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DESALINATION TECHNOLOGIES: A CRITICAL REVIEW

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ABSTRACT

The current world population is expected to increase to about 9 billion in the next fifty years, which will increase the intake of fresh water significantly. Purified water for drinking purposes has become problem especially in arid regions, and is considered, nowadays, one the most significant international health issue. Billions of Dollars are currently spent worldwide on different desalination technologies to produce fresh water from Brackish and Seawater in order to meet the world's population demand for drinking water. Demands for reducing the cost of the desalination processes by reducing/ eliminating the input energy have recently become a trend and significant topic for researches. Therefore, the need for decreasing or if possible eliminating the dependency of desalination technologies on fossil fuel and oil and make them environmentally friendly through integration with renewable energy sources has become inevitable. In this paper, a critical review of different aspects relevant to desalination technologies has been presented. The review includes demonstration and comparative study of the most popular desalination technologies currently in use and the focus is on Membrane desalination (MD). It also includes the advantages and feasibility of integration the desalination technologies with solar energy or waste heat sources. Recent developments in cost of Seawater and Brackish water desalination, types of membrane desalination, types of membrane, and fouling of membrane have been considered.

Keywords: Desalination, MD, Solar Energy, Solar Powered Desalination

1.0 INTRODUCTION

The most abundant substance in the world is water and about 97% of the water is seawater while the rest is fresh water. According to some reports about one billion people are not able to drink fresh water across the world. The number of current population is expected to jump to about 9 billion in the next fifty years, which will increase the intake of fresh water to a great extent. According to [1] purified water for drinking has become problem especially in arid regions, and is considered, nowadays, one the most significant international health issue. Figure 1 shows the increase in

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population and the water availability from 1960s to 2020s in south Mediterranean countries which include Saudi Arabia, Libya, Malta, Yemen, Jordan, and United Arab Emirates. It is reported that about 70% of the world population are going to face water shortage within the next fifteen years, and 80 - 90% of the population in the developing countries will be affected by diseases and 30% by death due to utilization of unhealthy and polluted water [2, 3]. Around 150 countries across the world are using different desalination methods to produce fresh water from blackish and seawater. The most popular five countries in desalination are KSA, USA, UAE, Spain, and Kuwait, but the largest desalination plant is Jabal Ali multi-effect desalination plant in UAE with 300 million cubic meters of water/year [4].

Billions of Dollars are currently spent worldwide on different desalination technologies for producing fresh water from brackish and seawater that could meets the world's population demand for drinking water. For instance, the current investment on Membrane desalination across the world is about $ 9.2 billion per year with annual increase of about 12%. Bahar & Hawlader [5] reported that about 15 million US$ have been spent on Seawater desalination project in Sarawak, Malaysia. Twelve thousands membrane plants are nowadays running worldwide capable to provide more than 11 billion gallons per day of fresh water according to American Membrane Technology Association [6]. Technological improvements, during last decades, have made desalination technologies particularly Membrane Desalination more efficient, more durable, and much less expensive due to integrating the renewable energy sources, as it will be discussed through this paper.

Desalination is defined as a process in which salt and minerals are removed from water. Desalination process generally consists of three major steps namely pre-treatment for the feed water, transferring the pre-treated water to a desalination unit, and post or final treatment processes for the product [7]. The process of converting brackish and seawater to fresh water (Purification) still requires large amount of energy (particularly in desalination methods that depends on phase change) which make it expensive. Demands for reducing the cost of the desalination processes by reducing/ eliminating the input energy has recently become a trend [8]. Therefore, overcoming the drawbacks of conventional brackish and seawater purification such as improving the fouling techniques, increasing the quality and productivity of purified water, decreasing the energy input required for the process, integration of solar and wasted heat with desalination systems still offer opportunities for new researches and developments. In this paper, a critical review of different aspects relevant to desalination technologies has been presented. The review includes demonstration and comparative study of the most popular desalination technologies currently in use and the focus is on Membrane desalination (MD). It also

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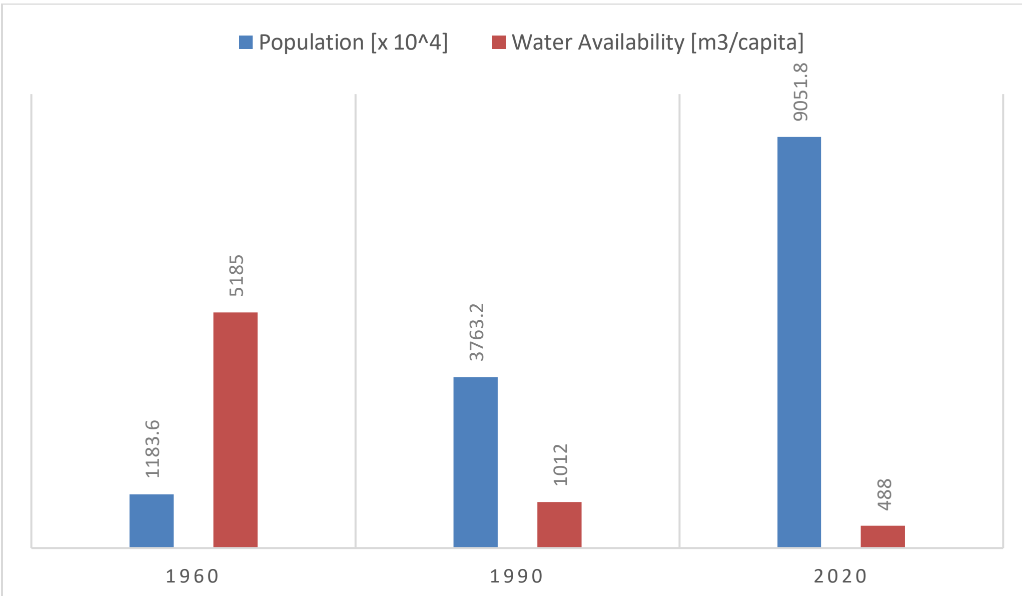

Figure 1: Water Availability and number of population for south Mediterranean countries with year (Source of Data: Tjandra [9])

2.0 TYPES OF DESALINATIONS TECHNOLOGIES

Desalination can be broadly categorized into one that requires thermal phase change and another without phase change. Thermal desalination includes MED, MSF, and mechanical vapor compression distillation (MVC), solar stills, and freezing, humidification–dehumidification (HDH), passive vacuum desalination (PVD), and thermal membrane (MD). Desalination without phase change includes electrodialysis (ED), Electrodialysis reversal (EDR), Reverse Osmosis (RO), and Forward Osmosis (FO). Heat pump systems could be integrated with desalination (also considered thermal phase) such as thermal vapor compressor (TVC), mechanical vapor compressor (MVC), absorption heat pump desalination (ABHP), and adsorption heat pump desalination (ADHP) [2, 10, 11, and 12]. Figure 2 represents the most popular desalination technologies currently used. The most popular desalinations systems are MSF, MED, RO, VC, and MD [9, 13]

MED is the oldest desalination technology refers to the middle of 19^{th} century. It involves heat transfer between the steam and

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seawater through different stages. The process is designed in a way to have high ratio of produced water and consumed steam (Input Energy) [10]. It can be operated in three configuration, namely, forward feed, backward feed and parallel feed. In this process, the feed seawater is passed through a sequence of parallel pressure vessels called effects (Usually, it has 2 – 14 effects). The heat required for evaporation is supplied to the first effect, and the latent heat due to vaporization is then delivered to the next effect [2]. MSF is a simpler and improved technology of MED, and it is more popular and widely used. It is reported that MSF requires more input energy and have higher operating temperature (90 – 110 °C) compared to MED [2]. It consists of different chambers (vessels) to heat up the seawater, and collect the condensate fresh water (sometimes it requires more than 20 stages). The most common advantages of MED over MSF is that it has higher efficiency, higher heat transfer coefficient, and required less water recycling. MED and MSF technologies require both electrical and thermal energies for pumps and evaporation which make the cost of desalination quite high [10]. Compared to thermal MD, the operating temperatures are higher which make MD technology more suitable for integration into renewable energy and waste heat e.g. Waste energy from air conditioners (Heat Pump System).

