Sustainable Options for Desalination: A look into Renewable Energies and Brine Disposal

by

Douglas Mizutani

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Supervisor: Ian K. Smout
BA Cantab., MSc Reading, CEng, FICE, MIAgrE, MCIWEM

Water, Engineering and Development Centre
School of Civil and Building Engineering

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Abstract

In today's present world, billions of people live without reliable access to clean drinking water, and as populations continue to grow, freshwater sources begin to disappear at an equally rapid pace. In an effort to combat these issues, desalination has been introduced as a solution to abstract water from untouched resources. However, while desalination can produce additional potable water, it is also heavily criticised for its flaws; namely cost, energy consumption, and environmental pollution. Thus, in order to promote desalination as a sustainable solution for both the present day and future, improvements need to be implemented to produce less costly, more energy efficient, and environmentally friendly desalination plants.

This paper reviews all of the current desalination methods in today's global market, evaluating which methods are most sustainable for the future of desalination. Options for renewable energies to replace fossil fuels are also studied, as well as various brine disposal methods which can produce more environmentally safe and sustainable desalination facilities. Among the literature reviewed, reverse osmosis was found to be the world's most sustainable method of desalination due to its energy efficiency and production capacity, while solar photovoltaics were found to be the popular choice among renewable energies. Zero liquid discharge was also found to be the most environmentally friendly method of brine waste disposal, although research in the field was very limited. Each method was closely evaluated and compared among its competitors, offering a detailed perspective on the sustainable state of desalination.

Keywords: desalination, sustainable, renewable energy, brine, reverse osmosis, membrane distillation, solar, wind, geothermal, zero liquid discharge

Executive Summary

Whether it is due to geographic constraints, lack of adequate water management, or a combination of both, billions of people around the world live without reliable access to clean drinking water. While societies develop and water demands grow, freshwater sources are becoming depleted, leaving behind water that is either inaccessible or unpalatable. In an effort to reduce water scarcity, desalination has been introduced as a viable solution to convert saline water into potable water. While desalination is heavily criticised for its flaws, including cost, energy consumption, and environmental pollution, it is nevertheless necessary for many desperate regions where no alternatives exist.

This paper reviews all of the current desalination methods in today's global market, evaluating which methods are most sustainable for the future of desalination. Options for renewable energies to replace fossil fuels are also studied, as well as various brine disposal methods which can produce more environmentally safe and sustainable desalination facilities. A thorough literature review of these three subjects (desalination, renewable energy, and brine disposal) is carried out, with a summary at the end of each section to easily evaluate and compare these numerous options. A case study analysis is also conducted, investigating pilot projects of RE-fuelled desalination plants and their performance outputs. Similarly, a summary comparison of each type of RE-desalination system is outlined to aid the reader in understanding which combination of technologies may be most suitable for the future of desalination.

In the results and discussion section, a selection matrix for each subject was made to quantitatively rank each desalination, renewable energy, and brine disposal method, marking which options are the most "sustainable" in comparison to the others. From this analysis, reverse osmosis was ranked as the most sustainable desalination method, followed closely by multiple effect distillation and vapour compression. Among renewable energies, the top mark was shared between solar photovoltaics, wind, and geothermal energy sources, as each RE provided valuable strengths and inherent weaknesses that it made it difficult to judge one above the other. For brine disposal methods, zero liquid discharge and submerged seawater discharge were tied for first, although both are extremely expensive but guarantee little harm to the environment.

A decision tree was also composed for each subject to aid decision-makers in choosing which option was most appropriate for their living conditions, as a method that scored high on the selection matrix did not guarantee that it was the most suitable for any circumstance. A list of general conditions from small rural villages to large developed cities was also matched with a combination of desalination – renewable energy – brine disposal systems that were best suited for that condition, with other considerations.

At the end of the report, several conclusions were made to researchers and engineers to help promote the sustainable growth of desalination, namely:

- To conduct more research and development for wave/tidal power
- To conduct more research and development for membrane distillation
- To conduct more research on the environmental effects of open brine disposal

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AC	Alternating Current
BCS	Baja California Sur
CPC	Concentrating Parabolic Collector
CSP	Concentrated Solar Power
CPV	Concentrating Photovoltaics
DC	Direct Current
DNI	Direct Normal Irradiance
ED	Electrodialysis
EDR	Electrodialysis Reversal
ETC	Evacuated Tube Collectors
ETSU	Energy Technology Support Unit
FO	Forward Osmosis
FPC	Flat Plate Collectors
FR	Freezing
G-MED	Geothermal Multiple Effect Distillation
HTF	Heat Transfer Fluid
IDA	International Desalination Association
JIS	Jain Irrigation Systems
LCOE	Levelised Cost of Electricity
LFR	Linear Fresnel Reflector
MD	Membrane Distillation
MED	Multiple Effect Distillation
MEDESOL	Seawater Desalination by Innovative Solar Powered Membrane Distillation System
MENA	Middle East and North Africa
MIT	Massachusetts Institute of Technology
MSF	Multi Stage Flash
MVC	Mechanical Vapour Compression
NCSC	Non concentrating solar collectors
NF	Nanofiltration
O&M	Operation and Maintenance
PDC	Parabolic Dish Collector
PSA	Plataforma Solar de Almeria
PTC	Parabolic Trough Collector
PV	Solar Photovoltaics
PV-ED	Solar Photovoltaic Electrodialysis
PV-RO	Solar Photovoltaic Reverse Osmosis
R&D	Research and Development
RE	Renewable Energy
RO	Reverse Osmosis
S-MD	Solar Membrane Distillation
S-MSF	Solar Multi Stage Flash
SP	Solar Pond
SPT	Solar Power Tower
SS	Solar Stills
St	Solar thermal
St-MED	Solar thermal Multiple Effect Distillation
St-RO	Solar thermal Reverse Osmosis
SWCC	Saline Water Conversion Company
SW-MVC	Solar and Wind Multiple Effect Distillation and Mechanical Vapour Compression
SWRO	Seawater Reverse Osmosis

