# Towards sustainability in water-energy nexus: Ocean energy for seawater desalination

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## Abstract

Seawater desalination is an important option for addressing the world's water supply challenges. Current desalination plants use enormous quantities of energy and cause a number of environmental issues. Renewable energy options, mostly solar and geothermal systems, have been examined in detail to supply the energy needed for water desalination. The co-location benefit of energy derived from the ocean to power seawater desalination processes is appealing. However, the promise and potential of ocean-based power generation for desalination systems has not been investigated in detail. The development of such systems has been limited due to technological and economic limitations of energy harvesting and transport as well as device maintenance under water. In this paper, we review the state of the art of ocean energy in desalination. It explores different sources of energy from the ocean that include electricity generation, as well as mechanical force and thermal energy and salinity gradients that can also be directly harnessed for powering the desalination processes. We also examine recent advances in scaling up for commercial deployment, and discuss relevant cost, environmental and social concerns. The great potential of ocean energy for seawater desalination in terms of diverse energy forms, flexible integration methods and various deployment strategies can provide important environmental, water and social benefits for seawater desalination, thus promote sustainability in water-energy nexus. The use of ocean energy in desalination applications could benefit the future development of ocean energy technology in renewable energy sector.

**Keywords:** Desalination; Energy; Ocean mechanical force; Ocean thermal gradient; Ocean salinity gradient; Sustainability

## Contents

## 1. Introduction

Desalination has been an increasing part of the water supply mix for urban and industrial use globally. Comparing with the capacity of 8.09 million $m^3$/day in 1980 [1], the global contracted desalination capacity by 2014 has increased more than 10 fold in 34 years to 90.07 million $m^3$/day. About 53% of the total capacity was installed in the past 10 years since 2005 [1], and currently desalination plants operate in more than 120 countries.

The largest use of desalinated water is in the Middle East and North Africa (MENA) region (due to the extreme freshwater scarcity and rapid population growth). Seawater desalination systems have been used for more than five decades in MENA, and they currently have over 50% of the world's desalination capacity [2]. Australia – the driest continent - also relies on desalination for urban freshwater supplies. Desalination plants supply 15% of the water in Sydney, 30% in Melbourne, and up to 50% in Adelaide, Brisbane and Perth [3]. While desalination has long been used in dry areas, regions with seemingly ample supply of water have also resorted to building desalination plants due to large urban growth and perceived future uncertainties in precipitation due to climate change. For instance, San Diego County in the US is building a desalination plant in Carlsbad for $1 billion that will provide 50 million gallons of water to serve about 8% of regional water demand [4]. London's Thames Water Company has also built desalination capacity to ensure reliability and continuity of urban water supply [5].

Desalination offers an important supply option for regional water security, however it comes with a high energy cost. Removing the salts from saline water is an expensive process and consumes much more energy than most other fresh water supply and treatment options. For example, the typical cost of membrane-based seawater desalination process is between \$0.5/$m^3$ and \$3/$m^3$ which is associated with plant capacity and feed water quality [6]. The amount of energy consumed in seawater desalination to provide 1 $m^3$ drinkable water is 10 times higher than that for the treatment of river or lake water [7]. Energy is the largest single variable cost for a desalination process, varying from 30% to over 50% cost of water produced. It is thus a. major factor impacting the extent and feasibility of desalination.

Current large-scale desalination technologies rely on thermal energy or electricity generated by fossil fuels. The high energy consumption in desalination not only results in an increase in the exposure of the water supply to energy prices but also raises concerns about environmental impacts. The intensive demand for heating or electricity results in greenhouse gas (GHG) emissions. The gas emissions to power desalination processes with fossil fuels also include carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide ($NO_2$), and sulfur dioxide ($SO_2$), all of which cause risks to public health [8]. In addition, all desalination processes regardless the energy source generate high temperature, high salinity brine containing a considerable amount of chemicals. Brine disposal can have serious impacts on marine ecosystem in near-shore environments.

Most efforts towards sustainable desalination have aimed to improve energy efficiency, the utilization of renewable energy, and the management of concentrated brine. In this paper we focus on the use of renewable energy. The use of solar and wind power for seawater desalination has been intensively studied [9-11]. There also have been efforts to explore the use of geo-thermal energy for desalination [11]. However, the full range prospects for using energy derived from the oceans for seawater desalination processes have not been extensively examined. Oceans represent a significant, predictable resource of renewable energy in various forms. For desalination, ocean energy has the unique advantage of natural collocation of production and use thereby eliminating the need for and costs of energy transmission.

In this article, we present an up-to-date and critical overview of ocean energy as a source of renewable energy for seawater desalination. To the best of our knowledge, this is a first attempt to present a comprehensive review of the prospects of ocean energy for desalination. We discuss the state-of-the-art technologies that have been developed (mainly in pilot and some limited commercial scale applications) along with various forms of ocean energy. Furthermore, we highlight social and environmental issues related to expanded use of desalination and its coupling with ocean energy.

## 2. Current desalination technologies

The range of commercially available seawater desalination technologies and their share in installed capacity is shown in Figure 1. multi-stage flash distillation (MSF), multi-effect distillation (MED) and reverse osmosis (RO) are the dominant technologies for seawater desalination while electrodialysis (ED) and nanofiltration (NF) are usually applied for brackish water desalination.  MSF and MED rely on phase-change processes in which water is converted to vapor and recovered by a subsequent condensation process while RO, ED and NF are non-phase change processes by using a semi-permeable membrane to separate salts from water.

**Figure 1**. Total worldwide installed desalination capacity by technology [1].

Desalination cost is affected by several major factors including: (1) feed water characteristics, and concentrated brine disposal; (2) plant capacity and footprint; (3) energy; (4) operation and maintenance. Energy affects not only the cost of produced water but also the choice of desalination technology. For instance, the largest desalination plants, especially those using thermal processes, are located in the oil-rich regions of the Middle East (Figure 2)

**Figure 2**. Gulf Cooperation Council (GCC) countries' share of global desalination by technology (left) and capacity (right) [12]. GCC includes Saudi Arabia, UAE, Kuwait, Qatar, Bahrain, and Oman.

### 2.1 Desalination with phase change

Seawater desalination technologies with phase change are summarized in Table 1. The energy cost is converted to a common base as equivalent electrical energy consumption per unit of produced water (kWh/m$^3$). MSF, and MED are most widely used phase change desalination technologies and dominated the desalination capacity before 1990s. Although the share of MSF and MED has been significantly reduced due to the development of RO, these two technologies still maintain their foothold as about 30% of total commercial desalination capacity (Figure 1). Most of the Vapor Compression (VC) processes are used for small to medium scale applications and generally integrated with MED plants [13-15].

**Table 1**. A summary of current desalination technologies with phase change.

Membrane distillation (MD), adsorption desalination (AD) and humidification-dehumidification (HDH) are emerging desalination technologies under lab to pilot scale tests. MD combines thermal process and membrane separation process in one unit. The vapor pressure is generated by thermal energy, typically from the burning of fossil fuels, and serves as the driving force. A hydrophobic membrane works as a barrier to allow the passage of vapor, but rejects the salts and other non-volatile compounds in the feed water. MD offers an operation at atmospheric pressure and relatively low temperature (30 to 90 $^{o}$C). Current AD processes employ a silica gel as the adsorbent to efficiently take up water vapor through the chemical potential of the unsaturated absorbent. The absorbent is regenerated by mild heating with an external thermal source (50 to 85 $^{o}$C) [21]. HDH relies on the fact that air can be mixed with significant quantities of vapor [26]. A flow of dry air is used to extract water vapor from saline water at the expense of sensible heat of saline water, causing cooling [27]. The humid air then contacts a cooling surface to condensate water vapor for product water recovery. The HDH process has a simple layout, low-cost construction and low requirement of maintenance. The thermal desalination technologies are more promising for industrial applications where waste heat or renewable energy is available.

In contrast to most thermal desalination processes requiring heating of saline water, freezing desalination (FD) recovers fresh water from saline fluid by freezing and crystallization. Ice crystals are then collected and melted. The melted ice water can reach three to six times less salt content when compared with the feed saline water [28]. Multiple freezing and washing steps can further reduce the salt content. However, high initial investment, high operational cost for ice separation and the persistence of the primary odor and taste of the water have limited commercial application of FD [29, 30].

## 2.2 Desalination without phase change

Single-phase desalination is a separation and purification process without phase change. Under non-phase change processes, the salt and other contaminants are separated from the feed water to produce clean water. The driving force in single-phase processes is either hydraulic pressure or an electric field, and electric power is the primary energy source for all of single-phase desalination processes (Table 2).

RO and NF are well-known membrane separation processes driven by hydraulic pressure. Due to its relatively low rejection of monovalent ions (such as $Na^+$ and $Cl^-$), nanofiltration is mainly used for water softening, specific removal of heavy metals and desalination of brackish water [31]. The most reliable membrane process for seawater desalination is RO, and it has the largest share of global desalination capacity (Figure 1). The cost and performance of RO systems are affected by membrane fouling related to pre-treatment methods, anti-scaling agents and membrane properties. Membrane modules are also a continuing challenge in further improvement of RO performance. The most widely used RO modules are spiral-wound which are difficult to clean and have limited packing density as well as filtration efficiency.

Forward osmosis (FO) is an emerging membrane technology with a range of possible water treatment applications including seawater desalination [32]. In the FO process, water is extracted from a lower osmotic pressure feed solution into a higher osmotic pressure draw solution while an FO membrane is a barrier to reject/retain solutes and contaminants. The osmotic pressure is the driving force to run the FO process. Therefore, almost no external hydraulic pressure is required in the process, but a post-treatment of the diluted draw solution (DS) is needed to recover product water and/or reuse draw solution component. Water flux decline due to fouling in the FO process is lower than conventional pressure-driven membrane processes because the FO process itself does not induce suspended solids and other organic contaminants into the membrane [33]. This also reduces the need for an extensive pre-treatment of feed water. FO is generally hybridized with other processes. In order to achieve an easier and more sustainable draw solution regeneration process, different novel draw solutions, such as ammonia-carbon dioxide, magnetic nanoparticles, hydrogel, divalent salts and switchable polarity solvent, have been studied in FO processes [34-38]. Most of the draw solutes investigated for FO desalination are not yet commercially feasible due to their material and regeneration cost, and maximum FO water fluxes.