Reverse Osmosis (RO) desalination technology is a hydrophilic process which depends on high pressure pump to force the feed water to flow through the membrane, as shown in Figure 3. The hydraulic required pressure ranges from 70 to 90 bars approximately according to Compain [14]. Osmosis phenomena is a process in which water penetrates the pores of the membrane from the low salt concentration side to the high salt concentration side. High hydraulic pressure require large amount of input energy to reverse the water flow, which increases the cost of the desalination process. Unlike integrated thermal powered or waste heat powered membrane desalinations where vapor of feed water flows through the membrane using free energy and the pressure near to the atmospheric pressure [1]. According to some reports, most of the installed capacity of seawater desalination systems during the last century was thermal desalination, but during the last two decades, Reverse Osmosis Membrane desalination systems had the largest installed capacity in the market.

Compared to MED and MSF, RO technology requires less energy due to the absence of evaporation process. Malek et al [13] reported that the required input energy for R.O desalination is about half of that required for MSF, and about 40% of required input energy can be recovered by using Pelton- Wheel impulse turbines or other energy recovery devices. RO desalination requires pre-treatment for the feed water unlike thermal membrane desalination where the pre-treatment is not required. The membrane life of RO is not high (about 2 years) due to the high

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hydraulic pressure applied, while the membrane life of thermal membrane desalination is more than 20 years. RO method require larger space than MD because of the additional auxiliary equipment. Cath et al [15] reported that increasing the salt concentration of feed in RO desalination leads to significantly decrease in process performance and increase the permeability of salt through the membrane unlike Direct Contact MD and other thermal MD where salt concentration of seawater has negligible effects. This makes it essential for membrane replacement with time in RO, more than thermal MD. Despite MD require pumps for feed and permeate, but the low required pressure makes the cost much less expensive than RO where high hydraulic pressure is required.

Cellulose acetate (CA) membranes were the most common membrane used in RO desalination. This type of membrane showed 99.5% salt rejection and mass flux values 5 - 11 gallons per day. The degree of acetylation influencing the performance of RO process. Higher acetylation lead to higher salt rejection but lower permeability, while lower degree means higher permeability. One of most common disadvantages of CA membrane is that it can hydrolyze over time, which decreases their selectivity, and salt rejection decrease with increasing the feed temperature that is why it is recommended to not operate RO over 35 ^{o}C. Unlike thermal membrane desalination methods where the increase of feed temperature brings a lot of advantages for the process. However, after 1972 thin film composite (TFC) RO membranes was introduced as alternative of CA, but the process with TFC still require more pretreatment to removed chlorine because it negatively affects the performance desalination process [10].

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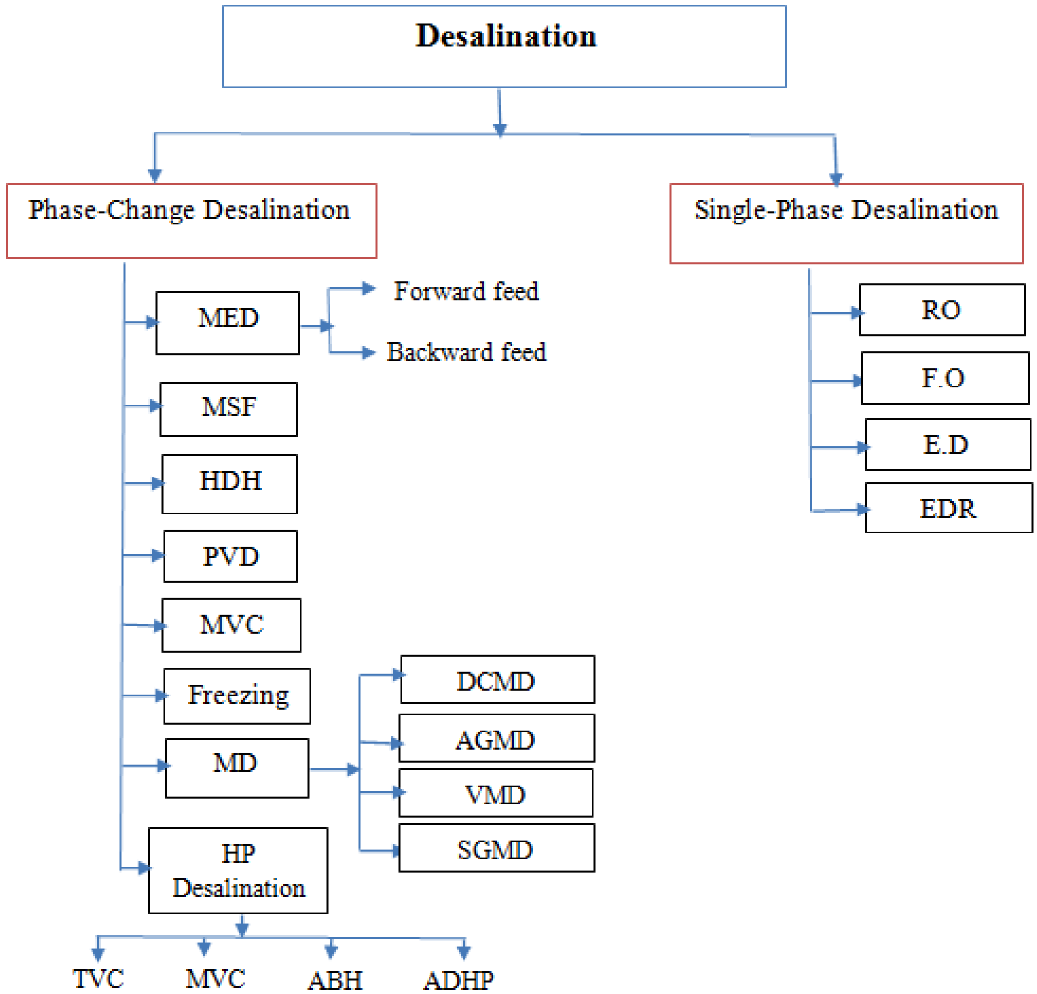

Figure 2: Types of Desalination Technology

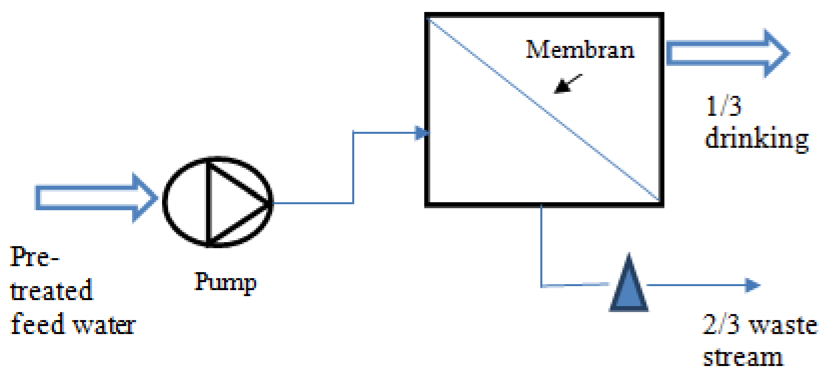

Figure 3: Schematic of Reverse Osmosis Desalination Technology

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Since Reverse Osmosis desalination requires high hydraulic pressure (Mechanical, not thermal energy), integrating it with organic Rankin Cycle (ORC) have been investigated and recommended by different researchers worldwide. Most efficient type of solar collectors that can be used in ORC to provide high temperature needed and the optimal area of collectors are still investigated.

