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Looking Beyond Energy Efficiency: An Applied Review of Water Desalination Technologies and an Introduction to Capillary-Driven Desalination

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Abstract: Most notable emerging water desalination technologies and related publications, as examined by the authors, investigate opportunities to increase energy efficiency of the process. In this paper, the authors reason that improving energy efficiency is only one route to produce more cost-effective potable water with fewer emissions. In fact, the grade of energy that is used to desalinate water plays an equally important role in its economic viability and overall emission reduction. This paper provides a critical review of desalination strategies with emphasis on means of using low-grade energy rather than solely focusing on reaching the thermodynamic energy limit. Herein, it is argued that large-scale commercial desalination technologies have by-and-large reached their engineering potential. They are now mostly limited by the fundamental process design rather than process optimization, which has very limited room for improvement without foundational change to the process itself. The conventional approach toward more energy efficient water desalination is to shift from thermal technologies to reverse osmosis (RO). However, RO suffers from three fundamental issues: (1) it is very sensitive to high-salinity water, (2) it is not suitable for zero liquid discharge and is therefore environmentally challenging, and (3) it is not compatible with low-grade energy. From extensive research and review of existing commercial and lab-scale technologies, the authors propose that a fundamental shift is needed to make water desalination more affordable and economical. Future directions may include novel ideas such as taking advantage of energy localization, surficial/interfacial evaporation, and capillary action. Here, some emerging technologies are discussed along with the viability of incorporating low-grade energy and its economic consequences. Finally, a new process is discussed and characterized for water desalination driven by capillary action. The latter has great significance for using low-grade energy and its substantial potential to generate salinity/blue energy.

Keywords: capillary-driven desalination; energy grade; viable desalination; emerging technologies

1. Introduction

Energy and freshwater production are heavily interconnected, termed the "water-energy nexus" [1–7]. Majority of the water on earth is in the oceans with high salinity and otherwise captured in the icecaps and glaciers [8], while most of human's energy usage (~90%) originates from fossil fuels [9]. Water desalination is the manifestation of the water-energy nexus with all the strategic considerations regarding to the availability of the two (Figure 1) [4,10].

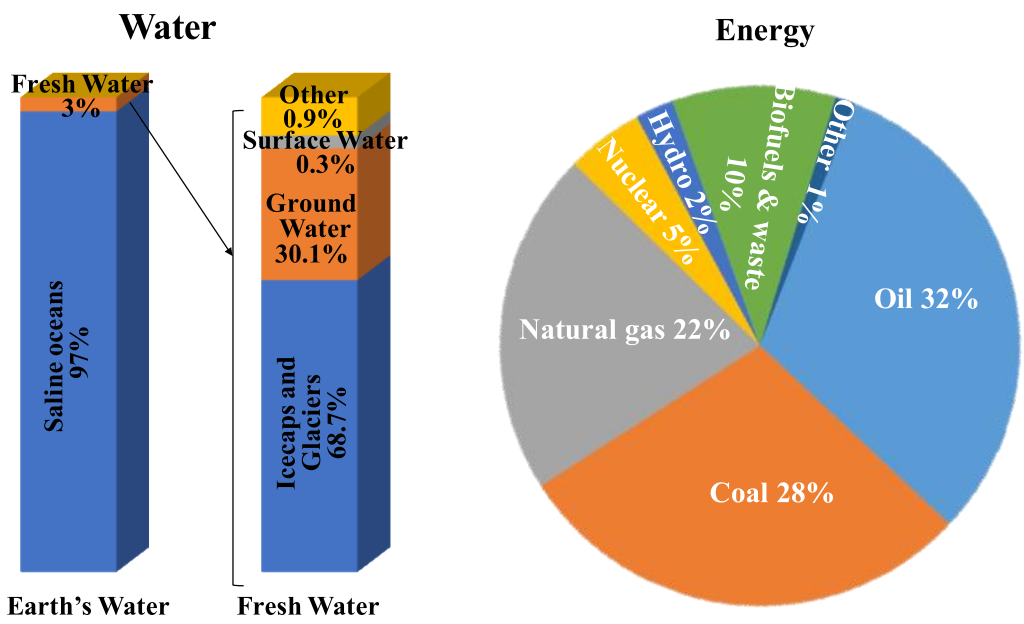

Figure 1. Current availability of water and energy resources [2,4,9].

There are two groups of desalination currently in use: physical processes, such as reverse osmosis (RO), and chemical processes, such as the newer zerovalent iron (ZVI) technology, discovered in 2010 and just starting to be commercialized [11–17]. Throughout this study, desalination has been mainly reviewed as a purely physical process: the physical separation of salt and water [18–28]. In this sense, water desalination is fundamentally a thermodynamic process with a minimum required work that is intrinsic thereto. This is known as the minimum thermodynamic energy of separation (MTES); the lowest possible energy that is required to separate the solute from water [29]. Attempts to minimize energy consumption toward MTES are only beneficial if they are also economically viable [30].

Most researches are mainly focused on the energy and yield efficiency of desalination techniques, with inadequate emphasis on industrial needs [31–33]. In the industry, all desalination systems are designed to optimize the delivered full cycle cost to the consumer as opposed to energy consumption [34]. Despite intensive research in this area, the energy consumption of water, desalination technologies have not substantially changed within the past decade [35]. The energy efficiency of most current desalination technologies is controlled by the thermodynamics rather than the rate of the operation [36,37]. For instance, carbon nanotube membranes, with high permeability, increase the flux rate rather than the energy efficiency [38,39]. Also, energy efficiency often serves in favor of reducing the final cost, but in some cases this synergy is violated [35]. In the latter scenario, energy makes a major contribution to the operational expenditure (OpEx) but not necessarily to the capital expenditure (CapEx) [35]. For instance, some RO strategies offer more energy efficiency at the cost of adding extra high-pressure pumps, which leads to a higher levelized cost of water (LCOW) [35].

RO is considered to be the gold standard desalination technique [40–49]. However, recent attempts have not been successful to reduce the gap between the current RO technologies and *MTES* significantly [35]. Moreover, only high-grade energy is applicable in RO desalination and additional energy requirements for pre/post-treatments are disregarded in most energy analyses [31–33,50,51]. On the other hand, thermal desalination techniques are more agnostic to the salinity level of the intake water, and high-grade energy can be replaced by low-grade energy for the most part [52–55]. However, low-grade energy (i.e., low- to medium-temperature heat, up to 400 °C) is harder to control, dissipates faster, and has lower exergy; entropy generation is more significant in thermal desalination plants [56–58]. One way to compensate for this energy inefficiency in thermal desalination is maximizing the latent heat recovery within the design or coupling the thermal plant with other thermal or power cycles, where heat is generated as a byproduct (e.g., power stations and supercomputer units) [59–62].

