

Review

Emerging Membrane Technologies for Water and Energy Sustainability: Future Prospects, Constraints and Challenges

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Abstract: The increasing demand for global energy consumption expedites major opportunities for the innovation of green energy technologies. Addressing the issue of sustainable energy is highly crucial for societies in order to maintain secure and balanced future progress in the economy and ecologically. Recently, there has been a growing interest in the development of improved and efficient sustainable energy technologies that are capable of reducing the global environmental footprint. The growing knowledge of hybrid techniques contributes to a decrease in the use of environmental resources while generating energy. However, various factors including the availability of natural resources, and different economic policies restrict the development of sustainable energies. Water and energy are the two major aspects for progressing towards a sustainable future. Recently, membrane-based technologies have begun to play an essential role in the advancement of sustainable energy and water demands. In this review article, the opportunities for membrane technologies dealing with water and energy sustainability have been analyzed.

Keywords: membrane; water treatment; desalination; energy; sustainability

1. Introduction

Sustainable energy is the key solution for addressing major concerns about the future such as climate change, environmental protection, and balanced growth of the economy and society. The past two decades have witnessed advancement in economic development in many nations. However, the rapid economic growth, industrial advancement, energy shortage, deterioration of the environment and increasing demands of growing populations pose a huge threat for future generations [1,2]. For many years, economic development has been the key focus of many policy makers in sustainable development until the inception of the Kyoto protocol agreement in 1997, which includes environmental quality as a crucial variable for sustainable development [3]. With global energy consumption and electricity demands expected to double in the next twenty-five years, major opportunities for innovation in how energy is produced, stored, transmitted and used have begun to open up. In particular, there is a huge interest in sustainable energy technologies capable of improving efficiency and reducing the global carbon footprint [4–6].

The development of sustainable energy is, however, restricted by various factors, such as the availability of natural resources due to regional differences, sensitivity to the environmental impacts of fossil-fuel based energy, increasing water scarcity, and differing economic policies. Development of an approach to sustainable energy that addresses environmental concerns, greenhouse gas emission, cost, availability of resources, and social impact is a huge challenge. The key focus for attaining energy sustainability is to reduce and slowly replace power generation by fossil fuels with renewable energy

sources [7–9]. Though some aspects of this sustainable approach are being adopted, there are others yet to be translated at a commercial scale. For instance, major concerns about carbon dioxide (CO₂) emissions in traditional fossil fuel-based power generation has paved the way for several sustainable energy sources such as wind and solar, along with CO₂ capture and sequestration technologies [10–13]. Apart from this, there is a growing recognition of technologies such as cogeneration plants, where a combination of techniques contributes to reduced water demand while generating energy, resulting in effective water use to meet the demand. Water and energy are the two key aspects for sustainable development for the future [14,15].

There is a significant amount of research and development work going on in the membrane sector, emphasizing the utilization of renewable energy in conjunction with membrane technology, although the efficiency of the process is still a high priority. Recently, membrane technologies have started to play a pivotal role in developing the infrastructure for sustainable energy, especially, in the water and energy sector. Some of the membrane-based approaches that are currently adapted at an industrial scale include desalination by reverse osmosis (RO), membrane-based bioreactors (MBR) for pure water generation, lithium-ion batteries, and membrane-based fuel cells and CO₂ capture [16–19]. Besides addressing the concerns related to energy demands and water scarcity, membrane technologies meet the criteria for sustainability in terms of feasibility, flexibility and adaptability. However, they still need to improve costs and affordability, which is achieved by advancement in membrane-based technologies. This review article aims to analyze opportunities for membrane technologies to tackle water and energy sustainability.

2. Role of Membrane Technology in Sustainable Water Generation

Membrane-based approaches for the generation of potable water mainly rely on desalination and waste water treatment processes [19–22]. The majority of the global reserves of water is saline and only 2.5% is available as fresh water. Moreover, only 0.007% of the total available stock is directly accessible for human use, as a major portion of the fresh water stock is either frozen in polar regions or difficult to access as remote aquifers [23,24]. Of this meager portion of the total available fresh water stock, some is polluted by industrial plants, mining, oil or gas exploration, use of fertilizers and pesticide residue from agriculture. Also, uneven distribution of the available water stocks pushes certain regions of the world to severe water scarcity. Hence, desalination and water reclamation is of utmost importance for securing localized water reserves for many arid regions and to meet the needs of our growing population [24].

With increasing demand for fresh water, various techniques have been developed in the past decades including vacuum distillation, multi-stage flash distillation (MSF), multiple-effect distillation (MED), and other membrane-based technologies, such as reverse osmosis (RO), membrane distillation (MD), etc., for sea water desalination. Among these technologies, membrane-based techniques such as RO, MD, and forward osmosis are seen as attractive alternatives due to their low energy consumption, lower capital requirements as well as less maintenance and lower operating costs. Figure 1 shows the transition of the desalination technologies from thermal to membrane and the expansion of the global market [25].

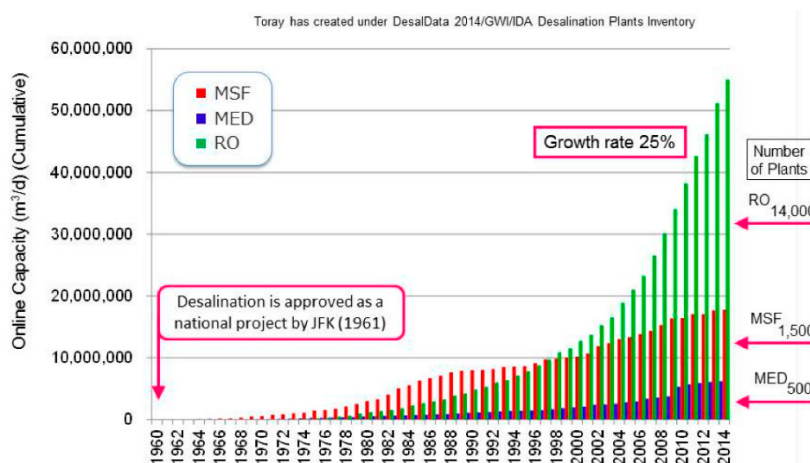


Figure 1. Online capacity of various desalination technologies and the expansion of the global desalination market [25].

2.1. Desalination

Desalination is a process for producing fresh water from either sea or brackish water, by removing the salt content either by membrane technologies or by a thermal distillation process. Desalination plays a key role in water sustainability for many countries across the world, especially in the Gulf Nations. For example, 100% of the water supply for both domestic and industrial use in Qatar and Kuwait is provided by desalination [26]. As per Desaldata, it has been reported that 63.7% of total desalted water is produced by membrane processes, which emphasizes the importance of membrane technologies in this application [2]. Various water sources for desalination includes 58.9% from seawater, 21.2% from brackish ground water and 19.9% from surface water and waste water. Water produced via desalination is applied in drinking water, agriculture, mining and removal/recover of rare earth elements (REEs) [27–34]. Regardless of the fact that is power demands have been reduced two-fold over the last 20 years, desalination, especially from seawater resources continues to remain a highly energy intensive process for the production of potable water [35].

As mentioned before, thermal and membrane processes are the two primary technologies that drive the desalination sector. In the thermal desalination process, energy is utilized in the form of heat to vaporize pure water from its salt mixtures, and in commercial membrane desalination processes, electric energy is used to run high pressure feed pumps to filter out the dissolved solids. In both processes, the stream of water containing less dissolved solid is the main end product and a concentrate water stream is the reject. Due to the progress in membrane technologies, desalination industries have gradually shifted towards it. By 2006, 96% of US based desalination industries and 56% of global industries had shifted from thermal-based to membrane-based processes [36]. Table 1 shows the energy consumption of different technologies used for desalination [37]. The membrane technologies, specifically the RO, are preferred over the other technologies, mainly due to lower energy requirements as can be seen from Table 1. The specific energy consumption (SEC) of different technologies varies widely, and depending on the process control and operation as well as the quality of the produced water, this value further differs significantly for a particular technology.

The energy consumption in a process typically contributes a significant amount to the total cost of desalination, hence, understanding various factors affecting the SEC of the process becomes highly important for the development of sustainable energy-water sources.

Table 1. Specific energy consumption (SEC) by different desalination techniques [37].