Electrodialysis Desalination (ED) is a process of removing salt from seawater by transforming the salt ions through membrane from the dilute solution side to the concentrated side due to applying direct electricity. Unlike MED, MSF, and MD where water is transformed by evaporation instead of salt ions. Ion-*exchange* process in ED in very expensive process and the membrane has very short life compared to other desalination technologies. Its application is still limited to low salinity water [14]. This is why this technology is - unpopular and not widely used. However, integration ED with Photovoltaic solar modules to exploit solar energy instead of fossil fuel have been investigated by different researchers in trying to reduce the cost of it. The common disadvantages of hybridization of ED with solar energy is that it is still not efficient and the seawater need to be recirculated many time to reach the final product [2].

3.0 MEMBRANE DESALINATION TECHNOLOGY

Membrane distillation is defined as a thermal powered process (or thermal diffusion driven process) in which phase change of the seawater takes place around the two side of membrane. The phase change is from liquid to vapor on one side of the membrane (Brackish or seawater feed side), and from vapor to liquid by condensation on the other side of the membrane [1]. This type of desalination known since 1962s and it still under developing stage [11]. Simultaneous Mass and heat transfer process occur during the membrane desalination. Heat transfer occurs in two mechanisms which are conduction heat transfer through the membrane material, and latent heat due to vapor. Mass transfer occurs in three process which are diffusive transport from the feed stream to the membrane interface, diffusive and convective transformation of the vapors through the membrane pores, and condensation of vapor on the other side of the membrane [15]. Vapor pressure difference between the two sides is considered the driving force of the mass transfer unlike other desalination (RO) where mass transfer process requires high hydraulic pressure by pump to take place [3, 15]. A relationship between vapor pressure of Seawater and pure water, and temperature is shown in Figure 4. Feed water enters the desalination vessels at 60 ^{o}C (0.18 bars) while pure water leave the desalination unit at 25 ^{o}C (0.03 bar). Thus a small pressure difference (around 0.15 bar) between the two sides of the membrane contributes the driving force for the membrane desalination.

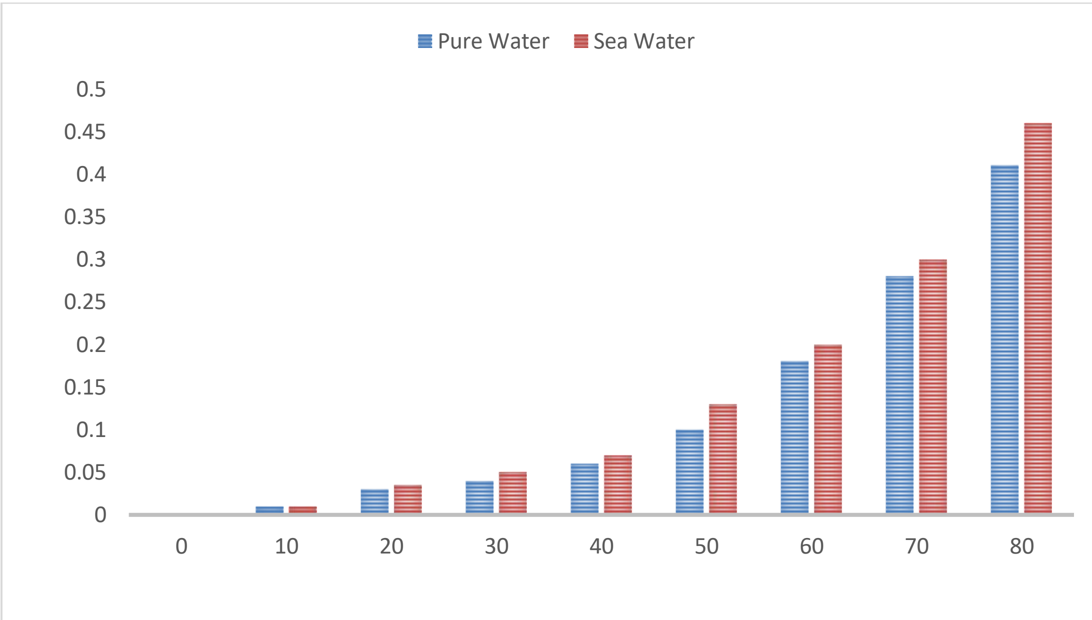

Figure 4: Vapor Pressure for Seawater and Pure water with Temperature (Source: [3])

MD operates at low temperature (323 – 363 K) which make it attractive process to be integrated with wasted heat recovery systems or renewable energy. Therefore, the high required energy for MD technology contribute to 40 -50% of the total process costs which make the applications of it limited in industry. Solving this problem by integrating MD technology with heat pump systems is a viable potential alternative because it decrease the cost to about half. According to [11, 16] the most common applications of the MD is desalination of seawater. MD applied in petrochemical, chemical, environmental, biotechnology (e.g removing toxic products from culture broths), pharmaceutical, and food industries because it produce very pure water [11]. The feed brackish or seawater in thermal membrane desalination is heated and vapor produced which will make pressure difference between the two sides of the membrane. The vapor passes through non-wetted pores of hydrophobic membranes, then it condensates on the cooled side to produce fresh water. Feed brackish or seawater usually contains impurities which form what so called deposit on the surface of the membrane. Formation of deposit on the surface of membrane must be prevented because it makes the membrane to lose its separation properties [16].

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The actual job of the hydrophobic membrane is to facilitate the movement of the water vapor through its pores and prevent the non-Volatile substances to pass. It must be highly porous, hydrophobic, allow to only vapor to pass through it, does not allow any condensation process to take place inside the pores, at least one side of it must be in contact with the process fluid;, it should not change the vapor-liquid balance of the different components in the liquid, and exhibit chemical resistance of the feed solution [1, 16]. The feed water cannot penetrate the pore of the membrane due to the surface tension force [11]. Usually polymers made-membranes "with a low value of the surface energy such as polytetrafluoroethylene (PTFE), polypropylene (PP) or polyvinylidene fluoride (PVDF)" can achieve these requirements. The pores of the membrane will be filled with vapor during the desalination process which will create and form a vapor gap between the two sides. In reality, pores of the membrane could be wetted little bit during the process which will decrease the created vapor gap. The possibility of liquid penetration into the pores (called liquid entry pressure of water LEPW) is affected by the feed and distillate hydraulic pressures, pores dimensions, liquid surface tension, and liquid contact angle, as shown in Equation (1). Cath et al [15] reported that LEPW is 200-400 KP for 0.2 micro pore size, and 100 KP for 0.45 micro meter. It is recommended that the pore diameter of membrane should not be more than 0.5 micro meter to avoid high liquid penetration (membrane wettability).

$$P_{Liquid} - P_{Vapor} = \Delta P_{interface} = -4\frac{\partial \beta cos_{\emptyset}}{dp} \quad (1)$$

Where β is pore geometry coefficient (for cylindrical pore equal 1), ∂ is surface tension of liquid, $\emptyset$ liquid contact angle, dp pore diameter, ΔP is liquid entry pressure.