In either case, the rejected thermal energy from thermal generators, or so-called waste/process heat, is used to preheat the intake water or bring it to the saturation point [60–62]. The average byproduct waste heat (33–56 °C) is far below the saturation point of water in common thermal desalination plants (70–100 °C) [63]. This mismatch becomes less significant by lowering the saturation point of water through novel designs and/or localized evaporation [6,20,64–66].

Unlike boiling, evaporation pertains to liquid surface, hence, energy can be concentrated on the surface molecules to make evaporation more efficient [64]. However, bulk and surface molecules are interconnected, and dissipation delocalizes the surficial molecular energy [64]. Inspired by trees, capillary-driven water ascension (CDWA) [67] has been used in efficient energy generation, energy harvesting, and capillary-driven desalination (CDD) [63,68,69]. In this technique, solar energy is directly concentrated on the surficial molecules to optimize evaporation [64].

A wise choice of making an advantageous desalination plant also depends on the total dissolved solids (TDS) of the input and output water (Figure 2) [70–75]. Desalination technologies yield freshwater with much lower and brine with much higher salinity compared to the input [76,77]. However, with the increase of environmental concerns, the zero liquid discharge (ZLD) approach has drawn substantial interest among academics, industrial communities, and governments [78,79].

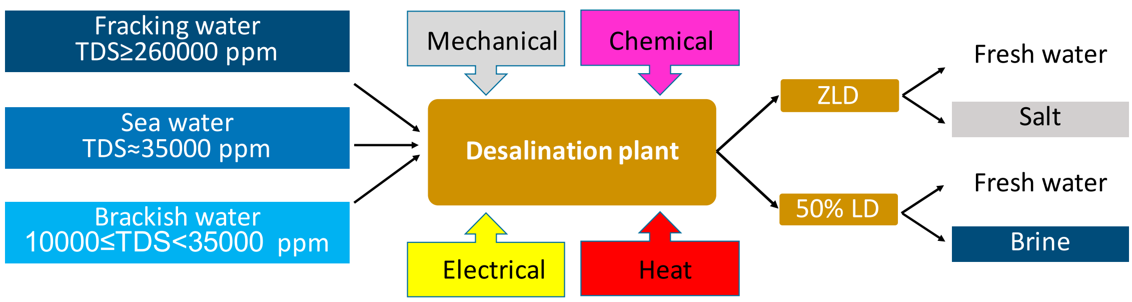

Figure 2. Inputs and outputs of a typical desalination process. TDS, total dissolved salts; LD, liquid discharge; ZLD, zero liquid discharge.

This review attempts to emphasize more on the fundamental strategies, which can fundamentally and yet practically improve desalination processes (Table 1). Few emerging technologies and strategies are discussed, which mainly increase the compatibility with low-grade energy via some fundamental strategies. The economic impact of those strategies is highlighted in two case studies. Finally, the newer CDD is introduced as a highly promising alternative to fundamentally improve desalination process, as it not only enhances the potential of using low-grade energy, but also can be employed to generate salinity energy.

Table 1. Fundamental strategies and their resulting impact in water desalination.

Fundamental Strategies	Fundamental Impact
Surficial energy localization	• Increasing the vaporization efficiency • Downgrading the input energy
Using degradable draw solution	• Transformation of reverse to forward osmosis • Downgrading the input energy
Depressurized heating	• Downgrading the input energy • Increase scaling
Pressurized heating	• Upgrading the input energy • Decrease scaling
Lowering saturation temperature	• Downgrading the input energy • Lowering the energy need

Table 1. *Cont.*

Fundamental Strategies	Fundamental Impact
Oversaturation	• Salt crystallization; beneficial only if heating and vaporization chambers are separated
Capillary action	• Separating bulk and surface molecules • Electric potential generation
Surface evaporation	• Minimization of energy loss in the bulk • Downgrading the input energy

2. Thermodynamics of Desalination

Dissolution of most salts in water is enthalpically negative ($\Delta H < 0$) and entropically positive ($\Delta S > 0$) and thus a spontaneous process ($\Delta G < 0$) [80–84].

$$\Delta G = \Delta H - T\Delta S \tag{1}$$

Desalination acts exactly in the opposite direction and the formerly released energy is the required *MTES* to drive the process [29]. In a reversible process, the output work is maximum and the input energy is minimum, and the input becomes the output, when the process is reversed [85–91]. Thus, the *MTES* is equivalent to the maximum energy produced by a mixing process before reaching equilibrium [85,88]. Following Raoult's Law for desalination of an ideal solution [92–96], the *MTES* (kJ/kg product) can be obtained for an aqueous solution with a steady flow from,

$$MTES = \frac{RT}{M_p}\left[\frac{x_s x_{w,p} - x_w x_{s,p}}{x_w x_{s,b} - x_s x_{w,b}}\left(x_{s,b} ln\frac{x_{s,b}}{x_s} + x_{w,b} ln\frac{x_{w,b}}{x_w}\right) + x_{s,p} ln\frac{x_{s,p}}{x_s} + x_{w,p} ln\frac{x_{w,p}}{x_w}\right] \tag{2}$$

In Equation (2), R is the ideal gas constant, T is the temperature of the feed water intake, M_p is the molar mass of the product water, and x_s, x_w, $x_{s,p}$, $x_{w,p}$, $x_{s,b}$, $x_{w,b}$ are the mole fractions of the salt and water in the feed water, product water, and brine, respectively [97]. This minimum energy depends only on the concentration of solutes regardless of any specific technology, mechanism, or number of stages [98,99]. Simple thermodynamic calculations reveal that the *MTES* is ideally 0.79 kWh/m^3 for full and 1.09 kWh/m^3 for 50% recovery of freshwater from typical seawater [100–105]. Using the second law efficiency, this value jumps to 1.9 kWh/m^3 [51]. In reality, the most efficient state-of-the-art technologies run between 2.5 to 5 kWh/m^3 [106]. The main goal of desalination is to minimize the discrepancy between the current technologies and the second law efficiency (1.9 kWh/m^3) [107–109]. This discrepancy is attributed to entropy generation in real systems that is governed by the irreversibility of the process [58,110–114]. In contrast to energy, exergy is always destroyed within an irreversible process, generating entropy [115–118]. The aforementioned *MTES* values are associated with a full desalination of seawater with 35,000 ppm concentration of solutes [2,29,119–124].