TDS	Total Dissolved Solids
TVC	Thermal Vapour Compression
UAE	United Arab Emirates
UNESCO	United Nations Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development
UV	Ultraviolet
VC	Vapour Compression
Wi-MVC	Wind Mechanicaal Vapour Compression
Wi-RO	Wind Reverse Osmosis
WEDC	Water Engineering and Development Centre
WHO	World Health Organization
WS	Water Scarcity
WWF	World Wide Fund for Nature
ZLD	Zero Liquid Discharge

Chapter 1: Introduction

In today's present world, billions of people live without reliable access to clean drinking water. Whether it is due to geographic constraints, lack of adequate water management, or a combination of both, it is clear that in order for society to progress and develop, water demands must be met on all levels. While populations and industries continue to grow, freshwater resources disappear at an equally rapid pace, leaving behind water that is either inaccessible (ice caps) or unpalatable (sea/brackish water). In an effort to combat these issues, desalination has been introduced as a viable solution to convert saline water into a valuable source of potable water.

However, while desalination can produce additional freshwater, it is also heavily criticized for its flaws, including cost, energy consumption, and environmental pollution. Despite these noticeable drawbacks, desalination is necessary for many desperate regions where no other alternatives exist. Thus, in order to promote desalination as a sustainable solution for both the present day and future, improvements need to be implemented to make desalination less costly, more energy efficient, and environmentally friendly.

Over the course of several decades, researchers have investigated new and improved technologies that can harvest power from the sun, water, wind and earth, in order to fuel society's energy needs from sources that are reliable and renewable. Today, the majority of the world's desalination plants are powered by fossil fuels, which unfortunately produce large amounts of carbon emissions and cannot be replenished. Replacing these fossil fuels with renewable energies (RE) could already improve the sustainability of desalination plants from an energy and environmental perspective, although cost remains a present barrier.

While renewable energies can already decrease or eliminate the harmful effects of carbon emissions in the atmosphere, salt deposits from desalination plants need equal attention. Once plants are able to separate salt compounds from fresh water, these salt bi-products (also known as brine) have to be deposited somewhere. Most plants return brine back to its original source water, although environmentalists are wary of the effects this could have on the local ecosystem. Thus, in order to promote desalination as a sustainable option for the future environment, careful consideration must also be given to methods of brine waste disposal.

1.1 Aims and Objectives

The overall aim of this research paper is to investigate the most appropriate options for desalination moving forward, with a focus on sustainability. This paper is not limited to any particular region or circumstance, but rather examines desalination for multiple situations based on economic, environmental, and technological factors. Thus the research paper will aim to achieve the following objectives:

- Identify and summarise key reasons desalination is necessary for many regions in today's world
- Investigate present and potential desalination technologies, renewable energies, and brine disposal methods, evaluating their sustainability performance based on environmental, economic, and technological factors
- Compare and contrast the combinations of desalination technologies with renewable energies, analysing their performance based on environmental, economic, and technological factors
- Identify what types of consumers can benefit from certain combinations of sustainable desalinated water supply, based on their size, location, and socioeconomic status

1.2 Research Questions

In order to achieve the objectives outlined above, the following research questions have been compiled to further investigate the future sustainability of desalination:

1) Under what circumstances does desalination become a necessary method of water supply?
2) Which desalination methods are most energy-efficient, environmentally friendly, and affordable? Are there some desalination methods that we can already eliminate moving forward?
3) Which renewable energies present the most promise for the future of desalination? Can these renewable energies be as reliable and affordable as fossil fuels?
4) What are the most environmentally safe and sustainable methods of brine waste disposal moving forward?
5) Under what socio-economic and environmental conditions does each RE-powered desalination method become an appropriate means of water supply?

1.3 Scope of the Project

As previously mentioned, this paper is not limited to any particular region or population in the world, but is rather open to all demographics. This includes small vs. large populations, developing vs. developed countries, and regions of different climates or geographic conditions (islands, deserts, coastlines, mountains, etc.). One of the objectives of this paper will be to identify the circumstances under which desalination becomes a necessary method of water supply, as well as the conditions that are most suitable for RE-powered desalination. Thus, in order to achieve these objectives, it is best not to focus on only one specific region or population.

The aim of this paper is not to find a single desalination technology that can serve every population from across all parts of the world. Rather, it is to understand what types of sustainable technology are currently available (not necessarily commercialised), and which consumers can benefit most from each of these different options. If there are two technologies that service the same group of consumers, then a comparison must be made to determine which technology is more beneficial for that specific demographic.

