# EXERGO-ECONOMICS OF DESALINATION SYSTEMS

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## Contents



## Summary

Global water demand is projected to increase by over 55% by 2050 mainly due to the high GDP growth rate that will increase water demand for manufacturing, power generation, and domestic sector use by 400%, 140%, and 130% respectively. This current demand trend will push 40% of the World's population below the water scarcity level by 2050. Presently, around 19.000 desalination plants in 150 countries are producing roughly 38 billion cubic meters per year ($Gm^3/a$). Seawater desalination considered is one of the most feasible and practical solutions to fill the supply-demand

gap. In this chapter, a detailed overview of desalination processes is presented. In Section 1, global water scarcity, drinking water standards, and treatment requirements are highlighted. Section 2 covers the basic understanding of desalination and related important terminologies. A detailed overview of all desalination processes is presented in Section 3 and their energetic and exergetic analyses are provided in Section 4. The energy recovery options, economic analysis, and renewable energy-driven desalination processes detail are provided in subsequent sections. Lastly, we also sketch the future roadmap for sustainability.

## 1. Introduction

Energy and water are interdependent and directly linked to valuable resources that support a country's gross domestic product (GDP) and population prosperity (Conway et al, 2015). Energy is required during water treatment processes, collection, and distribution. Similarly, water is also an important factor for every aspect of the life cycle such as feedstock crops, fossil fuel processing, and power generation (Rothausen and Conway, 2011; Jamil et al, 2021a). The mutual dependence between energy and water is intensified due to the growing demand for both necessities because of population increase, GDP growth, and climate change (Howells and Rogner, 2014) In 2010, globally, 20-terawatt hours (TWh) of electricity was produced in which fossil and nuclear fuel sources contributed over 80% followed by hydropower-17% and renewable only-2% as shown in Figure 1 (a) and the corresponding areas-wise generation is shown in Figure 1 (b) (van Vliet et al, 2016). It consumed around 583 $Gm^3$ of water, 15% of the total water withdrawals. The electricity production is expected to increase to 34TWh by 2030, 70% more than the 2010 generation capacity. Correspondingly, the water consumption for power generation is estimated to grow to 790 $Gm^3$, 37% higher than in 2010 (The United Nations 2014). Water consumption for fossil fuels power generation is 75 000 - 450 000 liters per megawatt-hour (l/MWh). On the other hand, Combined-cycle gas turbines (CCGTs) plants are due to cascading processes, and they generate less heat and require less water for heat rejection in cooling towers, around 570 - 1100 l/MWh (World Energy Outlook, 2021).

Currently, the global water consumption is 6 $Gm^3$/a, led by the Asia region followed by America and Europe as shown in Figure 2 (Ghaffour et al, 2013). By 2050, the global water demand is expected to increase by over 55% mostly intensified by population and GDP growth coupled with inefficient agricultural practices, higher energy demand, and urbanization. It is projected that the manufacturing industry will lead this demand by a 400% increase followed by power generation 140% and domestic 130%. This higher water consumption will force over 40% of the global population to live in water scarcity regions by 2050 (Elimelech and Phillip, 2011). The only practical and feasible water solution for future supplies is seawater desalination. Currently, around 20,000 desalination plants production 40 $Gm^3$/a in 150 countries and it is estimated to grow to 54 $Gm^3$/a by 2030, 30% more compared to 2017 as shown in Figure 3 (IWA, 2016).

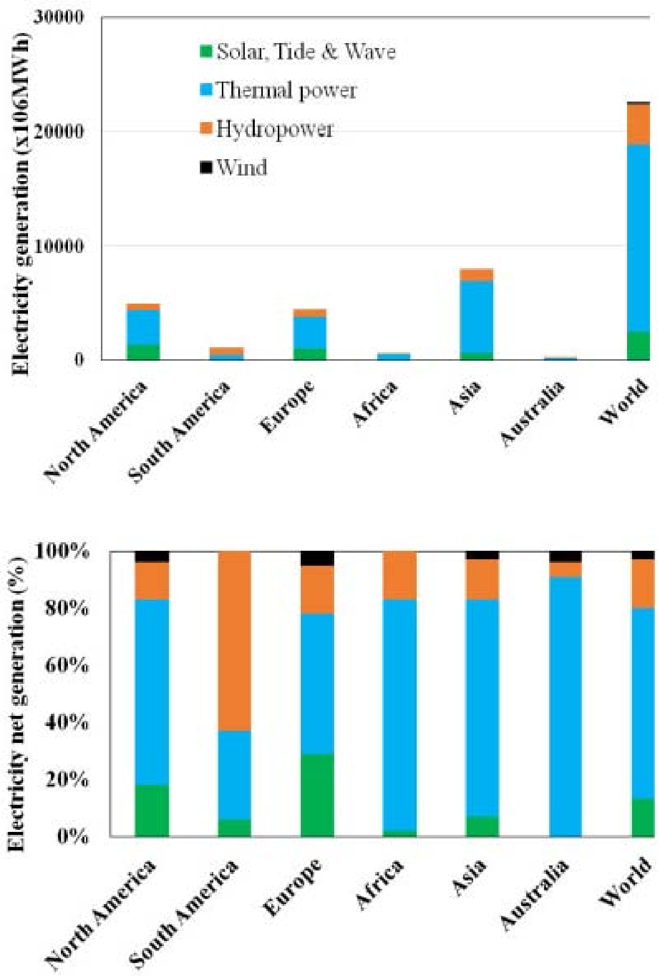


Figure 1. Electricity generation and energy mix at the different parts of the World (van Vliet et al, 2016).

