A MULTIDISCIPLINARY INTRODUCTION TO DESALINATION

ALIREZA BAZARGAN (EDITOR)

NOOR VIJEH

River Publishers

CHAPTER 12

State-of-the-Art Desalination Research

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12.1 Introduction

Water scarcity, along with the rapid development of urban areas is boosting the ever-increasing demand for safe and clean water [1, 2]. The urgent adoption of new water recycling technologies and the development of alternative potable water sources are necessary to address the ongoing drought experienced by almost 2.6 billion people around the world [2–4]. The United Nations Department of Economic and Social Affairs estimates that by 2025, two-thirds of the world's population will be living under water stressed conditions [5–7]. Hence, the development of novel desalination[1] technologies, and not incremental changes, is crucial to the realization of energy efficient and reliable desalination plants. This new generation of desalination plants is expected to provide low cost and high quality potable water to deal with the vast demand over the next decades.

This chapter will provide a review for some of the most recent research trends with promising laboratory results. Of course, the chapter is not exhaustive and some technologies have not been discussed.

A categorization of several desalination processes is shown in Figure 12.1.

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[1] Desalination is a process to remove salt from *saline* (the Greek word *alas* to Latin *sal*).

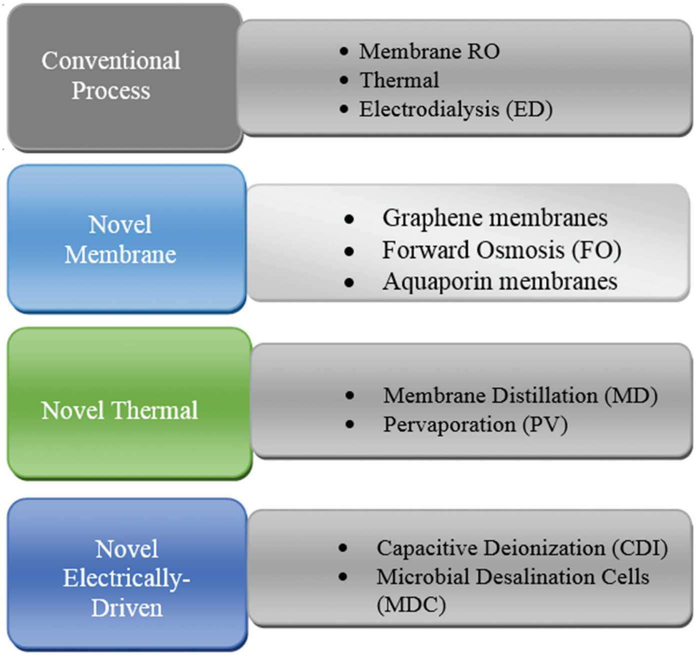

Figure 12.1 Categorization of desalination processes.

There are currently three methods of choice for sea water desalination; thermal distillation, reverse osmosis (RO), and to a much lesser extent electrodialysis (ED). Also, the high capital and energy costs of thermal desalination combined with corrosion problems often experienced in the plants have made them less attractive for large scale application in countries where the energy price is on the rise [4, 6]. However, solar thermal distillation and humid-air distillation technologies are finding an increased market-share for small communities in remote locations with access to solar energy [4, 8, 9].

12.2 RO Technologies

RO, which accounts for more than half of the world's installed capacity, although quite practical from the energy efficiency point of view ($\sim$5 Wh L^{-1} which can theoretically be decreased down to 2.5 Wh L^{-1}), suffers particularly from the high cost of electrical energy, corrosion and fouling problems. Moreover, although RO is being used as a state-of-the-art desalination technology, it still faces several challenges that should be addressed to realize a reduction in the total cost of water production. The first and foremost problem is fouling. To overcome such an issue, either membranes with low propensity to fouling should be developed or pretreatments with oxidants (e.g., chlorination with sodium hypochlorite) for biofouling control should be exercised. However, the current membrane technology implemented in RO systems has a low tolerance of such oxidants [9]. In order to avoid membrane scaling, besides antiscalant chemicals, strong acids (sulfuric or hydrochloric acid) can also be used; but their storage and transport contributes to the complexity of the overall processes leading to hidden risk factors [10]. Another ignored aspect of the process is the direct discharge of RO concentrates into seawater which may cause risk for the marine ecosystem and the environment depending on the coast morphology and size of application [11]. As the coast morphology can differ significantly in combination with a very big range of installation capacities, it is hard to generalize the environmental impact of RO concentrates; and a case by case evaluation is required.

Although many conventional and emerging technologies are being applied increasingly to decrease the environmental problems associated with RO plants, most emerging technologies are yet at their preliminary stage; having high capital costs while still encountering technical obstacles, renders them quite impractical for large-scale applications. As such, the direct discharge into seawater through proper diffusion mechanisms is still regarded as the most viable economic choice for RO technologies.

The cost of water produced by RO units can be categorized into three inter and intra-related components, namely: capital costs, energy costs and other operation costs. These are the driving force behind developing alternative technologies. Consequently, to reduce the total practical cost of RO units, progress in all three components should be made. Although recent works suggest that the theoretical minimum energy for water desalination can be approached, this seems more like wishful thinking rather than a practical approach. To illustrate this case, we should have a look at the principle operation of asymmetric RO membranes. It should be noted that for an effective desalination process, the diameter of the pores in the desalination membrane should be smaller than the hydration diameter of ions to effectually exclude them. Having larger pore diameters, typically results in a thick separation layer to guarantee acceptable salt rejection consequently leading to a reduced flux rate. Therefore, reaching the minimum theoretical energy required for the desalination process is impractical in real-world RO applications as the inherent energy losses from diffusion, viscous dissipations and other thermodynamic aspects play a huge factor governing the process. To overcome such an issue, however, hydrophobic membranes can be employed, in which the water flux can be more than three orders of magnitude higher than fluxes predicted by continuum hydrodynamic models [12–14]. Membranes fabricated from this method can exceed the salt rejection efficiency of currently used membranes with much higher flux (∼4 times higher) [15]. However, the hydrophobic nature of such membranes make them prone to biofouling [3]. Moreover, the high cost of the manufacturing process combined with the difficulty in the functionalization of the pore entrance, required to reduce hydrophobicity and increased selectivity, make these membranes challenging to fabricate, to say the least. Even if such a membrane can be fabricated, the increase in the flux rate is eventually ruled by the concentration polarization layer at the membrane (Figure 12.2). This ultimately means that the theoretical efficiency of RO systems cannot be achieved necessitating the need for the development of new technologies for desalination as alternatives or in combination with RO.