Technology	Specific Energy Consumption (kWh/m ³)		
	Electric	Thermal	Total Electric Equivalent
BWRO	0.5–3	-	0.5–3
SWRO	3–6	-	3–6
ED	1–3.5	-	1–3.5
EDR	1–2	-	1–2
MVC	7–15	-	7–15
FO	0.2–0.5	20–150	10–68
MD	1.5–4	4–40	3–22

BWRO = brackish water reverse osmosis; SWRO = seawater reverse osmosis; ED = electrodialysis; EDR = electrodialysis reversal; MVC = mechanical vapor compression; FO = forward osmosis; MD = membrane distillation; MSF = multi-stage flash; MED = multiple effect distillation; MEB = multi-effect boiling.

2.1.1. Reverse Osmosis (RO)

Reverse osmosis (RO) is the most common membrane-based desalination process that has been used across the world for many years [38,39]. The RO process works on the principle of rejecting colloidal suspension and dissolved salts from an aqueous solution, thus producing a concentrate brine and pure water which permeates through a semi-permeable membrane due to the presence of a pressure gradient across the membrane [40,41]. RO has been widely used in concentrating organic substances and is currently used in seawater desalination as well [42]. By applying pressure, the water molecules in the feed solution are forced to permeate through the membrane while retaining the dissolved solid contents. In order to overcome the osmotic pressure of the feed solution, high feed pressure ranging from 55–70 bar for seawater desalination, and between 10–15 bar for brackish water is required.

In general, the seawater desalination process flows through four stages where the feed water is pre-treated to remove any undesired large suspended particles and debris from the seawater. Pre-treatment is a requirement in the RO process in order to eliminate any undesirable content from the feed and to increase the membrane life-span by reducing fouling [31,43,44]. Typical pre-treatment processes for RO include chlorination, filtration, coagulation, multi-media filtration, and dechlorination. The choice of pre-treatment process depends on the composition of the feed source. Major considerations in designing a RO plant include total flux, recovery rate, permeate salinity, membrane life-span, power consumption and feed water composition. In comparison to traditional thermal distillation, corrosion of materials is less pronounced due to ambient operating conditions, less use of metal alloys and extensive use of stainless steel for operations [45–47].

Commercial interest in the RO process is increasing globally due to recent advancements in process features, which in turn lead to significant reductions in operation costs. These include advancements in membrane materials, module/process design, feed pre-treatment and energy recovery and reduction in energy consumption [48–51]. Although, significant advancements have been made in the last few decades in the manufacturing of such membranes and modules, the production of dependable, mechanically strong but thinner RO membranes with high chemical tolerance and anti-fouling properties remains challenging [52]. Over the past 30 years, salt passage has decreased almost seven-fold due to stringent pre-treatment processes and enhanced mechanical, biological and chemical strength of RO membranes and increased membrane permeability have reduced membrane cost per unit volume of water produced by more than 10 times [53]. Additionally, the combined effect of reduced fouling, polarization effect, decreased energy consumption and enhanced energy recovery has reduced the overall energy consumption for the RO process from 12 kWh·m⁻³ to less than 2 kWh·m⁻³ in the past three decades [28,40,54]. Although, the energy requirement has decreased significantly for the RO process, a minimum amount of energy is always required to separate the water from its salt solution, and this does not depend on the process, but on other factors, such as operational, water quality and system recovery [55–61]. The SEC of a RO plant is highly dependent on its treatment

capacity. In a large treatment facility, the efficiency gains connected with larger pumps can be highly beneficial [62]. Depending on the capacity, different types of energy recovery devices are also useful to reduce the SEC. As an example, plant capacity less than 5000 m³/day, can save 35–42% energy by using Pelton turbines whereas a plant capacity greater than 5000 m³/day, substantially reduces SEC by 55–60% using isobaric energy recovery devices [63].

Thermodynamic studies have showed that the minimum specific energy consumption for a 35 K ppm feed system with 50% recovery is about 1.06 kWh/m³ [4,64]. To carry out a RO process, it is always necessary to move the water in the opposite direction of the natural osmosis process. This requires a large amount of pressure on the seawater reservoir side. Theoretically, the pressure difference across the membrane needs to exceed 2.51 MPa (24.8 atm), and to produce 1000 cm³ water, the minimum work required is 0.7 Wh/L (0.7 kWh/m³). This represents the lower limit of the work investment as the system recovery (ratio of the product to feed water flow) approaches zero [64]. In a similar way, the theoretical minimum SEC was estimated as ~0.2 kWh/m³. However, the theoretical minimum may change with varying temperatures and concentration polarization. Several methodologies have been adopted to reduce the SEC including the use of energy recovery devices, utilization of sustainable energy resources, intermediate chemical demineralization, optimal process configuration and use of high permeability membranes [65,66].

The major advancement in RO comes from recent developments in polymeric membrane materials which has phased out in three different stages: (a) early trial and error testing of polymers; (b) use of suitable polymerization technique; and (c) study of membrane morphology with aid of advance characterization techniques [31,67,68]. Major breakthroughs in membrane fabrication came through Loeb-Sourirajan's asymmetric membrane in the 1960s [69], followed by cross linked aromatic thin-film composite membranes in the 1970s and 1980s [67,68,70,71], and with controlled morphological changes by monitoring polymerization reactions in the 1990s [71–80]. However, increasing permeability does not decrease energy consumption significantly, hence increased water-solute selectivity has become more important [81,82].

Recent advancements in nanotechnology and the emergence of novel materials such as graphene, nanotubes, nanocarbons, and nano-diamond, has contributed to the new class of membranes called nano-structured RO membranes in the millennium era [68,83]. Nano-structured RO membranes have been proposed to offer enhanced permeability, reduced fouling effects and improved membrane strength and selectivity. The major challenges for these nano-structured membranes are the higher cost of these nanomaterials, challenges in scale-up to commercial stages and safety concerns around the use of these nanomaterials [84–88]. Though these novel membranes are expected to outperform traditional RO membranes, they are at the initial stages of development and require further research and improvement before they can be taken to a commercial level [89].

RO provides the most viable solution for supplying fresh water in many places around the world, including the Gulf States, Mediterranean and Caribbean Islands. Major gulf countries, such as Kuwait, Qatar, etc. completely depend on desalinated water [90,91]. Initially, the desalination plants relied on thermal distillation processes, but after the 1980s, those were replaced with more efficient and economic RO technology. The energy requirement for RO processes was further lowered via extensive research in desalination practices. The development of superior membrane materials, energy efficient variable speed high pressure pumps and motors, and energy recovery devices have significantly lowered the energy requirement of this process. In comparison to the 1970s, the energy footprint of RO processes has decreased from 20 kWh/m³ to less than 2 kWh/m³ at this moment for seawater desalination and about 1 kWh/m³ for brackish water desalination [92,93]. The exergy analysis of various RO systems helped to develop an optimized energy system.

In 2002, Cerci et al. first performed an exergy analysis of a brackish water single stage RO treatment plant of 7250 m³/day operational capacity [94]. It was observed that the membrane module itself destroyed the largest amount of exergy, almost 75% of the total input, and by incorporating a pressure exchanger on the feed stream, the second law of efficiency of the plant (net salinity exergy

divided by the total exergy input delivered by the pumps) was increased from 4.3 to 4.9%. Another thermodynamic study dealing with real time data obtained from the Al-Hussein thermal power station showed that the throttling valves (56.8%) followed by the exergy destruction in the two stages RO units (21%) were mainly responsible for higher energy cost in this brackish water treatment plant [95]. The second law efficiency of the plant was observed to be very low (4.1%). To increase the efficiency or reduce the power input of the water treatment plant, it was recommended to use efficient pumps and motors equipped with adjustable drives, which can save up to 50% of the power consumption; and to replace the throttling valves by the energy recovery devices (ERDs) [96]. Further, the introduction of high-efficiency pumps and motors containing variable frequency drives increase this value up to 8.0% and reduce the overall cost of RO treatment significantly [97].

As the highly pressurized feed water consumes 70% of the total energy, it is thus extremely important to optimize the supplied water along with an improved recovery rate, and to implement efficient high-pressure pumps for energy saving. Kurihara and Takeuchi developed a low cost two-stage SWRO desalination system with a high recovery rate of ~60%, called a brine conversion system (BCS) as shown in Figure 2 [25]. This concept became an important research theme for the SWRO desalination system [98,99].