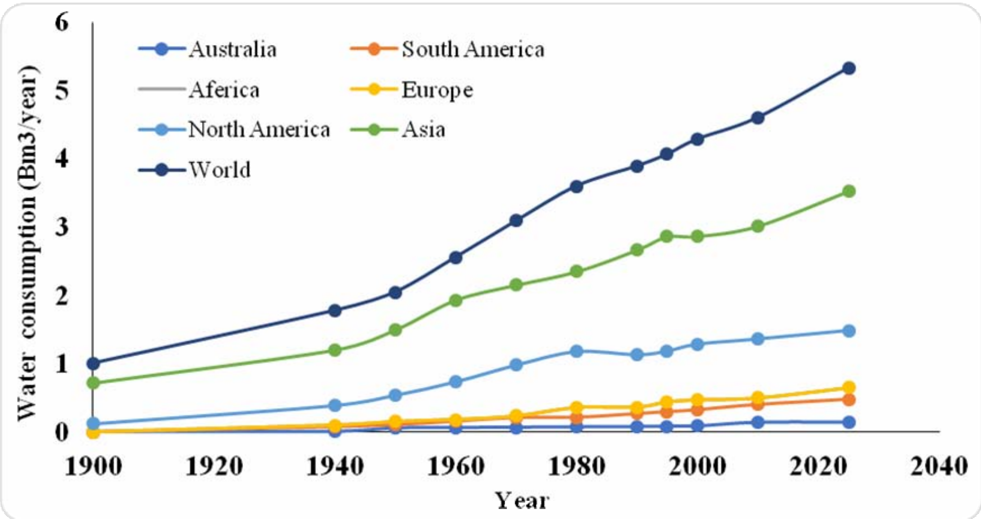


Figure 2. Global water consumption growth from 1900 to 2021(Ghaffour et al, 2013; Elimelech and Phillip, 2011).

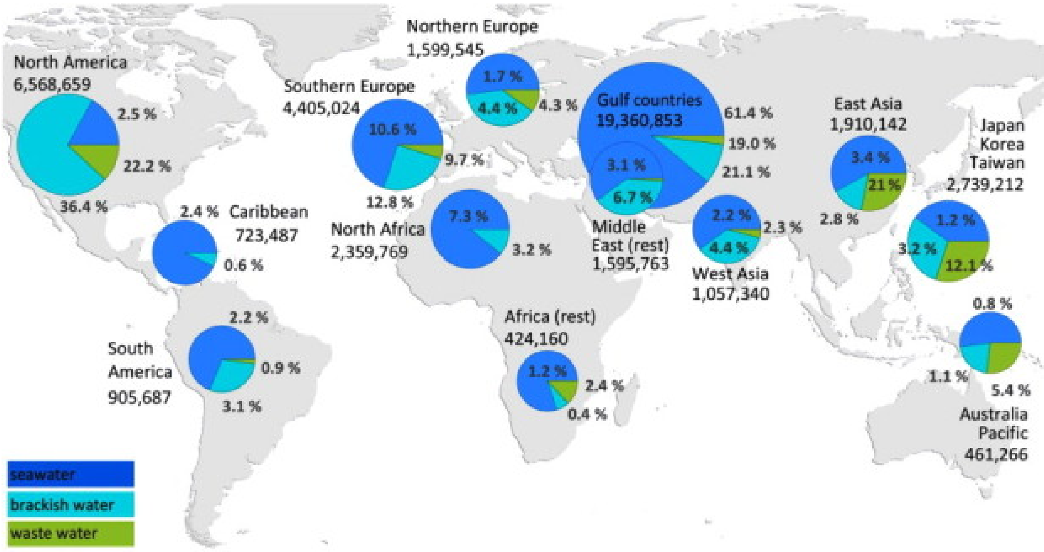


Figure 3. Global desalination capacities based on feed water quality (Ghaffour et al, 2013; Elimelech and Phillip, 2011).

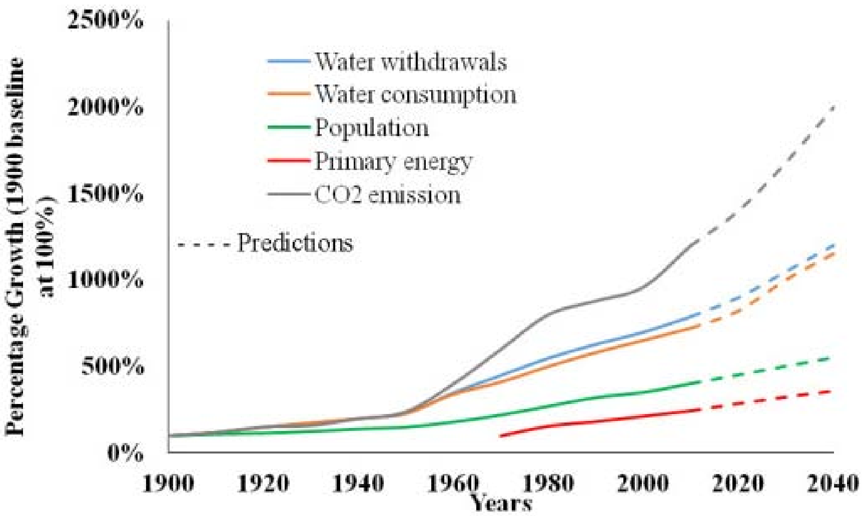


Figure 4. Water, $CO_2$ emission, and population percentage growth rate from 1900 to 2040 (Francey et al, 2013b ; Le Quéré et al, 2009 ; Friedlingstein et al, 2010; Peters et al, 2011).