12.3 Current State-of-the-Art Materials for Novel Membrane-Based Processes

To develop alternative solutions in water desalination processes requires significant advances in materials currently employed to achieve benchmark performance. The goal is, therefore, to improve on the positive aspects of the industry-standard materials or develop new materials of choice based on the required criteria while avoiding the negative effects [3]. The ultimate membrane should exhibit a set of specific characteristics including minimum thickness to allow for the highest flux possible, high mechanical strength to maximize its lifetime and well-defined pore sizes for increased selectivity [17–21].

To this aim, recently developed carbon-based materials can be regarded as potential materials of choice that might be used as an enabling platform for the development of membrane-based water desalination technology [22]. However, in order to achieve superb selectivity for various ions, controlled nanopores with precise functionalities should be introduced on the surface of the almost impermeable single-layer atom thick graphene [17, 23].

Graphene is defined as a two-dimensional material that consists of a hexagonal (i.e., honeycomb structure) lattice of covalently bonded sp^2 carbon atoms (Figure 12.3).

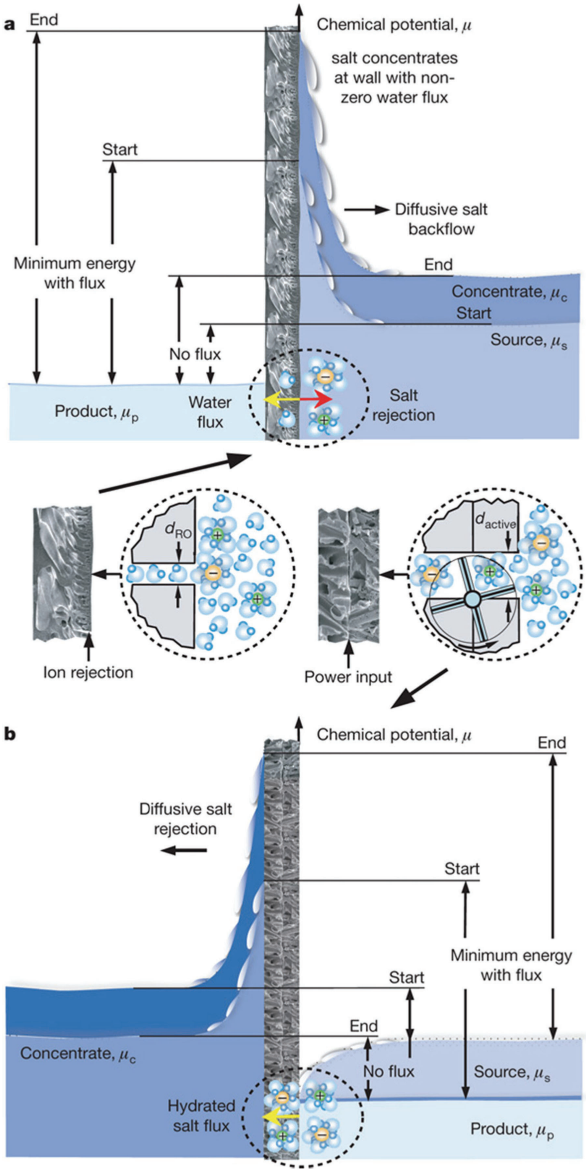

Figure 12.2 Concentration gradients in RO (a) and active (b) desalination membranes. The energy levels marked with ‘start’ and ‘end’ correspond to the evolution of each process. The darker blue color denotes higher concentration. Insets depict different mechanisms of salt ion separation. The active process with energy input shows a conceptual strategy for overcoming the Born barrier with fixed charges. Reproduced from Reference [3] with permission from Nature Publishing Group.

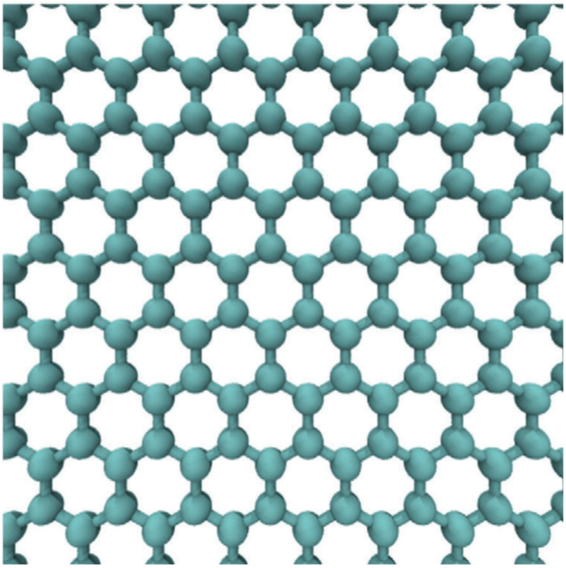

Figure 12.3 Crystal lattice of graphene [24].

Graphene has a large theoretical specific surface 2630 m^2g^{-1} and high electrical and thermal conductivity (ca. 5000 $Wm^{-1}K^{-1}$). Graphene in its free standing 2D form has been isolated in the past decade [25, 26].

Theoretical studies have suggested the possibility of the superior performance of graphene-based membranes to the current state-of-the-art polymer-based filtration membranes [25–30]. In contrast to polymeric membranes, in which the kinetics of water transport is slow, molecular dynamics studies show that the water permeability of graphene membranes is some orders of magnitude higher [27, 29]. This, combined with more than 99% salt rejection puts graphene at the forefront of research for developing new membrane technologies. At the same rejection rate, graphene membranes can provide water transport of 66 $L/cm^2 \cdot day \cdot MPa$ in contrast to RO membranes that can only provide about 0.01–0.05 $L/cm^2 \cdot day \cdot MPa$ [27, 31]. A schematic of water transport through a graphene membrane is depicted in Figure 12.4.

Following the lead of theoretical predictions, experimental research activities have begun to explore the possibility of the use of graphene monolayers as membranes with promising results [17, 32, 33]. Pore size tuning of graphene membranes for ion-selectivity can be performed employing ion bombardment and oxidative etching or plasma etching (Figure 12.5) [25, 32].