The performance of the MD depends on the membrane's module design. Capillary module is preferred over flat plate module because it helps in decreasing the temperature polarization according to Gryta [16]. Temperature and flow rate of the feed water is highly influencing the productivity of the membrane desalination. Higher feed temperature, higher permeate flux (higher mass transfer) and higher productivity. Distillate temperature is also affecting the thermal efficiency of the membrane if it is lower than 10 ^{o}C.

Three energetic inefficiencies are existent in membrane desalination technology which are temperature polarization, the hindrance of mass transfer of the vapor by the trapped air in the pores, and heat loss by conduction through the membrane [15, 16]. Temperature polarization occurs due to the heat conduction which need to be reduced in the process in order to minimize the heat loss. Temperature polarization coefficient (TPC) is defined as the ration of useful energy that required for mass transfer of the vapor to the total input energy of the desalination process, and it is usually between 0.2 – 0.9 depending on the membrane type. Mass transfer flux of vapor through the membrane is affected by the porosity of the membrane, pore size, its thickness, its wettability, and compaction. Cath et al [15] mentioned some techniques used to solve this problem included degasification of the working fluids in the MD, and placing both the feed and permeate streams under vacuum to control the partial pressure of air in the pores. Improving the porosity of the membrane could be the only available solution to reduce the conductive heat transfer loss in MD.

The most significant advantages, that make MD technology more attractive than other conventional desalination systems, are the low operating temperature difference, operates at hydrostatic pressure which is near atmospheric pressure unlike other that require high operating pressure such as Reverse Osmosis, Nanofiltration (NF), microfiltration (MF), and ultrafiltration (UF). Therefore, it reject totally all non-volatiles materials, produces high quality of water, does not require chemical pre-treatment. Salt concentration does not affects its performance, more suitable for seawater purification, and its application in industries are very wide [11]. Depending on literature, the mass permeate flux in MD increases by 21% for every 1°C increase in feed temperature and it is more than for RO. For instance, permeate flux for RO membrane is 18-341 while for MD is 351.

3.1 Types of Membrane Desalination

There are four different designs and configurations of membrane distillation currently used namely: Direct Contact Membrane Distillation (DCMD), Air Gap (AGMD), Vacuum (VMD), and sweeping Gas (SGMD). They differ from each other in the way of permeate collection, the reason for driving force formation, and mass transfer mechanism through the membrane [16]. The most common two configurations are DCMD and AGMD, but the highest thermal efficiency belongs to AGMD by 60% due to the existence of air gap. DCMD is considered a most cost efficient type when distillation process operates at higher temperature, and when waste heat recovery system is used to power the process [11, 16]. DCMD could be applied in nuclear desalination according to [11].This configuration also can be used for replacement of evaporation ponds for mineral recovery, in mineral production, where evaporation ponds used large land areas, consume a lot of time and energy, and big amount of water can be wasted to the atmosphere due to evaporation. Hickenbottom and Cath,[17] experimentally studied the performance of DCMD used for enhancement of mineral recovery from hypersaline solutions by replacing the evaporation pond by it. Water of more than 150,000 mg/L total dissolved solids was used as feed water, and it is found that DCMD was able to concentrate the feed solution to twice its original concentration, and water flux was 80%. It was concluded also that about 24 m^2 of membrane can replace 4047 m^2 of evaporation ponds efficiently with 170 times faster in concentrating hypersaline brines. Most of researchers have investigated the performance of the four configurations, but integration of thermal membrane distillation technology with solar energy still ongoing research and could be promising solutions to reduce the operation costs and improve its performance [1].

The mass transfer of permeate in MD increases with increasing feed temperature and, then, the permeate flux will increase as well [16]. This because the feed temperature has the highest impact on the permeate flux value, while the second highest impact on flux refers to feed flow rate and the partial pressure at the permeate side. Close and Sørensen [3] developed a mathematical model for DCMD in order to introduce the potential of this technology in desalination of Seawater, and to study the effects of different parameters on the permeate flux.

3.2 Types of Membrane

Different types of membrane used for purification of brackish and seawater such as Microfiltration (MF), Ultrafiltration (UF), Reverse Osmosis (RO), and Nano filtration (NF)

Membranes. This classification was depending on the pore size and diameter. Meanwhile, they can be categorized into isotropic and anisotropic membranes depending on the physical nature and composition of the membrane. Isotropic type have uniform composition and physical nature while anisotropic is not uniform and composes of different chemical composition layers. Isotropic can be phase inversion, track-etched, or expanded- film membranes and all of them are made mainly from hydrophobic polymers. Examples of anisotropic membrane are phase separation and thin film composite membranes [10]. Membrane might be single hydrophobic layer, bilayer consists of hydrophobic and hydrophilic layers, trilayer as hydrophobic/hydrophilic/hydrophobic or trilayer as hydrophilic/hydrophobic/hydrophilic layers [18]. It must have very small pore size (1 nano meter- 1 micro meter) and its porosity must be very high to maximize permeate mass flux. Khayet et al [18] experimentally investigated the performance of direct contact membrane desalination using bilayer hydrophobic/hydrophilic membrane. Temperature polarization coefficient and vapor mass flux permeability were studied. It was found that bilayer hydrophobic/hydrophilic membrane is promising in desalination because it decreased the conductive heat transfer through the membrane matrix by increasing the thickness, and increased the permeability through its pores.

4.0 INTEGRATION OF DESALINATION TECHNOLOGIES WITH SOLAR AND WASTE ENERGIES

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Desalination of brackish and Seawater require large amount of energy which is in some process contributes to more than 45% of the total cost of the process. Reduction of consumed energy by desalinations leads to a significant reduction in the process cost. One of the most attractive methods that could achieve this purpose is to use solar or waste heat as input energy in the thermal desalination methods such as MED, MSF, and thermal MD. Li et al [2] reported that about 8.78 million tons of oil are spent per year on desalination to get 1 million/m^3/day of fresh water. While the oil depletion idea has recently become widespread in media, the need for reducing or even eliminating this amount of oil and looking for alternative energy source for desalination has become inevitable. Therefore, Figure 5 shows the minimum required energy for desalination of seawater.

Baradey et al [19] mentioned different resources of waste heat, such as, Glass melting furnace, Cement kiln, Steel electric arc furnace, internal combustion engines, air conditioners, and Blast furnace slags. It would be more prudent to reuse or exploit this heat instead of throwing it away to atmosphere. Utilization of desalination technology as waste heat recovery system could bring a lot of benefits. Table 1 summarizes the typical temperatures that could be gained from different sources of waste heat. As membrane Desalination is a low operating temperature desalination process, it would be efficient to integrate it with a suitable waste heat source to decrease the cost and minimize energy consumption.

Solar energy is the most significant resource of renewable energy because the amount that can be gained from it is about 85 TW while the current energy demand across the world is just about 15 TW which means solar energy only can meet the current energy demand according to [20]. Integration of solar energy with desalination technology is not a new idea, antique sailors used simple solar stills to distillate seawater [14], but the combination between them nowadays would be more efficient due to recent advances in technology. The most significant recommendations that reported by the National Research council, in USA in 2008, about research areas related to desalination technologies are improving the performance of membrane desalination system, reducing the required energy for desalination process, and integration the membrane desalination technologies with renewable energy sources [21].

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Table 1: Typical temperatures of waste heat from different Sources at low, medium, and high level [19].