**Table 2**. Summary of current desalination technologies without phase change

## 3. Ocean energy for seawater desalination

### 3.1 Energy consumption in seawater desalination

Regardless of the separation mechanism (based on phase change or non-phase change processes), the thermodynamic analysis of minimum isothermal reversible work of separation shows that the theoretical minimum energy to remove salt from seawater is 0.79 kWh/m$^3$ at the recovery rate of 0% and 1.06 kWh/m$^3$ at the recovery rate of 50% for a typical seawater salt concentration of 35,000 mg/L [46, 47]. In the last few decades, desalination costs have been reduced by collocating thermal desalination process with thermal power plants to utilize waste heat, improving membrane properties, using high efficiency pumps, using energy recovery devices, etc. The energy consumption in desalination in this decade is one order of magnitude than that in early desalination plants in the 1960s (Figure 3).

**Figure 3**. Trends in energy consumption of seawater desalination [15].

However, with the rapid increase in desalination capacity, a significant amount of fossil fuel is consumed annually by seawater desalination process. For example, about 1.5 million barrels of oil equivalent is burned daily for desalination in Saudi Arabia [2]. Some estimates have shown that GCC countries consume 5-12% or more of total national electricity consumption for desalination [48]. Per unit production costs of water, cost of energy (including thermal and electricity) constitutes up to 48% of total cost for thermal seawater desalination (MSF and MED) and 32% for the RO seawater desalination process [49]. At present, RO is the most energy-efficient technology for seawater desalination at industrial scale. The further improvement of RO membranes, possible but difficult, may result in a 10-30% reduction in actual energy consumption of RO desalination [46]. It is considerably approaching the thermodynamic limit for seawater desalination. Considering the intrinsic energy inefficiency caused by friction, loss of heat, pressure trop and so on in practical operation, the potential for further reduction of fossil fuel consumed by desalination lies in applying renewable energy and recovering/reusing waste energy

### 3.2 Potential of ocean energy for seawater desalination

Renewable energy can reduce the consumption of fossil fuel for desalination. However, the dominant renewable sources (e.g. solar, wind, geothermal) either are highly location dependent or have intermittent power output. Besides the access to the saline water and the end consumers, a consistent power input is preferred in existing electricity powered desalination plants (mainly reverse osmosis) for an efficient water production and stable supply. In order to maintain the performance and efficiency of membrane modules, energy recovery devices and pumps, the flow rate cannot be reduced or increased at will. The disconnection between variable power generation of renewables (i.e. solar, wind) and the need for consistent power input for most desalination plants has limited the deployment of renewable energy in desalination. Therefore, the renewable energy often feeds the power into grid as indirect compensation to resolve problems with intermittent and variable intensities of power generation [47].

Within the renewable sources, ocean energy offers some notable advantages: 1) it is located close to where most of the population lives (and where the large-scale desalination systems are installed). Two-fifths of cities with populations of 1 million to 10 million people are located near coastlines while 14 of the largest 17 cities in the world are situated along coasts [32]; and 2) it can provide base load (consistently available) power unlike the intermittent solar and wind power. The ocean energy is a predictable and 7/24 energy source while solar and wind energy can be disrupted due to simple weather changes or have a limited period in a day for power generation; 3) There are three categories of ocean energy: thermal, mechanical, and chemical (salt gradient). The various forms of ocean energy can cover most coastlines of the continents. For example, the wave energy is abundant in the mid to high latitudes of both hemispheres while ocean thermal energy are rich across the tropic zone between $35^o$ latitude north and south of the equators. The tidal energy varies across the globe and can be amplified by basin resonances and coastline bathymetry in some areas (such as Bay of Fundy in Canada and Severn Estuary in the UK) while energy from salinity gradient can be harvested by specific technologies  regardless the location [50-53].

The technologies to harness mechanical (tidal and wave power) and thermal energy are the most advanced, while ocean chemical energy technology has only attracted significant efforts since 2000. We do not include offshore wind power as a type of ocean energy in this paper as it is not directly harvested from water.

The global ocean energy resource is estimated to be 8,000-80,000 TWh/year for wave energy, 800 TWh/year for tidal energy, 2,000 TWh/year for salt gradient (osmotic) energy and 10,000 TWh/year for ocean thermal energy [54]. Energy available from ocean currents is estimated at 5,000 GW worldwide with energy densities as high as 15 $kW/m^2$ [55]. Compared with other renewable energy resources, an important feature of ocean energy is its energy density, which is the highest among the renewable energy sources [56].

The various forms of ocean energy can be harnessed for electricity production that can be used for desalination. Additionally, some of the forms of ocean energy can be directly integrated (in the form of mechanical force, thermal resource or chemical potential), with various desalination processes (Figure 4). We now describe a number of different devices and systems that use ocean energy for desalination have been developed, and most are currently in pre-commercial stages.

**Figure 4**. Integration of ocean energy in seawater desalination.

### 3.2.1 Ocean thermal energy for seawater desalination

Ocean thermal energy is a form of solar energy absorbed and stored in the upper layer of the ocean. The French physicist d'Arsonval was the first in 1881 who suggested harnessing the temperature difference between the warm surface layers and cold deep layers of tropical oceans [57]. The simplest way to produce fresh water by ocean thermal energy is the evaporation-condensation cycle at a low pressure created by a vacuum pump. An experimental study on desalination system using ocean thermal energy showed that the yield of distillate can achieve about 3.5 L/hr under an evaporator temperature (warm seawater) of $30^{o}$ C and condenser temperature (cold seawater) of $10^{o}$ C. The salinity and total dissolved solid in distillate were much lower than World Health Organization’s acceptable limits for drinking water [58]. A spray desalination system was tested at Fiji Island in South Pacific Ocean. Warm seawater was evaporated in a spray flash chamber and the vapor was condensed by a plate-type heat exchanger (desalination condenser). A desalination rate of 1,000 tons per day was reported [59]. Based on similar technology, a barge mounted desalination plant (with a of capacity 1000 $m^3$/day) was successfully commissioned off the coast of Chennai in India in 2007 [60].

Ocean thermal energy can be harvested by ocean thermal energy conversion (OTEC) cycle where warm seawater (30–32 °C) on the top is utilized as the heating source and cold seawater (4–6 °C) at a depth of 1000 meter is the cooling source to drive a heat engine cycle and generate power [61, 62]. As shown in Figure 5, the plant could be land-based or located in floating platforms and operated by close-cycle using a working fluid (usually Ammonia) with warm and cold seawater, open-cycle using warm and cold seawater only, or hybrid cycles [63].

The utilization of ocean thermal energy for desalination by OTEC has been studied by a number of researchers. The electricity generated by an OTEC plant can power desalination processes such as in a RO system.

**Figure 5**. Schematic diagram of OTEC and integrated seawater desalination processes (upper, close-cycle; bottom, open-cycle (using sea water)).

The open-cycle or hybrid cycle OTEC plant can be dual-purpose for both power generation and desalination. In open-cycle OTEC plants, the warm seawater is vaporized to turn the low-pressure turbine. Once the electricity is produced the water vapor is condensed by cold seawater to make fresh water which is about 0.5–0.6% by volume of the input warm surface seawater [64, 65]. Rey and Lauro conducted a theoretical assessment of OTEC plants for seawater desalination [57]. Their preliminary calculation showed that the OTEC provides an economical method to co-generate potable water (distillate) and electricity. Funded by the U.S. Department of Energy and the State of Hawaii, a 210 kW open-cycle OTEC plant was built in Hawaii and operated for six years (1993-1998). The highest production rates achieved were 255 kWe (gross) with a corresponding net power of 103 kW and about 35,000 liters per day of co-generated fresh water [66]. A modelling case study in the Bahamas showed that the price of desalinated water by OTEC can be potentially reduced up to 77% comparing with conventional large scale desalination technologies [50, 67].

The hybrid cycle OTEC combines a close-cycle (first stage) for power generation and an open-cycle (second stage) for desalination. For every megawatt of power generated by a hybrid OTEC plant, nearly 2.28 million liters of desalinated water can be produced per day [68]. Moreover, the ‘by-products’ from OTEC plants can support other applications beyond seawater desalination, such as seawater air-conditioning, chilled soil agriculture; these additional revenue streams can further enhance the benefits of OTEC technology coupled with desalination process. Small- to medium-scale open-cycle OTEC can be deployed in remote, coastal or island regions where both electricity and fresh water are scarce. While the maintenance and operation costs of seawater based systems are comparatively higher, these systems may be useful for niche applications in remote or resource-limited settings.

Another promising desalination technology, utilizing ocean thermal energy, is Membrane Distillation (MD). The advantages of OTEC integrated with MD for power generation and desalination include reducing system size and enhancing power production rate [69, 70].

### 3.2.2 Ocean mechanical energy for seawater desalination

Although ocean currents move slower than typical wind speed, they carry greater energy resulting from the fact that water is more than 800 times denser than air. For the same surface area, energy contained in water moving equals that carried by a constant wind with over 9 times higher speed [55]. Mechanical energy from the ocean can be sub-divided into tidal, wave, and current energy. Similar to wind energy generation, the technology to harvest ocean mechanical energy involves the deployment of turbines or other hydrokinetic devices along the path of water motion. Most of the work on ocean mechanical energy conversion has focused on electricity production.

The flowing power of ocean waves varies with site and weather condition from less than 10 kW/m to higher than 100 kW/m [71]. In one study, it was estimated that for 1.6 meters high waves, a wave energy converter (WEC) with 7 meters diameter could generate 18 kW electricity or 235 $m^3$/day desalinated water, and the same production can be obtained by a hydrokinetic turbine at a current speed of 1.8 m/s [72]. Comparing with other renewable resources (e.g. wind, solar), the main advantage of ocean currents is that hydrokinetic devices can provide a highly predictable and relatively steady supply of energy [73]. For instance, the tidal energy, as the majority of ocean current energy, oscillates regularly a day with four periods of slack and for periods of peak current while the external factors such as weather give minor impacts. Moreover, the force (pressure) created by ocean mechanical energy can also be directly applied to pressure-driven desalination processes. The direct use of ocean mechanical energy would reduce the cost and energy losses associated with converting the energy into electricity and back to pressurized water. In most studies, ocean mechanical energy, mainly wave energy, is coupled with an RO plant. The reason is that the studies expect that it will be easy to use both mechanical force (pressure) and electricity to drive the RO desalination process. In addition, RO is the most energy-efficient technology nowadays for seawater desalination and it is the benchmark for further development and innovation in desalination technology.