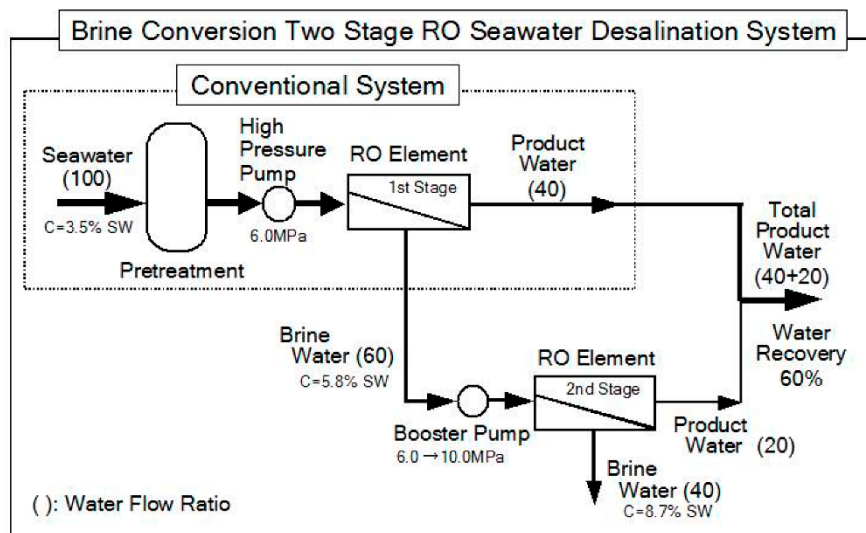


Figure 2. Two-stage brine conversion system (BCS) [25].

In this system, the feed concentrate (~58 K ppm) from the first stage RO modules was passed through the second-stage RO modules by applying high pressure 8–10 MPa via a pressure booster, and finally, rejecting a salt concentration of around 87 K ppm. The water recovery in the first stage was 40% with an additional 20% from the second stage. This development offers a reduction in plant space of up to 66%, expansion of the existent plant by simply adding the second stage, and lowering the disposal cost of the concentrated brine. The technology is also adopted in several plants in Trinidad and Tobago (136,000 m³/day) and in the Canary Islands (14,000 m³/day) [25]. In developing a sustainable desalination technology and building a strong water-energy relationship, the major key challenges are: reduction in overall energy consumption, low impact on the environment, and production of high-quality water with minimum cost.

2.1.2. Membrane Distillation (MD)

Desalination via thermal distillation processes mainly rely on the principle associated with the evaporation of saline water. The heat required in this process is either provided by the combustion of fossil fuels or by the sun. This technique was the earliest form of water treatment and is still a popular solution. Membrane distillation (MD) is an emerging technique that is currently being explored as a

possible alternative to the thermal distillation of highly concentrated feed solution. MD is a thermally driven, membrane-based separation process introduced in the late 1960s. Typically in the MD process, a hot brine solution passes on the feed side of the porous hydrophobic membrane that prevents the passage of liquid water, while allowing the vapor to diffuse through the membrane pores, which gets condensed either by cold water, air or vacuum on the other side of the membrane [100–103]. Total permeate flux of this process depends on the net transport of water vapor diffusing across the membrane pores from the hot feed side to the cold permeate side. A typical MD process operates at 60–90 °C, which is considerably lower than the traditional distillation process, and it has the potential to generate highly pure water as it facilitates the transport of the vapor phase only [100,104–106]. The lower operating temperatures of MD has created much interest in different industrial areas, including the food industry for concentrating fruit juices and sugar solutions; in the medical sector for biological fluid sterilization; and in environmental applications for the removal of volatile organic components (VOCs) and heavy metals from aqueous mixtures, although, the principal application of the MD process has been in the desalination area [107–112].

Like all other thermal processes, MD processes requires a significant amount of thermal energy to generate the water vapor from its liquid phase. Waste heat from industrial process or solar energy could potentially be an important alternate source of energy for this process. In the recent decade, the MD process has received much attention for its low energy requirement and production of high quality water and has been considered as a possible alternative for thermal desalination and the SWRO process or in combination with traditional desalination techniques to reduce operating costs and energy requirements [113–117]. Various types of membrane distillation have been in practice for several years, namely, direct contact MD (DCMD), vacuum MD (VMD), sweep gas MD (SGMD), and air gap MD (AGMD) based on the type of permeate side condensation process, with feed being in direct contact with the membrane in all the process [104,118,119].

The critical feature in the MD process is the membrane itself as it governs the total flux and selectivity of the process. However, the current throughput for the MD process is relatively low in comparison to RO processes due to inadequate membrane characteristics to provide higher flux and unfavorable economics of the process itself. Despite the advantages of the MD process including operating at low temperatures and atmospheric pressure, its ability to handle high concentration brine, and utilization of waste heat or solar heat for operations, the MD process suffers heavily due to the lower membrane yields [120]. It is critical that the membranes fabricated for MD process have suitable structural chemistry to achieve high performance. In an effort to address these issues, various research groups have contributed towards the development of novel membranes utilizing unique fabrication approaches and implementing suitable nanomaterials, which has provided control of the membrane structural chemistry, all of which are key factors for enhancing membrane desalination performance [121–124].

A comprehensive review of MD for desalination and the various operating parameters governing the overall performance, has been extensively reviewed earlier [118]. Various membrane characteristics that contribute towards the performances of MD include membrane thickness, porosity, liquid entry pressure, pore size, tortuosity, thermal conductivity, membrane surface area, roughness, and finally, the membrane material itself [106,125–129]. Over the recent decade, various researches have worked on incorporation of a wide range of metal/metal oxide nanoparticles such as zeolites, TiO₂, silica and silver into polymeric membranes. Incorporation of these metals/metal oxides provides remarkable advantages such as antimicrobial properties, super-hydrophobic or hydrophilic nature and ability to act as photo catalyst for the polymeric membranes. These features are attractive for membrane application especially for desalination as it mitigates biofouling and enhances membrane life-span [101,102,128,130–133]. On the other hand, carbon-based nanomaterials are emerging as novel materials with versatile properties that have great potential for membrane-based water treatment technologies. Carbon-based nanomaterials such as carbon nanotubes (CNTs), graphene/graphene oxide nanostructures, and nano-diamonds (NDs) are endowed with exciting properties like high

surface area, mechanical strength, electron affinity, smaller size, ability to modify functional properties that can enhance selectivity and are of great potential for membrane-based desalination [134–143]. The hydrophobic interior of defect free carbon-based nanomaterials provides a frictionless transport phenomena, which is of advantage for membrane-based treatment techniques [144,145]. Additionally, the membrane surface properties such as hydrophobicity and roughness can be altered by the use of functionalized carbon nanomaterials, which opens up avenues for enhancing membrane performance by altering its selectivity. The key feature of CNTs is their ability to reject salt and enable the transport of water vapor, which makes it the most favorable nanomaterial for desalination technologies. The small and controlled size of CNTs allow them to be designed for desalination membranes with well-designed flow patterns through the hollow core [4,146–149]. Numerous experimental and computational studies are under way to fabricate membrane with various carbon-based nanomaterials for scaling up and mitigating possible environment and health concerns.

Considering the sustainability of the process, two of the leading desalination technologies at this moment, thermal and RO, suffer from major drawbacks and technical difficulties [150]. Both of these processes are highly energy intensive either due to the heat requirement (thermal process) or the high-pressure demand (RO process), which create significant amounts of pollutants and undesired emissions. The scaling and fouling associated with these processes intensify the cost and complexity, which some of the major challenges of these processes. These shortcomings demand the quest for alternative sustainable, ecofriendly desalination techniques. Recently, MD coupled with a low-grade and renewable source of energy became a highly attractive alternative that considerably reduces the carbon footprint for water desalination. Judging by the fact that MD can be operated at relatively lower temperatures and has a wide tolerance range for operating conditions, a low intensity sustainable heat source should be sufficient to run the MD process. In this regard, coupling with solar energy can be utilized to supply the thermal energy necessary for the feed water. The use of solar collectors is another attractive way to utilize the solar energy as a heat source in MD. The solar collectors can supply the energy in the form of heat (solar thermal) or electrical energy (solar photovoltaic) [151,152].