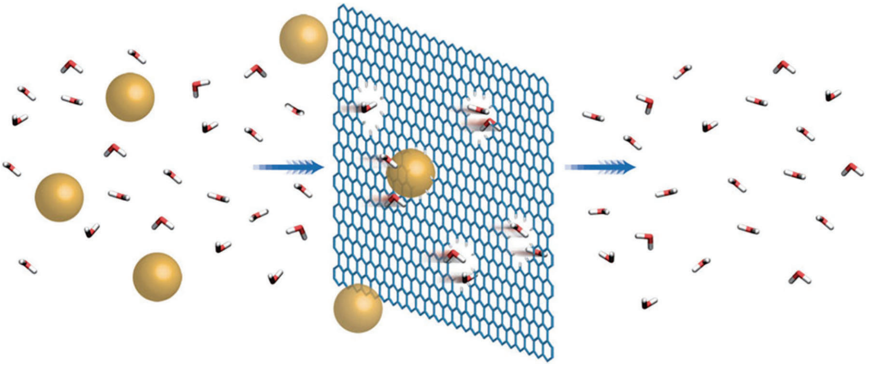

Figure 12.4 High pressure applied to the salt water (*left*) drives water molecules (red and white) across the graphene membrane (*right*), while salt ions (spheres) are blocked. Chemical functionalization of the pores with hydrogen (white) increases water selectivity, whereas functionalization with hydroxyl groups (not shown) increases the speed of water transport. Reproduced from Reference [27] with permission from Nature Publishing Group.

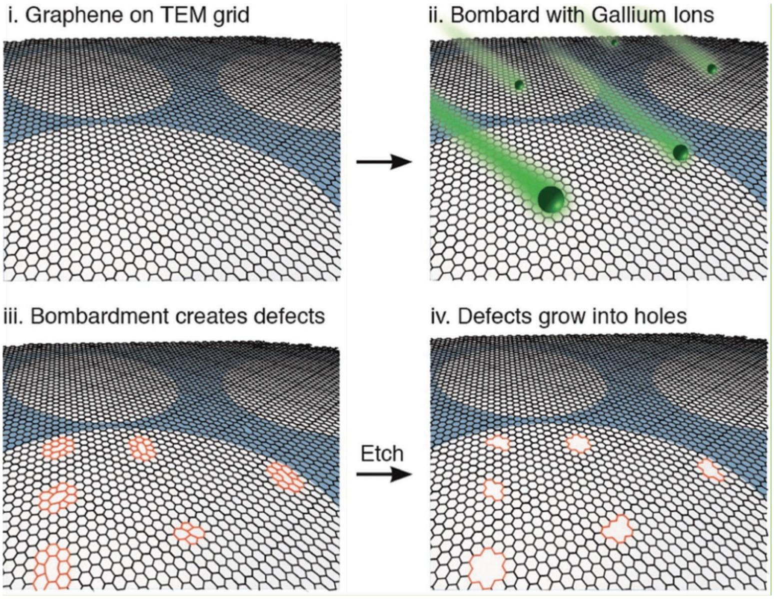

Figure 12.5 Process to create controlled pores in graphene membranes. Controlled sub-nanometer pores in graphene are created by ion bombardment followed by chemical oxidation. Ion bombardment generates reactive defect sites in the graphene lattice that preferentially etch during exposure to acidic potassium permanganate etchant. Reprinted with permission from Reference [32]. Copyright (2014) American Chemical Society.

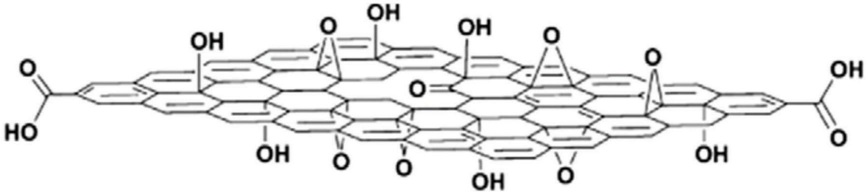

Figure 12.6 Graphene oxide structure [36].

However, the problem that should be addressed in all these systems is the cost-effective scalable manufacturing of large membranes with controllable pores and narrow size distribution while maintaining the structural integrity of the whole system; which is impractical with the current technology unless breakthroughs in the processing of graphene are achieved [27].

As such, current efforts are shifting towards using graphene oxide (GO) instead of graphene for practical applications [20–22, 34] (Figure 12.6).

The much lower scalable production cost of GO combined with its ease of processing into different shapes such as free-standing papers [18] fibers [35], etc. [37, 38] with sufficient mechanical strength can act as an enabling platform to process this material into different shapes desired for practical water desalination purposes based on their rheological properties (Figure 12.7) [22, 26, 38–40].

Although, the exact atomic structure of GO is still under debate, there are various oxygen functional groups that render GO a material of choice for these applications [19]. As an example, the presence of hydroxyl groups on the surface can increase water transport speed (Figure 12.2). Moreover, the structure of GO and its functional groups can be tuned and controlled based on the application, from a completely dense to a highly porous architecture (Figure 12.8).

Furthermore, the presence of multi-functionalities on the surface of GO can enable the easy decoration and hybridization of GO with different materials, resulting in an enhancement in ion selectivity and adsorption [19, 21, 22, 36, 40–47].

Although graphene-based membrane technologies are exciting for water desalination, the challenge of adding precise functional groups on the surface has served as a motivation to look for other candidates in the class of 2D materials that might act better than graphene. One of these recently explored candidates is the single atom-sheet molybdenum disulfide (MoS_2) [48, 49]. However, all the results are based on theoretical calculations and no experimental results are available, as of yet. Nevertheless, the theoretical calculations show that through mechanical induced stretching, the size of the nanopores in MoS_2 single layers can be adjusted leading to a biomimetic system with acceptable performance [49].