Delbuoy is the first technology to use ocean mechanical force from waves for desalination [74, 75]. The Delbuoy system included oscillating buoys subjected to waves for driving piston pumps. The pumps were anchored to the seabed and fed pressurized seawater to submerged RO modules. Delbuoy's technology has not been actively used since the late 1980's due to technical and economic barriers [76], however, the technology is recognized as seminal in the field of ocean wave powered desalination.

Since the 1990s, research for using ocean mechanical energy for desalination has remained consistently active, although it has accelerated over the last decade. [77, 78] studied the technical and economic feasibility of wave power for desalination using a water hammer. The device is similar to the hydro-ram widely used to lift water from streams and rivers. By utilizing wave motion, a water hammer can generate unsteady incompressible duct flow to create the hydrostatic pressure for reverse osmosis. The results showed that the proposed system is technically feasible to create direct pressure that is sufficient to drive RO desalination process. The technology could offer operational cost savings in comparison to conventional RO plants, irrespective of size, recovery rate, seawater types and seawater intake system. Other systems have included barges using McCabe wave pumps to supply pressured seawater to an RO plant for co-generation of electricity and desalinated water [79], and a wave jet combined with pressure intensifier device, turbine, and RO for desalination and electricity generation [80].

An autonomous wave-powered desalination system has also been studied [81]. The plant consists of the Oyster WEC, conventional reverse osmosis membranes and a pressure exchanger–intensifier for energy recovery. A hydraulic accumulator moderates the generated pressure while also providing energy storage. The conditioned pressurized seawater is fed directly to the RO plant. Numerical models show that the system could produce 102 $m^3$/hr of desalinated water (at a recovery rate of up 25-35%) with an average specific energy consumption of 2.1 kWh/m$^3$. Another proposed concept, namely AltoRO, consists of a Wave Roller WEC, an adaptive pressure generator, standard RO membranes and a hydraulic turbocharger for energy recovery. Numerical models estimate a minimum cost of water of 0.80 €/m$^3$ at 45 bar pressure level and a recovery rate of 30% [82].

In addition to hybrid RO processes, wave energy has also been integrated with MVC technology for seawater desalination. In one such system, the process was based on a wave energy converter, known as Edinburgh duck. The desalination duck uses VC principle to extract the salt from seawater. The wave motion changes the water level inside the duck body, generating sufficient pressure to drive MVC. The inner water is not only an inertial referential but also a double-acting piston. The process was designed to run at 100ºC, but the large size of ducks (typically 6–12 m in diameter) may minimize heat losses. The estimated specific energy for the system is in the range of 2.5–10 kWh/m$^3$ [83-86].

Some experimental studies at the lab scale have now reached the pilot and demonstration stages. A self-sustaining desalination system using ocean wave energy has been demonstrated in India with the desalinated water being supplied to the local fishing community [87]. The system includes an RO desalination plant of 10,000 L/day coupled with a demonstration wave energy conversion device with 2 and 5 kW resistive load using oscillating water column (OWC) technology (Figure 6). In the OWC system, a turbine generates electricity from compression and decompression of a column of air that is powered with the rise and fall of the waves. An alternator and a 120 V, 300 Ah Valve Regulated Lead Acid battery is used to maintain constant operation of desalination plant when the wave power varies with height and frequency.

**Figure 6**. OWC system for seawater desalination at Vizhinjam in India (upper left: the panoramic view; upper right: permanent magnet brush less alternator; lower left: Impulse turbine; lower right: the flow-chat of OWC system) [87].

The first commercial-scale wave-energy project is the Perth Wave Energy Project in Australia. It is the first commercial-scale wave energy array that is connected to the grid and has the ability to produce desalinated water. The plant uses a buoy fully submerged in deep water, away from breaking waves and beachgoers [88]. The buoys move with the motion of waves to drive tethered seabed pumps. The pumps pressurize water, which is delivered onshore via a subsea pipeline. On the shore, a part of high-pressure water is used to drive hydroelectric turbines to generate electricity, and the rest of high-pressure water is directly supplied to a collocated RO desalination plant capable of 150 $m^3$/day potable water production off CETO generated electricity or off grid. The first 240 kW peak capacity CETO wave unit (CETO 5) has operated successfully for 12 month [89]. It should be noted that the next generation of the system (CETO 6) will not use the heavy offshore lifts. The wave energy will be converted to electricity inside the buoy by a buoyant actuator and the rated capacity is expected to reach 1 MW [89].

### 3.2.3 Ocean chemical energy for seawater desalination

Ocean chemical energy can be harnessed from the salinity gradient between two fluids, commonly saline water (e.g., seawater, concentrated brine) and fresh water (e.g., river water, municipal wastewater). Forward Osmosis (FO), pressure retarded osmosis (PRO) and reverse electrodialysis (RED) are three major technologies involved in seawater desalination using ocean salinity gradient energy and have been demonstrated at pilot scale.

Osmotic pressure difference between a feed water (low salinity) and draw solution (high salinity) is the driving force of FO process. There are two FO desalination approaches including direct FO desalination and indirect FO desalination illustrated in Figure 7 [32]. In the case of direct FO desalination, fresh water is directly extracted from saline water (seawater or brackish water) as the feed and an osmotic reagent is used as the draw solution. Direct FO desalination is thus not powered by salinity gradient energy.  A post-treatment is required to recover desalinated water and regenerate draw solution. Unless free renewable energy or waste energy (e.g. waste heat) is available, FO cannot reduce the cost of energy required for desalination process, regardless of the type of draw solution used [41, 90, 91].

**Figure 7**. Layout of two FO processes for seawater desalination: (1) direct, and (2) indirect.

Conversely, indirect FO desalination is partially powered by ocean salinity gradient energy. Seawater is used as the draw solution while other quality-impaired water with low salinity is the feed (Figure 7). The osmotic pressure induced by the salt in seawater is utilized as driving force to extract fresh water from low salinity feed side. In addition to the free-of-charge draw solution (seawater), the attractiveness of this process is to extract clean water from the feed using free ocean energy (osmotic pressure), leading to partially desalinated seawater (diluted seawater) which can be further desalinated by a subsequent low-pressure reverse osmosis (LPRO) step as part of an FO–LPRO hybrid process, and reduce the total cost of the desalination process [92-93]. The process not only decreases the energy demand for the desalination but also reduces the cost for wastewater treatment. A number of studies have investigated different types of quality-impaired water as the feed including primary and secondary wastewater effluent, and urban runoff, [92, 94-96].

Although the quality-impaired water is used as the feed in the hybrid FO-LPRO process, it has been shown that the hybrid process works as a double barrier against most contaminants in feed water. FO coupled with low pressure RO is effective in rejecting contaminants such as heavy metal, nutrients, and organic micro-pollutants from quality-impaired feed water [95]. The salt removal is of up to 98% to produce desalinated water [93]. It was suggested that the FO–LPRO hybrid can approach a specific energy threshold of 1.3-1.5 kWh/m$^3$ for seawater desalination using a new higher flux FO membrane of about 10 L/m$^2$.hr [93]. The energy consumption reduction in FO-LPRO seawater desalination systems is mainly related to the utilization of the ocean osmotic pressure to partially desalinate (dilute) seawater in the FO step; this consequently reduces the hydraulic pressure required by the water recovery process (i.e. LPRO). Further reduction of energy consumption is possible if more ocean osmotic pressure is consumed in the FO step and the dilution rate of seawater increases before LPRO. Such an increase in the dilution rate would, however, represent a higher capital cost for the FO membrane area required. The sensitivity analysis in a life-cycle cost assessment of hybrid FO-LPRO system for seawater desalination and wastewater treatment showed that the most critical aspect in terms of economic feasibility for FO-LPRO system is the FO module cost. Compared with seawater RO (SWRO), the FO-LPRO systems have a higher capital expense (CAPEX), but lower operational expenses (OPEX) due to savings in energy consumption and fouling control. Total cost per cubic meter of water produced by the hybrid FO-LPRO desalination system is expected to be lower than that for RO seawater desalination [97].

The primary objective of RED and PRO process is not desalination but ocean energy harvesting (Figure 8). Both processes convert ocean salinity gradient energy to electricity. Therefore, they have great potential to be integrated in desalination processes, especially FO and RO, to recover and reuse salinity gradient energy from concentrated brine and thereby reducing the cost of seawater desalination as well as its environmental impacts. Integration of RED and PRO in conventional SWRO plant could offset the total capital cost by 42% [39].

Figure 8. The flow chat of PRO (left) and RED (right; CEM: cation exchange membrane; AEM: anion exchange membrane).

RED is an electro-chemical process that converts ionic flux directly into electric current. The technology employs cation exchange membrane (CEM) and anion exchange membrane (AEM) that are stacked alternatively in a module between cathode and anode. The salinity gradient coupled with ion exchange membranes selectively allows the counter ion permeation through the membranes from the concentrated solution to the diluted solution, and the net ion flux is converted to an electric current for power generation [98].

RED has been applied to extract energy from the concentrated brine in FO and RO desalination processes [99]. The maximum power densities with the RO brine and FO brine were 1.48 and 1.86 W/m$^2$, respectively, using river water as the low concentration solution. By integrating RED to recover energy from concentrated brine, the energy cost could be lowered by approximately 7.8% for RO; a more dramatic decrease of 13.5% was found with FO. The study of different configurations of the hybrid RED–RO processes confirmed that RED–RO hybrid process configurations are superior to conventional RO process for seawater desalination. The RED-treated seawater has a lower salt concentration and serves as the feed water for the RO to reduce the pump work. The concentrated brine from the desalination process provides the RED a better high salinity source for the energy recovery. The two main advantages of this process is that total energy consumption can be markedly reduced and that the brine management is built into the hybrid process towards a zero liquid discharge (ZLD) system with a higher recovery [100].

MD can provide highly concentrated brine and thus it is expected that there will be benefits in its integration with RED for desalination and salinity gradient power recovery. A hybrid process combining RO, MD and RED was studied for near-ZLD and low cost desalination [101]. The RO concentrated brine was post-treated by a MD step to further increase water recovery rate and brine concentration. The highly concentrated brine after the MD process was used for energy generation in RED where the natural seawater was used as low concentration fluid. Experimental data showed the possibility to obtain an open circuit voltage (OCV) in the range of 1.5–2.3 V and a gross power density of 0.9–2.4 W/m$^2$ (membrane pair) while the overall water recovery rate approached 92%.

A RED based system to generate electricity (i.e., not coupled with a desalination process) was tested as a pilot plant for over five months in the South of Italy. The RED unit was equipped with 50 m$^2$ ion exchange membranes using natural brackish water and almost saturated brine from a local salt works. The achieved power in typical conditions was around 35–40 W (i.e. power density of 1.5–1.7 W/m$^2$), with peak values around 45 W.