Source of Waste Heat	Typical Temperature (^{o}C)
Aluminum Refining Furnace (High)	650-760
Steel Heating Furnaces (High)	925-1050
Open Hearth Furnace (High)	650-700
Solid Waste Incinerators (High)	650-1000
Glass Melting Furnaces (High)	1000- 1550
Steam Boiler Exhausts (Medium)	230-480
Reciprocating Engine Exhausts (Medium)	315-600
Drying and Baking Ovens (Medium)	230 – 600
Annealing Furnace Cooling Systems (Medium)	425 – 650
Air Conditioning and Refrigeration (low)	32-88
Air Compressors (low)	27-50
Cooling Water from Injection Molding Machines (low)	32-88

According to Hawlader et al [8] integration of renewable energy for the conversion of seawater into fresh water by using thermal distillation process is the most attractive application of renewable energy. Therefore, according to Summers and Lienhard [22] utilization of solar energy to operate membrane distillation system is considered a promising alternative to produce cost-effective portable water. It is reported that solar assisted seawater desalination is technically feasible, but hybrid solar-fuel or low temperature wasted heat could be more efficient and cost effective [2]. The combination of solar desalination with heat pump system represents a big progress in solar- powered desalination technology [9, 23]

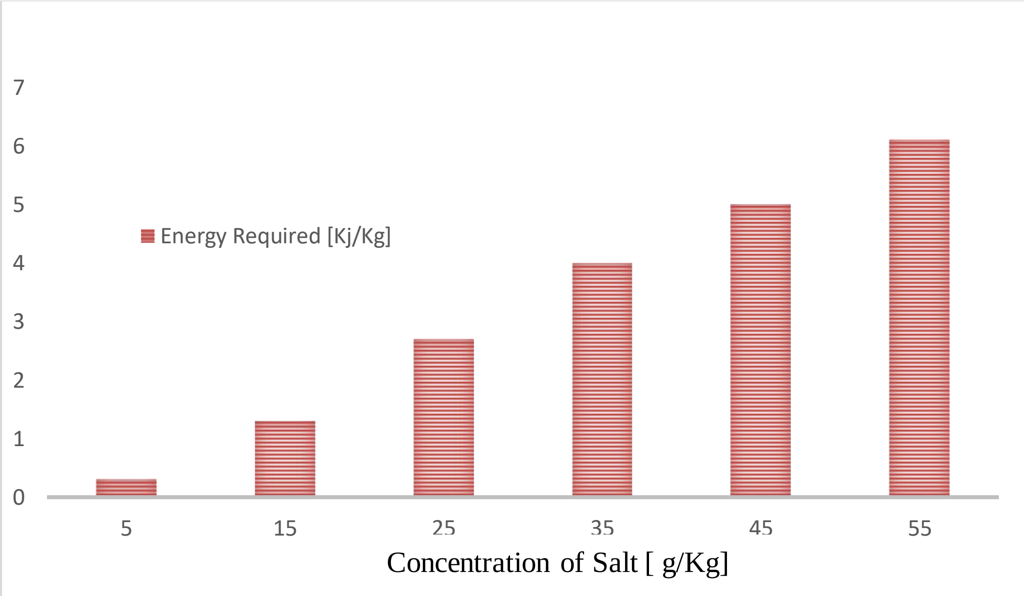

Figure 5: Energy Required for Desalination of Seawater (Source of Data: Li et al [2])

4.1 Feasibility of Solar-Powered Desalination Technology

To investigate the feasibility of integrating solar and desalination technology, a systematic evaluation for solar-desalination technology is needed. This evaluation includes different areas, such as, thermal efficiency, coefficient of performance, performance ratio of desalination, costs of the system, the annualized cost, the life-cycle savings (LCSs) and payback period. Zakaria et al [24] conducted an economic optimization for solar assisted heat pump (SAHP) desalination system. The system consists of SAHP system and MSF desalination unit. The economic analysis showed that the Payback period of such system is around 3.5 years for 900 L/day water production and evaporator collector area of 70 m^2. This study indicates that the integration of solar energy and waste heat from heat pump system with desalination technology is economically feasible. Compain [14] studied the feasibility of coupling different desalination technologies with renewable energy sources and concluded that the combination between them would decrease the cost of desalination process. Meanwhile, Buschert and Bitzer [25] studied the feasibility of integrating solar energy with desalination plant by introducing a mathematical modeling of a solar integrated desalination plant intended to be built in Hurghada in Egypt. The most common desalination method that is able to operate efficiently on renewable energy sources is the membrane distillation, as shown Figure 6. This can be attributed to the fact that MD has low operating temperature

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compared to other medium and high operating temperature desalination methods. Figure 7 represent the proper desalination technology to be integrated with solar energy.

4.2 Categorizes of Solar powered desalination systems

Solar powered desalination system is categorized into two sub systems, namely: solar thermal-assisted systems and solar photovoltaic-assisted systems. However, they also can be divided into direct and indirect systems depending on way of utilizing energy from sun. In the direct system,the heat gained and desalination process occurs within same system, while this two processes occur in two separate sub-systems in indirect method . Direct solar assisted desalination systems are competitive with indirect type in small scale production because it costs less than indirect system, as it is considered simpler in design. The most dominant application of direct systems is found in solar stills. Solar stills are categorized into basin still, tilted-wick solar still, multiple-tray tilted still and concentrating mirror still.

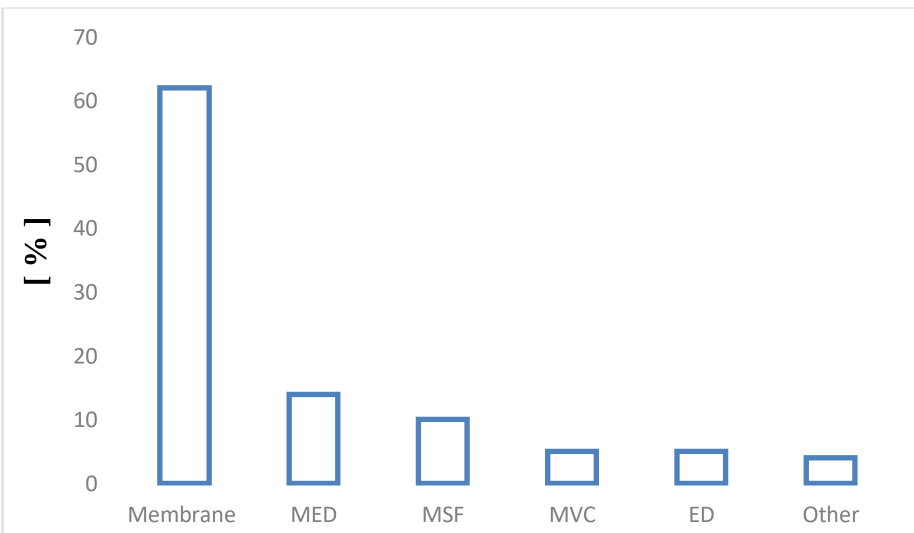

Figure 6: Integration of Renewable Energy with Desalination Methods (Source of Data: Summers & Lienhard [22])