Heat and work are considered low-grade (disordered) and high-grade (ordered) forms of energy, respectively [125–128]. The quality difference can be assigned to the two forms of energy, in which transforming one form to the other is more efficient than its opposite direction [129–134]. For instance, work can be efficiently converted to heat, e.g., electric heater with near-100% efficiency, whereas maybe only half of the input heat (50%) turns to work, e.g., heat engine [135–137].

$$W = Q\left(1 - \frac{T_c}{T_h}\right) \tag{3}$$

Based on Equation (3), heat (Q) can be transformed to work (W) more efficiently, when the temperature difference between the hot (T_h) and cold (T_c) sources is higher. Also, production and storage of thermal energy is easier and cheaper, on the other hand electricity is often more environment friendly, i.e., less CO_2 production [138–142]. Entropy generation (S_g) in a thermal-based process can be evaluated from Equation (4) [58,110].

$$S_g = Q\left(\frac{1}{T_c} - \frac{1}{T_h}\right) \quad (4)$$

Entropy generation decreases as the process approaches the isothermal condition, i.e., $T_c \rightarrow T_h$.

$$S_g = \frac{A}{\rho T}(\Delta p - \Delta \pi)^2 \quad (5)$$

In a membrane-based process however, entropy generation, per unit area, per kg fresh water, (Equation (5)) decreases as the process approaches the isobaric condition, i.e., hydraulic (p) and osmotic (π) pressures have similar magnitude at the end and beginning of the device, $\Delta p \rightarrow \Delta \pi$ [110,121,143–147].

3. Conventional Desalination Technologies

To treat large volumes of highly saline water, in locations where energy costs low or when a waste heat source is available, thermal desalination is still the most practical technique [148–151]. Thermal desalination commonly involve processes with large thermodynamic irreversibility [31,152,153]. High energy consumption and CO_2 production are two major downsides of this approach [34,142]. In a thermal desalination process, water is vaporized and subsequently condensed in a separate vessel after being circulated to release the extra thermal energy including the latent heat. Evaporation consumed considerable energy but is in principle a reversible process, therefore, entropically favorable. Freeze desalination crystallizes water to form ice and separates salts from the ice; it is often both energetically and entropically unfavorable and thus less cost-effective with large irreversibilities [70,154–157]. However, in low temperature regions, freezing desalination eliminates the need for collecting and storing heat, where lack thereof is desirable [157–160]. High-temperature desalination suffers from two major risks: corrosion and scaling [161–164]. Over the decades, numerous thermal desalination techniques have been developed to address these risks, as well as to increase the efficiency of the process [103,165–170]. Those include multi-stage flash (MSF) distillation, multi-effect distillation (MED), vapor compression (VC), and humidification–dehumidification (HDH) [171–184]. The main difference between MED and MSF is the heat transfer and evaporation method; in the MED, seawater comes in direct contact with the heat exchanger, whereas in the MSF, energy transfer occurs via heat convection in seawater [167,185–190]. In both MED and MSF, the heat transfer between water and vapor occurs in multiple steps in an attempt to recover the latent heat (Figure 3a,b) [191–193]. This is done by compressing water vapor in a vapor compression (VC) device and passing hot air through liquid water and ultimate separation of the two in HDH [111,177,184,194–199]. In an efficient VC design, increasing the pressure of the vapor increases the condensation temperature, therefore, the vapor serves as the heating source for feed water; no need for an extra heat exchanger [177,199]. This heat exchange occurs directly between air and vapor in HDH desalination [194,198].

In membrane-based desalination, water is separated from its solute by membrane, a selective barrier which allows the separation of solvent and solute using a combination of diffusion and sieving [200–208]. Diffusion of chemicals from a lower to a higher concentration (chemical potential) causes osmotic pressure [209]. This diffusion can be reversed if a pressure higher than osmotic pressure is exerted to overcome the chemical potential flow [38,50,210–212]. In this sense, membrane designs which encourage sieving over diffusion are less energy intensive [202,203]. In other words, selectivity of new membrane designs should be of higher importance compared to their permeability.

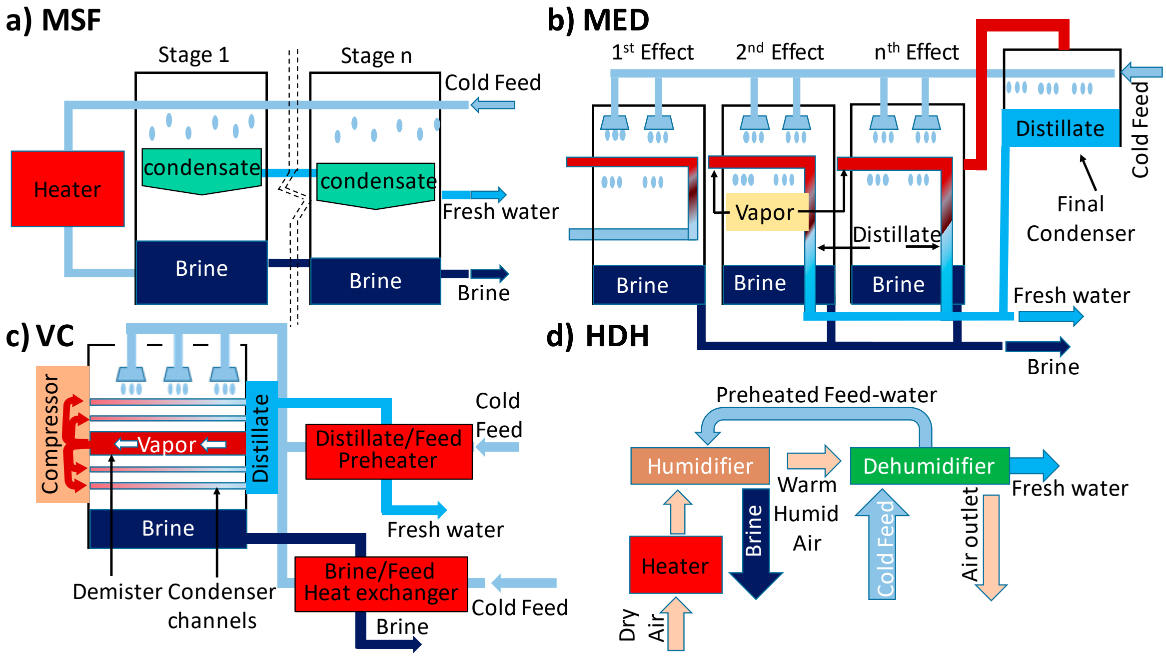

Figure 3. Typical scheme of thermal-based desalination modules; (**a**) multi-stage flash (MSF) distillation, (**b**) multi-effect distillation (MED), (**c**) vapor compression (VC), and (**d**) humidification–dehumidification (HDH).