The net power output oscillated around an average of 25 W [102]. In November, 2014, the Netherlands officially opened the world’s first pilot RED power plant using seawater and river water for blue energy generation. The plant is located on the Afsluitdijk, a dyke separating the Ijssel Lake from the Wadden Sea. The technology will be tested from 2015 to 2017, and the plant is expected to reach a power output of 0.5-2 MW between 2018 and 2020. Up-scaling to commercial stand-alone power plants is estimated to take place around 2020 [103].

PRO is an osmotically-driven membrane process that is similar to FO process, but there is an applied hydraulic pressure on the draw solution. The volume expansion in the draw solution by extracting fresh water from the low salinity side using osmotic pressure is restricted and increases the hydraulic pressure of the draw solution reservoir. The pressurized flow of draw solution is then driven through a hydro turbine to generate power [104]. Similar to RED, PRO technology can be employed as an energy recovery process in desalination. A recent study comparing the energy efficiency and power density in PRO and RED shows that PRO is particularly proficient at extracting salinity energy from large concentration differences. PRO can achieve both greater efficiencies (54−56%) and higher power densities (2.4−38 W/m$^2$) than RED (18−38% and 0.77−1.2 W/m$^2$). The better performance of PRO to recover salinity gradient power is attributed to the superior efficiency of PRO membranes in terms of better water permeability and less salt leakage [98]. The desalination process (i.e. RO and MD) coupled with PRO may process unique advantages of high water recovery rate, huge osmotic power generation, and minimal environmental impacts [105]

Theoretically, use of RO brine in PRO was found to reduce the net specific energy consumption of a seawater RO system by 40 to 58% [106, 107]. The maximum power density of PRO could achieve 10 W/m$^2$. The minimum net specific energy consumption of the modeled RO-PRO system was 1.2 kWh/m$^3$ at 50% RO recovery using energy recovery devices and PRO to recover energy from both remaining pressure and salinity gradient in RO concentrated brine [106]. In most experimental studies integrating PRO with RO for desalination, municipal wastewater is employed as the low salinity feed water for PRO, which could be a possible energy-saving strategy to combine municipal wastewater treatment and seawater desalination, and further promote sustainable urban water management and water reuse in coastal cities. A similar strategy is also applied in hybrid FO-RO processes: wastewater containing organic foulants is used as feed (low salinity) in FO while draw solution is seawater. In one such system, the specific energy consumption of PRO-RO was about 20% lower than hybrid FO-RO process for the production of 159 $m^3$/h of desalinated water [107].

A salinity-solar powered RO system involving Photovoltaic (PV), PRO and RO has also been developed in which annual fresh water production of hybrid PV-PRO-RO process was increased more than nine times compared with a stand-alone PV powered RO plant. The application of PRO to harvest salinity gradient power from RO brine can improve the energy efficiency of the entire process and prolong the operational hours over night time [108]. PRO has also been integrated with MD desalination process to maximize water recovery rate and power generation [105]. The additional advantage of PRO-MD configuration is that the elevated temperature of brine from MD could increase the water flux as well as power density in PRO [109, 110].

The Japanese Mega-ton Water System project, a government funded academia-industry collaboration research project, constructed a PRO pilot plant at Fukuoka in Japan to use RO brine and treated wastewater for power generation (Figure 9). A maximum PRO power density of 13.3 W/$m^2$ was achieved [111]. The Korean National Research Project, Global MVP (Membrane Distillation, Valuable Source Recovery, and PRO), directly uses the harvested osmotic pressure rather than converting it to electricity. RO brine and treated wastewater in a PRO process is coupled with high efficiency (up to 97%) isobaric pressure exchangers to recover osmotic pressure for pre-pressurizing the feed seawater before RO, which substantially lowers the overall desalination energy consumption [112]. The aim of both Mega-ton and Global MVP project is to make desalination plants more energy efficient by utilizing osmotic pressure and environmentally friendly by reducing brine concentration and volume.

**Figure 9**. PRO plants in Japanese Mega-ton project (upper left: the panoramic view of PRO prototype plant; upper right: PRO membrane module) [111], and Korean GMVP project (lower image).

RED is more attractive for power generation using river and seawater; FO is suitable to be a pre-treatment method for seawater desalination; and PRO seems to be more beneficial for power generation using concentrated saline brines [113]. The additional advantage of integrating FO, PRO or RED with desalination process is that the hybrid processes (e.g. FO-LPRO, RED-RO, PRO-RO) can expand the portfolio of technologies to combine seawater desalination and wastewater treatment, consequently reduce the environmental impact of desalination due to brine disposal and promote wastewater recycle and reuse. The cost of membranes and membrane modules is the largest factor impacting commercial-scale application of salinity gradient energy in desalination. The cost of commercially available FO, PRO and RED membrane modules is about 2-3 times higher than that of RO membrane modules, since most of these modules are produced in small-scale fabrication lines that include a significant amount of manual labor. Many major membrane producers, such as Fujifilm, Toray, Toyobo and GE, have engaged in developing and manufacturing novel FO, PRO or RED membrane and modules. Therefore, the scaled up industrial production is expected to reduce costs of FO, PRO and RED membrane modules in the future.

There are more salinity gradient energy technologies that are gaining attention such as capacitive mixing, hydrogel swelling, hierarchical nanofluidic devices and hydrocratic generators [114-119]. These energy technologies are in nascent stages, however, and have yet to be integrated with desalination processes.

## 4. Current State and Future Prospects of Ocean Energy

In the sector of renewable power generation (excluding hydropower), solar and wind are dominant based on the amount of investment and installed capacity. Most ocean energy installations are in the form of pilot or demonstration projects. Ocean energy capacity, mostly tidal power, was about 530 MW. This is a very small fraction when compared with solar PV (139 GW) and wind (318 GW) in the total renewable power sector (not including hydropower) of 560 GW at the end of 2013 [120]. Ocean energy technology development continues to grow with increasing attention to renewable energy systems. Global ocean energy investment grew by 110% between 2013 and 2014 - although from a very low level (Figure 10). The European Union (EU) has implemented support mechanisms to aid the development of ocean energy and aims to reach more than 100 GW of combined wave and tidal capacity installed by 2050 to satisfy 10-15% of EU energy demand [121-124]. However, ocean energy saw a 42% slip in the global new investment between 2014 and 2015 (Figure 10). The main reason is that solar and wind are becoming more and more dominant in the renewables while small sectors are losing relative importance [125], but potential of ocean energy remains and construction continues on demonstration projects off the coast of Scotland, Brittany, and Nova Scotia. In addition, the efforts are underway to support larger projects in UK, Irish and French waters [126].

**Figure 10.** The rise in investment to renewable energy from 2013 to 2015 (Graphed with the data from [124] and [125]).

The rate of deployment of offshore wind power generation in terms of capacity is expected to be similar to that of onshore wind power systems, with a time gap of about 15 years. The ocean energy deployment is expected to have a time gap of about 10 years behind offshore wind [121]. Market maturity and deployment level of tidal and wave energy devices has advanced the most of all ocean energy technologies by far and show the highest global interest. Early in 1960s, France built the tidal power plant with an installed capacity of 240 MW on the mouth of the La Rance River in Brittany. The Sihwa Lake tidal power station in Korea was launched in 2011 with a capacity of 254 MW. The leading tidal energy technologies are at the stage where market pull mechanisms are starting to promote the uptake of the technology [122].

Given the early stage of technological development and deployment when compared to other energy systems, a number of barriers must be overcome within the ocean energy sector (Table 3). Integration with desalination will entail additional challenges. The extensive knowledge and operational experience from other industrial sectors such as offshore oil and gas installations can help advance technology development for ocean energy. Furthermore, public-private partnerships and increased funding support can enhance research and development and share investment risks.

The utilization of marine resources for seawater desalination should be considered in an integrated approach. Ocean energy technologies with different forms can be used for different applications such as for offshore wind farms, offshore oil and gas operations, and desalination plants. These systems can share some common sub-systems (e.g. seawater intake, grid connection, common marine equipment) that can reduce infrastructure costs, lower operation and maintenance costs and yield higher energy output per unit of marine area.

In densely populated coastal urban regions, with rising demand of fresh water, the high cost of current desalination methods could promote the incentives for using ocean energy technologies. As discussed in Section 3.2, ocean energy technologies can not only be used in stand-alone power generation (as in other renewable energy systems), but can also be adapted and integrated to be a part of desalination process. Integrated ocean energy devices can utilize the seawater intake and pretreatment system from desalination plant, and thus reduce the cost for piping system and marine bio-fouling control when supplying energy to the desalination process. Among the ocean energy technologies, salinity gradient energy technology seems most promising for near-term deployment since PRO and RED devices can be added to any existing desalination plant as an energy recovery system to recover the energy from seawater or brine without major reconstruction of desalination plants. Integration of ocean mechanical and thermal energy devices with desalination process requires a significant modification of plant design, especially the seawater intake system, therefore we estimate that adoption of these systems within desalination plants will be further out in the future.

**Table 3.** Development status, levelized cost and existing barriers for power generation by ocean energy technology.

## 5. Environmental and social impacts

### 5.1 Environmental impacts

Environmental concerns related to the inputs and outputs of desalination processes is summarized in Figure 11. Apart from the indirect impacts associated with desalination which should be analyzed in a life cycle assessment, the direct impacts on the marine environment arising from the operation of desalination plant, mainly including the intakes and outfalls of the system, has attracted great attention. The major environmental impacts of intake system are impingement and entrainment of marine organisms, causing a reduction in fish, invertebrates and ichthyoplankton in general [132]. The environmental impacts of desalination outfall system are mainly caused by disposal of concentrate from desalination process. After removal of fresh water, the concentrated brine contains the rejected salts, chemical from pre- and post-treatment operations (e.g. NaOCl, $FeCl_3$, acids) and metals from pipe corrosion (e.g. Cu, Fe, Ni, Mo, Cr), which lead to the negative effects on local marine ecosystem near the point of discharge [132, 133].

**Figure 11**. Environmental impacts associated with inputs and outputs of conventional seawater desalination processes.

With conventional sources of energy (based on fossil fuel) a typical RO plant with 100,000 $m^3$/day capacity can generate about 692 tons $CO_2$/day, while emissions associated with thermal MSF and MED processes are one order of magnitude higher than RO [134, 135]. Brine is an unavoidable desalination by-product containing thermal, chemical and saline pollution that is most commonly discharged to the ocean. The environmental impacts will grow in the near future with expanding use of current desalination technologies. For example, it is expected that desalination will have larger environmental impacts by 2050 in GCC countries, as the annual volume of brine produced will be approximately 6 folds higher than the amount now, and the incremental volume of GHG emissions will be approximately 400 million tons of carbon equivalents per year [2].