The conventional desalination processes are not only energy-intensive but also environment unfriendly. The current installed capacities are contributing around 76 million tons per year (Mt/a) of $CO_2$ and it is estimated to increase over 250 Mt/a by 2050 (Global Clean Water Desalination Alliance - "H2O minus $CO_2$," 2015). The global $CO_2$ emissions increased 20% from 36.1 Gt/a (Giga ton per year) in 2013 to 43.2 Gt/a in 2019, consuming 2/3 of COP21 $CO_2$ emission targets, and the remaining is estimated to exhaust by 2050 (International Energy Agency. 2013). The percentage of global water consumption and withdrawals, $CO_2$ emission, and population growth is summarized in Figure 4 (Friedlingstein et al, 2014; Raupach et al, 2007). The water consumption and withdrawal, $CO_2$ emission, and primary energy consumption growth is

1000%. 1500% and 200% respectively (Francey et al, 2013a). The highest growth rate of $CO_2$ emissions is strongly coupled with power generation and water production processes (Yaqoob et al, 2021a&b ). The performance improvement of both processes is important to limit emissions and protect the environment (Francey et al, 2013b ; Le Quéré et al, 2009 ; Friedlingstein et al, 2010; Peters et al, 2011).

### 1.1. Water Treatment Processes and Energy Demand

Higher extraction and consumption of ground water are causing its table to drop at a faster rate. Over 1.2 billion people globally are affected by physical water scarcity and an additional 500 million population is approaching the same situation (UNESCO, 2019). In addition, as per the UN report, around 850,000 people die every year from diarrhea due to unsafe drinking water and lack of hygiene (Li et al, 2013). The recent COVID pandemic worsens this situation and where water is not readily available people may decide their priorities, drinking over hand washing, thereby adding to the likelihood of diarrhea and other diseases (Patel et al, 2021). For drinking, water treatment processes are required to achieve WHO quality standards (1000 $m^3$ per person per year) to avoid waterborne diseases (Quintuña, 2020; Kalbusch et al, 2020). The energy required for water treatment is dependent on feedwater type and major sources are, lakes, rivers, ground water, wastewater, and seawater (Jamil et al, 2021b). A summary of energy required for various feedwater treatments is presented in Figure 5 (IRENA, 2015; Walsh et al, 2015; Al-Zubari, 2017). It can be seen that seawater treatment requires the highest energy due to large salt contents that require extensive pre-treatment and actual treatment processes. In addition to a large amount of carbon emissions, seawater treatment also rejects chemical-laden brine that affects marine life. The fresh water shortage can be partially (50% of 40% gap) addressed by wastewater treatment and water conservation (Dawoud, 2012). The remaining gap (50% of 40%) can only be closed using desalination processes (McKinsey & Co., 2009) which at present are energy intensive and environment unfriendly.


Figure 5. Assorted feed water types and the typical amount of energy required for their treatment as per WHO standard (IRENA, 2015; Walsh et al, 2015; Al-Zubari, 2017).

## 2. Desalination Processes

Desalination is a process of separating freshwater from saline feedwater which can have different salinity content levels depending upon the fee source as shown in Figure 6. For this purpose, energy is supplied across a separating medium to split the freshwater from the feed stream and to reject the brine stream as shown in Figure 7 (Jamil, 2017). The separation mechanism varies with the technology employed e.g., semi-permeable membrane in reverse osmosis (RO), hydrophobic membrane in membrane distillation, heat exchanging tubes in evaporation-based systems, and flash chambers in flashing-based systems, etc. Similarly, the input energy can be electrical energy (e.g., RO) or thermal energy (steam for evaporation and flashing) (Shahzad et al, 2017a). In the simplest operating scenario, the process starts as the feed water (brackish or seawater) is supplied to the separation section after appropriate pretreatment particularly in membrane-based systems for longer membrane life (Ng et al, 2015). The distillate stream is supplied to the users after mineral adjustments to meet the drinking water quality and the brine stream is rejected back to the reservoir. However, in the advanced systems, some additional sections have also been incorporated with the desalination systems to increase the overall system's performance (Chen et al, 2020). For instance, the energy recovery sections are employed to utilize the waste heat which reduces the input energy (Jamil et al, 2020a). Similarly, brine management like partial recirculation, zero liquid discharge (ZLD) systems improve the recovery ratio and mitigate the environmental footprints to minimize the risks to the aquatic life in the natural water sources (Chung et al, 2017; Chen et al, 2021).

Commercially, there are two major desalination processes, pressure-driven, and thermal energy-driven. Pressure-driven processes are seawater reverse osmosis (SWRO) and thermal energy-driven are multi-effect desalination (MED), multistage flash (MSF), and adsorption cycle (AD) (Nassrullah et al, 2020). There are other innovative processes such as forward osmosis (FO), capacitance deionization (CDI), membrane distillation (MD), freezing, gas hydrates (GH), and humidification dehumidification (HDH) (Suwaileh et al, 2020). Most of these processes are at the small laboratory stage and need a large-scale pilot demonstration for commercial applications. Installed capacities of desalination processes and the share of different technologies are presented in Figure 8 (Eltawil et al, 2008 ; Mabrouk et al, 2015). In Gulf Cooperation Council (GCC) countries, thermally driven processes are more favorable since feed water quality varies throughout the year that SWRO processes are unable to handle. It can also be noticed that over 60% of desalination processes are applied on seawater followed by 23% on brackish water, 7% on river water, 5% on wastewater, and 6% on other sources (Shahzad et al, 2017b). Recently, many hybrid processes have been proposed to overcome the design and operational limitations of individual conventional technologies such as RO-MSF, MSF-MED, and MEDAD (Ahmed et al, 2020). Some of these hybrid processes show great improvement in terms of energy efficiency due to the excellent working synergy of processes. The capital expenditure (CAPEX) and operational expenditure (OPEX) of desalination technologies depend on several parameters. Some technologies CAPEX are highly expensive due to the costs of land, engineering, unit purchase, transportation, and installation, etc., and others are leading in terms of high OPEX such as energy, maintenance, spares, and labor but the overall water production cost is defined in $/m$^3$ (Mezher et al, 2011; El-Nashar, 2001). A brief description of different desalination processes is presented in the following.