However, in analysing the sustainability of future desalination projects with renewable energies, the following has been left out due to complexity and limited research time:

- Social acceptability – although one of the pillars of sustainability includes social acceptability, the premise of this paper overlooks this factor because of the large population that is covered within the scope. Populations from different regions have different perspectives and approaches when it comes to installing new infrastructure, thus analysing the social consent of each regional sector would be extremely time-consuming and difficult to evaluate. The case studies presented in this paper also disregard social acceptability in the analyses of their renewable-energy desalination projects, as most are only on the level of pilot testing. It is assumed that the main causes of social opposition to desalination are increased water prices and harmful environmental emissions. However, it is the author's aim to find desalination facilities that are both cheap and environmentally safe, while delivering high-quality water at a reliable rate. Thus, if the objectives of this research paper are achieved correctly, it is assumed that the installation of these renewable energy desalination plants will not conflict with the consent of the public. Research on the social acceptance of desalination plants can be found on the internet, although most of these studies are focused on developed countries with conventional desalination such as Australia.

- Political government – the study of interested nations and their governing body have also been left out of the report. Each nation has a different political agenda that can either promote or dissuade the installation of renewable-energy desalination plants, and this can heavily affect the choice of which RE-powered desalination method is most appropriate for the population. However, due to the amount of time needed to investigate each region's political interests, and the frequency with which political agendas can change over time, the analysis of this report will disregard political governments as a factor in evaluating RE-powered desalination technologies.

1.4 Relevance of Research and Potential Use

Technology is constantly evolving, aiming to improve previous performance and bring greater benefits to the public. One of the aims of this paper is to provide information on the latest updated technology that can improve desalination costs, energy consumption and environmental effects. Although there are many papers that are published every year to demonstrate the results of their desalination inventions, there are fewer papers published that compare these new methods to one another, and analyse their benefits to the public as a whole.

Additionally, many researchers focus the results of their desalination technology on water quality, energy consumption, and cost, often neglecting environmental impact. Scientists who have studied the effects of brine disposal on the environment have aided in this regard, although similarly, the scope of their research is usually narrowed down to a specific circumstance, such as brine disposal from large-scale thermal desalination plants. As a result, this paper aims to gather this information from technological and environmental researchers to provide a larger perspective on how desalination can produce sustainable water supply from an economic, environmental and technical perspective.

It is the author's intent that this research paper provides policymakers, engineers, academics, and the general public a greater knowledge about desalination and its potential for sustainable water supply moving forward. Providing this type of knowledge can raise awareness for better water management, offering solutions that are cheaper, healthier, and more reliable for the future. There are many knowledge gaps within this research that the author attempts to investigate, although it is the hope that any questions left unanswered can be resolved by future researchers with a similar interest in water sustainability.

1.5 Water Scarcity

As a result of population increase and industrial development, the demand for water is rising at an alarmingly quick rate, in some cases surpassing the freshwater resources normally available. WHO (2011) estimates that almost one-fifth of the world's population live in areas where water is physically scarce, while Mekonnen and Hoekstra (2016) claim that nearly 4 billion people live under conditions of severe water scarcity at least 1 month of the year. Although these numbers differ, based on the methods used to calculate and define "water scarcity," there is undoubtedly a shortage of water for over 1 billion people, and this will continue to grow without immediate action.

According to UNESCO (2012), hydrologists define an area as being "water stressed" when the average annual freshwater supply drops below 1,700 m^3 per person and "water scarce" when water supplies are below 1,000 m^3 per person. When supplies are below 500 m^3, this is defined as "absolute scarcity." Figure 1 below illustrates areas around the globe that experience water scarcity according to this definition.