Since fossil fuel powered desalination processes are approaching the benchmark of energy consumption as described in section 3.1, it will become ever more critical to increase the share of renewables in the energy portfolio for desalination. When desalination is integrated with renewable energy models, an up to 80–85% reduction of most relevant airborne emissions can be achieved [136]. The benefits of ocean energy to improve environmental impacts of desalination are similar to those of wind, solar and other renewables.

While ocean energy technologies provide benefits of reduced greenhouse gas emissions, there are possible environmental risks that need to be identified and mitigated. In 2001, the British Government concluded that, “the adverse environmental impact of wave and tidal energy devices is minimal and far less than that of nearly any other source of energy, but further research is required to establish the effect of real installations” [137]. The U.S. National Renewable Energy Laboratory (NREL) conducted lifecycle assessment studies on GHG emissions of renewable energy technologies. The lifecycle GHG emission estimates for different renewable energy technologies are listed in Figure 12 [138]. Ocean energy, wind and hydropower are estimated to have lower lifecycle GHG emissions than other renewables. It should be noted that the lifecycle GHG emission estimates in Figure 12 were conducted for the purpose of electricity generation. In desalination applications, ocean power is more favorable than hydropower and wind power regarding the geographic location and process integration.

In the case of direct use of ocean energy in its natural form (i.e. thermal, pressure and salinity gradient) in desalination, the lifecycle environmental impact of ocean energy will be further reduced. Because ocean energy technology is integrated into the desalination process as a part of the feed water intake system, post-treatment process or energy recovery device, the other environmental impacts, such as hot and concentrated brine disposal in ocean energy powered desalination would be similar to those of conventional desalination process.

**Figure 12**. Estimates of lifecycle GHG emissions of renewable energy technologies (Graphed with the data from [138]).

Besides GHG emissions, other effects of installation, operation and maintenance on the marine environment need to be assessed. Due to the installation and operation of wave, tidal, current and thermal energy converters, some major environmental concerns are sub-sea noise and vibration, cables and motional apparatus (e.g. turbine blades), and electromagnetic fields that may affect migratory species and marine mammals. There is currently a lack of understanding of the long-term environmental effects of new ocean energy systems, however knowledge and experience from operation of other systems, particularly offshore wind energy and offshore oil & gas operations can be useful. The ongoing research on the environmental impacts of ocean energy systems indicates that underwater environmental risks from ocean energy technologies are relatively low [138, 139], and further research is currently being carried out to assess long-term cumulative environmental impacts. In general, the ocean energy recovered from salinity gradient would be more favorable than other ocean energies regarding the marine environmental impacts. As mentioned above, the salinity gradient energy devices (PRO and RED) can be installed and operated as a part of desalination plant rather than a stand-alone system separated from desalination plant. Consequently, there is no additional impact on marine environment caused by integrated PRO or RED units comparing with existing desalination plant. More importantly, the by-product (concentrated brine) from desalination process is used for harvesting energy. Thus, the combination of PRO or RED with existing desalination plant not only deploy the renewable energy but also help to reduce the negative environmental impact caused by disposing concentrated brine from desalination process.

### 5.2 Social impacts and economic concerns

With respect to social impacts there are aesthetic and use-related issues. The aesthetic concerns of the ocean energy generation infrastructure can mostly be avoided, as most ocean energy devices are submerged. The loss of competing uses of coastal space is the largest social impact of ocean energy. The location of ocean energy infrastructure can result in the loss of access to space for competing uses, such as for fishing, shipping, defense, tourism, recreation, and environmental conservation [130]. For some desalination applications, however, the ocean energy devices have typically small to medium scales. In some applications (i.e. ocean salinity gradient energy), the ocean energy device is fully hybridized into the desalination plant rather than in the marine environment. Other social impacts of the deployment of ocean energy in desalination are generally considered to be negligible or positive. For instance, ocean energy devices do not require additional land occupation or the relocation of local inhabitants. Furthermore, concurrent with the demand of desalination there is now an increased understanding of the need for waste water recycling. Wastewater is often involved in hybrid desalination process assisted by ocean salinity gradient energy. The co-benefits of this hybrid process can promote public awareness and acceptance for water recycling and reuse.

The long-term finance requirement for renewable project in terms of the pay-back period represents a major barrier for project developers [140]. At present, ocean energy costs are still higher than the cost of other renewables for electricity generation. Desalination provides market entry opportunities where ocean energy technologies could compete with other grid-connected renewables. Comparing to a standalone ocean energy project, desalination can integrate ocean energy technology in a specific sector at small to medium scale with minimum environmental, social, cost and revenue stream risks. In addition, diversity of ocean energy makes it flexible to be complemented with other renewable energy options in desalination (e.g. salinity-solar powered RO) for improved predictability, decreased variability, spatial concentration, and socio-economic benefits [130].

## 6. Conclusion and future perspectives

Ocean energy can be employed to drive in the entire seawater desalination process from feed water intake (e.g. pressurized seawater) to the post-treatment (e.g. brine management) stage at small to medium scale. Application of ocean energy in desalination can not only displace use of fossil fuel (and decrease GHG emissions), but also help to relieve environmental impacts of desalination by reducing concentrated brine disposal. The diverse forms of ocean energy in combination with various desalination technologies and supplemented with other renewables can overcome the general limitations of intermittency and variable supply.

Ocean salinity gradient energy is the most promising ocean energy in the near term for large-scale desalination because the salinity gradient energy devices (e.g. PRO, FO and RED) can be fully integrated into the current desalination technologies, and there are no additional environmental and social risks comparing with existing desalination plants. The modular design of ocean salinity gradient energy device, based on membrane technology, can allow for easy scale up. The utilization of other ocean energy systems for desalination is strongly reliant on further research and development, and progress is being made by large original equipment manufacturers (OEMs) around the world including Alstom, Andritz Hydro, DCNS, Hyundai Heavy Industries, Kawasaki Heavy Industries, Lockheed Martin, Siemens, and Voith Hydro.

The increasing need for freshwater supplies in coastal regions will drive demand for desalination systems, and ocean based energy for powering the desalination processes offers advantages of fossil fuel use reduction and lower GHG emissions. However, marine technologies are new, and their cumulative environmental impacts are poorly understood. Therefore, further research is needed on the environmental, social and economic impacts along with comprehensive assessments of benefits of co-generation systems of energy and desalinated water production.

Ocean energy technologies coupled with desalination can be useful for niche applications and may serve as the best option for some regional contexts (such as in remote, coastal locations). In other regions, market-driven mechanisms can involve industry R&D activities, such as module fabrication and membrane development, for reducing process costs. We anticipate that regional water scarcity along with need for using sources of energy that reduce GHG emissions, will drive further development and use of ocean energy in desalination sector.

## ***Nomenclature***

| | |
|---|---|
| AD | adsorption desalination |
| AEM | anion exchange membrane |
| CAPEX | capital expense |
| CDI | capacitive deionization |
| CEM | cation exchange membrane |
| CETO | |
| CO | carbon monoxide |
| DS | draw solution |
| ED | electrodialysis |
| EU | The European Union |
| FD | freezing desalination |
| FO | forward osmosis |
| GCC | Gulf Cooperation Council |
| GHG | greenhouse gas |
| HDH | humidification-dehumidification |
| LPRO | low-pressure reverse osmosis |
| MD | membrane distillation |
| MED | multi-effect distillation |
| MENA | the Middle East and North Africa |
| MSF | multi-stage flash distillation |
| MVC | mechanical vapor compression |

| | |
|---|---|
| NF | nanofiltration |
| NO | nitric oxide |
| $NO_2$ | nitrogen dioxide |
| NREL | The U.S. National Renewable Energy Laboratory |
| OCV | open circuit voltage |
| OEMs | original equipment manufacturers |
| OPEX | operational expenses |
| OTEC | ocean thermal energy conversion |
| OWC | oscillating water column |
| PRO | pressure retarded osmosis |
| PV | Photovoltaic |
| RED | reverse electrodialysis |
| RO | reverse osmosis |
| $SO_2$ | sulfur dioxide |
| SWRO | seawater reverse osmosis |
| TVC | thermal vapor compression |
| VC | vapor compression |
| WEC | wave energy converter |
| ZLD | zero liquid discharge |

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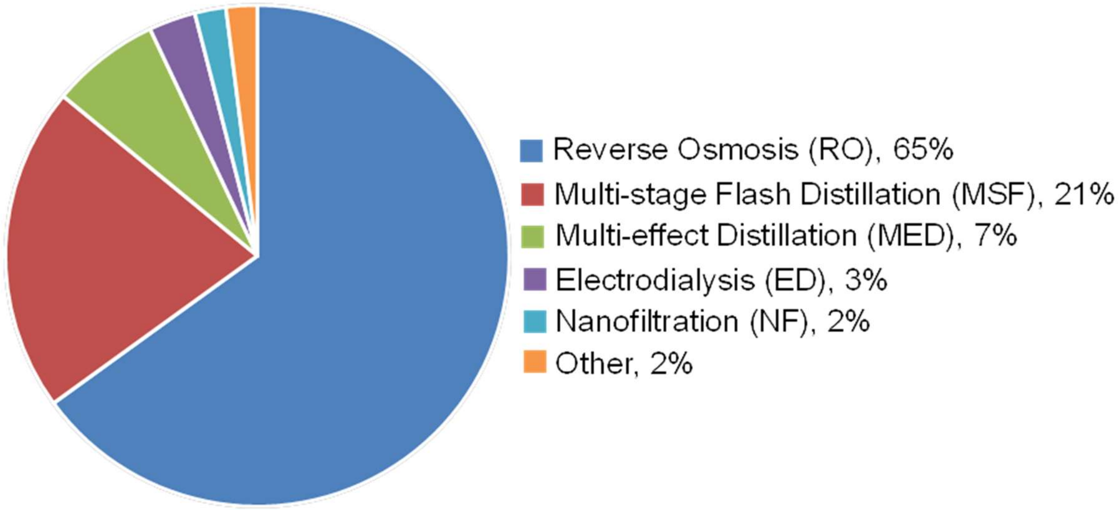