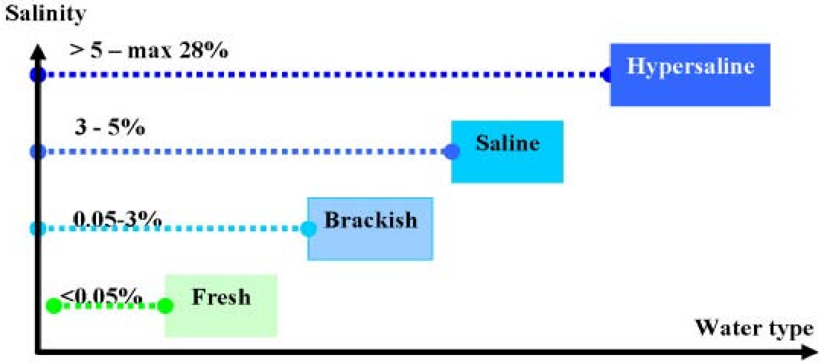


Figure 6. Water type and salinity level.

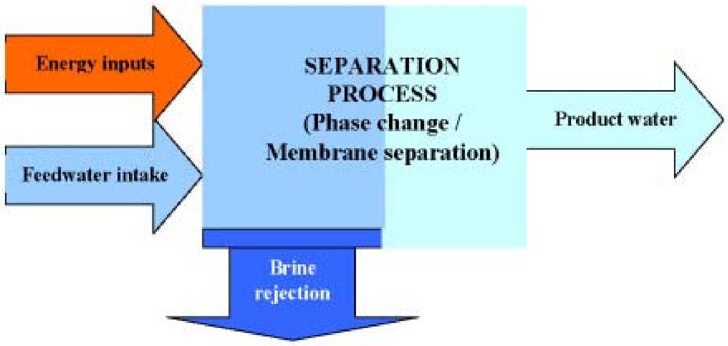


Figure 7. The basic principle of water desalination (Clayton, 2015).

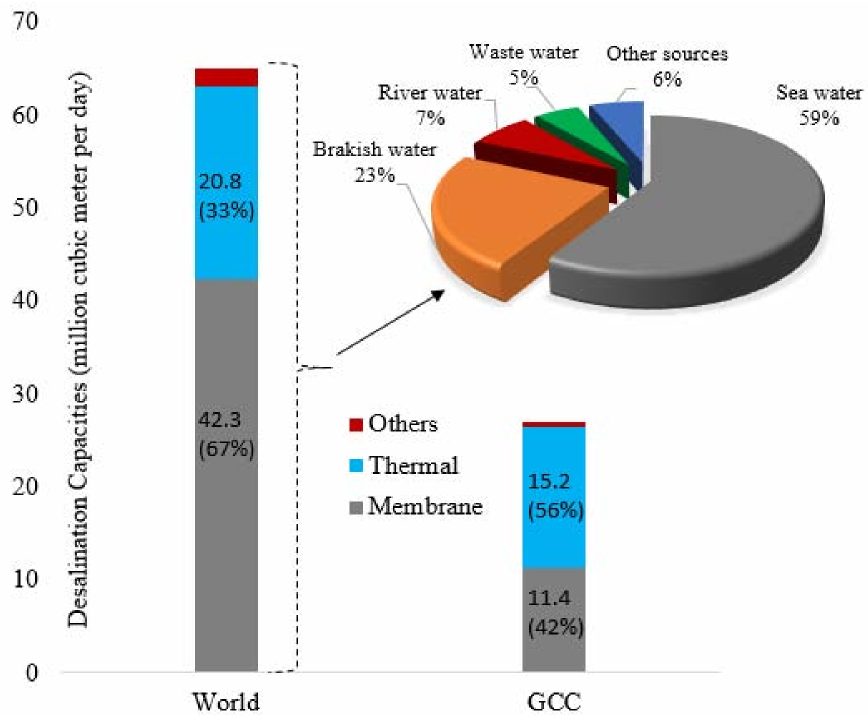


Figure 8. Total desalination installed capacities and share of different technologies in the World and in GCC countries (Eltawil et al, 2008; Mabrouk et al, 2015).

### 2.1. Membrane-based Systems

In these systems, energy is supplied across a membrane surface to extract fresh water from the saline water stream. The amount and type of energy depend upon the membrane type used as many membrane-based systems like membrane distillation, ultrafiltration, nanofiltration, and forward osmosis, reverse osmosis systems are used (Linares et al, 2016; Qureshi and Zubair, 2016a).

#### 2.1.1. Reverse Osmosis

Among membrane-based systems, the most used one is the reverse osmosis (RO) system which uses a semipermeable membrane to separate undesirable constituents from the feedwater. A pressure differential is maintained across the membrane surface to overcome the osmotic pressure using a high-pressure pump (HPP) (Qureshi and Zubair, 2016b). The RO operation involves pumping of intake seawater to a pretreatment section using a feed pump (FP) where chemical pretreatment is conducted to improve the membrane life. This pretreated feed is then supplied to a membrane module at very high pressure (for seawater 6-8 bar) to produce product fresh water (Qureshi and Zubair, 2015). The product stream is then sent to the post-treatment section for mineral dosing (to meet drinking-quality standards) and the brine is rejected back to the sea. However, in the advanced systems, the high-pressure brine stream is sent to an energy recovery section where the pressure energy is partly recovered using a Pelton turbine or pressure exchanger to raise the pressure of the feed stream as shown in Figure 9 (Jamil and Qureshi, 2016c). This energy recovery has been reported to reduce the input energy up to 24-25% thus improving the overall system efficiency and reducing the operational cost (Jamil and Qureshi, 2016c). Some of the recent improvements in RO technology are its integration with other systems like solar-driven phase change material assisted RO (Abbasi et al, 2019), solid oxide fuel cell integrated RO (Chitgar et al, 2019), etc.