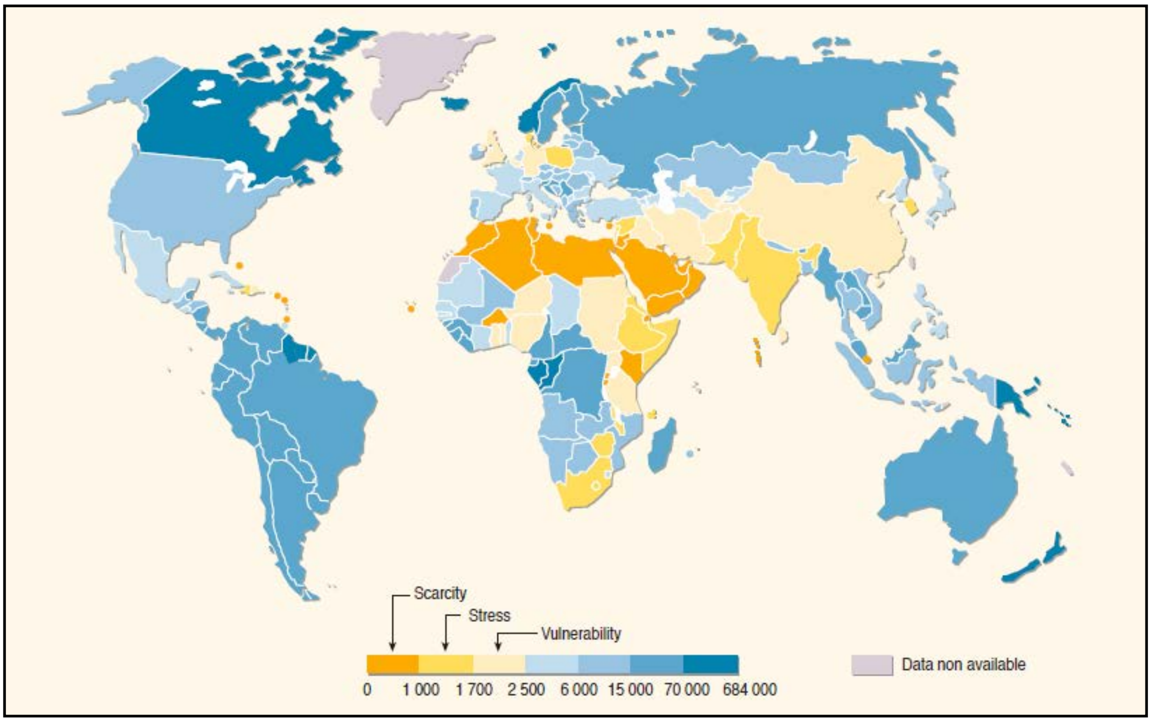

Figure 1: Global Freshwater availability in 2007 (m^3 per person)
Source: UNESCO, (2012)

In comparison, Mekonnen and Hoekstra (2016) challenge the definition of water scarcity (WS), stressing that human water demand also needs to be considered. According to these two researchers, WS should simply be water demand divided by freshwater availability, and should be classified as low if WS is less than 1.0, moderate if WS is between 1.0 – 1.5, significant if WS is between 1.5 – 2.0, and severe if WS is above 2.0. From this, Mekonnen and Hoekstra compiled the following maps using data from 1996-2005, illustrated in Figures 2 and 3 below.

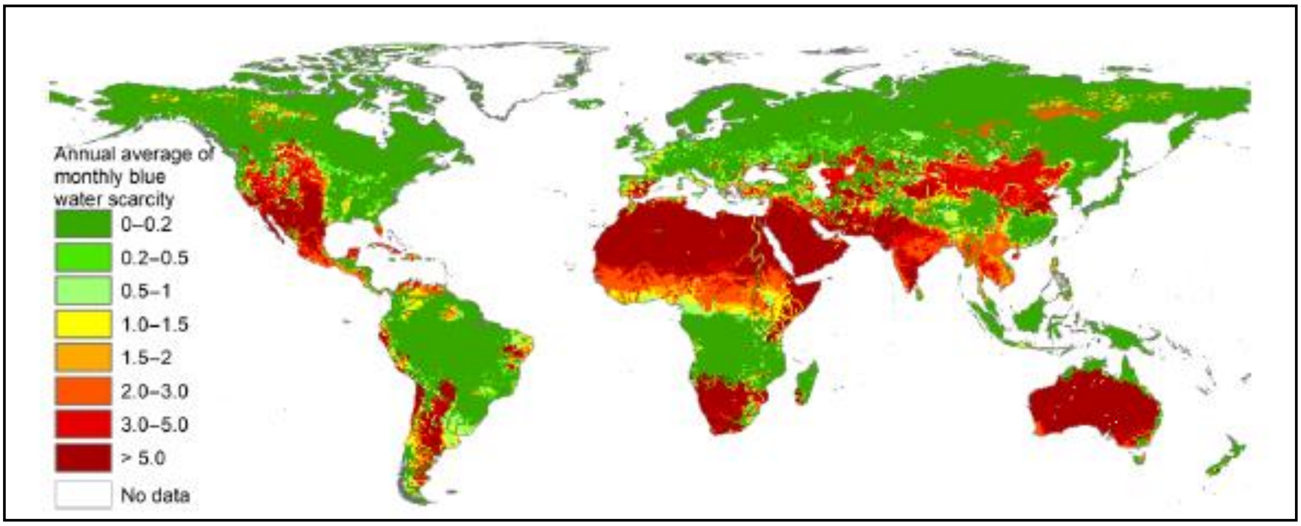

Figure 2: Global annual average Water Scarcity 1996-2005
Source: Mekonnen and Hoekstra, (2016)

