------------------|----------------|-------------|--------------|
| MSF system with a solar pond energy collection and storage system [91] | Qatar (5.5–6) | 80,000 | 55–80 | 1000 | 2.85 | NA |
| Solar pond/MSF system [92] | Tripoli, Libya | 70,000 (2.5 m depth) | 90 | 1579 | 1.8 | 31 |
| PTC and a solar pond with MSF system [93] | United Arab Emirates | 530,000 (4 m depth) | 100 | 1880 | 1–5 | 4 |
| LT-MED coupled with SGSP [94] | Perth, Western Australia | 2.2 m depth | 50–90 | 2.3 | 1.7–3.4 | 3 |
| MED-SGSP [95] | Melbourne, Australia | 50 | 50–90 | 2.3 | 1.7–3.4 | 3 |
| MED-SGSP [96] | Univ. of Ancona, Italy | 625 (3.5 m depth) | 65 | 30 | 3.66 | 4 |
| ASBS-SSP [97] | Egypt | 0.088 m depth | 45–47 | 1.57–5.29 | NA | NA |
| SSS-SBS-mini solar pond [45] | Madurai, Tamil Nadu, India (615 W/m²) | 0.3 m depth | 50–60 | 4–7 | 1.29 | NA |
| DCMD-SGSP [98] | Chile | 1.7 m depth | 40 | 0.00116 m³/d/m² | NA | NA |
| DCMD-SGSP [99] [100] | Chile (240 W/m²) | 0.98–1.03 m depth | 40–50 | 0.0012 m³/d/m² | NA | NA |
| DCMD-SGSP [101] | RMIT Bundoora, Australia (310–700 W/m²) | 50 (2.05 m depth) | 45 | 0.0012 m³/d/m² | NA | NA |
| Chimney-SGSP [102] | Northern Victoria, Australia | 60,000 (3 m depth) | 50–75 | 90000 kWh/year | NA | NA |
| FO-solar pond [103] | Chabahar, Iran | 10,000 (1.5 m depth) | –80 | 5210 m²/2 years | NA | NA |

ASBS: active single basin solar still; SSP: shallow solar pond; DCMD: direct contact membrane distillation; SSS: stepped solar still; SBS: single basin solar still

### 5 Discussion

Seawater desalination plays a critical role in increasing the total amount of freshwater, guaranteeing a water supply for coastal and island residents, and providing a stable supply of industrial water. In the near future, conventional energy will continue to be the main power source for seawater desalination, but solar energy can be used as a supplementary source.

#### 5.1 Solar system considerations

Given that 70% of the global population lives within 120 km of the ocean, desalination technology is a reasonable approach to addressing water shortages. Desalination improves the water quality, greatly mitigates water shortage problems, and improves the quality of life and economic status. At present, humans mainly use fossil energy. The heavy consumption of fossil fuels has caused serious ecological and environmental problems such as global warming. Moreover, the uncontrolled use of fossil fuels will exhaust the limited reserves. Therefore, demand needs to be controlled, and alternative energy sources need to be developed.

Table 7 compares the costs of solar-driven desalination systems. There is still much room for improving the combination of solar energy and desalination technologies; the desalination cost accounts for 10%–20% of the total cost, while the solar system cost makes up 15%–70%. In short, the technical feasibility is normally not an obstacle compared to economic and dependability considerations.

#### 5.2 Comparison of solar-powered processes

In a solar-powered desalination system, solar radiation is either collected by a thermal collector (e.g., MSF, MED, HDH, SC, and SD) or converted to electricity (e.g., RO, ED, and MVC). Table 8 compares some of the major solar-powered desalination processes. Solar thermal-driven
desalination is very well-developed, while increasing focus is being given to PV cells. PV panels can easily be integrated with RO plants, which are a mature technology. Much research has recently been dedicated to the development of long-life membranes in relation to graphene and 2D membranes. The desalination cost is influenced by many factors, including the solar energy collector system, solar radiation, and desalination system energy transition efficiency. Research on low-cost solar desalination has generally been concentrated on SD and RO, which are suitable for small-scale water production and remote areas. For these solar desalination systems, solar/fossil/desalination hybrid systems can mitigate the intermittence of solar energy.