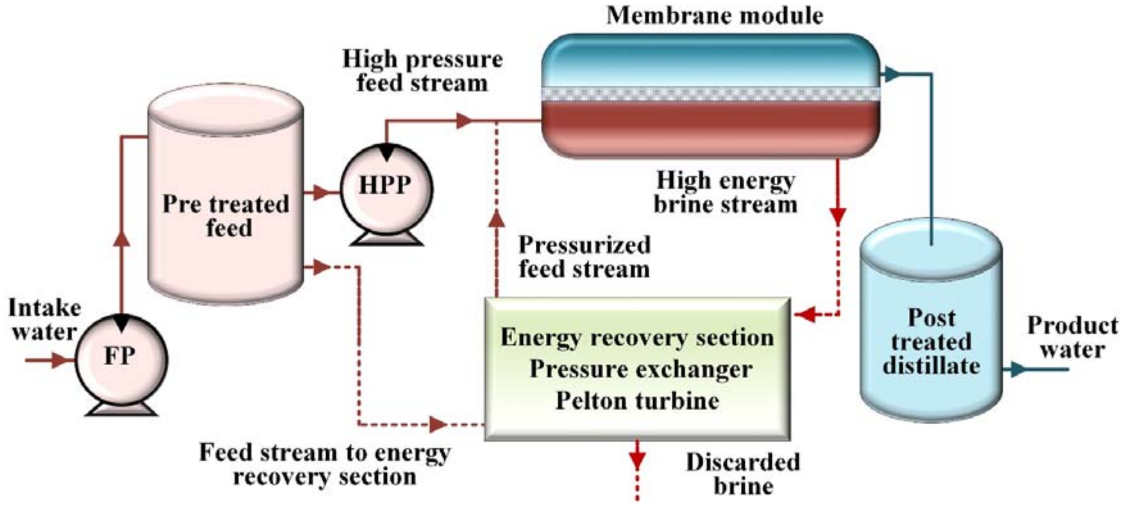


Figure 9. Schematic of RO system (Jamil and Qureshi, 2016c).

The main limitation of these systems is the membrane life which is particularly of concern while treating harsh feeds (high temperature, salinity and biological contaminants). In such situations, the system performance is limited because of the issues like extensive pretreatment, high membrane replacement frequency, low operational availability, and high maintenance downtime and cost.

## 2.2. Membrane Distillation

In membrane distillation, a micro-porous hydrophobic membrane is employed to separate pure water from a salt solution or feed water as shown in Figure 10 (Lee et al, 2018). The hydrophobicity of the membrane creates a gas-liquid interface and prevents the mass transfer of the feed water. It works based on temperature as well as pressure gradient across membrane that creates vapor pressure difference to evaporate volatile components through the pores (10 nm – 1 μm) and it is intensified via diffusion and/or convection of the compartment with high vapor pressure (Mustakeem et al, 2021). The vapors are then transported to the low-pressure compartment for condensation to produce distillate (Amy et al, 2017).

In comparison with RO, MD is less susceptible to flux limitations caused by concentration polarization, whereby a higher concentration of matter is obtained on the supply side (Fortunato et al, 2018). Theoretically, MD offers 100% retention for non-volatile dissolved substances, whereby there is no limit on the supply concentration (Elcik et al, 2020). In comparison with traditional distillation, MD possesses typical basic advantages of membrane separation, namely simple up-scaling, simple operations, the possibility for high membrane surface/volume ratios, possibility to treat flows with heat-sensitive components and/or a high suspended particle-content at atmospheric pressure and a temperature below the boiling point of the supply (El-Bourawi et al, 2006).

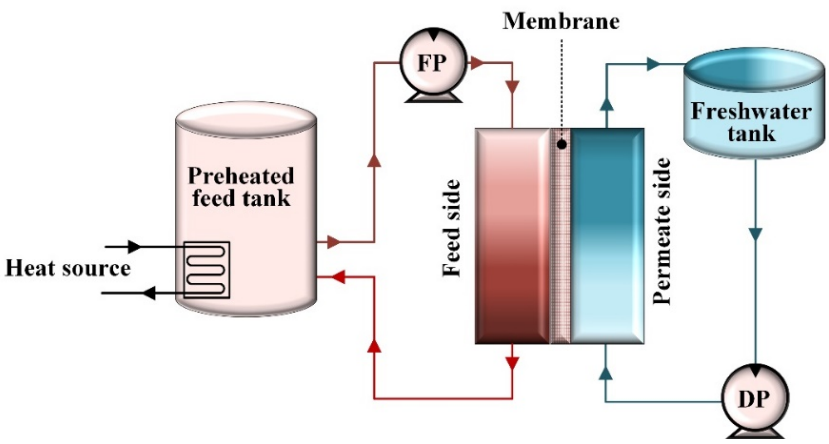


Figure 10. Direct contact membrane distillation process (Lee et al, 2018).

## 2.3. Thermal Desalination Systems

In thermal-based systems, steam is used to extract the fresh water in vapor form from the saline water stream which is later condensed as a distillate. These vapors are produced due to either flashing at temperature and pressure differential in the flash chambers or evaporated on the tubes in the evaporators. The formation of vapor containing freshwater is achieved due to boiling point elevation (BPE normally < $1^{o}$C) of the brine due to the presence of salts. This high-temperature brine is rejected back to the sea (El-Dessouky and Ettouney, 2002). The working principles of some of the common thermal desalination systems are outlined in the following.

### 2.3.1. Multi-Stage Flash

The multi-stage flash (MSF) is one of the oldest active desalination technologies developed in 1957 by Westinghouse (EI-Dessoukey et al, 1986). Silver (1957) outlined the standard features and patented the technology for the first time with some improvements in plant area and economics. Though multi-effect desalination (MED) was proposed in the meantime, yet it could not get significant popularity because of high salt scaling issues on the evaporator tubes as the antiscalants were not well developed back then. So, the flashing chambers turned out as the viable solution to produce vapors from the saline feed without using tubes. In these systems, the vapors are produced because of the difference in pressure and temperature as the preheated feed is led into the cascade of flash chambers. The vapors produced are condensed by exchanging heat with the feed water in the coils thus preheating it before entering the steam-operated feed heater as shown in Figure 11**.** Based on the brine flow the two major MSF types are once through MSF and brine recirculation MSF. The MSF with brine recirculation has shown better performance and is considered an industry standard. Some other improvements in the systems include high productivity operation, incorporation of energy recovery sections, and integration with other thermal systems (Mabrouk et al, 2007a).