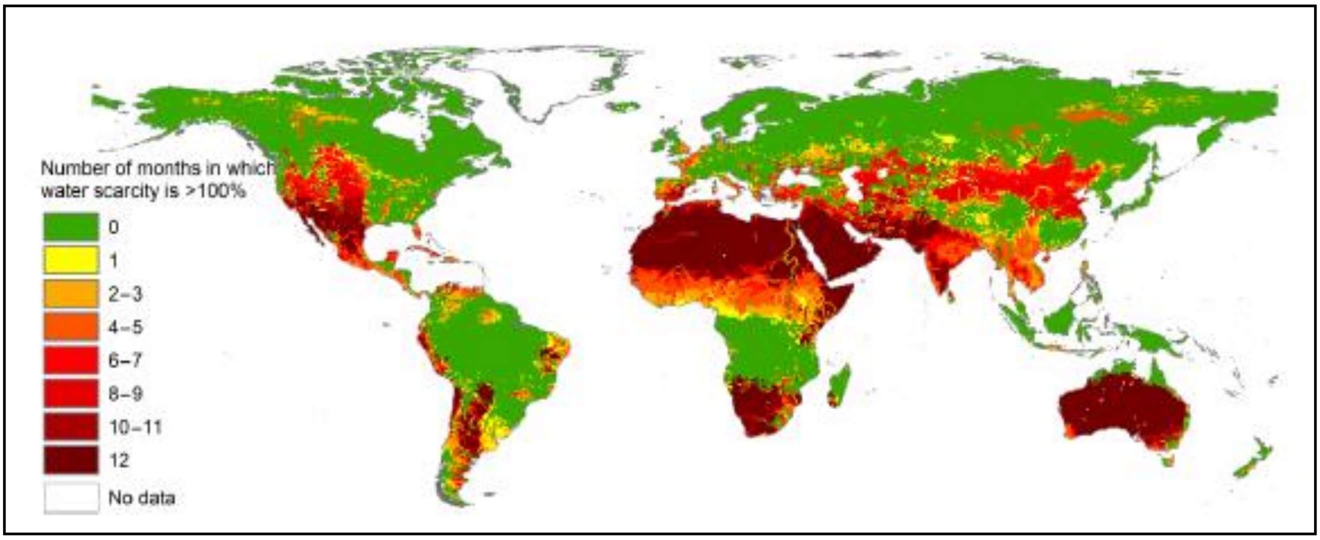

Figure 3: Number of months per year in which WS>1.0
Source: Mekonnen and Hoekstra, (2016)

From their findings, Mekonnen and Hoekstra concluded that severe water scarcity was prevalent in areas of high population density (e.g. London), heavily irrigated agriculture (mid-west United States), hot arid climates (Sahara desert), or a combination of the three (Nile delta). However, attributing water scarcity to these three factors alone is not enough.

In addition to the hydrological definition of "water scarcity," UNESCO (2012) continues by stating that water scarcity is not only a function of water resource *availability*, but also a function of *access*. In this regard, it acknowledges *economic scarcity*, where water is inaccessible due to human, institutional and financial constraints, as opposed to *physical scarcity* which is attributed to geographic limitations. Figure 4 on the next page illustrates this difference in water scarcity, highlighting regions such as the Middle East to be victims of physical climate conditions, whereas most of sub-Saharan Africa is restricted by institutional and economic barriers.

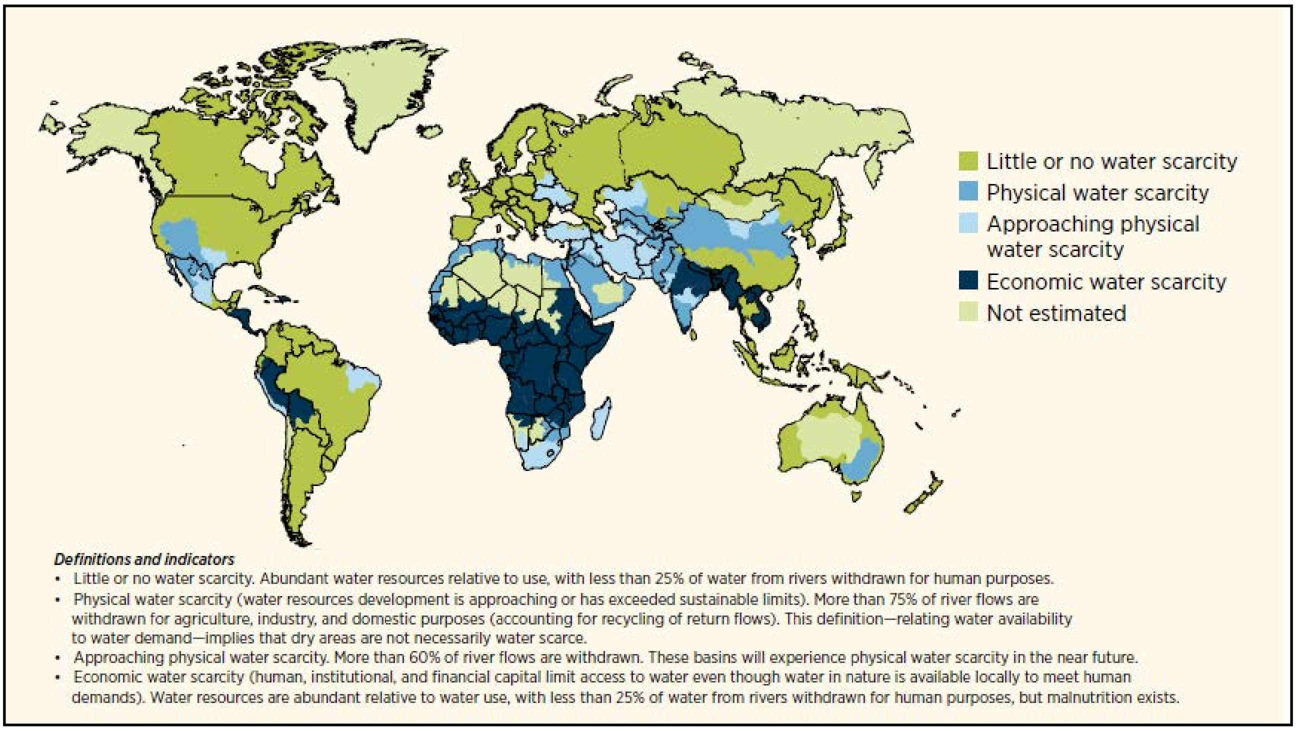

Figure 4: Global Physical and Economic Water Scarcity
Source: UNESCO, (2012)