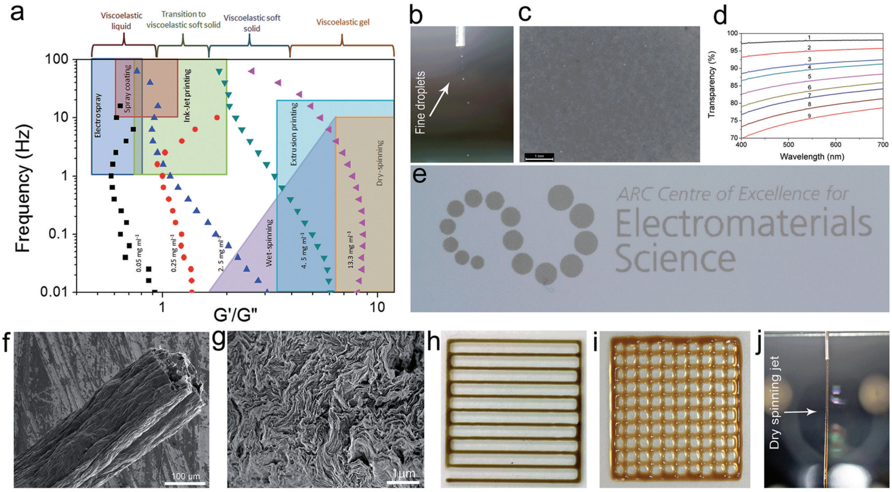

Figure 12.7 A correlation between rheological properties and the key prerequisites for various manufacturing techniques have enabled us to process and fabricate GO via a wide range of industrial techniques. **(a)** Ratio of elastic and storage moduli for various GO concentrations measured over a range of testing frequencies. Overlaid are the approximate processing regimes for a number of industrial fabrication techniques. When the viscous modulus (G'') dominates, the GO dispersion is suitable for high rate processing methods where the dispersion must spread on contact with the substrate. However, when the elastic modulus (G') is high the rheological properties suit fabrication methods requiring the dispersion to keep its given shape, such as extrusion printing and fiber spinning. **(b)** Photograph of electro-spraying of a viscoelastic liquid of a GO dispersion at a concentration of 0.05 mg ml^{-1}. **(c)** Photograph of a GO thin film that was spray coated and thermally reduced (overnight at 220°C) utilizing a transitional state to a viscoelastic liquid GO dispersion of 0.25 mg ml^{-1}. **(d)** Transparency of the spray coated reduced GO thin films as a function of coating layers; the numbers show the number of coating layers. **(e)** Ink-jet printed ACES logo using an LC GO viscoelastic soft solid at a concentration of 0.75 mg ml^{-1}. **(f)** As-prepared wet-spun fibers from an LC GO viscoelastic soft solid at a concentration of 2.5 mg ml^{-1}. **(g)** Cross-section of the wet-spun LC GO fiber, showing that GO sheets are stacked in layers with some degree of folding and are ordered due to the formation of nematic liquid crystals. **(h)** Extrusion printed pattern using an LC GO viscoelastic gel of 4.5 mg ml^{-1}. **(i)** Multi-level extrusion printed 3D architecture using an LC GO viscoelastic gel of 13.3 mg ml^{-1}. **(j)** Dry-spinning of LC GO fibers utilizing an LC GO viscoelastic gel of 13.3 mg ml^{-1}. Reproduced from Reference [38] with permission from Royal Society of Chemistry.

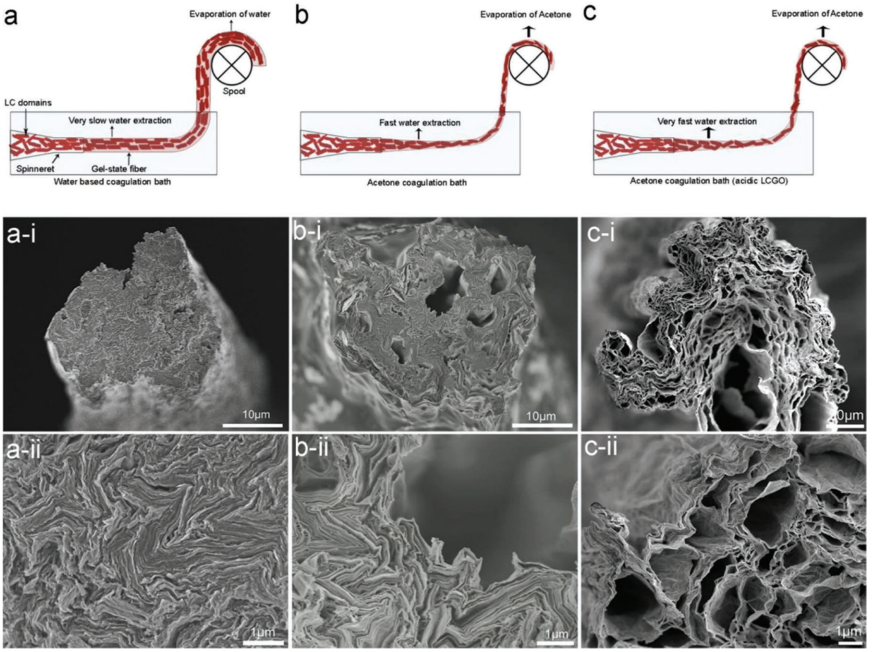

Figure 12.8 Proposed strategies for the evolution of structure in different coagulation baths from highly dense (left) to highly porous architectures (right). **(a)** Employing a water-based coagulation bath results in slow expulsion of water from the as-injected gel-state fiber-like structure. Therefore, to be able to pick up such fibers, the length of the bath should be optimized to enable the formation of a solid-like sheath around the core of the fiber. The fiber can then be taken from the bath and transferred on a spool for the evaporation of the water from the fiber, resulting in a highly dense structure **(a-i and a-ii)**. **(b)** Using an acetone coagulation bath results in the high rate of water extraction from the surface as a result of the difference in inhibition rate consequently leading to higher rate of solidification and porous fiber structure **(b-i and b-ii)**. **(c)** The slight acidic condition of LC GO dopants (pH ~3) further changes the difference in inhibition rate, resulting in much higher water extraction rate and consequently more porous geometry **(c-i and c-ii)**. Reprinted with permission from Reference [20]. Copyright (2014) American Chemical Society.

12.4 Forward Osmosis (FO)

Forward osmosis[2] or direct osmosis is a separation/desalination method with remarkable and versatile industrial application in the field of water and wastewater treatment [50–52]. In FO, we exploit the osmotic pressure between two solutions of different concentrations. The solutions are separated

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[2] From the Greek word osmos that means impel, push.

by a semi-permeable membrane. One solution is concentrated (draw) and the other is more dilute (feed). The difference of osmotic pressure forces water (without the salts) to permeate across the membrane from the dilute side to the concentrated side. After the permeation of water, it is separated from the draw solution to yield desalinated water. A mixture of ammonia and carbon dioxide has been used as the predominant draw solution which ensures a high pressure. An advantage of this draw solution is the ability to be regenerated by thermal energy [53].

A remarkable advantage of the FO process is the low proneness to fouling because the structure of the foulant layer formed is different from the layer in RO. The cake layer of RO is compact, whereas the FO cake is thicker but less compact. In some cases, high salinity waters have high fouling potential. FO is more effective in treatment of these difficult waters. These waters include landfill leachate, industrial waste water and flue gas desulphurization wastewater for which the concentrate is treated as hazardous waste and must be minimized.

The ability of FO as pre-treatment to remove dissolved constituents from the feedwater can also help conventional RO desalination to satisfy strict water quality requirements. Generally, FO is not proposed to replace RO, but rather to be used for feed waters that cannot be treated by RO efficiently.

12.5 Aquaporin Membranes

Aquaporins are protein channels that control water flux across biological membranes. They are found in human tissues with the purpose of rapid transport of water molecules across cell membranes. Due to osmotic gradients only water molecules are transported by diffusion while charges are rejected. Kumar et al. (2007) have used the protein Aquaporin-Z from *Escherichia coli* bacterial cells in a polymeric membrane [54].