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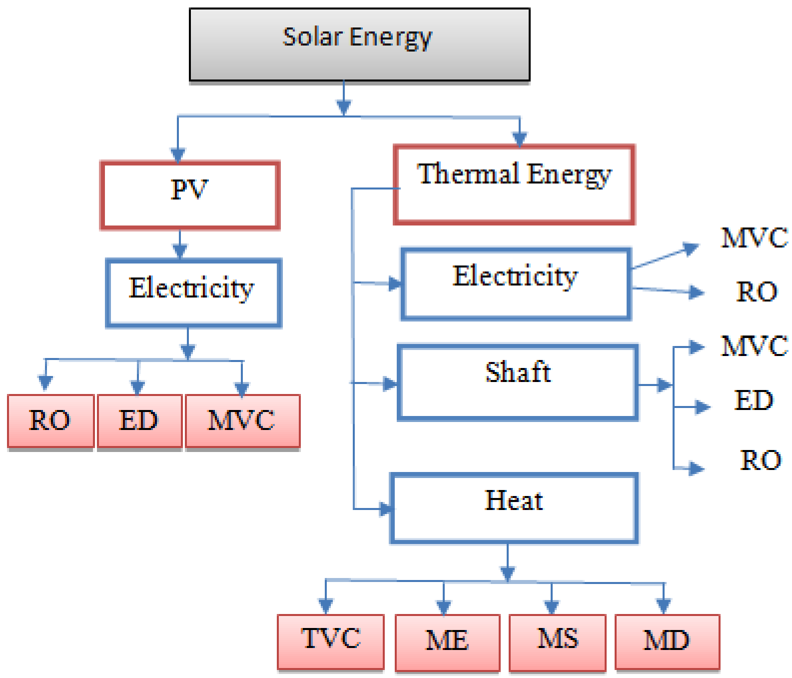

Figure 7: Proper Integration between Desalination methods and Solar Energy

4.3 Recent Attempts to Improve the Solar-Powered Desalination Technology

Numerous of studies have been conducted to integrate desalination with solar or waste thermal energy. A single effect desalination system, for purification of seawater, connected to a solar assisted heat pump system was fabricated and evaluated by [8]. The main components of the system were solar evaporator collector, compressor, condenser, desalination chamber, vacuum pump, and feed tank. R134a was used as refrigerant in this system. The heat input to desalination that required for evaporation and producing steam was exploited from solar and wasted heat from condenser. The performance ratio and COP of the system were experimentally recorded. The performance ratio fluctuated from 0.77 to 1.15, and the COP was between 05 and 0.7. The problems, in this system, are that R134a contributes to Global Warming and Ozone Depletion, so that it must be replaced by other natural refrigerants, such as, CO_2. Therefore, Single effect desalination process is not a low operating temperature process, and it is more suitable for marine not for domestic applications, such as hospital and hotels, so that it would be more prudent to use other types of desalination such as thermal membrane distillation which has lower operating temperature (40 -100 ^oC), and lower cost. It is reported that MD is more suitable for purification of seawater than other desalination technologies [16].

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Tjandra [9] conducted his master thesis on solar assisted heat pump desalination system. The system consisted from solar assisted heat pump system working on R-134a, and single effect desalination unit. The feed temperature to the desalination chamber was 70 ^{o}C. The system showed COP up to 10 with water production of 1kg/hr. It is concluded that integrating solar energy with desalination is promising solution to reduce the desalination cost. Selvi and Baskaran [1] introduced a novel solar powered thermal Direct Contact Membrane Desalination system for well water purification. The system performance was compared with conventional Reverse Osmosis desalination system. Thermal efficiency of solar Powered DCMD was less than RO, but the cost of the system was lower. This opened the door for developing these systems using renewable energy or waste heat. Integration of thermal membrane desalination with heat pump systems or solar assisted heat pump systems is recommended as well.

Hidouri et al [26] proposed Simple Solar Still Distiller Hybrid with heat pump (SSDHP). Solar distillation (Solar Still) technology has been used in this study. Performance of Simple Solar Still SSD was compared to SSDHP. The daily output increased from 2 -12 L/m^2 and the efficiency increase from 20 to80%. The disadvantages of such integration is that both condenser and evaporator were used for the desalination purpose only which does not offer another potential applications such as cooling or water heating. Walton et al [27] integrated solar ponds with air gap membrane desalination to study the performance of the system and evaluate the membrane fouling due to local water. It is concluded that mass flux fluctuated was about 6 L/m^2/hr and it was decreasing with increasing the salt concentration. When the temperature of feed below 13^{o}C, the flux decreased by 50%. High quality fresh water could be achieved from AGMD. It is also found that this technology is superior in low grade heat energy and could be more competitive if latent heat recovery is coupled with it.

The dependency on solar energy only in direct solar-desalination systems might not be viable and feasible solution because the sun is available during the day only while it is absent during the night. One of the most common solutions that used and largely studied to solve this problem is to use thermal storage materials (latent and sensible storage material) with direct solar-desalination systems (solar stills). Different researchers mentioned that latent heat storage materials are better and more efficient than sensible heat storage materials. Mohan and Soundarajan [28] conducted a study on solar stills-desalination unit connected with latent heat storage material (Paraffin Wax) and solar collectors to enhance the productivity of distillate of the system. Solar collectors are used for the purpose of increasing the temperature of the solar still while paraffin Wax was used to store the sun energy. Results revealed that

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combination of solar collectors and thermal energy storage materials could increase the productivity of water.

Cath et al [15] studied the performance of direct contact membrane desalination system using three hydrophobic micro porous membranes with low temperature of feed stream (40°C). The objective of the study was to maximize the flux of permeate through the membrane by decreasing the temperature polarization coefficient and using low temperature of feed. Mass transfer of the vapor was highly improved, and the salt rejection was about 99.9%. Byrne et al [29] theoretically and experimentally investigated the performance of heat pump system for simultaneous cooling and desalination. Photovoltaic Panel was used to provide electricity to the compressor. Air Gap MD type was integrated with heat pump system. The objective of the study was to determine the productivity of the desalination unit depending on the cooling loads of refrigerator, and to compare its performance with and energy consumption with Reverse Osmosis unit operating on waste heat of chiller. It was concluded that coupling of AGMD with heat pump system could offer different benefits, and the system was consuming more energy than R.O coupled with outdoor condenser at temperature more than 30 °C.

5.0 COST OF SEAWATER DESALINATION

Seawater desalination is considered the most costly process to produce fresh (drinking) water because of high capital and energy costs [2]. Cost of Seawater desalination process is the most significant factors that affect the project of producing superior water. It is reported that the ongoing reduction in Membrane Desalination cost through the last decades is the most attractive aspect which made the MD the most favorable process in United State over other desalination process according to Water Association Desalination Committee [30]. According [6] the most hindrance prevented usage of desalted water in wide range to meet the nations demand in the past is that the desalination process was very costly and too expensive. Recent advances in technology, especially in membrane desalination technology, has made the desalination process much less expensive than ever. Figure 8 shows the reduction in cost of seawater MD for the last three decades. It can be seen from the figure that the cost of steam production have been reduced to zero after 1972, while the cost of electrical power still contributes to about half of MD process costs until 2010 which has to be reduced or even eliminated. It is reported that the cost of RO desalination in 1990s was 1 $ for every cubic meter of salinity water, but it decreased to 70 cent after ten years. It is also expected that the cost of RO will goes down by 20% in the following ten years [10]. Kesieme et al [31] reported that 81% of the total RO desalination costs refer to energy

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consumption and fixed charges, and the water production costs from DCMD is competitive with MED, MSF, and RO desalination technologies but it is cheaper when it makes use of waste heat as energy resource. Dey et al [32] mentioned that the cost of seawater desalination would decrees significantly if waste heat (in the form of low pressure stream or from nuclear reactor) utilized in desalination. It is also reported that replacing the MED and MSF modules with AGMD module could lead to reduce the cost of seawater desalination to 0.26 $\$/m^3$ [31]. Figure 9 shows a comparison between reduction in costs of seawater and brackish desalination through last decades. The reduction of the process cost was related to the improvement in manufacturing methods, the high competitions for membrane, and the noticeable depletion of regular groundwater resources.