Fritzmann et al. (2007), along with Elimelech and Phillip (2011), agree that water scarcity is created by a myriad of factors outside of water demand and hydrology, stating that pollution and climate change are also important contributors that can significantly influence the future of water availability. While groundwater aquifers and fresh surface waters are already decreasing due to heavy exploitation, contamination via unprotected waste can exponentially eliminate the amount of freshwater sources available, requiring extra treatment and associated costs. Additionally, regions that currently face little or no water scarcity may fall victim to the unpredictable effects of climate change, which could modify precipitation patterns and endanger aquifer replenishments.

According to the World Bank (2012), the combined effects of population and prosperity in the Middle East and North Africa (MENA) region have already cut the amount of fresh water available in half from 3,000 m^3/capita to 1,500 m^3/capita between 1975 and 2001. Presently, the average MENA citizen has a little over 1,000 m^3 of freshwater per year, and the gap between demand and supply is predicted to quintuple by 2050, from today's 42 km^3 per annum to approximately 200 km^3 per annum (World Bank, 2012). The Baja California Sur (BCS) state of northwest Mexico is also falling victim to water scarcity, due to rapid tourism, population growth, and heavily irrigated agriculture that has forced inhabitants of the state capital in La Paz to live on 436 m^3 of freshwater per year (Bermudez-Contreras, Thomson and Infield, 2008). According to UNESCO's hydrological definition of water scarcity, both populations in MENA and BCS are currently living in conditions of moderate to severe water scarcity.

Nearly 100% of BCS's freshwater sources come from underground aquifers (Bermudez-Contreras, Thomson and Infield, 2008) despite decreases in volume from overexploitation and salt water intrusion. Similarly, many coastal areas and island states such as Pakistan and the Philippines struggle with salt water encroachment from rising sea levels, and inland areas such as Libya have to access deeper groundwater sources containing salts from thousands of years that have not been actively diluted by recharge (Groves, 2012). Although groundwater sources are generally clean and accessible, they only account for 0.90% of the Earth's water reserves, whereas saline sources, such as the ocean, make up 97% (Drioli, Ali and Macedonio, 2015). The remainder of the Earth's water reserves are in the form of glaciers and ice caps (2.1%), which are best left untouched; otherwise this could create significant damage to both local and global environments.

In this context, it should come as no surprise that water scarcity exists when billions of people are relying on less than 1% of Earth's water reserves, especially when the recharge rates of these sources are significantly smaller than the rate of withdrawal, and salt water intrusions are a legitimate threat. While saline water is prosperous and plentiful, WHO (2011) states that water with a total dissolved solids (TDS) level of 600 mg/L or less is generally considered good, while TDS levels of 1000 mg/L or more are considered unpalatable. Total dissolved solids generally comprise of inorganic salts and small amounts of organic matter, and are the principal measuring unit for water salinity. Table 1 below outlines the different levels of salinity for various water resources:

Table 1: Water sources and salinity levels

Source: Adapted from Ruskulis, (2002)

Water Source	TDS salinity level (mg/L)
Freshwater	< 500
Brackish Water: Low	1,000 – 5,000
Brackish Water: Moderate	5,000 – 10,000
Brackish Water: High	10,000 – 30,000
Seawater	> 35,000

In addition to the information provided in Table 1, it should be noted that brackish, or saline groundwater, reserves in various parts of the world have recorded TDS levels as high as 235,000 mg/L (Ruskulis, 2002).

Despite different methods of defining and measuring water scarcity, there is an overall agreement that more than 1 billion people currently live in water scarce areas. Whether this is due to geophysical, economic, or political reasons, over one-fifth of the Earth's population lives with limited access to drinking water every day, and this figure could easily rise to more than half the global population with additional threats such as climate change. The amount of accessible freshwater is constantly decreasing due to exploitation and salt water intrusions, therefore other sources of water need to be considered to fill the gap between supply and demand.

1.6 Desalination as a necessity

Several measures such as water conservation, infrastructure repair, and improved catchment systems can alleviate stresses on water supply; however, these practices can only improve the use of existing water resources, not increase them (Elimelech and Phillip, 2011). According to Elimelech and Phillip (2011), the only solution to increasing water supply beyond what is available from the hydrological cycle is through desalination or water reuse.