Solar collector devices are used to absorb solar energy and then transfer the energy into a collection media. Common solar collectors include the flat-plate collector (FPC), evacuated tube collector (ETC), compound parabolic collectors (CPC), parabolic trough (PTC), linear Fresnel (LFC), parabolic dish reflector (PDR), central receiver collector (CRC), and the solar pond, which can be categorized according to the temperature level that the collection medium can reach [153]. Low temperature collectors (FPC or improved FPC, ETC) operate below 80 °C, which may not have application to conventional distillation systems, but are highly useful for MD applications. In the medium temperature collector (ETC, CPC, PTC etc. working in the range of 80–250 °C), a heat exchanger is applied to transfer the absorbed heat. Parabolic troughs or dishes or central receiver systems are mainly used as high temperature collectors, which focus the inbound sunbeams onto a receiver that collects the solar energy via a heat transfer fluid. The concentrated high solar energy is able to generate high temperature gradients and can be utilized either directly in thermal desalination process or applied to produce electricity using a steam turbine. By increasing the size of the high temperature collector and by implementing the sun tracking device, the efficiency can be enhanced sufficiently to supply the heat for large-scale thermal desalination processes. On the other hand, the low and medium temperature collectors may not be suitable for operating the conventional distillation process, but are highly appropriate for MD desalination that requires a relatively lower temperature gradient for water vapor generation. A schematic of a solar heating-assisted MD desalination system is presented in Figure 3.

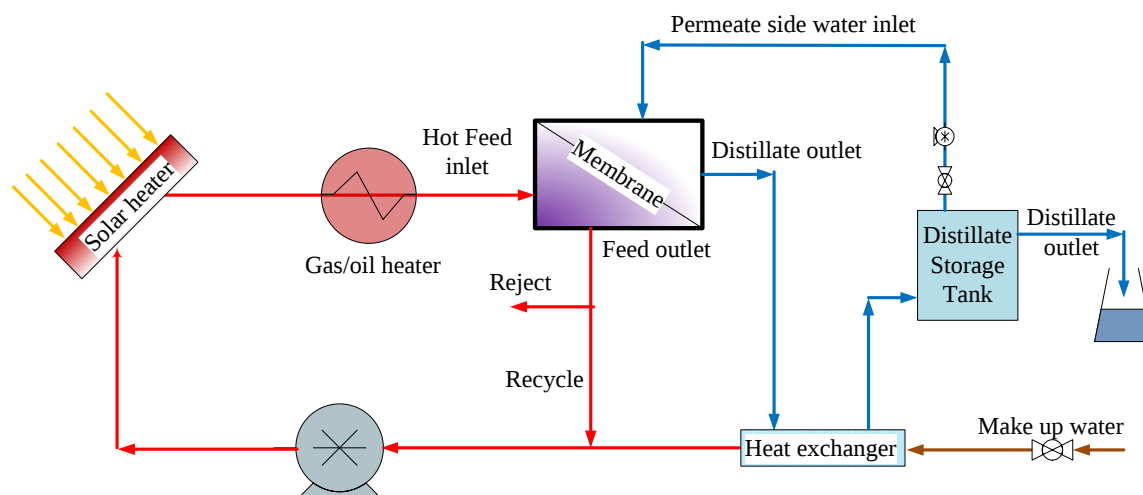


Figure 3. Schematic of solar heating assisted membrane distillation (MD) desalination.

The utilization of a solar pond, which is basically a large pool of salt water that is able to collect and store the solar heat energy is another way of transferring the solar energy into the heat energy required for MD [154]. In a solar pond, there are three layers with varying salinity known as the upper convective zone (UCZ), non-convective zone (NCZ) and lower convective zone (LCZ). The salinity of the UCZ is closer to fresh water whereas in the NCZ, the salinity increases with the increasing depth of the pond, and reaches the saturation point in the LCZ zone. The LCZ zone can absorb and store up to 40% of the total energy received from the sun and the temperature rises up to 80 °C [155]. This stored energy can be utilized to heat the feed water, and the reject can be recycled back to the LCZ zone in the solar pond. A number of research studies have been conducted to investigate the ability of coupling the most sustainable solar energy and desalination [152]. An MD system connected with a solar pond as a heat source is considered one of the most suitable solar powered membrane desalination systems in terms of the energy cost and environmental safety as it offers the least expensive way to heat the brine and the waste generated is recycled back [156].

Another interesting way to convert solar energy is the use of photovoltaic (PVC) cells, which convert it into electrical energy by transferring the electrons. The PVC cell is the key component in PVC applications and is considered as a direct current power generator. The PVC cells can be categorized as first generation, which includes crystalline silicon (c-Si) technologies, second generation, which includes amorphous silicon thin-film (TF) technologies, and the nano-PVC technologies as third generation. PVC capacity has been increasing very fast and in 2016, a 50% growth was observed and the cumulative installation capacity reached at least 302 GW, which is 1.8% of the global electricity consumption [157]. The crystalline silicon technology is still leading the PVC market with the highest conversion efficiency (15–18%). The thin film PVC technology is growing very fast due to its high efficiency and lower cost. However, the lack of availability of the PVC materials and its initial investment costs hinder its implementation and further development in MD systems.

Several solar power stations have been built throughout the world to supply sustainable heat energy to desalination industries and local regions for domestic usage. One of the largest concentrated solar power (CSP) plants, SHAMS, is situated in the city of Madinat Zayed, Abu Dhabi, in the United Arab Emirates (UAE). The CSP 100-MW plant has been operating since March 2013, covers 2.5 km² and supplies over 20,000 homes. Another large CSP plant was built and aims at treating 60,000 square meters of seawater daily for the northeastern city of Al Khafji in Saudi Arabia. In Chile, a project has been undertaken for the development of a large-scale desalinator powered with photovoltaic energy by Powered Water Trends Industrial and Almar Water Solutions [158]. KRYSTALLTM, in Switzerland is one of the world's first high-volume, 100% solar-powered turnkey water purification systems enclosed within 40-ft (12.2 m) containers that have been successfully desalinating water by utilizing solar energy.

However, because the solar radiation flux fluctuates significantly and is not continuous, a thermal energy storage (TES) system must be equipped with the desalination system for continuous operation. Among various TES systems, sensible heat storage, latent heat storage and thermos-chemical storage systems are most common and have been commercialized. Recently, researchers have shown interest in working with highly efficient nanofluids as the feed solution for solar energy harvesting in MD due to their localized surface plasmon resonance phenomenon [159]. The suspended nanoparticles (NPs) in the nanofluids absorb solar radiation and then dissipate through Landau damping, which causes a significant increase in temperature. The use of non-conventional heating sources, such as microwave heating can be useful for MD operation. Direct measurements have shown a reduction in power consumption by over 20% when microwave heating was used during experiments [160].

Coupling solar energy collector with an MD system has shown great potential in recovering pure water and waste water concentration as MD can operate at low temperatures, as well as having the capability of bearing wide variation in operating parameters. Researchers have made substantial efforts to implement solar energy resources into the MD system, specifically, inclusion of solar PVc cells to deliver the electricity required for feed pumps and other equipment, and the solar thermal collectors for supplying the heat to the feed solutions. Hogan et al. from the University of New South Wales, first published their work with a hollow fiber membrane MD system of $0.05 \text{ m}^3/\text{day}$ capacity using a 3 m^2 flat plate solar collector [161]. The results revealed that the system required 55.6 kWh/m^3 of total energy, and generated a water vapor flux of $17 \text{ L/day} \cdot \text{m}^2$ of collector area, which is highly comparable to that reported for solar multi-stage flash distillation and multiple-effect distillation. Cabassud et al. proposed four different possible ways of coupling solar energy with MD systems: (1) feed solution was supplied by a salinity gradient solar pond (SGSP); (2) the MD module was immersed directly in the SGSP; (3) solar collectors were used to heat the feed solution; and (4) solar collectors were placed directly on the membrane to heat the feed. The schematic of the proposed configurations is shown in Figure 4 [151,162]. The results showed that the modules with solar collectors generated higher water flux compared to those with solar ponds.