The gain output ratio (GOR), second law efficiency, and the product cost for MSF plants range from 2 to 7, 1.8 to 2.3%, and 1.8 to 2.7 %, respectively (Mabrouk et al, 2007b) and show close competition with other thermal systems. However, some of the common drawbacks of MSF plants include high brine salinity, brine recycle flow rate, and comparatively larger condenser heat transfer area (Van der Bruggen and Vandecasteele, 2002).

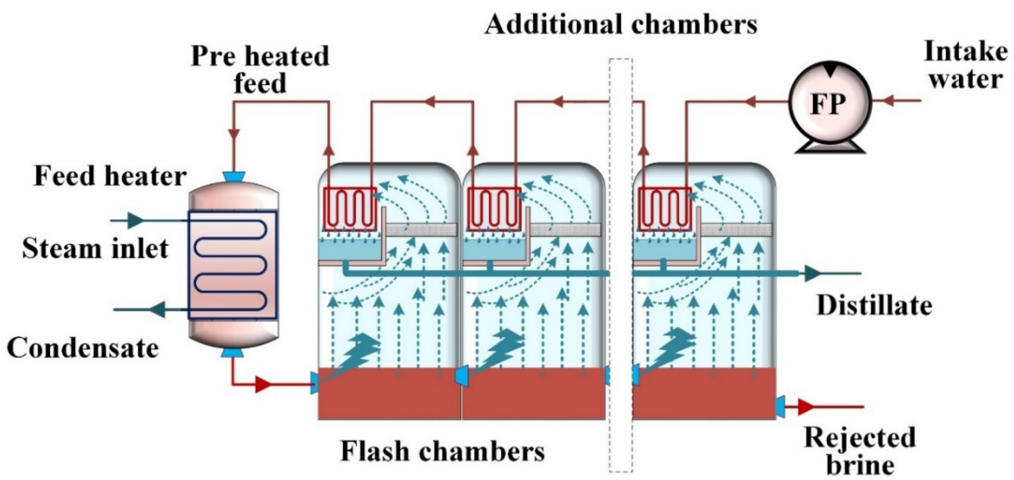


Figure 11. Schematic of MSF with brine circulation (Junjie et al, 2007).

### 2.3.2. Multi-Effect Evaporation/Desalination

The multi-effect evaporation/desalination (MEE/MED) is has received significant attention in the past three decades because of lower energy consumption, higher latent heat transfer, low-temperature operation, ability to use waste heat, and lower product cost because of hybrid system operations (Rostamzadeh et al, 2020). In these systems, intake seawater is sprayed on the evaporator tubes after being preheated in the vapor condenser (Christ et al, 2017). The steam is introduced in the evaporator tubes of the first evaporator from an external steam generation facility which may be a boiler or bleed steam source like the power plant, process industry, etc. (Jamil et al, 2021c). The vapors produced in the first evaporators are subsequently used as steam in the next evaporator and so on. The vapors from the last effect are condensed in a vapor condenser by exchanging heat with the intake seawater to achieve feed temperature as shown in Figure 12 (Abid et al, 2020). Depending upon the feed requirement, the extra seawater is discarded as cooling water after condensing the vapors. Based on the feed spray in the evaporators, the MED systems can be categorized as a forward feed FF (the total feed is sprayed in the first evaporator), parallel feed PF (feed is equally sprayed in all effects), parallel crossfeed PCF combination of forward and parallel feed) as shown in Figure 13 (Elsayed et al, 2018).

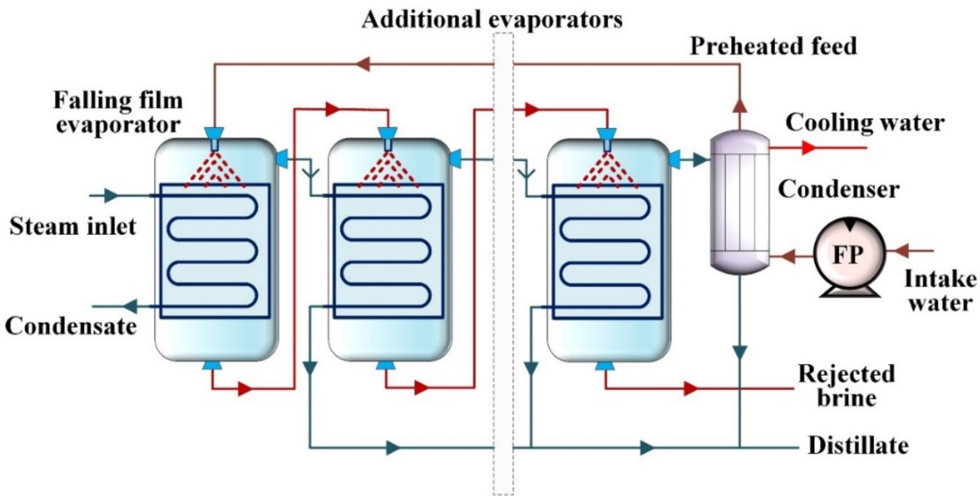


Figure 12. Forward feed MED system (Abid et al, 2020).