Aquaporin membranes have shown promise for desalination processes. Due to the absence of applied pressure, it is expected that the energy consumption will be lower in comparison to RO membranes. However, there are not enough available reports of experimental data using real feed sources. Membranes based on aquaporins are not yet fully commercialized [55]. A short review article by Tang et al. (2013) has summarized the status and prospects of biomimetic aquaporin membranes concluding that: “based on their unique combination of offering high water permeability and high solute rejection, aquaporin proteins have attracted considerable interest over the last years as functional building blocks of biomimetic membranes for water desalination and reuse. Several design approaches have been pursued in facing the challenge of making the biomimetic membranes as stable, robust, scalable, and cost-effective as their polymeric counterparts in the form of existing technologies such as RO membranes. One type of approach aims at making ultrathin <10 nm supported films with incorporated aquaporins. While attractive in terms of flux potential this approach rests on the ability to form large defect free membranes—a technical challenge yet to be met—even at the square micron scale. Other designs use aquaporins stabilized in vesicular structures as a structural and functional element. Recent progress with this type of design, involving interfacial polymerization, has led to large (>400 cm^2) robust membranes (with lifetime of months) with water permeabilities >4 L m^{-2} h^{-1} bar^{-1} and salt rejection values $>96\%$". [72]

12.6 Thermal-Based Processes

The most important conventional thermal distillation processes are multistage flash (MSF), multi-effect distillation (MED), and vapor compression (VC). In the past decades, modifications to thermal-based desalination processes have been studied expansively in order to increase the process efficiency.

Recent research and development have also focused on a combination of phase change and membrane utilization. Two methods of this category are discussed briefly here: **membrane distillation** and **pervaporation**. Other methods based on pure thermal principles have also been developed aiming at reducing the energy consumption. This category includes technologies such as **humidification–dehumidification** and **adsorption distillation**.

12.6.1 Membrane Distillation

Membrane distillation (MD) is a thermal-based desalination process that is being considered as a possible alternative to conventional desalination technologies such as MSF and RO [56, 57]. In MD water vapor molecules evaporate from the feed solution and are transported through the pores of hydrophobic membranes as distillate (the size of the pores is 0.1–1μm). The MD membranes are fabricated mainly from polymeric materials such as PTFE (polytetrafluoroethylene), PP (polypropylene), PE (polyethylene) and PVDF (polyvinylidene fluoride). The driving force in MD is the vapor pressure difference across the membrane. The operating temperature of MD is low, ranging from 50–90°C and the operating pressures are lower than conventional pressure—driven membrane processes such as RO.

Moreover, MD has the theoretical ability to achieve 100% salt rejection. The low operating temperature permits the utilization of low grade heat such as conventional solar energy, geothermal and waste heat. When energy sources of this type are available, MD might be competitive with RO. A number of configurations have been reported.

In MD, the role of the membrane is crucial since the selected membrane must satisfy strict requirements: to have suitable porosity, to be hydrophobic (should not be wetted by liquids), to allow only the vapour to transport through the pores, to have no capillary condensation inside the pores etc. It has been observed that wetting of the membrane surface during prolonged use leads to accelerated deposition of organics. Wetting and fouling of the membrane require pre-treatment of the feed water source [58].

Research regarding MD has been growing exponentially in recent years. Meanwhile, pilot plant demonstrations are also underway. In the past couple of years, several review papers on MD have been published. Three recommended reviews published within the past couple of years, each covering an aspect of MD desalination, are as follows:

- A review on fouling of membrane distillation
  Naidu, G., Jeong, S., Vigneswaran, S., Hwang, T. M., Choi, Y. J., and Kim, S. H. (2016).
  Desalination and Water Treatment 57 (22), 10052–10076.
- Critical review of membrane distillation performance criteria
  Luo, A., and Lior, N. (2016).
  Desalination and Water Treatment 57 (43), 20093–20140.
- Membrane synthesis for membrane distillation: A review
  Eykensa, L., De Sittera, K., Dotremonta, C., Pinoyc, L., and Van der Bruggen, B. (2017).
  Separation and Purification Technology 182, 36–51.

12.6.2 Pervaporation (PV)

A well-known application of pervaporation is the separation of liquid mixtures like dehydration of organic solvents and evaporation of volatile compounds from aqueous solutions (commercialized process). Nowadays, pervaporation is also being considered as an attractive and promising method for water desalination although is not yet commercialized. In PV, generally certain components of the feed solution permeate preferentially through a dense porous membrane acting as a molecular sieve and evaporate downstream as shown in Figure 12.9.

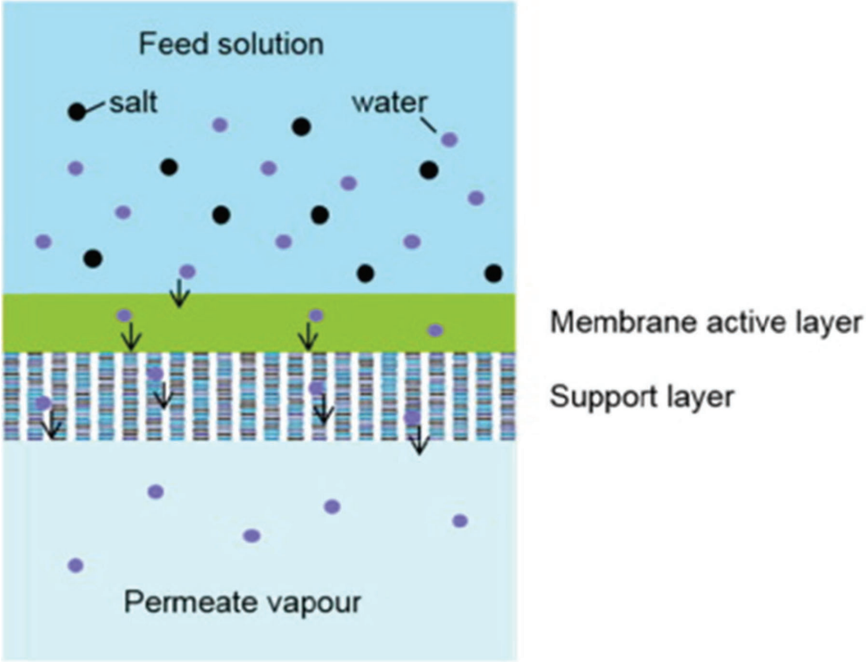

Figure 12.9 Desalination by the pervaporation process as water passes through a dense pervaporation membrane [59].