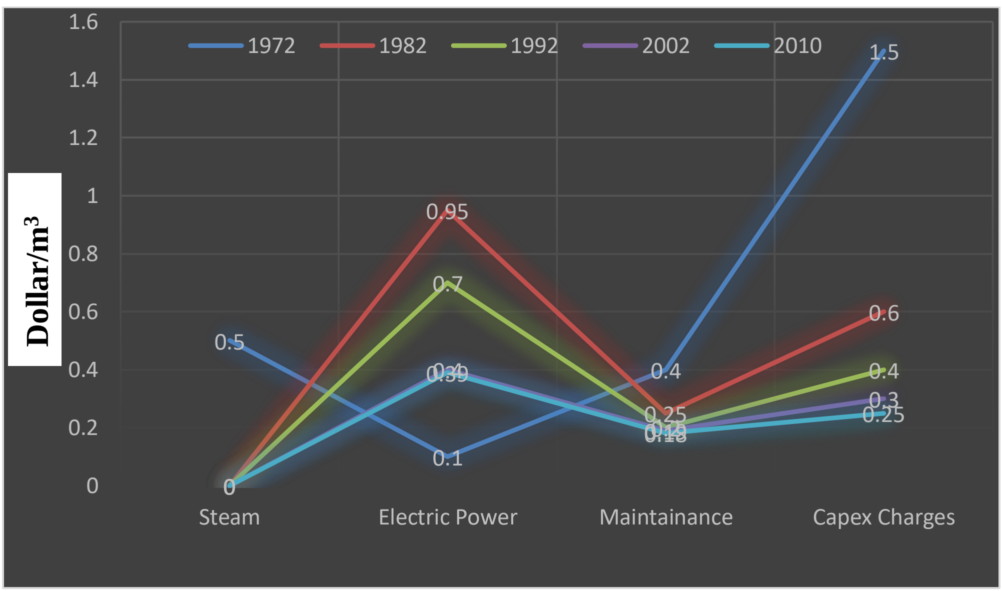

Figure 8: Reduction in Seawater Membrane Desalination Cost through last three decades. (Source of Data: Water Association Desalination Committee [30])

A high energy requirements for desalination technology contribute to 40 -50% of the total process costs which make the applications of it limited in industry. Solving this problem by integrating MD technology with heat pump systems is a viable potential alternative because it decreases the cost to about half. Table 2 shows a comparison between costs of conventional desalination process and renewable assisted desalination. In some countries such as Australia, the cost of Seawater and Brackish water desalination could increase with increasing amount of Carbon dioxide emitted by the desalination due to the taxes enforced by the government. Figure 10 shows the costs of different

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desalination methods including carbon dioxide taxes.

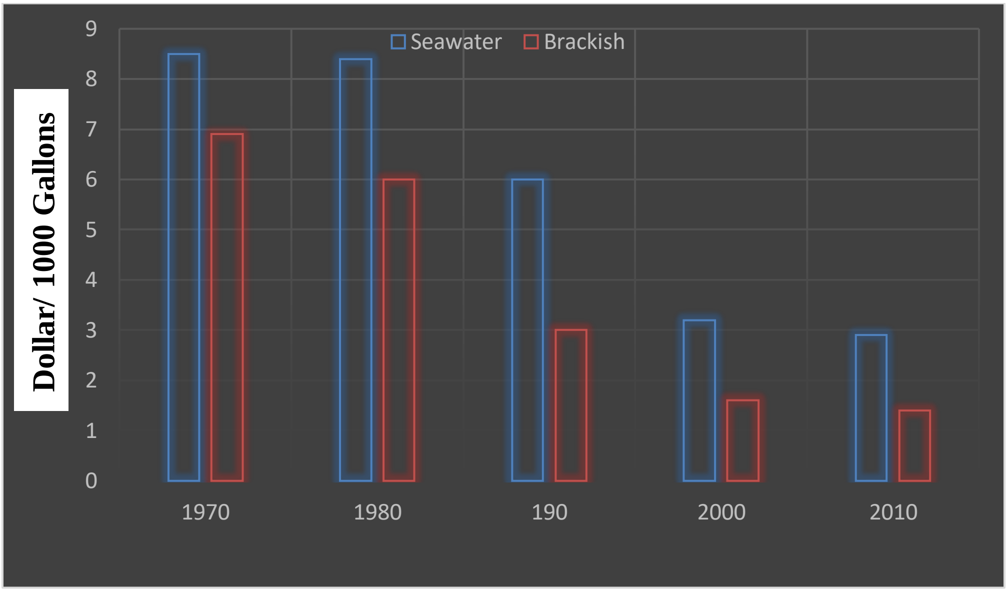

Figure 9: Reduction of Seawater and Brackish Desalination Costs Through the last decades (Source of Data: American Membrane Technology Association [6])

Table 2: Conventional Desalination and Renewable Assisted Desalination Costs

Desalination Type	Capital Costs (%)	Operational Costs (%)	Energy Costs (%)
Reverse Osmosis	22-27	14-15	59-63
MSF	25-30	38-40	33-35
Renewable assisted	30-90	10-30	0-10

Cost of desalination is highly affected by the amount of the salt that has to be removed, and the capacity of the plant. Larger amount of salt higher cost while larger plant capacity decreases the cost of the desalination, as shown in Figure 11. Fresh or drinking water requires salinity level less than 250 mg/L. The salinity level in brackish and seawater are about 2000-5000 mg/L and 24000 – 42000, respectively. This amount may differ from one location to another. Figure 13 shows the total dissolved solids in different types of water. From Figure 12, the TDS of fresh water is less than 1500, while for Seawater is more than 10,000. Membrane desalination has ability to reject

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about 99.3% of the salts dissolved in seawater according to [10].

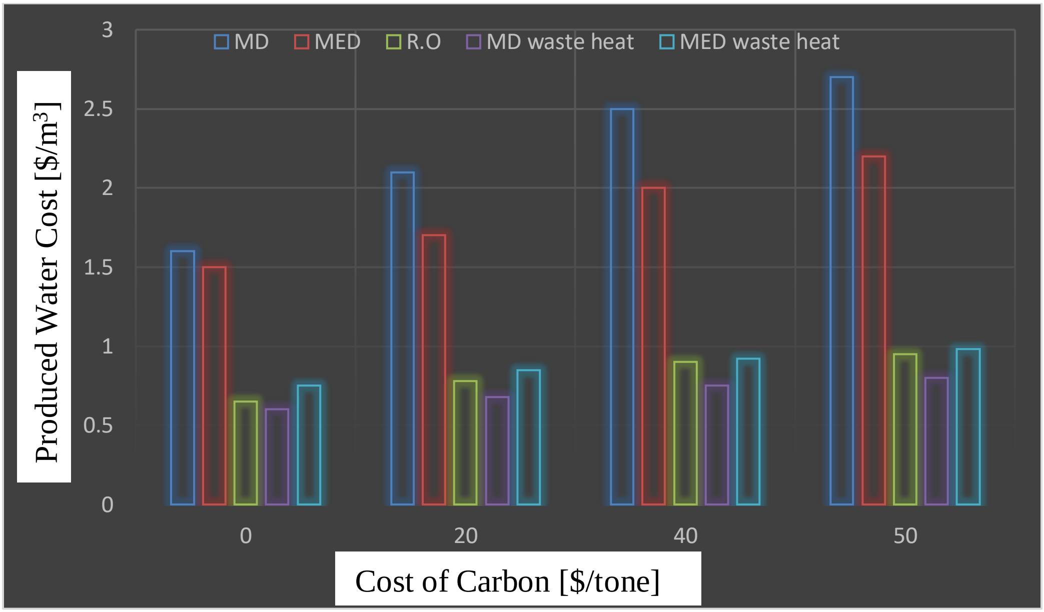

Figure 10: Effect of Carbon Taxes on Different Desalination Technologies (Source of Data: Kesieme et al [31])