**Figure 1**. Total worldwide installed desalination capacity by technology [1].

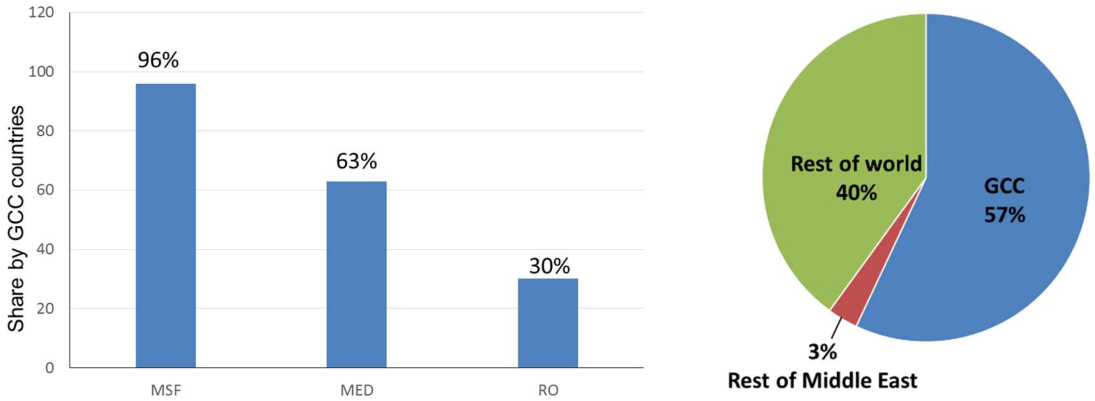


**Figure 2**. Gulf Cooperation Council (GCC) countries' share of global desalination by technology (left) and capacity (right) [12]. GCC includes Saudi Arabia, UAE, Kuwait, Qatar, Bahrain, and Oman.

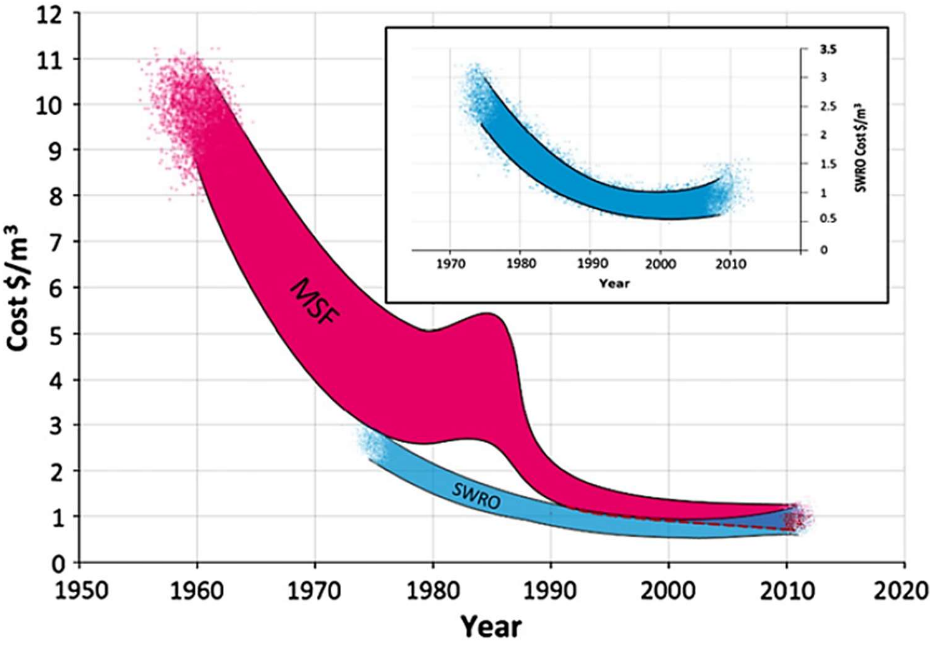


**Figure 3**. Trends in energy consumption of seawater desalination [15].

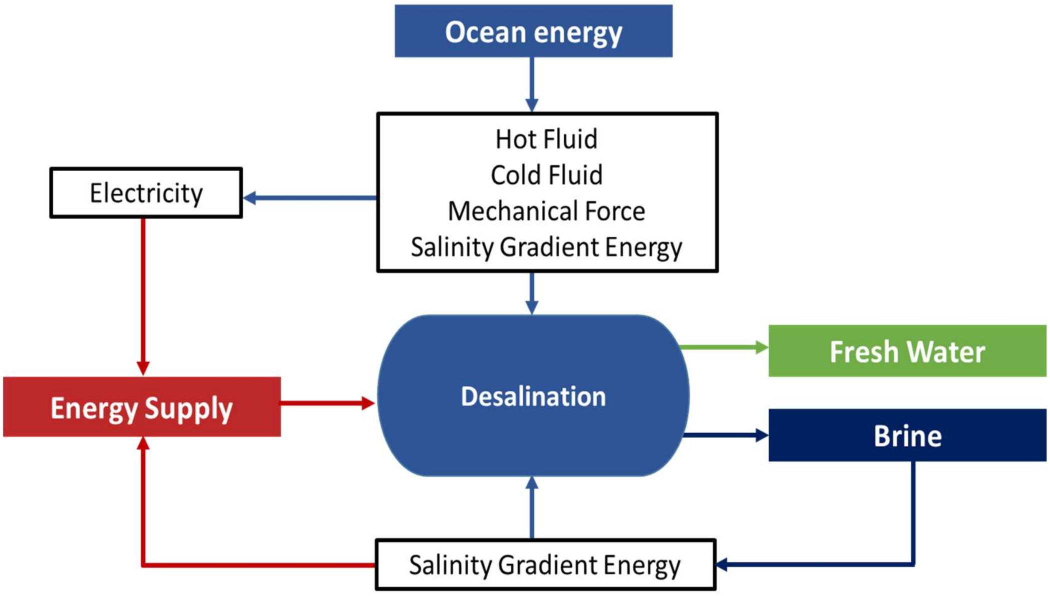


**Figure 4**. Integration of ocean energy in seawater desalination.

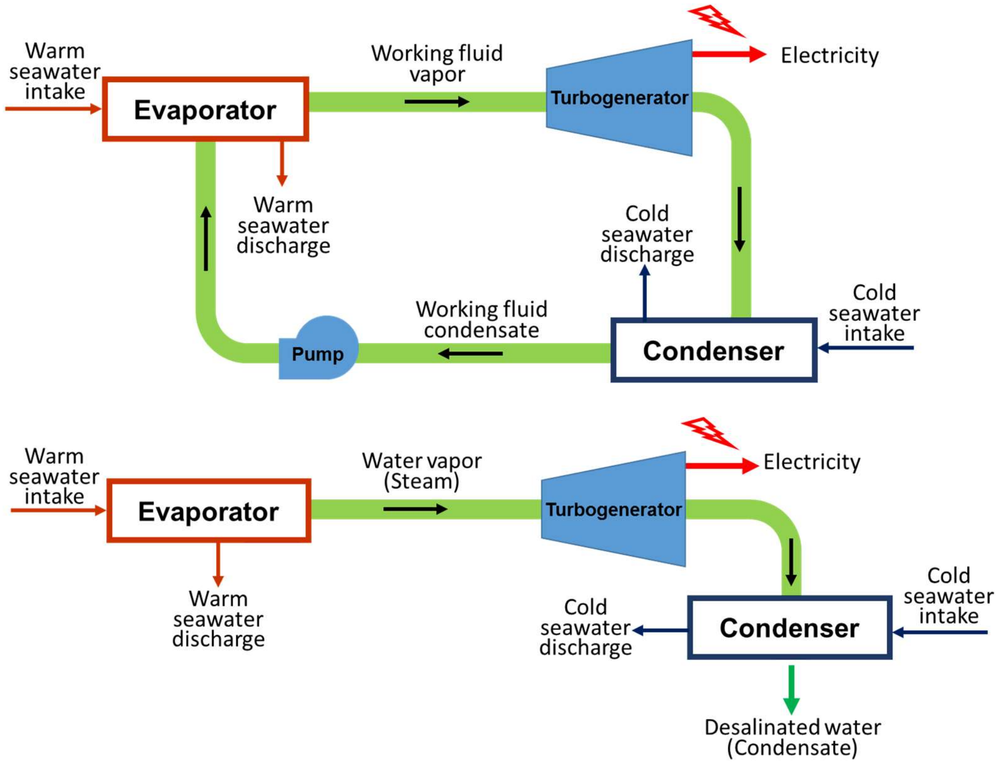


**Figure 5**. Schematic diagram of OTEC and integrated seawater desalination processes (upper, close-cycle; lower, open-cycle (using sea water)).

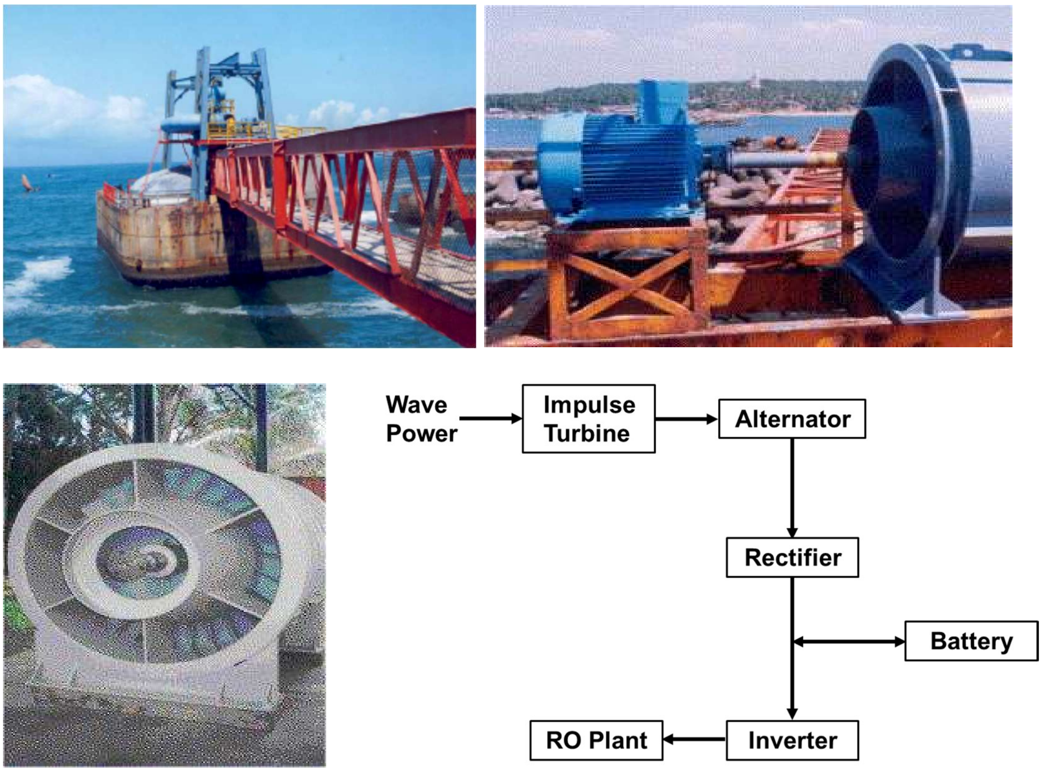


**Figure 6**. OWC system for seawater desalination at Vizhinjam in India (upper left: the panoramic view; upper right: permanent magnet brush less alternator; lower left: Impulse turbine; lower right: the flow-chat of OWC system) [87].