The driving force in PV for the mass transfer of permeate is the chemical potential gradient between the feed side and the permeate side of the membrane. For desalination purposes, PV includes a combination of diffusion of water through a membrane and its evaporation into a vapor phase (freshwater) on the other side. PV and MD are often confused because they both have a membrane with an upstream side in contact with hot feed liquid, and a freshwater permeate vapor that emerges on the downstream side of the membrane. However, the two processes have at least three distinct differences [59], the most fundamental of which is as follows: the membrane employed in the two processes is inherently different. In MD, the membrane does nothing more than act as a support medium for the vapor–liquid interface and does not actually contribute to the separation performance. However, in PV, a dense molecular sieve membrane is required with high selectivity to allow only certain components in the feed solution to be transported through. In other words, in PV, the membrane functions as a selective barrier for separation between the liquid feed and vapor phase. Under similar conditions, MD has significantly higher fluxes than PV, whereas the selectivity of PV is considerably higher.

Many kinds of membranes can be used for PV such as polymer-based (sulfonated polyethylene, cellulose acetate), inorganic (zeolite, amorphous microporous silica), hybrid materials, etc. The main advantage of PV over RO is the ability to handle a wide feed concentrate range in contrast to RO (because the phase change process need not overcome the osmotic pressure of the feed). Bench-scale or pilot-scale studies have been performed however a lot of research should be done to improve the efficiency of the PV process before it will become commercially attractive [59]. PV has displayed very high salt rejection, generally above 99.9%. Favourably, the salt rejection can remain more or less independent of any variation in operating conditions.

12.7 Novel Electrically-Driven Processes

12.7.1 Capacitive Deionization (CDI)

Capacitive deionization is an alternative desalination method being developed, probably more efficient for low-salinity feed water sources (total dissolved solids, TDS $<$15,000 mg/L). In CDI technology, a saline solution flows through an unrestricted capacitor-type module that consists of many electrodes having high-surface areas. In general, a carbon aerogel of high specific surface area (400–1100 m^2/g) and a very low resistivity $<$40 mΩcm is utilized. A power source creates an electric field that provokes adsorption of anions and cations of the solution on each electrode. After adsorption of ions, the saturated electrode is regenerated by desorption of the ions under zero potential or reverse electric field (potential reversal). Consequently, the absorption ability of the electrode is the most important parameter of this method [60].

The main advantages of CDI include: the absence of external pressure, high rejection of salts, and the possibility of electrode self-cleaning by polarity reversal. However limited data regarding desalination of seawater using CDI is available. Several modifications to CDI have been reported in order to increase efficiency, including:

1. M-CDI (membrane-CDI)
   Recently a modification to CDI in which ion–exchange membranes are utilized for selective transport of ions to the electrodes has been proposed [61]. This innovation has led to higher efficiency and lower energy consumption.

2. Flow through electrode CD
   In this case the feed water flows through the electrodes, instead of flowing between them. And instead of carbon aerogels, a new material called hierarchical carbon aerogel monoliths (HCAMs) is used as the electrode. The porous carbon permits less separation between electrodes leading to better performance of the system. This method is of course faster than conventional CDI, is more energy efficient and is operated without membrane components. Also, it has been reported that the constant current (CC) operation mode consumes much less energy than the constant voltage (CV) mode [62].
3. ED (electrodialysis) combined with CDI
   Another system has been proposed utilizing ED (electro dialysis) combined with CDI [63]. The system includes a three-step process: the water flows in a cell with positively and negatively charged electrodes. The electrode surfaces are covered with ion–selective membranes, and ions in the feed water are attracted to the opposite charged electrodes, passing through the selective membrane and finally accumulating on the electrodes in the third step, due to its porous structure. When the electrodes have been saturated, their polarity is reversed (potential reversal).

12.7.2 Microbial Desalination Cell (MDC)

Since 1972 fuel cells based on biological activity have been demonstrated for electricity production. The first direct biochemical fuel cell is the well-known sulfate reduction cell. A smooth platinum sheet covered with species of *Desulfo vibrio desulfuricans* can serve as the biocathode in the microbial fuel cell (MFC). Seawater is the electrolyte that contains *Al*gae for nutrition and sulfate anions for metabolism. A magnesium sheet serves as a counter electrode. On the biocathode the following reaction takes place consuming electrons:

$$SO_4{}^{2-} + 4H_2O + 8e^- \xrightarrow{\text{bacteria}} S^{2-} + 8OH^-.$$

A potential difference develops between the cathode and anode that can generate electricity. In the same way, when the bacterial metabolism liberates electrons the electrode acts as the bioanode [64].

It is noteworthy to mention that the above reaction explains the biological corrosion[3] of iron materials in the soil due to the presence of sulfate reducing

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[3] Biocorrosion, microbiologically induced corrosion (MIC).

bacteria using sulphate anions for their metabolism. Under such conditions, the corrosion rate (anodic reaction) accelerates [65]. It is known that the corrosion phenomenon can be interpreted as a short-circuited galvanic or corrosion cell [66].

The recently developed microbial desalination cells (MDCs) are based on the same principle and can be considered as an extension of the microbial fuel cell [67, 68]. An MDC can treat wastewater containing bacteria with simultaneous production of electricity [69].

As shown in Figure 12.10, an MDC consists of an anode and cathode chambers and in the middle a chamber of desalination constructed by an anion-exchange membrane (AEM) and a cation-exchange membrane (CEM) on either side. An external wire is used for closing the circuit. The middle chamber is filled with the water to be desalinated. In the anode chamber, oxidation (degradation) of organic matter by bacteria producing CO_2 and H^+ takes place. In the cathode chamber, usually O_2 uses the electrons from the anode undergoing reduction and producing water. Consequently, a potential difference develops between the cathode and anode. In the middle chamber, the anions (such as Cl^- and $SO_4{}^{2-}$) migrate from the saltwater across the AEM into the anode, while the cations (such as Na^+ and Ca^+) move across the CEM into the cathode chamber. This electrochemical mechanism can

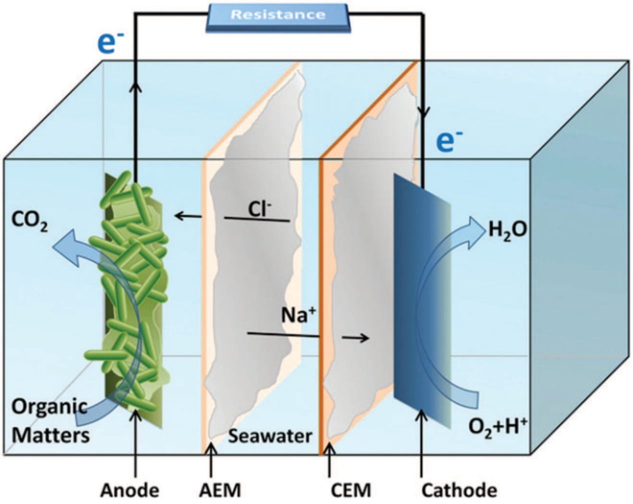

Figure 12.10 A typical scheme of a microbial desalination cell (MDC). AEM: anion exchange membrane; CEM: cation exchange membrane [68].

remove more than 99% of the salt from the saline water and simultaneously produce enough energy for the operation of the system.