RO is a single-phase desalination technique (Figure 4a), which almost entirely requires high-grade energy [213–215]. RO is hard to go off-grid; significant (often economically unreasonable) number of solar panels is required, which makes it economically unviable [216–218]. Moreover, RO is better designed for continuous operation, while renewable energies fluctuate over time [219,220]. The lower recovery limit of RO is governed by the osmotic pressure and the upper limit by the chemical composition (scaling) and energy consumption [213,215,221]. Most researches have been conducted in designing new membranes with desired permeability [219,220,222]. However, a breakthrough to resolve the aforementioned issues cannot only be achieved within membrane developments [35]. Commonly, about one third of the cost of a RO process is energy consumption, 40% CapEx, 25% OpEx such as labor, maintenance, consumables, membrane replacement, and so on. Major engineering and construction cost include: 22% high-pressure pump and high alloy steel, 21% material, 18% civil engineering, 17% other services, 8% pretreatment, 7% intake and outfall, and 7% membrane and pressure vessels [152,223–227]. Accordingly, reducing the number of high-pressure pumps and the amount of high alloy steel cut the final cost more significantly compared to further membrane improvements. In RO, 40% of the flow energy stays in the brine, which can be recovered by pressure exchangers with very high efficiency [228]. Most of the energy loss occurs as the water passes through the membrane, i.e., large pressure drop [215,229]. Another issue regarding the energy loss or entropy generation is that the applied pressure has to increase within the device to overcome the osmotic pressure [230–232]. When the upper limit is set to ensure the water flow, pressure thus the entropy generation will be higher in most of the device than what it ought to be (hydraulic pressure >> osmotic pressure) [121,145,233,234]. As already mentioned, adding more pumps with different pressures throughout the device is one solution for this issue, though usually economically unfavorable [35]. Electrodialysis (ED) is another commercialized membrane-based desalination technique (Figure 4b) [235–241]. Electrodialysis moves salts through charged membranes and traps them in alternating channels, using electric potential [242–245]. This technology is less energy intensive and more compatible with renewables, while less applicable for large scale and high salinity desalination [50,76,246,247].

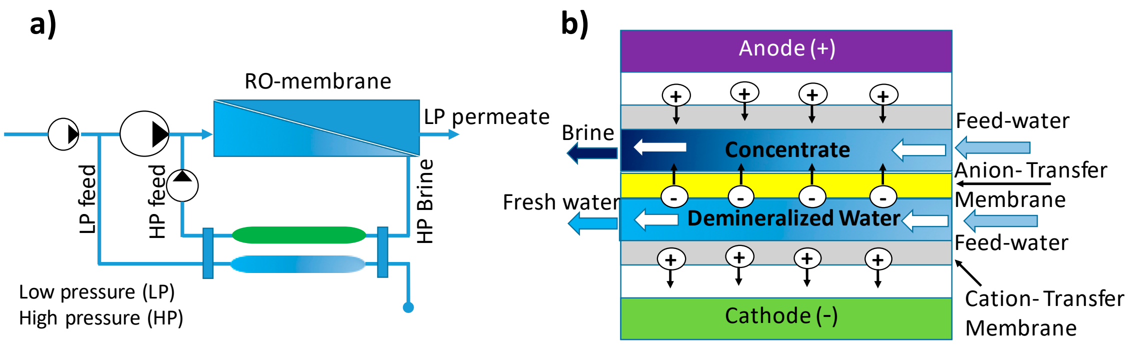

Figure 4. Typical scheme of membrane-based desalination modules; (**a**) reverse osmosis (RO), (**b**) electrodialysis (ED).

In the past decade, the dominance of RO over other desalination techniques has been due to its high scalability and relatively low energy requirement, neglecting the extra energy required for any additional treatment and the quality of this energy (Figure 5) [248–250]. In the following section, the merits of this dominance are investigated.

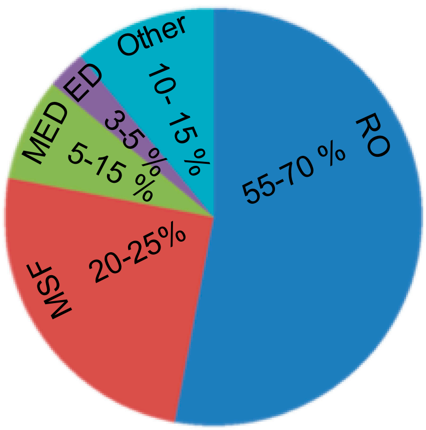

Figure 5. Contribution of different techniques in the current water desalination market.

4. Emerging Technologies

There are many concerns related to desalination technologies, namely, energy consumption and quality, environmental and technological compatibility, and more importantly economic considerations [251–258]. To address energy concerns, significant interest surrounds using waste heat, which in turn suffers from three major risks: (1) it requires capital investments for recuperators, (2) design modifications to account for heat load or temperature differences, and (3) low exergetic efficiency [31,32,35,259–263]. The first two can be managed by applying strategies in which hot and cold sources come into direct contact [66,264–268]. The third issue is more fundamental and can only be addressed if the desalination technique itself or some outside operational conditions provide a way to increase the potential of using waste heat [58,184,269]. Another step towards energy efficiency is to modify the plant to use ubiquitous renewable energies [65,237,238]. In addition to the above challenges, renewables are very dilute and intermittent [217,262]. To resolve the latter two, renewables should be harvested and stored in a most compatible and economical way [57,197,249,261]. In this sense, generating and storing low-grade energy from renewables is more compatible with thermal-based desalination [52,54,77,269]. Batch and semi-batch plant designs are other strategies to cope with intermittency of the renewables, both more compatible with thermal desalination [29].

Brine disposal and greenhouse gas production are two main environmental concerns [142,265]. Research on zero liquid discharge (ZLD) aims at eliminating brine disposal and can be better utilized in thermal desalination (Figure 6) [78,255]. In term of greenhouse gas production, membrane-based desalination is a cleaner technology in general, however, a well-designed combination of thermal desalination and a waste heat generating industry can be even cleaner [63,269]. Increasing compatibility with renewables is another step toward cleaner desalination [55,77,124,270–273]. The followings are a few innovative thermal-based and hybrid strategies, in most of which the ultimate goal is reconciliation between desalination and low-grade energy.

Figure 6 represents a distillation strategy that addresses the problems associated with traditional distillation: (1) scaling, (2) heat loss. Scaling reduces thermal conductivity and thus increases the amount of energy required to heat seawater up to saturation point [55,274,275]. It also results in serious maintenance issues that are costly and time consuming [276–279]. One strategy to address the issue of salt scaling is to utilize a pressurized chamber to prevent boiling and slow the formation of solid deposits scaling. Under pressure, seawater can be heated to very high temperatures. Maintaining pressure at 7×10^5 psi allows seawater to be heated to 300 °C without boiling and thus reducing scaling. This is done by separating the heating of the water from vaporization of the water. Once heated to 300 °C, the seawater is released through a nozzle into a flash chamber, where a portion of water turns into steam. The sudden decrease of pressure causes the hot seawater to separate into steam brine and salt. The brine and salt crystals fall to bottom of the chamber, where the salt crystals are separated from the brine and removed. This manages the scaling problem but does not solve the issue of the loss of thermal energy. To address the issue of thermal efficiency, a vapor compressor can be used to compress and heat the steam, so it condenses at higher temperature. The compressed hot steam enters a heat exchanger and provides majority of the thermal energy required to heat the seawater in the heating chamber. After exchanging heat with the seawater, the vapor condenses to warm distilled water. The second heat exchanger is added to heat the seawater and cool the distilled water [280]. Such strategies are best for places such as California, where environmental regulations and concerns about marine ecosystems withstand large-scale desalination as a solution to its water crisis [281].