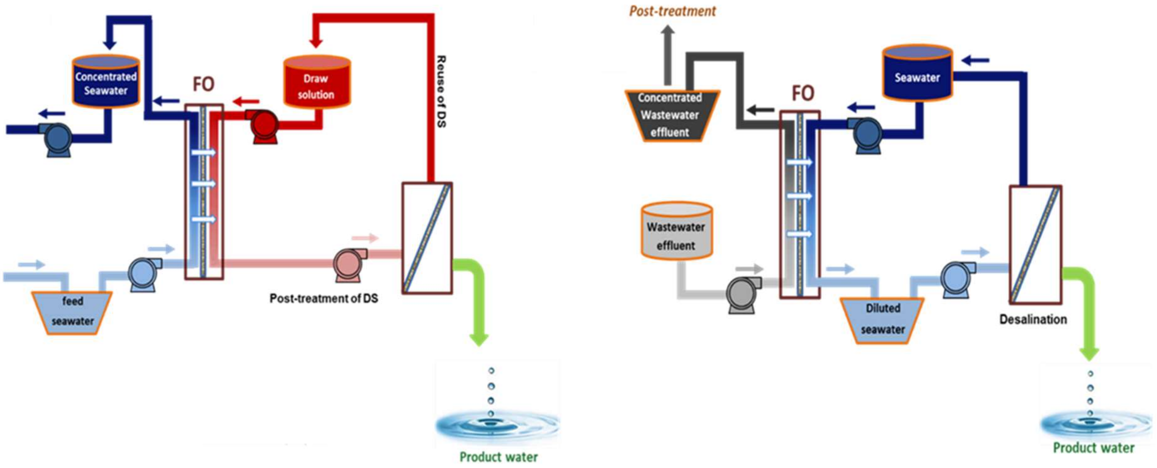


**Figure 7**. Layout of two FO processes for seawater desalination: (left) direct, and (right) indirect.

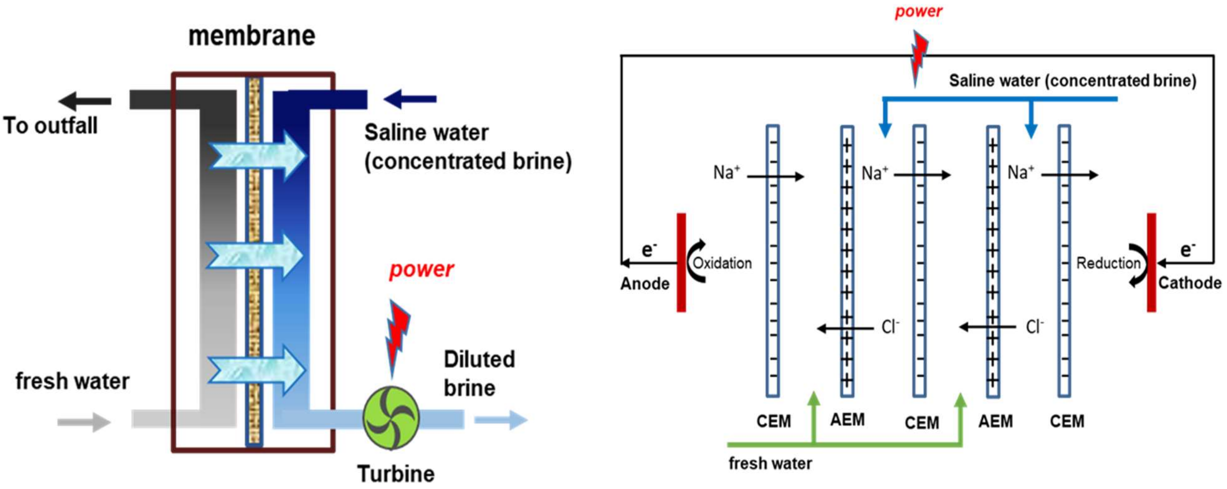


**Figure 8**. The flow chat of PRO (left) and RED (right; CEM: cation exchange membrane; AEM: anion exchange membrane).


PRO plant in Japanese Mega-ton project

PRO plant in Korean Global MVP project

**Figure 9**. PRO plants in Japanese Mega-ton project (upper left: the panoramic view of PRO prototype plant; upper right: PRO membrane module) [111], and Korean Global MVP project (lower image).

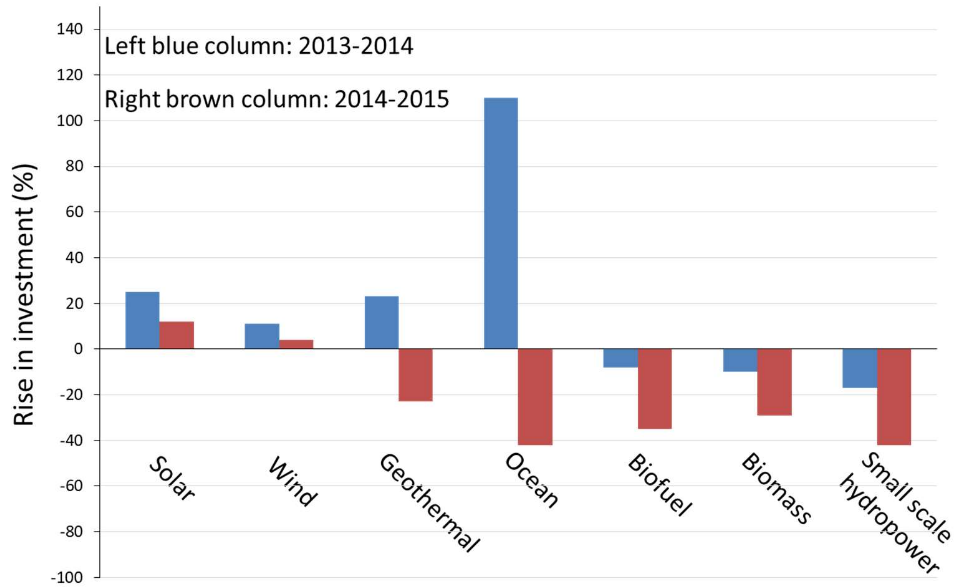
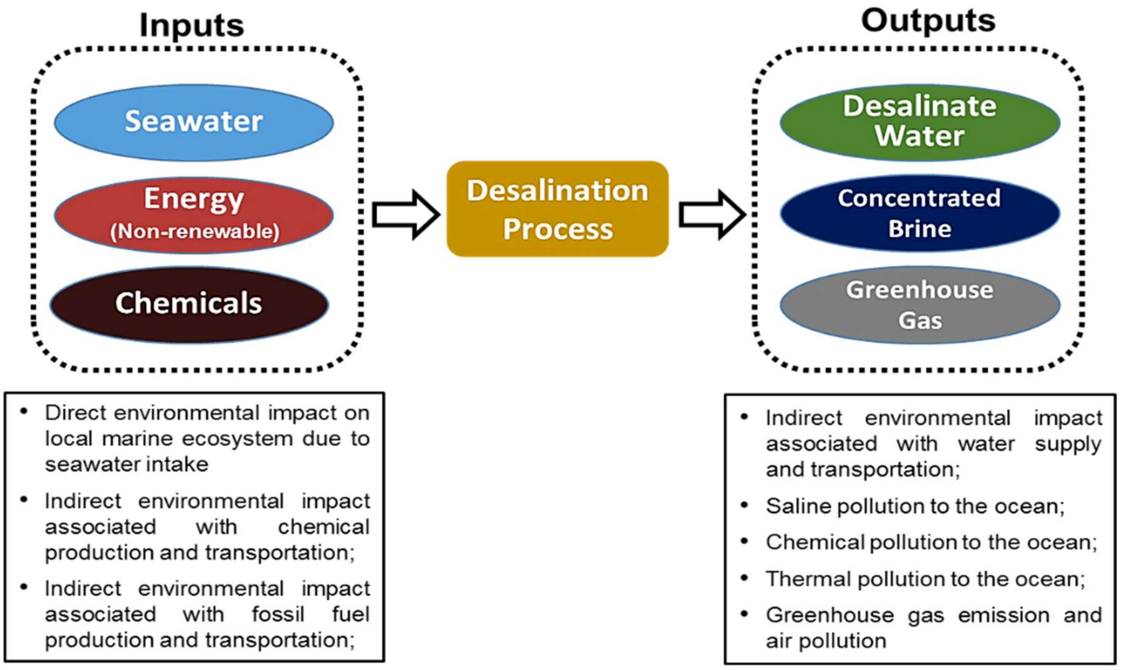


**Figure 10.** The rise in investment to renewable energy from 2013 to 2015 (Graphed with the data from [124] and [125]).