The crucial parameter is the formation of the biofilm by accumulation of bacteria adhered to the anode. It is noteworthy that biofilms are created in the human body as well for example sulfate reducing bacteria in the oral cavity [70].

As stated, due to electricity production of the microbial cells, an external energy source is absent and therefore energy consumption is minimal. This may be the biggest advantage of the MDC. The desalination performance of conventional MDC can be increased by using multiple pairs of ion-exchange membranes (IEMs) inserted between the anode and cathode chambers as shown in Figure 12.11. This is called the stack structure MDC. Stacked MDCs achieve more efficient desalination when compared to single chamber MDCs [71] due to improvement of charge transfer.

In a conventional MDCs, the different chambers are separated by ion exchange membranes. In the anode, the oxidation of the organic material releases protons (H^+) which are not allowed to diffuse to the cathode where hydroxyls (OH^-) are produced through the reduction reaction according to the following equations:

$$n(CH_2O) + n(H_2O) \quad nCO_2 + 4ne^- + 4NH^+ (\text{anode})$$

$$O_2 + 2H_2O + 4e^- + 4OH^- \ (\text{cathode})$$

This may create an imbalance of pH inside the cell because pH increases in the anode and decreases in the cathode. The pH changes can negatively

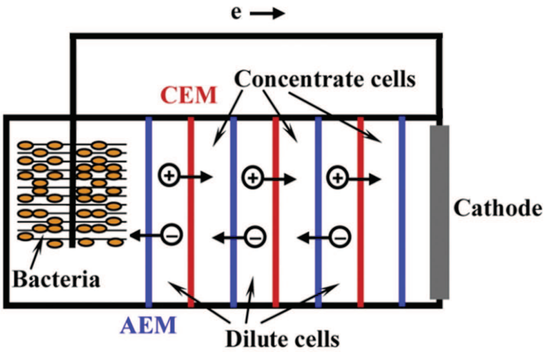

Figure 12.11 Stack structure microbial desalination cell (MDC) modified from reference [71].

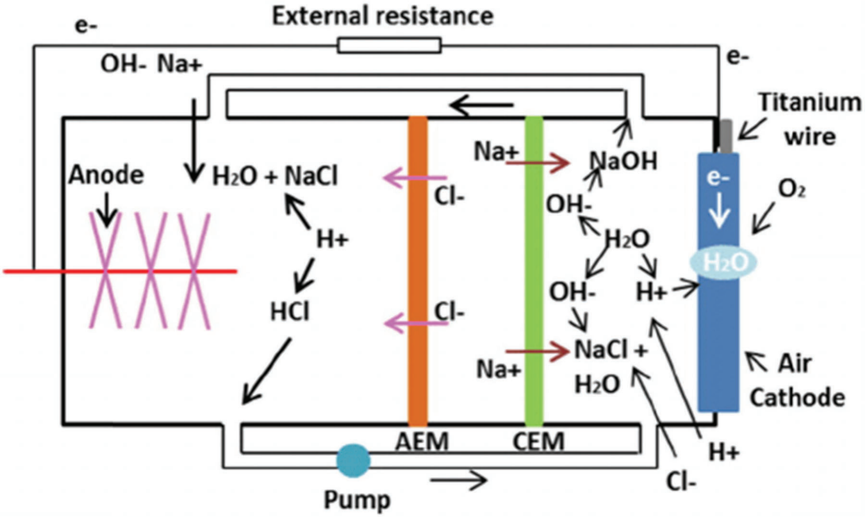

Figure 12.12 Recirculation microbial desalination cell (r –MDC) [69].

influence the metabolism of the bacteria. In order to tackle this problem a recirculation MDC has been developed as shown in Figure 12.12.

It is reported that the main advantage of the r-MDC is the increase of desalination efficiency [69]. In general, microbial desalination technology is still at lab-scale and pilot-scale evaluation. Intensive research is necessary in order to elucidate the details.

Acknowledgements

The authors would like to thank Professor Dr rer.nat.TUM D.K.Yfantis for his helpful suggestions.

Assessment of New Desalination Technologies Using the Coefficient of Desalination Reality (CDR)

Tom Scotney, Deputy Editor, Global Water Intelligence, UK

Although the desalination market may be dominated by a few established technologies, a diverse and changing landscape of technological innovation is constantly at work. Below a variety of emerging technologies in desalination that seek to address desalination's biggest obstacles, such as energy use, volume reduction, and membrane improvements, among others are outlined. Bridging the gap between the lab and the field is a notoriously difficult process, particularly in the water market. While a huge amount of innovation goes on at a technological level, it can often be decades before even a tried and tested technology becomes standard for installations. The slowness of adoption is a result of a number of factors, including:

- The difficulty of replicating field conditions—which often include low or variable water quality—in the lab.
- Problems of scale that often emerge when looking to take a test-level process up to a working plant size.
- Conservative attitudes to new technology in a sector with a high level of exposure to public opinion.
- The fact that water utilities—which are often supported by government subsidy instead of income from their customers—have less incentive to reduce their operating costs.

This makes it very difficult to assess the likelihood of success for new desalination technologies going forward, even if they offer strong benefits on paper.