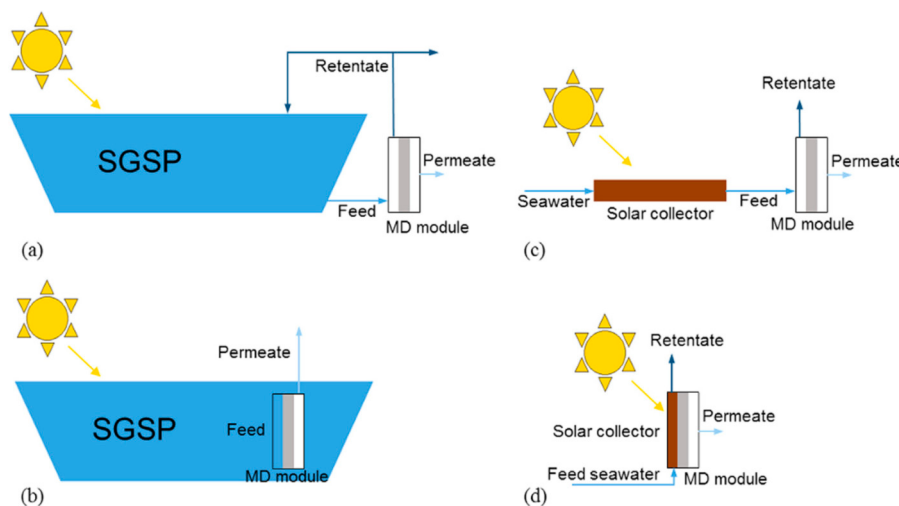


Figure 4. Four configurations coupling MD and solar energy: (a) feed water supplied by a SGSP; (b) module submerged directly in a SGSP; (c) feed water fed by solar collectors; (d) feed water heated directly on the membrane surface [151,162].

Ma et al. checked the feasibility of a vacuum MD-solar heating integrated small scale desalination system for populations residing on islands or in remote coastal areas without electricity or freshwater [151]. The system required 239 kWh/m^3 specific pumping energy and produced $8 \text{ kg/m}^3 \cdot \text{day}$ fresh water with a gained output ratio (GOR) as high as 0.71 without heat recovery from condensation. Rahaoui et al. used the surface of the solar pond as a heat sink for the permeate water

by incorporating floating cooling pipes, which also work as a wave suppressor to reduce wind driven surface mixing [163]. However, the implementation of solar energy in MD desalination plants remains a complicated issue and many techno-economical aspects need to be considered. The availability of suitable space near the seawater resources and land cost could be important issues. The accessibility of sunlight throughout the year, concentrating and storing the energy also needed to be addressed.

Among other sustainable energy sources, the hot water from the cooling circuit of thermal engines could possibly supply the low-grade heat required for MD. The temperature in this process normally reaches up to around 90 °C, which is perfectly appropriate for MD operation [164]. In geothermal areas the temperature of the hot brackish water (ranging from 145 °C–170 °C) is reduced to irrigate green houses and feed desalination plants. During the cooling process, the thermal energy is wasted and released to the atmosphere. The use of thermal salt water springs in a MD unit directly is a viable option for treating the water and utilization of heat. The hot produced water or fracking flowback is usually first cooled to a temperature below 55 °C and stored in a tank for further treatment or use. The inherent heat of this effluent could possibly be treated with MD as MD can handle higher salt concentrations. The waste heat from industries and specifically from power plants may act as a possible source of low-grade heat for MD. The amount of energy released from power plants as waste heat in the USA is observed to be more than 5000 TWh/year with another 3000 TWh/year from the industrial sector [165]. However, the temperature range is highly uncertain as most of the heat discharge from power plant remains below 42 °C. Direct treatment of power plant effluent or utilization of flue gas as a heat source to run low temperature MD operation is also another option. Another important source of waste energy is the nuclear power station. The aqueous radioactive waste from the nuclear plant containing chemicals and radiochemical compounds, could possibly be treated via the MD technique to utilize the available waste heat in the plant. The usage of waste heat from these resources in the MD process also offers additional environmental benefits by reducing the discharge temperature and quantity to meet environment protection regulations.

On a small-scale basis, the capability of MD processes can be improved by incorporating plasmonic and nanophotonic materials on the membrane surface followed by irradiation with UV light or sunlight [166,167]. The addition of plasmonic nanoparticles in the membrane enhances the water vapor flux in vacuum MD by 11 times, and the temperature at the membrane interface was found to be higher than the bulk temperature. These low capacity portable MD desalination systems would be suitable in places where the supply or availability of electric energy is limited. However, the enhancement of low driving forces is still a crucial challenge that needs to be overcome for feasible application of MD desalination systems.

2.1.3. Other Membrane Processes

Nowadays, the membrane processes used in various desalination technologies are taking a leading role, especially RO which holds the majority of the world's market share (60–90%). Among other thermal evaporative processes, MED and MSF technology still lead the desalination process in Gulf countries. However the limitations of the RO process and other thermal evaporative processes have paved the way for other emerging membrane-based processes for desalination such as pressure-retarded RO (PRO), forward osmosis (FO), membrane capacitive deionization (MCDI), electrodialysis (ED), nanofiltration (NF), pervaporation, etc. [2].

Recently, forward osmosis (FO) has received increased attention as an emerging purification technique and it has been investigated thoroughly for desalination in both the academic arena and industrial sectors decade [168–170]. The technology was initially proposed to be a breakthrough in terms of lower power consumption and higher water recovery, however, challenges associated with membrane back salt diffusion, draw solution recovery, and membrane regeneration limit its energy efficiency and feasibility for desalination.

In comparison to the traditional RO process, which requires higher hydraulic pressure, FO occurs spontaneously as it operates under osmotic pressure, thus reducing fouling or scaling and

brine discharge [168,171]. The FO process is similar to that of its counterpart RO in terms of process requirements. FO requires a selectively permeable membrane separating two fluids with different osmotic pressure and purifies as a two-step process, i.e., dilution of the draw solution and generation of fresh water by purifying the draw solution. Though the cost of operation and construction of FO desalination plants is lower than that of traditional RO plants, energy requirements for water recovery is of great concern [172]. The key driving force for successful operation of the FO process are the properties of the membrane and selection of the draw solution, which dictates the efficiency of the FO process. The cost of FO plants can be reduced by use of efficient membranes that offer high flux and draw solutions with desired properties that are technically viable [173]. Currently, FO membranes are fabricated with a thin rejection layer and a support layer with high porosity and low tortuosity to mitigate concentration polarization effects on the membrane [174,175]. Similarly choosing a suitable draw solution with zero toxicity, that exhibits high osmotic pressure with minimum reverse diffusion, and that simultaneously provides efficient recovery of water is of great importance. Major disadvantages of the FO process are the per unit cost for production of freshwater for the amount of water treated, and the effect of concentration polarization on either side of FO membranes, which in turn affects transmembrane osmotic pressure, resulting in reduced flux and water recovery. These factors significantly impact the operating cost of FO processes [176–181].

Alternatively, PRO is a method of producing renewable energy from a mixture of two streams with varying salinity, where surface water and seawater are separated by a semi-permeable membrane [182]. Permeate from the diluted feed stream migrates to the concentrated draw stream under pressure via osmosis. A unique feature of the PRO process is that it facilitates the conversion of osmotic pressure difference between the separated solutions to hydraulic pressure, which is in turn utilized for generation of power driven by the hydro-turbines. This technique can be cost effective with optimized maintenance of osmotic pressure [18,183–185]. O'Toole examined the net specific energy production from a river-to-sea PRO system using a novel simulation technique that combines parasitic loads and efficiencies of the PRO facility components. The maximum specific energy available and the recovered overall net specific energy at 291 K was found to be approximately 0.72 kWh/m³ and 0.12 kWh/m³ of permeated water, respectively. The values suggested that the PRO process can recover 55% of the Gibbs free energy of mixing [186]. Although, theoretically a substantial amount of energy could possibly be extracted from the rivers meeting the sea, the density of this energy is significantly low, that is, 0.256 kWh/m³ for the feed water. Therefore, a large volume of water needs to be pumped to generate the energy for conversion. The effectiveness of the energy conversion depends on the energetic cost of operation and losses during energy extraction [187]. Again, the profound challenge for the technical and economic feasibility of the PRO process is a lack of commercial availability of PRO specific membranes. PRO membranes are similar to FO membranes in terms of structural attributes, but unlike FO membranes, PRO membranes are highly prone to fouling due to absence of cross-flow with reduced hydrodynamic shear, which adversely affects the PRO process [39,188]. Several studies have focused on developing membranes specifically for PRO processes with the ability to generate high power densities [189,190]. Often deformation of membrane structures is of huge concern due to high pressure conditions. So as to mitigate the impact of heterogeneous compaction and high-pressure deformation of membranes, membranes for the PRO process are fabricated as surface containing sponge-like structures with strong mechanical strength [185,191–193].