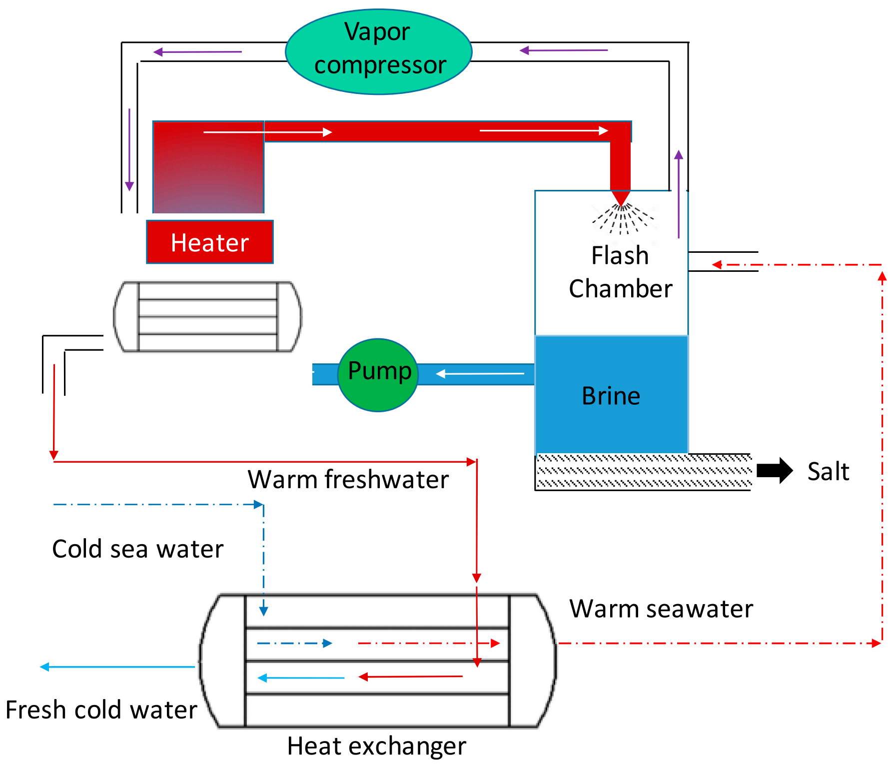

Figure 6. A thermal-based desalination strategy designed by EFD corporation.

Using chemicals in water purification is of a great importance, especially for feed water that contains microorganisms and organic pollutants [282–288]. Variety of chemicals are used for different purposes, such as antimicrobial, degradative, coagulative, (photo-)catalysis, azeotrope breaking, and hydrophobic/hydrophilic agents [65,160,289–303]. Figure 7 however, represents a method to use chemicals in water desalination as a draw solution. Any high contaminated water sample can be used as a draw solution for a less contaminated sample (e.g., seawater for brackish water) in a forward osmosis (FO) process. FO can be used as a pretreatment to decrease the salinity of water without direct energy input. In the hybrid design shown in Figure 7a, ammonia and carbon dioxide gases are dissolved in water to create the draw solution. The advantage of using such a draw solution is that both gases can be recovered with the aid of low-grade heat at the final step (Figure 7b, phase 2) to obtain freshwater [35,304,305].

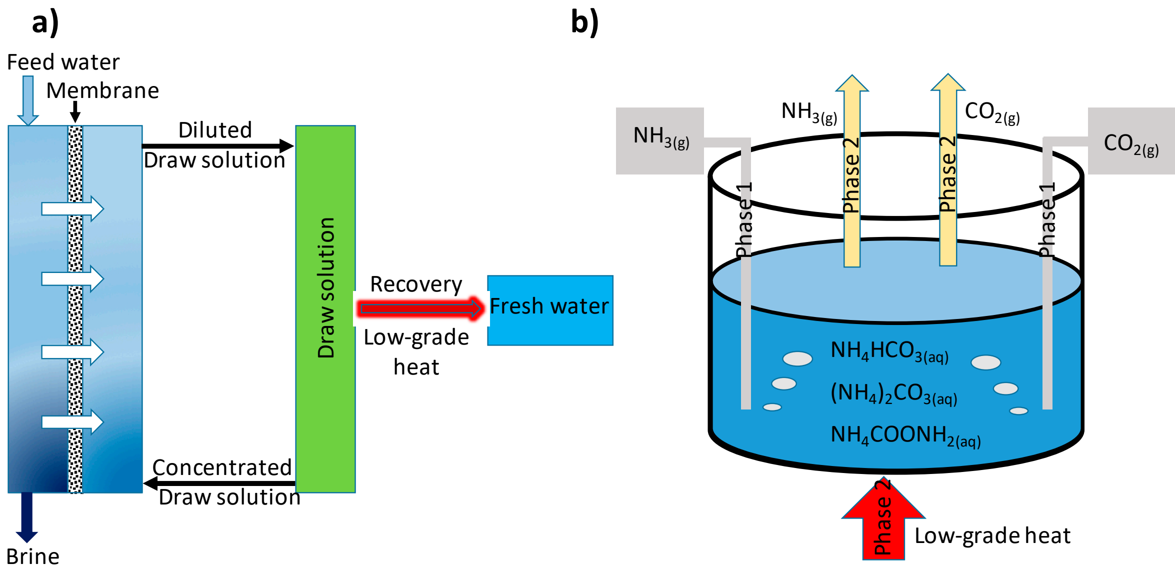

Figure 7. Hybridization of thermal- and membrane-based desalination; (**a**) whole plant, (**b**) draw solution.

Diffusion-driven desalination (DDD) process is a unique technology, which provides the means for low-temperature, low-pressure desalination and operates off of waste heat (Klausner et al. 2004, 2006, Khan et al. 2010; Alnaimat and Klausner 2012; Alnaimat et al. 2013). A schematic diagram of the DDD process and system is shown in Figure 8. The process includes three fluid circulation systems: freshwater, air/vapor, and saline water. Low pressure condensing steam heats the saline intake water in the saline water system. Afterwards, the heated feed water is transferred to the top of the diffusion tower. The feed water partially evaporates and diffuses into air. In the diffusion tower, the evaporation depends on the bulk air and concentration gradient at the vapor/ liquid interface. Consequently, the water is collected in a packed bed in the diffusion tower and a thin film of saline water forms over the packing material. The upward flowing air comes into contact with the water film through the diffusion tower and partially evaporates it, and the unevaporated water will be discharged. Low humidity cold air enters the bottom of the diffusion tower in the air/vapor system, being humidified and heated by the saline water as it moves upward through the tower. After leaving the diffusion tower, saturated air/vapor mixture comes into a direct contact with condenser, where it is dehumidified and cooled by cold water. The discharged water from the condenser will be cooled in a heat exchanger by the entering saline water that in the freshwater system.