### Table 7 Solar-driven desalination system cost

| Main characteristics | Location/irradiation | Desalination cost (%) | Solar system cost (%) | Others Cost (%) | Capacity |
|----------------------|----------------------|-----------------------|-----------------------|----------------|----------|
| HDH/OWCA [105]       | 0–5000 W/m²          | 10.4                  | 20.8                  | 68.8           | 22 L/d   |
| HDH/ OACW [106]      | 300–550 W/m²         | <20                   | 67.7                  | >12.3          | 0.6–1.2 m³/d |
| ORC-MED [57]         | Suez Gulf region, Egypt (503 W/m²) | 10   | 15   | 75  | P<sub>mean</sub> = 100 m³/d |
| Wind-PV-diesel-battery-RO [78] | Bozcaada Island, Turkey (1000 W/m²) | 16.7 | 50 | 33.3 | P<sub>mean</sub> = 24 m³/d P<sub>out</sub> = 2.20 $/m³ |
| Collector + MED with flash evaporation(for large system, 6 m³/d)[107] | NA | 30 | 60 | 10 | P<sub>mean</sub> = 6 m³/d |
| Collector + MED with flash evaporation(for large system, 0.3 m³/d)[107] | NA | 26.7 | 66.7 | 6.6 | P<sub>mean</sub> = 0.3 m³/d |
| Solar pond + MSF with PTC [93] | United Arab Emirates | 43.1 | 50.2 | 6.7 | P<sub>mean</sub> = 1880 m³/d |
| PV + RO with two-stage ORC [108] | NA | 61 | 39 | NA | NA |

### Table 8 Comparison of different solar-powered desalination processes

| Direct desalination process | Indirect desalination process |
|------------------------------|-------------------------------|
| Solar chimney | Solar distillation | Solar HDH | Solar-MED | Solar MSF | Solar RO |
| Operating temperature (°C) | 27.2 | >30 | 70–90 | 35–100 | 35–120 | 20–40 |
| Pretreatment requirement | Low | Low | Low | Low | Low | High |
| Construction area | Large | Large | Medium | Medium | Large | Low |
| Energy recovery | Wind turbine generation | — | Latent to latent | Latent to latent | Sensible to latent | Pressure recovery |
| Plant components | Solar collector, chimney, turbine generators, condenser, desalination pond | Solar collector, condenser, solar still, pump, insulation | Solar collector, humidifier, condenser, air blower, water pump | Solar collector, evaporator, condenser, heat engine | Solar collector, flash box, heat engine | Solar collector, membrane, pump, energy recovery system |
| Strengths and weaknesses | Byproducts like salt are obtained, strong adaptability, low water production cost; high capital cost | Simple structure, minimal maintenance and operating cost, produced water is of high quality; Low efficiency and production | System is flexible, low installation cost; high capital and water production costs | Proven technology, system can operated below 70 °C, distillate is of high quality; high capital cost and corrosion problems | For large-scale plant; system can tolerate feed water of any quality; corrosion due to high temperatures; high capital cost, high energy consumption | Simple structure, flexible operation, low water production cost; cannot treat high-salinity water; Membrane has high cost |
6 Outlook and conclusion

Historical data have shown that, although water scarcity is more serious in northern China, it has also emerged as a problem in some regions of southern China. High water consumption in the northern area is mainly concentrated in Tianjin, Hebei, Shandong, and other places with heavy industrial activity. In the south, most seawater desalination plants are on islands for civilian use and are mainly distributed in Zhejiang, Fujian, and Hainan. From a technical perspective, the thermal method provides stable and reliable operation and high water quality, but it has a high energy consumption. The membrane method has the advantages of low energy consumption, low capital costs, and greater operating flexibility, but the maintenance is high.

With regard to solar energy resources, China has an annual insolation of $1.39 \times 10^{16}$ kWh. Provinces like the Qinghai–Tibet Plateau, northern Gansu, northern Ningxia, and southern Xinjiang receive the highest annual solar radiation in the world. Some portions of Liaoning, Tianjin, Shandong, Hebei, southwestern Shanxi, Jilin, southern Guangdong, southern Fujian, northern Jiangsu, and northern Anhui also receive fairly good amounts of annual radiation. Since Liaoning, Tianjin, Shandong, and Hebei receive the most radiation, they can harness the solar insolation with appropriate technology in the desalination sector to solve the water scarcity crisis faced by the country.

The 13th Five-Year Plan for the utilization of seawater proposes that, by 2020, the total scale of seawater desalination in China will reach more than 2.2 million tons/d. By the end of 2017, the seawater desalination scale was approximately 1.2 million tons/d, which is still 1 million tons/d short of the planning target. The Chinese government is moving towards the desalination application market and publishing relevant policy rules to accelerate desalination.

SWRO and LT-MED have generally been adopted in completed seawater desalination plants based on the characteristics of China’s energy structure. MED is dominant in hydropower projects. Combined technologies (e.g., MED+TVC or MED+RO), is also a development trend to complement technologies. Liaoning and Tianjin have built desalination plants with scales of 87,664 and 317,245 tons/d, respectively. In addition, Liaoning and Tianjin have sufficient solar energy resources of 1400–1700 and 1300–1500 (kWh/m²)/d, respectively. Solar-powered desalination engineering is highly feasible in Liaoning and Tianjin because of China’s solar radiation distribution and desalination plant locations.

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