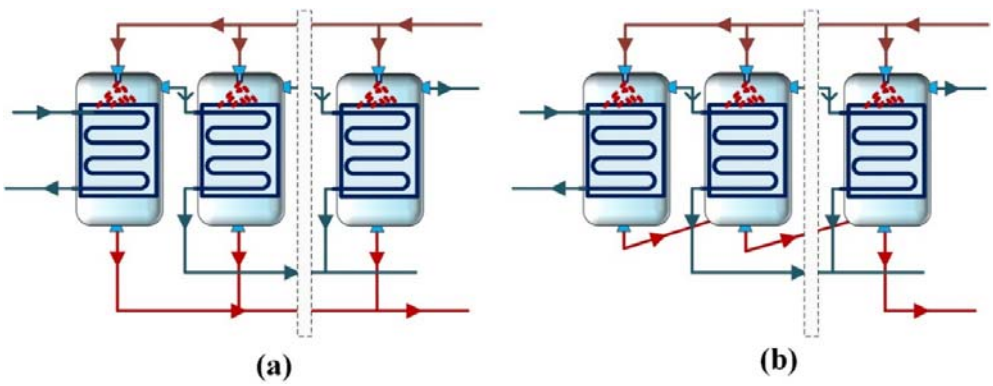


Figure 13. Multi-effect desalination evaporator arrangement for (a) parallel and (b) parallel cross feed arrangements (Elsayed et al, 2018).

One of the major developments in this technology is its integration with other thermal systems like adsorption systems (MED-AD) (Shahzad et al, 2015), and power plants (Jamil et al, 2021c)which significantly improved the system performance and reduced freshwater cost. The performance parameters of conventional standalone MED systems are reported as performance ratio 6, specific energy consumption 2 kWh/m$^{3,}$ and second law efficiency 7%.

### 2.3.3. Vapor Compression MED System

The vapor compression-based desalination systems operate by compressing the vapors from the last effect of the MED system and using it as steam in the first evaporator (Farahat et al, 2021). The two common vapor compression-based systems are thermal vapor compression (TVC) and mechanical vapor compression system (MVC) (Shahzamanian et al, 2021; He et al, 2018). In TVC a thermal vapor compressor is used while in MVC systems a mechanical vapor compressor is used as shown in Figure 14 (Jamil and Zubair, 2017a). The vapor compression arrangement enhances the operational capability like MED can operate on electrical energy, minimum external steam involvement, less investment on steam generation facility. However, these systems (particularly MVC) are only preferred for production capacities ≤ 5000 m$^3$/d (Ettouney et al, 1986 ; Ettouney, 2006 ; Eisavi et al, 2021).

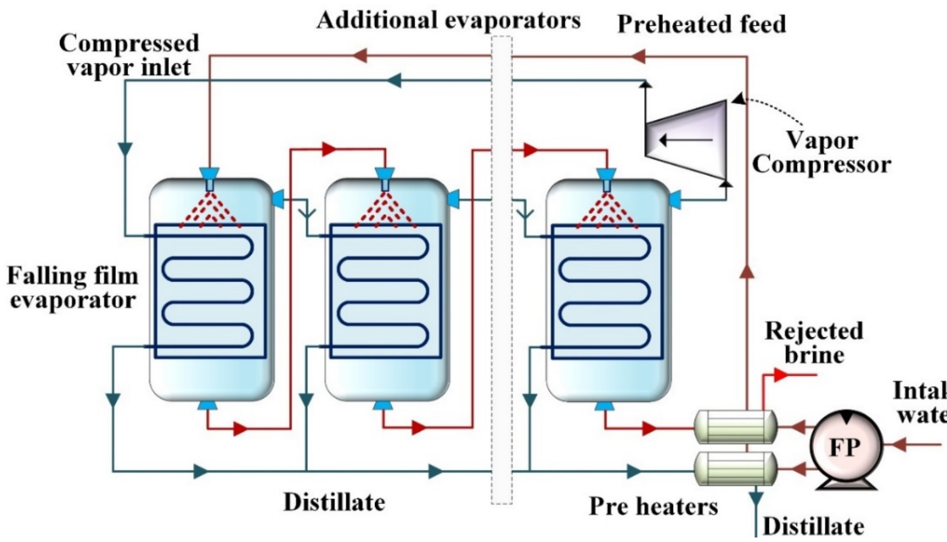


Figure 14. Schematic of MED-MVC system.

### 2.3.4. Multi-effect Desalination Hybrid with an Adsorption System

Although thermally-driven desalination processes such as MED and MSF are highly preferable in GCC countries, their performance is limited by operational temperatures. For example, MED processes can only operate from top brine temperature at 65C to bottom brine temperature at 40$^{o}$C (Shahzad, 2013). The top brine temperature is controlled by scaling and fouling chances whilst the bottom brine temperature is set by seawater cooled condenser (Son et al, 2020). Between these two operational temperature differentials, several heat recoveries are directly proportional to process performance. Overcoming anyone of limitations can help to enhance the system performance.

Recently, AD cycle hybridization with MED system also called MEDAD cycle was proposed to overcome bottom brine temperature limitations. This innovative MEDAD cycle has been extensively investigated at the King Abdullah University of Science and Technology in Saudi Arabia. In a hybrid scheme, as shown in Figure 15, the AD cycle is integrated into the last stage of the MED system to bypass the conventional condenser. In this case, the last stage vapor from MED is directly adsorbed onto the silica gel of the AD cycle that helps to reduce the stage temperatures to as low as 5-7°C (Shahzad et al, 2017b). The excellent thermodynamic synergy between MED and AD cycles boost the water production 2-3 folds at the same heat input as compared to conventional MED systems (Shahzad et al, 2014). This high-performance improvement can only be achieved by the integration of two thermally driven systems as they have excellent thermodynamic synergy.