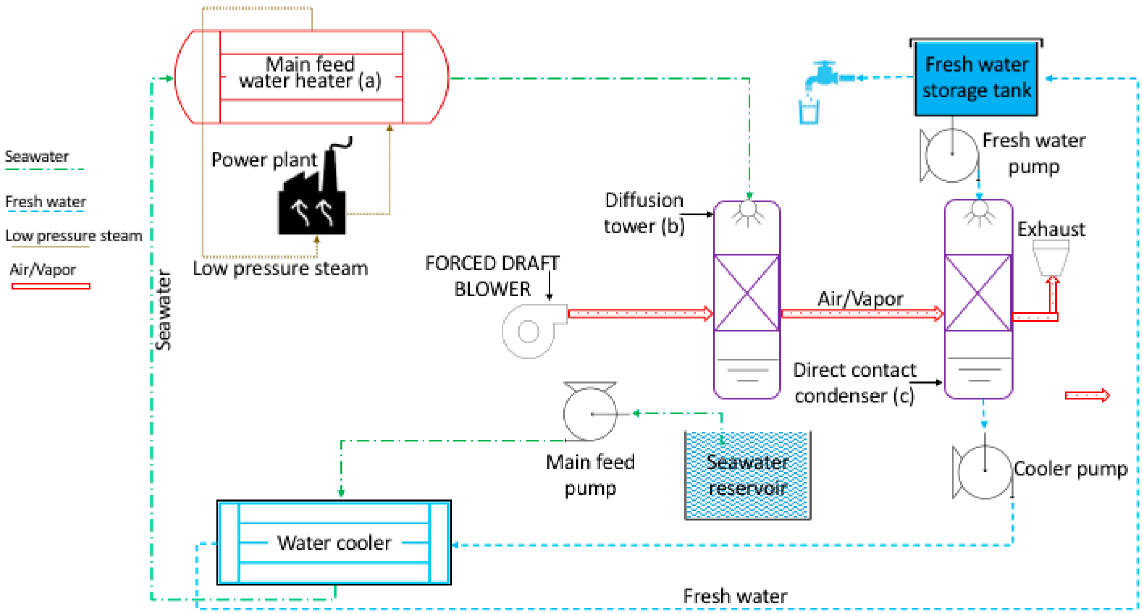

Figure 8. A schematic design of a diffusion-driven desalination (DDD) unit [306].

5. Economic Analysis on Two Case Studies

In this section, economic analyses are represented for two case studies based on: (1) in situ data from Marshal Islands, [307–312] (2) thermodynamic analysis for a novel desalination idea, designed by the authors. In economic terms, the contribution of each component (energy, CapEx, and OpEx) should be considered (in some analyses, energy and OpEx are in the same category). A cost breakdown for each component is shown in Figure 9, [152,224,313,314] as well as the energy quality spectrum from the lowest grade (low temperature heat) to the highest (electromagnetic) [315]. In membrane-based technologies, CapEx usually is the main contributor [316–318]. In thermal-based technologies, especially the traditional ones, cost of energy is the dominant component [250,319–322]. Using Equations (6)–(8), Table 2, and considering available waste heat, typical LCOW is calculated for MED and RO technologies. Table 2 shows that without using waste heat MED is ~2.5 times more cost-intensive than RO. However, if MED is coupled with a source of waste heat, this ratio turns to MED's benefit, while energy consumption never drops and only the quality of energy changes.

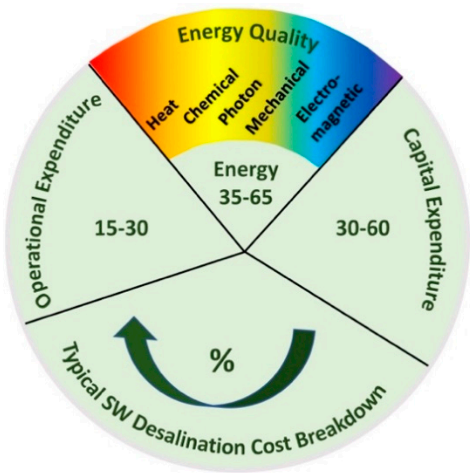

Figure 9. Typical seawater desalination cost breakdown and energy quality.

Table 2. Input variables for the LCOW evaluation of MED and RO techniques.

	MED	RO
Electricity demand (kWh/m^3)	1.50	4.3
Electricity cost (USD/kWh)	0.2–0.5	0.2–0.5
Heat demand (kWh/m^3)	52.6	N/A
Fuel price (USD/lit)	1.0–2.0	N/A
CapEx (USD/m^3/day)	1700	2320
OpEx (except electricity, USD/m^3)	0.3	0.3
Lifetime (years)	25	25
LCOW (USD/m^3)	4.5–8	1.7–3
$LCOW_{WH}$ (USD/m^3)	0.98–1.45	N/A

In Equations (8)–(10), I_0 is the investment in USD, A_t is the annual total costs in USD/annum, M_{el} is electricity output in kWh per year, i is the interest rate, n is the economic lifetime in years, and t is year of operation $(1, 2, \ldots, n)$ [312].

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el}}{(1+i)^t}} \tag{6}$$

$$LCOW = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_w}{(1+i)^t}} \tag{7}$$

$$A_t = OpEx + LCOE \tag{8}$$

Figure 10 represents a novel desalination design to treat high salinity water in locations where water carries an initial pressure, such as fracking water [323–325]. This pressure can be used to run the water through different filters against gravity and push it all the way up to the top of distillation tower. Thereafter, by opening the upper faucets and blocking the adjustable sieving filter, the disposal pond is filled up to a certain level and a strong vacuum is made at the top of the tower without using any extra energy. This vacuum serves two purposes: (1) azeotrope breaking, (2) lowering the saturation point of water allowing the use of low-grade energy. At this point, volatile gases (if there is any) can be separated by increasing the temperature just several degrees Celsius. By setting up the maximum temperature at the saturation point of water (40–50 °C), nonvolatile substances will be left behind. Altering the temperature, volatile gases and water vapor can be separated using the lower pumps. At this stage, most salts have been already separated by the filters, and the brine collector trap the leftover salts. These traps can be cleaned when needed, leaving the re-vacuum operation for the upper pump. Whenever water level falls below a certain point the lower faucets will automatically open and fill up the pond again. The second phase is for further purification (if needed) takes advantage of interfacial evaporation on the surface of membrane. There is a cold and warm water stream on the top and bottom of the membrane, respectively, to trigger the interfacial evaporation. This interfacial evaporation is based on the thermal difference of the water streams on two sides of the membrane at each point, rather than the bulk temperature. Making the disposal pond right around the drilling well minimizes the gas leakage and pressure drop that is needed for the water elevation. Eventually the brine, including salts and nonvolatile substances, is collected in the pond and the brine tank.