MCDI is a membrane-based CDI process, that relies on application of electrical potential difference across oppositely placed porous electrodes placed in front of ion-exchange membranes [194–196]. MCDI operating at constant current mode, can produce freshwater with uniform effluent concentrations. Unlike traditional CDI systems, the introduction of membranes prevents adsorption of ions during the regeneration process. Energy requirements are significantly lower than other traditional approaches, which makes MCDI an attractive alternative for desalination [196–198]. Similar to other approaches, the overall performance of MCDI greatly depends on optimization of materials and processes. Key features that are attributes for optimization of ion-exchange membranes

are high ion selectivity and good chemical durability that enhances ion exchange capacity and electrical conductivity to render low resistance. Recent studies have exhibited the enhanced performance by MCDI equipped with CNT electrodes by minimizing ion desorption [199–201]. The right combination of materials and optimized conditions have increased the efficiency of salt removal capacity in the MCDI process by 50% in comparison to the traditional CDI process.

In low-salinity desalination technology, electromembrane processes, such as, electrodialysis (ED), electrodialysis reversal (EDR) and electrodeionization (EDI), are still making a steady and significant contribution. Recently in South Africa, an EDR plant was established with a maximum capacity of 10,000 m³/day for brackish water treatment. The use of ED or EDI in several industrial sectors including brine concentration in sea-salt manufacturing, fruit juice processing, and generation of ultrapure water for electronics, were observed to be more suitable than commercial RO processes [202–205]. Luo et al. have proposed power free electrodialysis (PFED) for water desalination by integrating it with reverse electrodialysis (RED) as an energy donor [206]. The results established the feasibility of the integration process and successfully generated potable water for drinking. The coupling of the ED process with renewable energy sources, such as PVc and wind energy make ED extremely promising as the membrane process match the fluctuating behavior of these sustainable sources [206,207]. The use of PVc to power the ED desalination of brackish water was observed to be highly promising considering the sustainability of this process with minimum environmental effect [208]. Although a wide range of treatment capacities (1–200 m³/day) have been reported, most of the plants were small and treated brackish water. The SEC of the ED-PVc plant without any storage was observed to be in the range of 0.4–4.0 kWh/m³. The SEC of a typical brackish water EDR process is ~10% lower than that of the RO process. PVc supported ED process for the treatment of brackish water reduced the energy consumption up to 0.724 kg CO₂-eq·m⁻³. The PVc-ED process reduced the emission of greenhouse gases of an order of magnitude. However, for the seawater desalination, the energy consumption increases significantly for ED, which makes RO a preferred technology [209].

Despite the benefit of the ED process in desalination technology, there are several hurdles that need to be overcome to obtain the full potential of this process. One of the challenging issues is the implementation of ED with the PVc process and matching the treatment capacity with intermittent output of solar energy. Other issues are the establishment of an appropriate energy storage device that can efficiently store the excess energy produced by the PVc unit and supply energy during deficient times, and finally, the shorter life time of the membrane functioning at elevated current densities and higher feed salinity.

Another alternative method that has shown high potential for energy efficient desalination is pervaporation (PV). The high energy conservation efficiency of the PV process along with its ability to handle high salinity, high salt rejection and lower cost make the process suitable for desalination [210,211]. The use of hydrophilic membrane materials also effectively reduces the membrane fouling compared to membrane distillation. Although, the PV process has been mainly used to separate miscible liquid mixture systems through a dense selective layer, it is being now tried for desalination purposes [212,213]. The PV process involves several complex sub-processes: sorption of the preferential component into the membrane at the feed side; diffusion of the sorbed species through the membrane under a concentration gradient between feed and permeate side; and finally, desorption of the permeants. The desalination process in PV can be considered as the removal of free water molecules from the larger hydrated salt ions. As the diffusion of solid solute is restricted through the membrane, the process offers complete salt rejection. However, the unavailability of high-performance PV membranes for desalination having both high flux and selectivity is the major problem with this process. Researchers have developed novel hybrid composite membranes to overcome this challenge. A novel polyvinyl alcohol (PVA)-based thin film nanofiber pervaporation composite membrane was synthesized and tested for desalination performances at room temperature. The water flux reached as high as 8.53 L/m²·h and 7.24 L/m²·h at 5000 ppm and 35,000 ppm NaCl concentration, respectively, with a salt rejection higher than 99.5% [212]. All of these newly developed membranes

have shown significantly higher salt rejection, however, the water fluxes that were obtained were quite low. The introduction of nanomaterials can often resolve this issue due to their unique properties. The synergetic effect of GO and polyimide (PI) in GO-PI mixed matrix membranes have shown enhanced flux of $36.1 \text{ kg/m}^2\cdot\text{h}$ with 99.9% salt rejection [214]. Polyacrylonitrile (PAN) supported thin graphene oxide (GO) composite membranes with 2D nanochannels were fabricated by using a vacuum filtration-assisted assembly method for pervaporative desalination of 35,000 ppm brine at 90°C , which exhibited a very high water flux of about $65.1 \text{ L/m}^2\cdot\text{h}$ and 99.9% salt rejection [215]. The incorporation of silica NMs into the PVA matrix via a sol-gel reaction technique exhibited very high water flux of $96 \text{ L/m}^2\cdot\text{h}$ treating 2000 ppm saline water [216]. Although, PV is considered as an energy saving process, a significant change in enthalpy and Gibbs energy occurs in this process, which is quite similar to that of the RO and MD processes. The energy efficiency is primarily determined by the availability of the renewable energy sources, like solar or waste heat, etc. that is required to heat the feed solution. The electrical energy utilization for the pumping of the feed and the permeate water also contribute a significant amount of energy consumption during the desalination process.

2.1.4. Hybrid Membranes Process

There is growing emphasis on combining two or more desalination processes to form an integrated approach, so that these processes complement each other by diluting the disadvantages of a single process by itself. These combined processes are win-win as the efficacy of these processes are higher than an individual stand-alone approach. This solution overcomes the barriers of the individual process and increases overall performance by integrating the processes. For instance, in a FO-RO hybrid mode, FO acts as a pretreatment process reducing the feed salt concentration, which upon introduction to the RO process requires lower hydraulic pressure and reduces fouling [1,217,218]. The economic evaluation of the FO-RO hybrid system, carried out by Blandin et al. has shown the benefit of the hybrid process over a stand-alone RO system in terms of energy and operational costs [219]. The analysis revealed that improvement in water permeation flux above $30 \text{ L/m}^2\cdot\text{h}$ is certainly required if the process is to be economically viable, which is a major constraint with current commercially available membrane systems. Similarly, in the case of PRO-RO hybrid systems, PRO serves as a pretreatment technique that reduces the brine salt concentration, which in turn enhances the efficacy of the RO process [220,221]. In the hybrid FO-RO process, the FO can effectively function as a pre-treatment for the RO process that reduces the membrane scaling and fouling in the RO process, and on the other hand, the RO can be efficiently utilized to recover the draw solution. Overall, the hybrid systems result in enhanced membrane performance, reduced energy requirements, and increased productivity in comparison to individual stand-alone processes [222]. The hybrid FO-RO process still requires significant development before reaching its full commercial potential.

The unique features of MD allow it to be integrated with other membrane processes including RO, nanofiltration (NF) and FO. In general, MD is implemented within RO and FO systems in two ways: either using the RO or NF concentrate as feed to the MD; or the permeated water from RO or NF as the feed to the MD [223]. The use of RO reject as MD feed allows the hybrid system to concentrate further beyond the RO upper concentration limit of 70 K ppm salt concentration. This system not only offers enhanced water recovery, but also reduces the disposal issue of concentrated brine. Research data showed that the integration of vacuum-enhanced direct contact membrane distillation (VEDCMD) has achieved water recoveries up to 81% from the brines, however, it suffers from scaling on membranes [224]. The other option for feeding the RO or NF permeate is mainly concerned with the pretreatment of MD feed. The utilization of RO or NF successfully removes the scaling salts that are responsible for rapid flux reduction, membrane wetting and salt leakage [225]. Integration of MD in the regeneration step of FO draw solution was observed to be highly efficient and allows the FO system to generate potable water from the feed solution. Xie et al. demonstrated the treatment capacity of the FO-MD hybrid system for small-scale decentralized sewer mining [226]. High water recovery up to 80% was observed along with removal of trace organic contaminants ranging

from 91–98% treating raw sewage as feed. The integrated hybrid systems need to be explored further for practical application.