Table 12.1 Assessment of new desalination technologies by CDR rating

Technology	**Developer**	**CDR**
Cavitation with coagulation	CaviGulation	1
Electromagnetic frequency technology	Paramount discoveries	1
Novel multi-stage flash technology	Centriforce	1
Magnetic desal	Blue Fin Water	1.4
Biomimetic ultra-thin membrane	AguaVia	2
Boron nitride nanotube technology	Australian National University	3
Sonic desalination	Globe Protech	3.3
AirDrop irrigation desalination	Swinburne University of Technology	3.4
Aquaporin nano-polymer membrane vesicles	Danfoss AquaZ	3.5
Microbial desalination fuel cell	Penn state/Tsinghua University/KAUST	3.5
Multi-effect drying and condensation	3MW	3.5
Graphene-based membrane permeation	University of Manchester	3.7

Carbon nanotubes	Porifera/NanOasis	3.9
Decanoic acid solvent extraction process	MIT	3.9
Radial de-ionization	Atlantis Technologies	3.9
Solvent-extraction desalination	MIT	3.9
Autonomous desalination module	Aquamodule	4
Biomimetic aquaporins	Aquaporin A/S	4
Solar sponge	MIT	4.3
Locally powered water distillation system	Dean Kamen	4.5
Carbon nanotube membrane distillation	New Jersey Institute of Technology	4.6
Membrane distillation + vapor compression	Dais Analytic	4.8
Capacitive deionization	Atlantis	4.9
Graphene membrane	Lockheed	4.9
Clathrate separation	Aqueous Logic	5
Desal with deep sea pressure differentials	Econopure	5
Electrochemical desalination	Evoqua Water Technologies	5.2
Microbial desalination	Microbial Desal Cell	5.2
Microbial electrolysis and desalination cell	University of Colorado	5.2
Upflow microbial desalination fuel cell	University of Wisconsin–Milwaukee	5.2
High-res. Electrical impedance spectroscopy	INPHAZE	5.4
Multifunctional TiO_2 nanocomposite membrane	NanoSun/Nanyang Technological University	5.6
DNA UF membrane	Cerahelix	5.9
Membranes without feed spacer mesh	Aqua Membranes	6.3
Hydrophilic graft of RO membranes	Samueli School, UCLA	6.4
Ion Concentration polarization	MIT and Pohang University of Science and Technology	6.5
Membrane distillation with solar pond	University of Nevada-Reno and Col. Sch. Of Mines	6.5
Vacuum-based evaporative process	New Mexico state university/ Sterling Water	6.5
Electrochemically mediated desalination	Okeanos Technologies	6.6
FO thermolytic draw solution	Trevi Systems	6.6

(*Continued*)

Table 12.1 Continued

Technology	**Developer**	**CDR**
Brine squeezer (High recovery RO)	Osmoflo	6.9
Low-temperature evaporator	Hittite	7
Humidification-dehumidification process	MIT/King Fahd University of Petroleum	7.1
Dissolved air filtration and microfiltration	Technical University of Berlin	7.4
Pervaporation for subsurface irrigation	DTI-r	7.5
UFO-MBR	Colorado School of Mines	7.5
Nonmetallic tubes	Technoform	7.8
Indirect fired steam generation	Hipvap	7.9
Zero discharge desalination	University of Texas-El Paso	7.9
Polymeric membrane (PolyCera)	Water Planet Engineering	8.3
Multi-stage flash fluidized bed evaporator	Klaren BV	8.4
Chemical crystallizer	Advanced Water Recovery	8.6
Ion exchange with bridges and solar ponds	Saltworks	8.6
Vacuum multi-effect membrane distillation	Memsys clearwater	8.7
Membrane capacitive deionization	Voltea	8.8
Wind-aided intensified evaporation	Ben Gurion University	8.8
Manipulated osmosis (forward osmosis)	Modern Water	8.9
Nano-engineered composite membranes	Nano H_2O	8.9
Anti-biofilm selenium compound	Selenium, ltd	9.1
Closed-circuit desalination	Desalitech	Commercialized
Dewvaporation	Altela	Commercialized
Flat sheet UF	Microdyn-Nadir	Commercialized
FO membranes (particularly for pre-treatment)	Porifera	Commercialized
Humidification-Dehumidification	Gradiant	Commercialized
Continuous Ion exchange	Clean TeQ	Commercialized
Membrane distillation	Memsys	Commercialized
MVC crystallizer	SaltTech	Commercialized
Nano composite membrane	NanoH_2O (LG Chem)	Commercialized
Package plant	Water Planet Engineering	Commercialized
SDI/MFI monitor	Convergence	Commercialized
Thermolytic FO	Oasys	Commercialized
Fibracast UF membrane	Anergia	Commercialized

Source: GWI, 2016.

One gauge of a technology's potential is the Coefficient of Desalination Reality (CDR). Developed by the Water Desalination Report (WDR) publication, it serves as an indicator of WDR's confidence that a product or process is based on sound scientific principles, is commercially viable in the market for which it is intended, and will be available within a reasonable time frame.

It is determined using a 1- to 10-scale that considers three separate aspects of a particular process:

- Laws of Nature Assessment: Gauges a process' apparent adherence to the basic laws of physics.
- Commercial Assessment: Predicts the commercial and competitive viability of the technology.
- Deployment Assessment: Assesses the plans and schedule for commercialization.

The sum of the three scores is averaged, and false, misleading or ridiculous claims made about competing technologies by the technology's proponents may result in point reductions.

A 1.0 is the lowest possible score and indicates a high degree of skepticism based on the available information. It does not necessarily mean a process is without merit, however, and may only indicate there is not enough information for a proper evaluation. A perfect score of 10.0 indicates that a technology has been successfully commercialized.

Admittedly, a CDR is somewhat subjective and it should not be considered to be WDR's final assessment of a process' viability. As new information is made available for review, the CDR may be revised.

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A MULTIDISCIPLINARY INTRODUCTION TO DESALINATION

Alireza Bazargan (Editor)

Although more than 70% of the globe is covered with water, only a small portion is suitable for direct human use, making the scarcity of freshwater one of our planet's most serious challenges. In this context, desalination, defined as "the separation of salts from water", is one of the possible solutions for appeasing our ever-increasing thirst.

By drawing upon the expertise of a remarkable team of international authors, this book aims to provide a simple, encompassing, and "multidisciplinary" introduction to desalination. The particular forte of this publication is its inclusive yet straightforward nature. In other words, the unique assortment of reader-friendly chapters is designed to cover the topic of desalination as a whole, and strike a delicate balance between the technical and non-technical.

To this end, the book is divided into five general sections:

- The first section presents an overview of water scarcity, followed by a review of integrated water management and the alternatives to desalination. The fundamentals of desalination are also provided, including simple water chemistry;
- The second section covers conventional desalination technologies, including thermal and membrane processes. The topics of pre- and post- treatment are given due credit, as all desalination plants are more or less reliant on them;
- The third section reviews the history of how desalination technologies originated, including a review of today's R&D activities and cutting edge research. The topic of membrane manufacturing is also covered;
- Section four is concerned with energy and environmental issues, including the application of renewable and nuclear energy, energy minimization, brine management, and environmental impacts;
- Finally, section five covers the social and commercial issues, ranging from rural desalination to politics. Desalination costs and economic feasibility are discussed, as well as issues in business development and future market prospects.

ISBN 978-87-93379-54-1

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