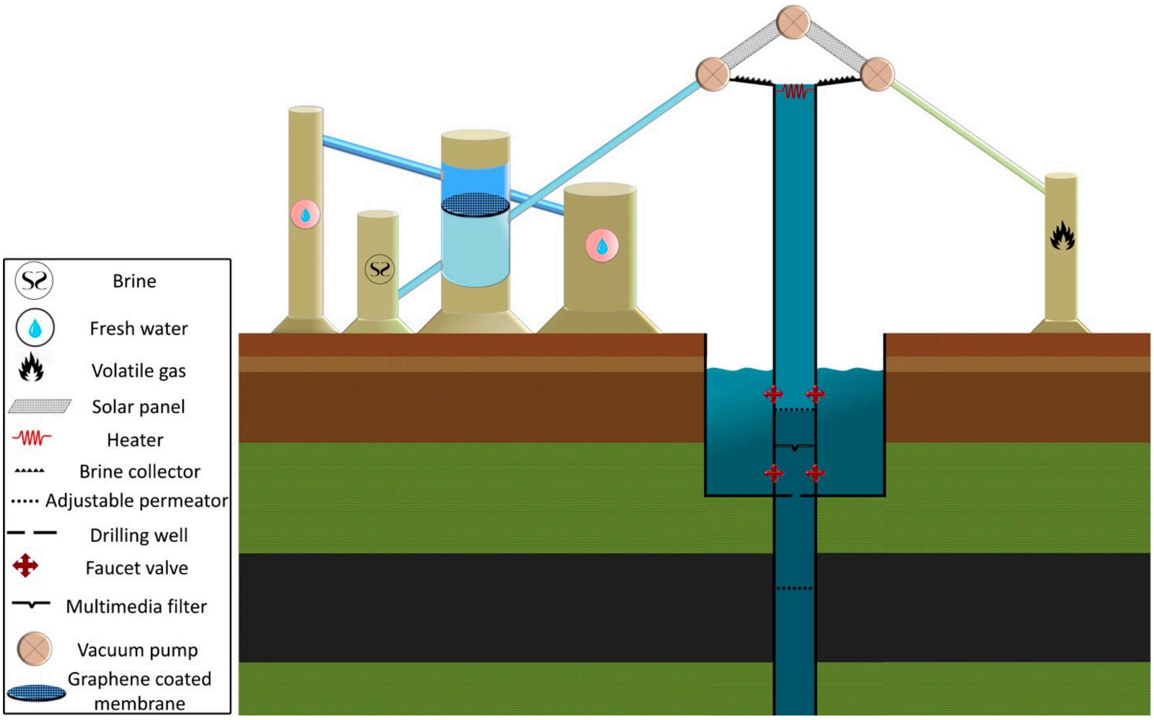

Figure 10. Schematic of the novel off-grid desalination plant, designed for off-grid treating of high salinity water in medium scale.

The calculated values for the LCOW demonstrate the economic flexibility that is achieved by coupling this process with low-grade/waste energy (Table 3). In this estimation, only the first phase (distillation tower) is considered and the benefits of azeotrope breaking is neglected.

Table 3. Operational parameters for the proposed design in comparison with conventional distillation.

Water Back Pressure	Tower Height	Saturation Temperature	Saturation Pressure	LCOE	LCOW
~2 atm	33 ft	40–50 °C	0.12 atm	~60%	50–90%

6. Capillary-Driven Desalination

Capillary effect can be used to avoid most of energy dissipation by separating the bulk and surface molecules [64,68]. This capillary action is generated by using microchannels with low thermal conductivity (insulating) and high hydrophilicity, which optimizes mass transfer and energy dissipation [63,64]. At each step, surficial water molecules are transferred through capillary microchannels to an absorptive and hydrophilic evaporation plate, where a low-grade energy source, such as sunlight or waste heat, provides sufficient energy for the phase change [64,68,326–329]. This idea was initially introduced by Ghasemi et al. to generate solar steam by heat localization (Figure 11) [64].

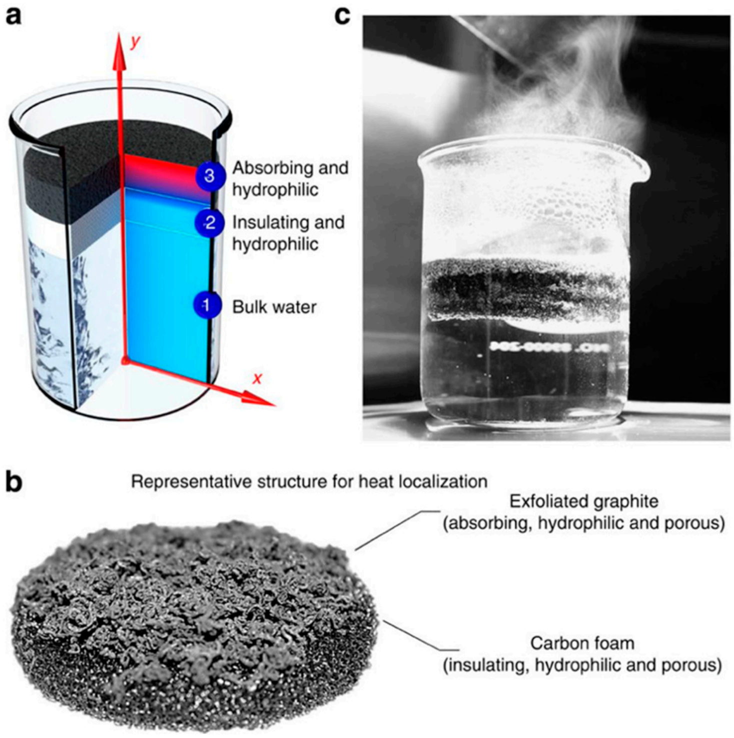

Figure 11. (**a**) A schematic structure and temperature distribution of a capillary-driven water ascension (CDWA) system. (**b**) The double layer structure consisting of capillary channels and evaporation plate, both being hydrophilic to drive the capillary ascending of water to the surface. (**c**) Enhanced steam generation under the solar illumination [64].

Traditionally, bulk water is uniformly heated up to a high temperature for vapor generation [64,68]. However, evaporation is a surface process, in which the high-energy salt water molecules at the surface are easily transported into the vapor phase. The conventional bulk-heating approach, therefore, leads to large amount of heat loss to the unevaporated part of water [64,68]. Bulk heating introduces a large lag and response time because of its large thermal inertia [63,64,69], but surface evaporation has minimal thermal inertia and responds very quickly to the change in the energy input, and allows for tighter process control for water quality and reducing energy consumption [64,68,330]. However, developing materials for long-term solar desalination through heat localization remains an open challenge due to fouling of the structure after a short period of time [64,68,269]. A porous polymer skeleton with embedded graphite flakes and carbon fibers has shown anti-fouling characteristics in the capillary micro-channels [68]. This cost-effective and durable material with easy fabrication procedure provides a path toward large-scale efficient solar desalination. Also, low-grade heat capillary-driven desalination is an efficient and environmentally friendly technology [64,68]. It has been demonstrated that, this strategy can not only be used in desalination and energy harvesting, but also in energy generation from the difference in salinity of water (saline energy) at the two ends of capillary microchannels (Figure 12) [331].