Recently, nanofiltration (NF) has become highly important as an integrated process for commercial desalination industries. NF of aqueous and organic solutions has been used commercially for quite some time [227–229]. This pressure driven membrane process works with the membranes with a pore size in between RO and ultrafiltration (UF). NF operates at much lower pressure compared to RO, generates high water flux with high rejection for scale forming bivalent ions, and requires less initial investment [228]. A numbers of studies have been conducted to evaluate the potential of the NF technique under various application conditions and areas [230]. Various commercially available membranes, such as NF90, NF 200, NF270 (Dow Filmtec, Dow Chemical Company, Midland, MI, USA), and N30F (MICRODYN-NADIR, Wiesbaden, Germany), K-SR2 (Koch Membrane Systems Inc., Wilmington, MA, USA), ESNA1-LF2 (Hydranautics, Oceanside, CA, USA), and NF99HF (Alfa Laval, Richmond, VA, USA) have been investigated and their performances in terms of water flux and salt rejection have been analyzed by using the Spiegler–Kedem and Steric Hindrance Pore models [227,228,231,232]. The membranes have shown reasonable flux with high rejection to divalent ions. In general, the NF process has been used effectively for the purpose of softening of water, reduction of TDS of seawater and removal of disinfection precursors, often as a pretreatment process for commercial desalination or water treatment industries. The combination of NF with other membrane separation processes was observed to be beneficial in terms of overall recovery and energy requirements. A recent study with nanofiltration (NF) membranes as a pre-treatment with MED was conducted by the Saline Water Desalination Research Institute (SWDRI) of SWCC and the Water Re-use Promotion Center (WRPC) of Japan together with Sasakura Engineering Co. Ltd. showed promising results in increasing the top brine temperature (TBT) from 65 °C up to 125 °C [233]. The development of two stage NF-NF desalination systems was observed to be more effective than a conventional single stage RO system in removing mono and bivalent ions from seawater, as well as 20–30% lower energy costs. A simulation with two-stage NF desalination at 35,000 ppm feed concentration, with 37 bar and 19 bar pressure at the first and second stage, respectively, showed a recovery of 59% and 67%, respectively [234]. This energy efficient dual stage NF desalination system was adopted successfully for a daily water production plant in Long Beach, CA, USA. The research analysis of dual-stage NF seawater desalination revealed that the pressure drop along and through the membrane was the main reason for exergy destruction in the membrane element [235]. The dual stage NF may increase the capacity compared to the conventional SWRO process as higher membrane components are required, however, the lower operating cost reduces the operating cost. The permeated water does not need to re-mineralize to attain drinking water quality.

The integration of NF with other separation techniques often offers the synergetic efficiency of both processes. Implementing NF with a RO desalination system may increase the cost and intricacy of the process; however, it was observed to be beneficial through the removal of bivalent ions from the RO feed system, thus reducing the operating pressure. Research studies have shown that the NF process significantly reduced the hardness of the feed solution prior to introducing it into the RO system, which helped to achieve a 27% reduction in water production costs compared to SWRO [228]. The average normalized permeate flux of RO and the NF-RO integrated system for desalination of MBR effluent under a similar recovery rate (~69%) was observed to be 86.0 L/m²·h and 96.9 L/m²·h, respectively [236]. The integration of NF with FO has also indicated a promising future in the desalination and water treatment sector. Kim et al. performed an environmental and economic life cycle assessment (LCA) that compares the fertilizer drawn FO-NF hybrid system in the desalination of mine impaired saline groundwater with two conventional RO hybrid systems [237]. The FO-NF hybrid system exhibited better performances in terms of lower energy consumption and operating cost, and required less cleaning chemicals. The utilization of NF with the MD process has also been investigated. Karakulski and Gryata studied the production of demineralized water via an NF-MD hybrid system [225]. It was observed that the scaling of calcium carbonate (CaCO₃) salt on MD

membrane drastically decreases the performance. The softening of the feed water via the NF system enhanced the performance of the MD module without increasing the energy requirement significantly.

Although the research has shown promising outcomes from the implementation of hybrid membrane systems in desalination and water treatment industries, the integrated systems need to be evaluated further to overcome their drawbacks. More studies are required to evaluate the overall energy consumption of the hybrid process as increase in energy consumption for a particular part may influence the energy consumption of the following process. The economic analysis of the mixed systems is one of the most important and crucial factors for determining the process viability, and very little information is available in this context.

3. Role of Membranes in Sustainable Energy

The importance of membrane processes in a large number of industrial applications has increased significantly due to their low energy requirements. The production of alternative energies has been intensified extensively through the application of membrane technologies. In this context, Kondrateva et al. demonstrated a promising membrane-based renewable energy source based on osmotic pressure difference arising from water-salinity gradients [238]. It has been observed that the PRO process can generate power up to 1 MW/m³ of freshwater that passes through the system per second [239]. The membrane processes are now becoming highly popular in other energy sectors such as batteries and fuel cells, purification of biofuels, etc.

3.1. Batteries and Fuel Cells

With evolving clean technologies for power generation, energy storage devices are gaining importance and are expected to play an important role in the storage of electricity. Among various energy storage devices, batteries and fuel cells are of great importance due to their high-energy densities. Batteries simply convert stored chemical energy to electrical energy, and require recharging upon exhaustion. Proton-exchange membrane fuel cells (PEMFCs) are polymer electrolyte membrane fuel cells commonly used in automotive applications for their rapid start-up and shutdown capabilities and are capable of withstanding thermal shock and high temperature corrosion [240–243]. Over the last decade, significant progress has been achieved through the synthesis of novel materials, optimization of the design and process conditions in enhancing the stability and performance of the anion exchange membrane fuel cell (AEMFC) [244,245]. Lithium ion batteries (LIBs) are strong competitors for fuel cells, and are usually used in portable electronic devices and microelectronic devices with the advantage of a long life span. Membranes play a key role in both LIBs and PEMFCs by physically separating two different electrodes (anode and cathode) from electrical shorting and simultaneously serving as a electrolyte reservoir for ionic transport [242].

LIBs are composed of an anode, a cathode and an electrolyte, in which discharged lithium ions migrate from anode to cathode across the electrolyte to produce current. In the presence of an external current, lithium ions are re-migrated back to the anode, thus allowing the batteries to be well equipped for future use. The key role of the membrane is to separate two electrodes so as to prevent short circuit. The role of the LIB separator is to provide electrochemical stability, mechanical strength, quick wettability, uniform thickness and pore size, high porosity and tortuosity and good thermal stability [246,247]. Researchers have recognized that membrane lithium air batteries (LABs) are more suitable than non-membrane LABs as an alternative energy source for future applications [248]. Different microporous membranes fabricated from polypropylene (PP) and polyethylene (PE) have been used most commonly based on the desired characteristics for LIB. However, their poor thermal stability, low wettability and inferior electrolyte retention impacts the process negatively and reduces battery performance. Alternately, microporous PVDF membranes provide good mechanical/thermal stability, good wettability, electrochemical stability and good physiochemical interaction but also produce lithium fluoride, which can potentially affect the process [249–252]. Recent studies have mainly focused on fabricating ion membranes that demonstrate high thermal and mechanical stability

and good interfacial compatibility between the electrodes. Apart from LIB, redox flow batteries (RFBs) have shown immense possibilities in the area of large-scale energy storage and fueling electrical automobiles [253]. The choice of active materials, electrolytes and membrane materials are the main concern in designing both aqueous and non-aqueous RFBs [254]. The membrane itself is one of the most crucial and costly part in RFBs. The membrane plays an important role in separating the anolyte and catholyte, while allowing the charge carrying ions through it to maintain electrolyte balance and electrical neutrality. Nafion-based membranes have been used widely in the fabrication of efficient RFBs [255]. The RFBs prepared by using vanadium as an active material (VFRB) are one of the most common and widely developed systems and they have shown long life of about 200,000 cycles for over 10 years in Japan [256]. However, the higher cost of the ingredients and lower energy density of RFBs (20–60 Wh/L for VFRBs) hinder its implementation. The fabrication and employment of an aromatic poly (ether sulfone) composite ion exchange membrane exhibited enhanced stability with a coulombic efficiency of 99.36% and an energy efficiency of 81.61% at the current density of 140 mA/cm^{−2} [257]. A highly conductive and chemically stable separator fabricated from flat porous glass membrane as an alternative to polymer membrane has been developed. The voltage, coulombic and energy efficiency of 85.1%, 97.9% and 76.3%, respectively, was achieved for the vanadium redox-flow battery in 20–60 mA/cm² [258].