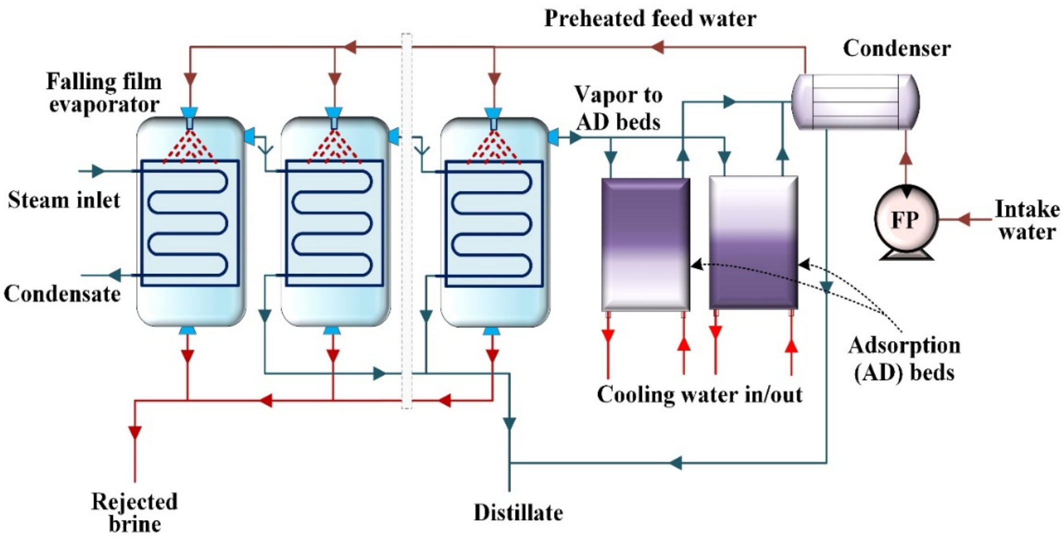


Figure 15. Multi-effect desalination hybrid with adsorption desalination system (Shahzad et al, 2014).

### 2.3.5. Direct Contact Spray Evaporation

Direct-contact spray evaporation and condensation (DCSEC) is appeared as a promising desalination method that mitigates scaling issues and high capital costs faced by the traditional thermal desalination technologies (MSF and MED) (Chen et al, 2020). In DCSEC technology, the spray of feed water and fresh water is used for direct contact evaporation and condensation, respectively, which leads to efficient and strongly enhanced heat and mass transfer in the system as shown in Figure 16 (Qian et al, 2020). The seawater is preheated externally before being injected through a nozzle into the hollow evaporator chamber. The latter is controlled to a temperature lower than the feed water, giving a liquid superheat that promotes liquid flashing. The excess energy of droplets causes the phenomena of liquid flashing, and the vaporization occurs from the droplet surfaces over milliseconds (Qian et al, 2020). The evaporator’s generated vapors are diverted to the adjacent condenser chamber due to a small pressure difference caused by the condensation effect. The condensation is achieved by the spraying of distillate which is at a lower temperature. Such flash evaporation process is repeated in multiple stages before the feed is discharged as brine. The resultant flashed vapors then flow to the condenser, condensed by the subcooled freshwater spray (Alrowais et al, 2020).

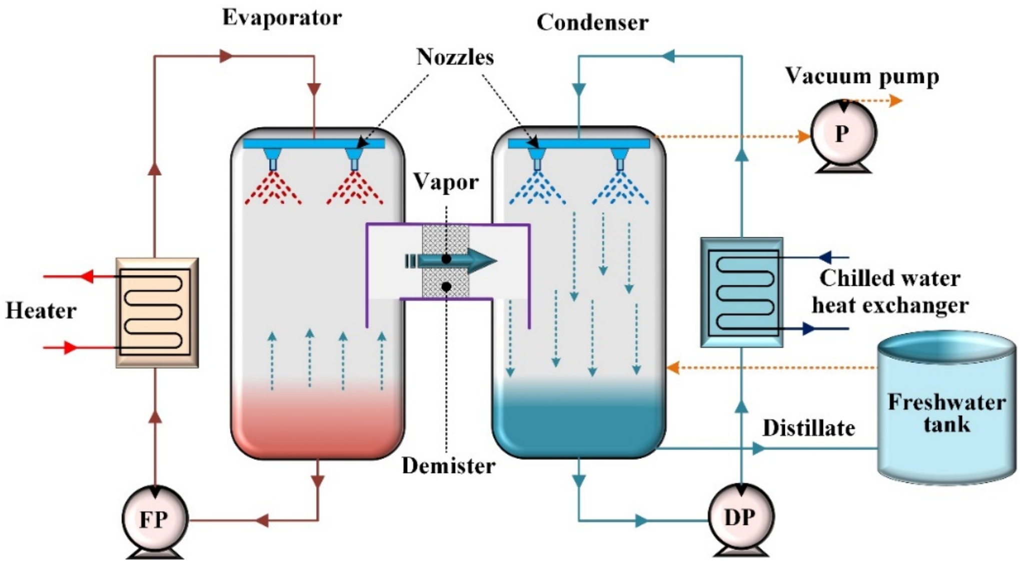


Figure 16. Direct-contact spray evaporation and condensation process (Qian et al, 2020).

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## Biographical Sketches

**Muhammad Ahmad Jamil** is a PhD student in the Mechanical and Construction Engineering Department, Northumbria University, Newcastle Upon Tyne UK. He is working on commercial buildings and data centre cooling using non-conventional air-conditioning technology. The work involves, design, fabrication, commissioning, and testing of commercial scale system. Before that he has served as a lecturer and coordinator labs at the Department of Mechanical Engineering, Khwaja Fareed University of Engineering and Information Technology, Rahim Yar Khan. His job involved teaching, development and instructing of undergraduate labs. Besides, he has been involved in technical inspection, purchasing, commissioning, and training of different thermal systems.

He earned his master’s degree in Mechanical Engineering from King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia, in 2017. During masters, he has worked in the field of water desalination where he worked on the development of exergoeconomic model for water treatment systems. The model combined exergy and economics to simultaneously analyse thermodynamic and monetary performance of the water treatment systems. He has worked as a collaborator in various funded projects at the national and international levels. Currently, he is working in the fields of cooling, heat transfer, and clean water.

He has published 30 peer reviewed journal papers and has presented in various conferences. He has been awarded best researcher award (2019-2021).