While desalination can provide additional water to regions that are desperately in need, organisations such as the World Wide Fund for Nature (WWF) are worried that desalination plants can divert attention from less costly and more environmentally benign alternatives, which include water recycling and water use efficiency improvements (Dickie, 2007). Indeed, desalination is a costly and energy-intensive measure that requires large amounts of investment, and is best avoided if possible. Table 2 below lists a number of disadvantages related to desalination, and possible alternatives that can be considered instead:

Table 2: Disadvantages and Alternatives to Desalination
Source: Adapted from Shaqour, (2010) and Ruskulis, (2002)

Disadvantages	Alternatives
• High capital and operations costs • Energy-intensive; emissions from fossil fuels are source of pollution • Requires professional expertise • Unplanned brine disposal may contaminate and pollute surrounding soils and freshwater • Brine disposal may also have negative effects on local marine wildlife	• Transport water from another area by vehicle • Support informal processes (e.g. water carriers) • Drill deeper boreholes at depths where water is known to be cleaner • Improve rainwater harvesting and storage • Pipe in water from more distant sources • Implement wastewater recycling

While many experts agree that desalination should be one of the last options considered in eliminating water scarcity, many regions must rely on desalination as all other alternatives are either physically inexistent or economically unfeasible. Some countries such as Qatar and Kuwait are 100% dependent on desalinated water for all domestic and industrial demands (Ghaffour et al., 2015), and many other countries from North Africa to the Caribbean Islands similarly face the same circumstances. For all the disadvantages and risks that desalination creates, there are also many advantages and benefits that desalination offers, outlined in Table 3 on the following page. In addition, Table 4 lists circumstances under which desalination can be beneficial for small/medium scale communities, although many of these reasons can also be attributed to large-scale societies.

Table 3: Benefits of Desalination
Source: Adapted from Shaqour, (2010) and Cooley, (2010)

Benefits of Desalination	
Water supply reliability	Less dependence on weather rainfall and increased resilience to natural disasters or other threats to water systems
High quality water	Removes a number of impurities in final distilled product
Local control	Rather than relying on neighbouring groups for water resources, communities have control over their own water sources
New unexploited aquifers	For inland areas, there is suddenly potential to withdraw water from untouched brackish aquifers
Higher crop yield	Increased water supply will allow farmers to plant more crops, including more diverse crops that normally require higher water demand
Economic growth	Increases in water supply from desalination can provide better standards of living on a domestic level while increasing business on an industrial level, creating more jobs for local people

Table 4: Beneficial desalination circumstances for small-medium scale communities
Source: Ruskulis, (2002)

Desalination at small or medium scale could offer particular advantages if:
The community is relatively self-contained and not highly dependent on other communities
Alternate water sources are impractical – too far, too deep, or rainfall is limited
There is already some desalination being undertaken nearby
There is political and donor support to enable testing and optimising operation
Local skills can be readily adapted to building, operating, and maintaining desalination units
More specialised technical support and materials for building and spare parts are available

The island of Mallorca serves as a great example when referring to desalination benefits, as water scarcity greatly affected the island until desalination plants were installed. Before the arrival of desalination, Mallorca was traditionally dependent on shipments from the Spanish mainland for water, until increasing tourism and agriculture threatened the region's water supply (Fritzmann et al., 2007). Once a desalination plant was built near Palma, the island was able to reduce its price of water and remove the constraints that limited its economic development.

Countries from the Middle East and North Africa region (MENA) lead the world in desalination technology, as more than 60% of the world's desalination capacity is supplied within this region, and over half of all municipal water supplies have been desalinated since 1990 (World Bank, 2012). According to the World Bank (2012), all MENA countries have reasonable access to seawater, as most major population centres are located close to the sea due to historical maritime trade. Apart from Europe and the Middle East, China is also making a push towards desalination, as plans have been made to increase China's desalination capacity from 120,000 m^3/day in 2005 to 3,000,000 m^3/day by 2020. According to Dickie (2007), China's population survives with per capita supplies of less than a quarter of the world average, and this can be attributed to its socio-geographic mismatch, whereby 40 percent of the country's population lives in coastal areas that form only 13 percent of the country's land area. This is common in most countries around the world, as major cities have often been developed around coastlines to facilitate trade and transport, but given China's massive population count, this water demand is exceptionally higher than most.

Following this pattern of proximity to seawater and arid climate, the British Geological Survey, Institute of Hydrology, and Energy Technology Support Unit (ETSU) compiled the following table outlining the number of countries in each continent with significant lengths of coastlines and less than 200 mm of precipitation per year. This table can serve as an indication of where desalination is most suitable for countries that face geographic water scarcity, although most countries in this list have already installed desalination facilities. According to Ryan (1998), nearly 80% of the world's population lives within 100 km of a coastline.

Table 5: Countries with significant lengths of arid coastline
Source: ETSU et al., (1996)

Continent	Country	Estimated Length of arid coastline (km)
Africa	Afars and Issas	244
	Egypt	2,420
	Ethiopia	1,010
	Libya	1,685
	Mauritania	666
	Morocco	452
	Namibia	1,385
	Somalia	2,955
	Sudan	716
	Tunisia	500
	Western Sahara	907
	Subtotal	12,940
Oceania	Australia	4,700
Asia	India	1,105
	Iran	1,834
	Pakistan	2,437
	Saudi Arabia	1,666
	Subtotal	7,791
Central and South America	Argentina	1,700
	Chile	1,574
	Mexico	3,800
	Peru	2,329
	Subtotal	9,403
Total		**34,834**

Over the last few decades, the desalination market has grown at a rapid pace, with facilities installed in almost all continents across the world. As shown in Figure 5 below, the market with the largest installed capacity is the Gulf or Middle East region, due its source of low cost fossil fuels and hydrological need for water, followed by the Mediterranean, American, and Asian markets. As predicted by Fritzmann et al. in 2007, the global capacity of desalination facilities would more than double from 31 million m^3/day in 2005 to 63 million m^3/day in 2015. However, in the most recent edition of the International Desalination Association (IDA) yearbook, the global commissioned desalination capacity was marked at 86.5 million m^3/day (Figure 6 below), surpassing Fritzmann's prediction by nearly 40 percent.