The applications of PEMFCs have been increasing in the area of transportation, and portable and stationary power generation. In transportation, PEMFCs have replaced internal combustion engine units in many light weight vehicles, utility vehicles and regular domestic vehicles, which range from 20 kW to 250 kW, due to their higher efficiency and lower greenhouse gas emissions [259–261]. Likewise, portable PEMFCs are preferred for the generation of high energy power and lower charging time, and typical power for such devices ranges from 5 to 50 W. This has also been explored for high power requirements ranging from 100–500 W or <5 W for low power requirements [262,263]. Portable PEMFCs are predominantly applied in various portable electronic devices such as laptops, mobile phones, electronic chargers, electronic toys, radio-controlled cars, battery powered boats and robots, emergency lights, and so on [264]. Stationary PEMFCs are quite common in residential applications and household usage where the waste heat of fuel cells is utilized. The most common example of stationary PEMFCs are back-up power generators. However, economic viability of scaling up this application depends on the efficiency of fuel cells and the associated costs. The major approach in reducing the overall cost is to reduce the cost of the membrane itself [265]. It has been observed that with expansion in current, the voltage decreases slowly due to the losses related to the fuel cell. The regulating mechanism is highly important in handling large rated power systems and the problems associated with structural planning and arrangements needed to be thoroughly investigated. The integration of an efficient energy storage system is extremely necessary to maintain the consistency of fuel cell-based power systems [266].

3.2. Membranes for Biofuel Purification

Biofuels produced from biomass is a form of fuel for transportation, and is well established in countries such as Brazil and Sweden. Unlike fossil fuels, biofuel sources are easily accessible, have reduced CO₂ emission, are environmentally friendly, biodegradable and sustainable [267]. The major drawback is the feedstock cultivation and demand in conjunction with food supply. Biofuels are of two main categories; first, biodiesel (fatty acid methyl ester (FAME)) produced by transesterification of vegetable oil or animal fat by methanol, and second, bioethanol produced from fermentation of biomass [268–270]. Membrane technology plays a major role in the production of both bioethanol and biodiesel.

In the case of biodiesel, the membrane process is used for purification by removing glycerol from the product stream and to retain unreacted lipid within the membrane by the two basic principles of size exclusion and perm-selectivity [269,271,272]. In the case of size exclusion, either carbon-based membrane or ceramic membrane is used because of its high resistance to degradation and corrosion

under a rough production environment. Based on the polarity of oil droplets and methanol in the product stream, a two-phase system of oil droplets and product is generated [268,273–279]. Since oil droplets are larger in size than the product biodiesel, the byproduct is filtered by a membrane through the size exclusion principle whereas, purification based on membrane selectivity requires a non-porous dense hydrophilic polymeric membrane, such as polyvinyl alcohol (PVA). The separation is based on interaction between the component of interest and the membrane. For example, glycerol and methanol have strong interactions with –OH groups present in PVA via hydrogen bonding, which facilitates transport of glycerol through the membrane. This allows constant removal of byproducts from the product stream while retaining the biodiesel [275–277]. This process can produce high quality biodiesel with a nearly 93.5% conversion rate without further purification steps.

The commercial production of biodiesel from ethanol and vegetable oils suffers a number of difficulties in the separation and purification steps of the synthesized esters. During the transesterification reaction process, large amounts of water are used to remove the by-product. The use of a solvent and alkali resistant ultrafiltration (UF) membrane was observed to be useful as an alternative for the washing process. Membranes fabricated from poly(vinylidene fluoride) and poly(sulfone) material have been employed to reduce glycerol content of the biodiesel solutions [278]. The poly(vinylidene fluoride) membrane successfully reduced the water usage (only 0.5 wt% water) and separated glycerol up to 67% from a biodiesel sample. Recently, catalyst immobilize membranes were fabricated to combine the two-step process to a single step process, where acid catalyst membranes were esterified with 5-sulphosalicylic acid to introduce sulfonic groups to the polymer matrix or by blending polystyrene sulfonic acid to the polymeric matrix used for fabrication. Additionally, amino functionalized CNTs or similar heterogeneous catalyst can be embedded in the polymeric matrix to form catalytic membranes [273,279]. In the case of bioethanol, membrane technology plays a vital role in the separation of algal biomass for fermentation by microfiltration and ultrafiltration, followed by membrane distillation (MD) or pervaporation for further purification of ethanol from the fermentation broth. In the downstream purification process of bioethanol, the integration of membrane techniques with traditional bioreactor facilitates recycling of cells and residual sugars to the fermentation unit. The novel compact, ecofriendly sugarcane juice plant design exhibits high productivity (14.6 g/L/h), yield (48%) and concentration capability (97.6 g/L). The product mixture was then finally concentrated up to 98% purity via a solar-driven DCMD process [280]. However, like any other membrane process, fouling is a major challenge in biofuel purification [281–283]. The effect of membrane properties and their impact on biofuel purification is yet to be explored for scale of the process.

4. Future Prospects

The interrelationship between water and energy is intensifying significantly as a result of their ecological, regional and economic implications. The major challenges in this century for developing sustainable desalination technologies are: reducing energy consumption, lowering the environmental effect; and minimizing water production costs.

Membrane and membrane-based technologies have been applied widely in various water purification and waste treatment applications, either individually or in combination with other processes. Currently, membrane processes such as RO, FO, UF, NF, MD are being used in seawater desalination, and waste water treatment applications. The effective utilization of membrane technologies as a sustainable solution for different applications requires novel membrane materials along with customized separation characteristics. Although, significant improvement in the desalination sector has been observed in terms of high permeation rate and salt rejection, membranes with controlled and distinct pores, tailored functionalities and defined passage channels for specific constituents could further lead to enhanced separation, purification and recovery of important products from various resources. Recent developments in polymeric materials and the emergence of nanomaterials have paved the way for more membrane-based processes for various applications with potential industrial use. However, the fabrication of new membrane materials with improved chemical

and thermal stability for the treatment of industrial effluents needs to be explored in future. Depending on the requirements of specific applications, water quality could be monitored and alternative water treatments should be implemented, which remains an open challenge. Despite its advantages, huge effort is still required to mitigate some of the key concerns such as fouling, selectivity, polarization in case of membrane desalination process, and higher recovery with respect to the amount of feed treated. Membrane processes play a major role in both water purification and sustainable energy generation either individually or in combination with other membrane-based techniques, or by utilization of low-cost heat sources to make the process economic and viable for industrial applications. Membranes have started to play an important role in energy sectors, ranging from biofuel production to fuel cell application. Their performance in these sectors also depends on the quality and availability of the membrane components, hence it is important to achieve the synthesis of highly chemical, thermal and oxidative resistant materials. In summary, membrane-based approaches open up avenues for the development of a sustainable environment with respect to water treatment and energy generation, with ongoing challenges for material scientists and membrane technologists to develop new, robust materials and economic hybrid processes.

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Abbreviations

AEMFC	anion exchange membrane fuel cell
AGMD	air gap membrane distillation
BCS	brine conversion system
BWRO	brackish water reverse osmosis
CDI	capacitive deionization
CNT	carbon nanotube
CPC	compound parabolic collector
CRC	central receiver collector
CSP	concentrated solar power
DCMD	direct contact membrane distillation
ED	electrodialysis
EDR	electrodialysis reversal
ERD	energy recovery devices
ETC	evacuated tube collector
FO	forward osmosis
FPC	flat plate collector
GO	graphene oxide
GOR	gained output ratio
LCZ	lower convective zone
LFC	linear Fresnel collector
LIB	lithium ion battery
MBR	membrane bioreactor
MCDI	membrane capacitive deionization
MD	membrane distillation
MEB	multi-effect boiling
MED	multiple effect distillation
MSF	multi-stage flash
MVC	mechanical vapor compression

NCZ	non-convective zone
ND	nano-diamonds
NF	nanofiltration
NP	nanoparticle
PEMFC	proton-exchange membrane fuel cell
PDR	parabolic dish reflector
PRO	pressure-retarded reverse osmosis
PV	pervaporation
PVc	photovoltaic
PTC	parabolic trough collector
REE	rare earth element
RFB	redox flow battery
RO	reverse osmosis
SEC	specific energy consumption
SGMD	sweep gas MD
SGSP	salinity gradient solar pond
SWRO	seawater reverse osmosis
TES	thermal energy storage
TF	thin-film
UCZ	upper convective zone
VEDCMD	vacuum-enhanced DCMD
VMD	vacuum MD
VOC	volatile organic components

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