- Direct environmental impact on local marine ecosystem due to seawater intake
- Indirect environmental impact associated with chemical production and transportation;
- Indirect environmental impact associated with fossil fuel production and transportation;

- Indirect environmental impact associated with water supply and transportation;
- Saline pollution to the ocean;
- Chemical pollution to the ocean;
- Thermal pollution to the ocean;
- Greenhouse gas emission and air pollution

**Figure 11**. Environmental impacts associated with inputs and outputs of conventional seawater desalination processes.

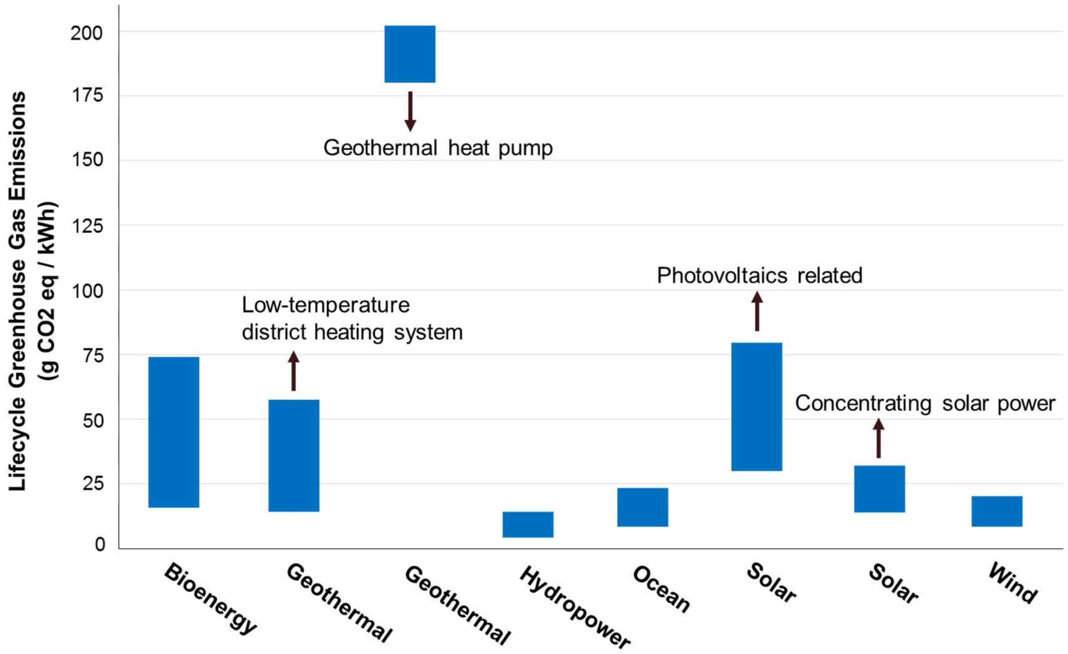


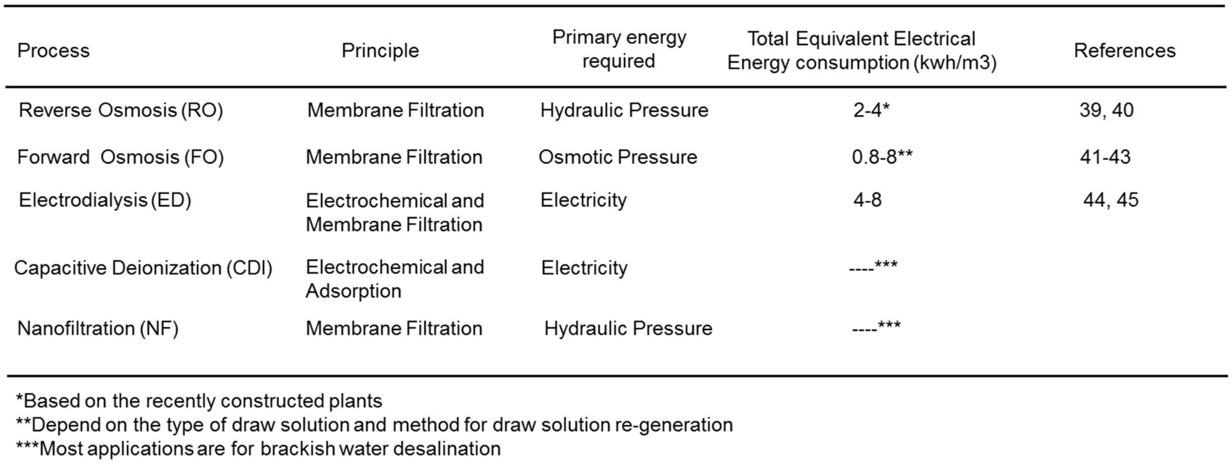
**Figure 12**. Estimates of lifecycle GHG emissions of renewable energy technologies (Graphed with the data from [138]).

**Table 1**. A summary of current desalination technologies with phase change.

| Process | Principle | Primary energy required | Total Equivalent Electrical Energy consumption (kwh/m3) | References |
|---|---|---|---|---|
| MSF | Evaporation | Thermal | 55-57*; 10-16** | 15 |
| MED | Evaporation | Thermal | 40-43*; 6-9** | 15 |
| Vapor Compression | | | | |
| Thermal Vapor Compression (TVC) | Evaporation | Thermal | 6-12*** | 15-17 |
| Mechanical Vapor Compression (MVC) | Evaporation | Pressure | | |
| Membrane Distillation (MD) | Evaporation and Membrane Separation | Thermal | 5-13**** | 18,19 |
| Adsorption Desalination (AD) | Evaporation | Thermal | 1.2-5.6**** | 20， 21 |
| Humidification-Dehumidification (HDH) | Evaporation | Thermal | 140-550*, 45-100 ** | 10， 23， 23 |
| Freezing Desalination (FD) | Crystallization | | 8-24**** | 24, 25 |

* Without waste heat and/or renewable energy
** With waste heat and/or renewable energy
*** Most VC process is integrated with MED
**** Depend on the source of heat and process configuration.

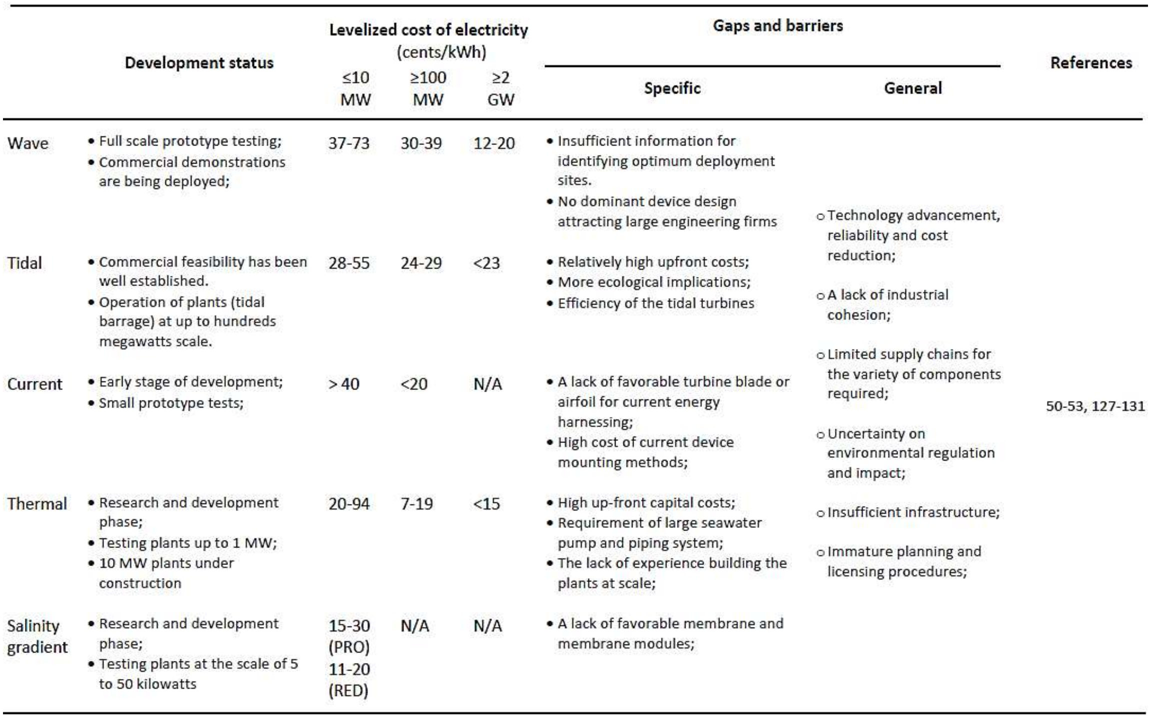
**Table 2**. Summary of current desalination technologies without phase change



| Process | Principle | Primary energy required | Total Equivalent Electrical Energy consumption (kwh/m3) | References |
|---|---|---|---|---|
| Reverse Osmosis (RO) | Membrane Filtration | Hydraulic Pressure | 2-4* | 39, 40 |
| Forward Osmosis (FO) | Membrane Filtration | Osmotic Pressure | 0.8-8** | 41-43 |
| Electrodialysis (ED) | Electrochemical and Membrane Filtration | Electricity | 4-8 | 44, 45 |
| Capacitive Deionization (CDI) | Electrochemical and Adsorption | Electricity | ----*** | |
| Nanofiltration (NF) | Membrane Filtration | Hydraulic Pressure | ----*** | |

*Based on the recently constructed plants
**Depend on the type of draw solution and method for draw solution re-generation
***Most applications are for brackish water desalination

**Table 3.** Development status, levelized cost and existing barriers for power generation by ocean energy technology.



| | Development status | Levelized cost of electricity (cents/kWh) | | | Gaps and barriers | | References |
|---|---|---|---|---|---|---|---|
| | | ≤10 MW | ≥100 MW | ≥2 GW | Specific | General | |
| Wave | • Full scale prototype testing;<br>• Commercial demonstrations are being deployed; | 37-73 | 30-39 | 12-20 | • Insufficient information for identifying optimum deployment sites.<br>• No dominant device design attracting large engineering firms | ○ Technology advancement, reliability and cost reduction;<br>○ A lack of industrial cohesion;<br>○ Limited supply chains for the variety of components required;<br>○ Uncertainty on environmental regulation and impact;<br>○ Insufficient infrastructure;<br>○ Immature planning and licensing procedures; | 50-53, 127-131 |
| Tidal | • Commercial feasibility has been well established.<br>• Operation of plants (tidal barrage) at up to hundreds megawatts scale. | 28-55 | 24-29 | <23 | • Relatively high upfront costs;<br>• More ecological implications;<br>• Efficiency of the tidal turbines | | |
| Current | • Early stage of development;<br>• Small prototype tests; | > 40 | <20 | N/A | • A lack of favorable turbine blade or airfoil for current energy harnessing;<br>• High cost of current device mounting methods; | | |
| Thermal | • Research and development phase;<br>• Testing plants up to 1 MW;<br>• 10 MW plants under construction | 20-94 | 7-19 | <15 | • High up-front capital costs;<br>• Requirement of large seawater pump and piping system;<br>• The lack of experience building the plants at scale; | | |
| Salinity gradient | • Research and development phase;<br>• Testing plants at the scale of 5 to 50 kilowatts | 15-30 (PRO)<br>11-20 (RED) | N/A | N/A | • A lack of favorable membrane and membrane modules; | | |