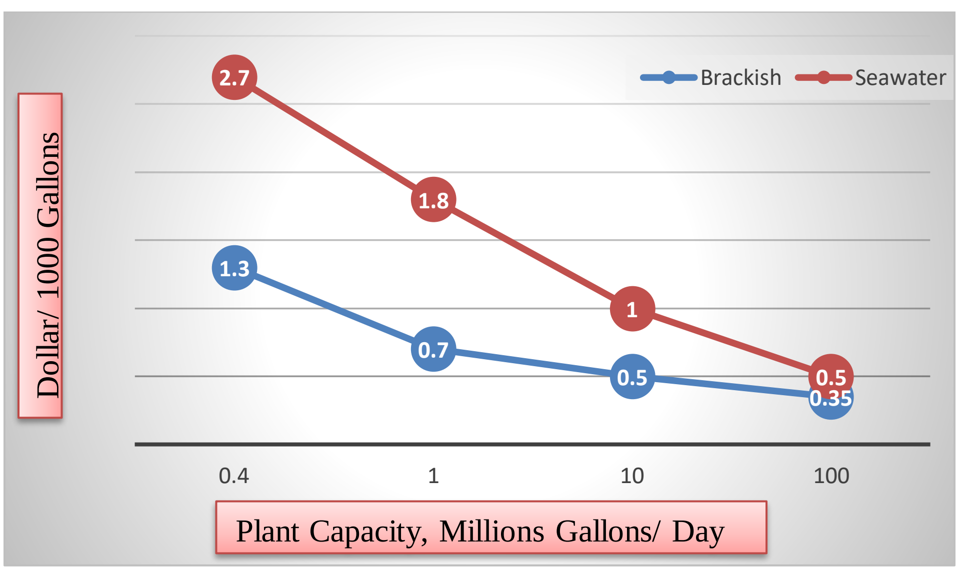

Figure 11: Maintenance and Operation Cost for Brackish and Seawater Desalination Plants
(Source of Data: American Membrane Technology Association [6])

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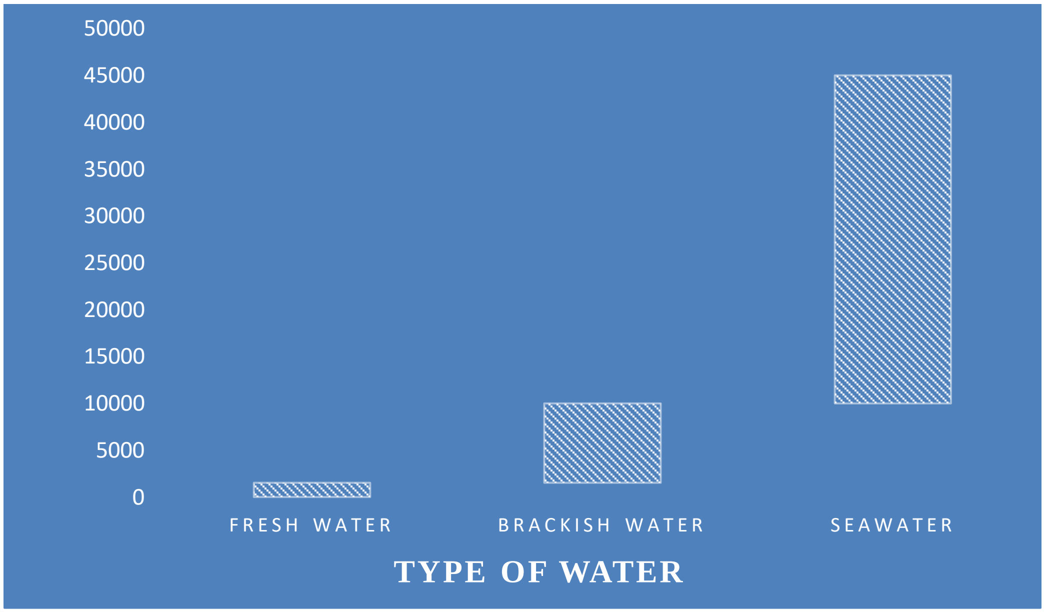

Figure 12: Total Dissolved Solids in Different Types of Water (Source of Data: Li [12])

6.0 MEMBRANES FOULING AND CLEANING

It is defined as a reduction in the permeate flux value due to sedimentation dissolved materials or substances on the membrane pores or surface. One of the major problems that membrane distillation process still suffering from is fouling of membrane, which requires cleaning. Many types of fouling might happen in membrane distillation system such as particulate and colloidal fouling, inorganic fouling or scaling, biological fouling, and organic fouling [33]. The mechanisms in which the fouling of membrane occur can be classified intro four main areas: adsorption (could occur due to interaction between solutes and membrane material at the surface or inside the pores), blocking of the pores due to accumulation of solutes inside the pores, Gel formation, and Bio-fouling due to growth of bacteria at the surface of the membrane [16]. Bio-fouling is the most harmful type because it is difficult to remove it. Organic type is very common and popular in Reverse Osmosis desalination technology [10]. Pre-treatment of feed and optimal operating conditions (Temperature, pressure and velocity) could be useful techniques in minimizing the amount of accumulated fouling. High accumulation of fouling on the surface or inside the membrane pores led to increase the resistance of the membrane which will increase the energy consumption of the distillation process and decrease the vapor gap . However, it leads to a decrease of the permeate flux which will affect both the quality (productivity) of the whole process, and the membrane operational life.

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In order to use the most efficient cleaning technique for the membrane, fouling properties must be identified and characterized. The most used technique for characterization of it is autopsy of membrane, which help in determining the organic and inorganic material. Other nondestructive methods have been used such as Scanning Electron Microscope (SEM) for inorganic materials, Fourier Transform Infrared Spectroscopy (FTIR) for organic materials, Targeted Energy Dispersive X-Ray Analysis (T-EDXA), and Total Direct Count for bio-fouling, Membrane Fouling Simulator (MFS), Visual Observation methods, Ultrasonic Time-Domain Reflectometry (UTDR), Magnetic Resonance Imaging (MRI), chemical solutions, and Physic-Chemical method. Table 3, presents some types of membrane fouling and recommended chemical solutions for cleaning. However, Chemical and biological analysis of the feed water could be helpful step in the determination of the type of fouling. Hsu et al [34] recommended the ultrasonic cleaning technique for DCMD because it is able to increases the life of the membrane, and restore the flux rate.

Table 3: Types of Fouling with Recommended Chemical Solutions

(Source of Data: Arnal et al [33])

Type of fouling	Recommended chemical solutions
Colloidal	NaOH solutions, chelating agents and surfactants
Organic	NaOH solutions, chelating agents and surfactants
Metal oxides	Citri acid with low pH or Na2S2O4
Silica	NaOH solutions with high pH
Carbonate scales (CaCO3)	Citric acid or HCl with low pH
Sulphate scales (CaSO4, BaSO4)	HCl solutions or sequestration agents (EDTA)
Biofilms	NaOH solutions, chelating or sequestration agents, surfactants and disinfectants

7.0 CONCLUSION

The process of converting brackish and seawater to fresh water still requires large amount of energy (particularly in desalination methods that depends on phase change) which make it expensive. Demands for reducing the cost of desalination processes by reducing/ eliminating the energy consumption have recently become a trend and significant topic for research due to increasing the oil prices through last decades. Solar energy is the most abundant energy source, available most of the year,

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and free. Integration desalination methods (particularly MD) with solar energy, heat pump, solar assisted heat pump helps in solving the environment issues such as global warming and reducing the cost of the process.

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