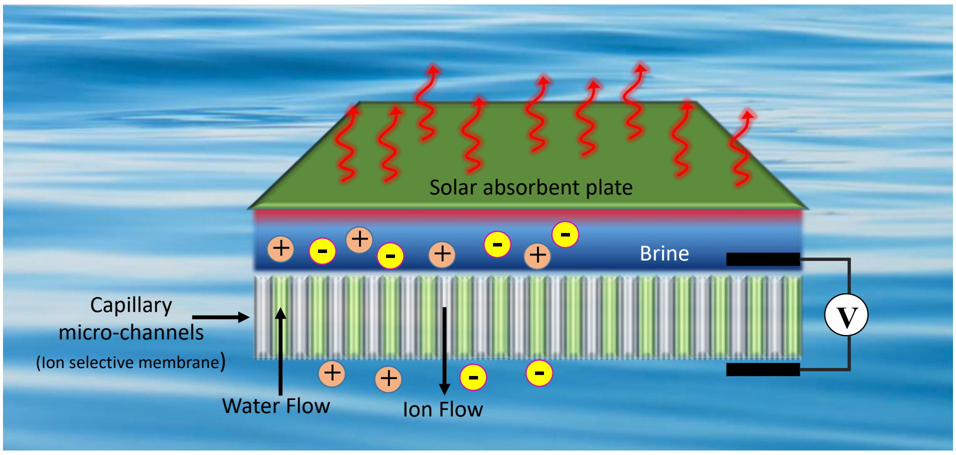

Figure 12. Schematic design of capillary-driven desalination/energy harvesting.

Table 4 summarizes the efficiency of CDD/CDWA systems made of different materials for capillary channel and evaporating plate, some of which being used for saline energy generation [331,332].

Table 4. Efficiency of CDD/CDWA systems.

Ref	Capillary Channel	Evaporator	Irradiation/ Temperature	Efficiency
[64]	Carbon foam	Exfoliated graphite	10 kW·m^{-2}	85%
[69]	Porous NiO disc	TiAlON-based	1 kW·m^{-2}	73%
[333]	Nano porous filter paper	Gold plasmonic nanostructure	2.3 kW·m^{-2}	87%
[269]	NiO wick	Naval brass	34 °C	65%
[68]	Rayon carbon fiber	Exfoliated graphite	1 kW·m^{-2}	63%
[330]	Cellulose fiber	Au/Ag-PFC	1 kW·m^{-2}	86%
[334]	Polytetrafluoroethylene	Graphene-based film	1 kW·m^{-2}	79%
[335]	Cotton rod-polystyrene	Graphene oxide	1 kW·m^{-2}	85%
[78]	Cellulosic filter paper	Graphene oxide (lifted)	0.82 kW·m^{-2}	78%
[336]	Basswood	Graphene oxide	12 kW·m^{-2}	83%
[337]	((Functionalized-)Chemically reduced-)Graphene oxide		1 kW·m^{-2}	38–48%
[338]	Hierarchical graphene foam	Graphene nanoparticles	1 kW·m^{-2}	93%
[339]	Polyacrylonitrile	CB-PMMA	1 kW·m^{-2}	72%
[331]	Nafion membrane	Carbon nanotube	1 kW·m^{-2}	75%
[340]	Pristine draft paper	Pencil-drawn-paper	1 kW·m^{-2}	80%
[67]	Basswood	Carbonized wood	10 kW·m^{-2}	87%
[341]	GO/NFC	CNT/GO	1 kW·m^{-2}	86%
[332]	Carbon cloth	Graphene	1 kW·m^{-2}	83%

7. Conclusions

Taken together, there is no single universal remedy to resolve the problems in the current desalination technologies. Full consideration of physicochemical, geographical, and economical parameters is required to choose one approach over the others. However, recent researches imply that CDD has made a good compromise between water production and energy consumption, and with more industrial intuitions it could alleviate the barriers hindering its wide-scale implementation. In this article we argued that most attempts aimed at lowering energy consumption toward MTES will not lead to commercially more viable desalination as they have not within the past decade. Instead, the main emphasis should be on increasing the ability of the system to use low-grade energy that is cheap and omnipresent. A successful strategy does not necessarily decrease the energy consumption, rather, it enables the system to take advantage of low-grade energy. This can require fundamental transformations to in the foundation of desalination technologies. Our economic analyses, as well as those of others, demonstrate that the main influence of using low-grade energy is not improvements in energy consumption but pronounced in the final cost of freshwater. This also has the major benefit of compatibility with low-grade energy from renewable energy source such as industrial waste heat. These can vastly impact renewable energies penetration, water production, and industrial efficiency, otherwise referred to as the water-energy nexus.

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Abbreviation

A	Surface Area	n	Economic Life Time in years
A_t	Annual Total Cost in USD/Annum	OpEx	Operational Expenditure
CapEx	Capital Expenditure	P	Pressure
CDD	Capillary-Driven Desalination	Q	Heat
CDWA	Capillary-Driven Water Ascension	R	Ideal Gas Constant
C_{el}	Cost of Electricity	RO	Reverse Osmosis
DDD	Diffusion-Driven Desalination	S_g	Entropy Generation
DOE	Department of Energy	SWRO	Seawater Reverse Osmosis
ED	Electrodialysis	t	Year of Operation
FO	Forward Osmosis	T	Temperature
G	Gibbs Free Energy (Exergy)	T_c	Temperature of Cold Source
H	Enthalpy Change	TD	Thermal Desalination
HDH	Humidification Dehumidification	TDS	Total Dissolved salts
i	Interest Rate	T_h	Temperature of Hot Source
I_0	Investment in USD	VC	Vapor Compression
LCOE	Levelized Cost of Electricity	W	Work
LCOW	Levelized Cost of Water	WH	Waste Heat
LD	Liquid Discharge	x_s	Mole Fraction of Salt in Feed Water
MD	Membrane Desalination	$x_{s,b}$	Mole Fraction of Salt in Brine
MED	Multi-Effect Distillation	$x_{s,p}$	Mole Fraction of Salt in Product
M_{el}	Electricity Output in kWh/Year	x_w	Mole Fraction of Water in Feed Water
MSF	Multi-Stage Flash	$x_{w,b}$	Mole Fraction of Water in Brine
M_p	Molar Mass of Product Water	$x_{w,p}$	Mole Fraction of Water in Product
MTES	Minimum Thermodynamic Energy of Separation	ZLD	Zero Liquid Discharge
MVC	Mechanical Vapor Compression	π_i	Osmotic Pressure
M_w	Produced Water/Year		

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