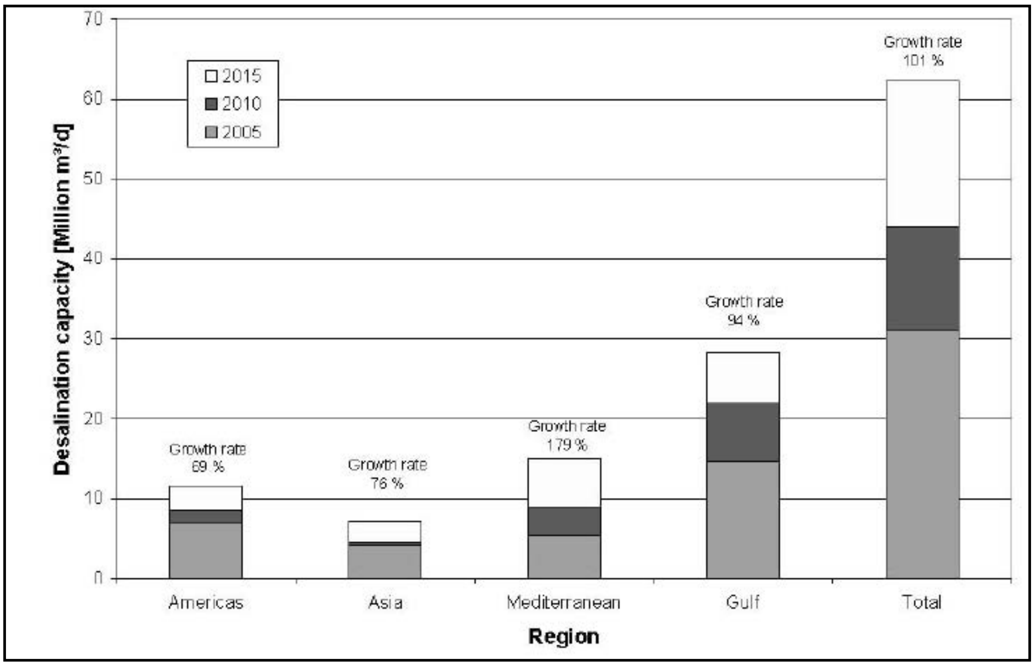

Figure 5: Expected growth of desalination capacities around the world
Source: Fritzmann et al., (2007)

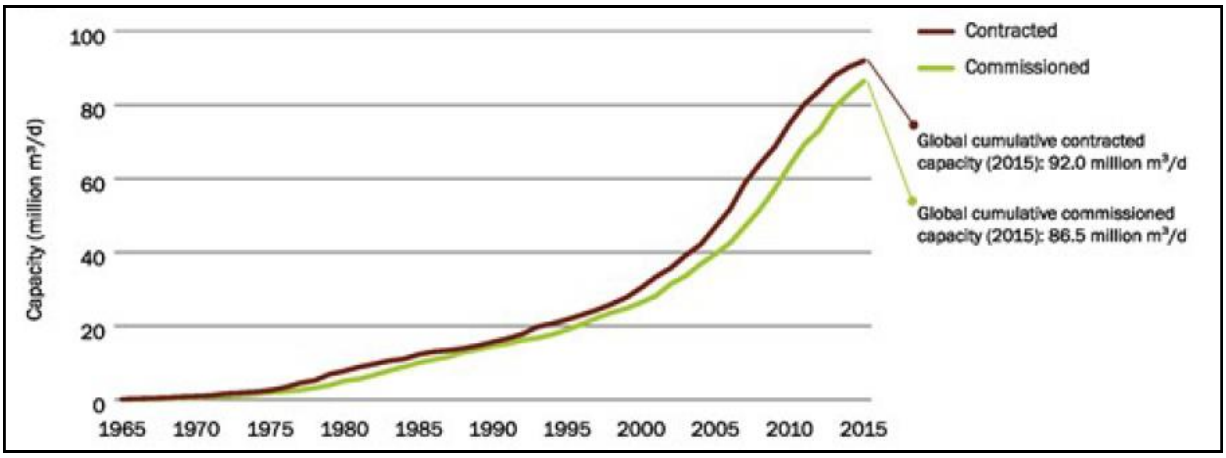

Figure 6: Global cumulative installed contracted and commissioned desalination capacity
Source: IDA, (2016)

Similar to the calculations made to measure global water scarcity, predictions of future desalination growth may be underestimated. Although water conservation methods such as wastewater recycling are highly encouraged, the amount of water needed to supply current demands is far too great to be met by these methods. Desalination is quickly becoming a global necessity, especially during this time of high population and economic growth, thus greater attention needs to be invested in creating more affordable and reliable desalination plants that will deliver sustainable solutions for many generations to come.

1.7 Environmental and Energy Sustainability

When measuring the sustainability of present-day desalination plants, one of the largest noticeable defects is the amount of energy needed to desalinate water, and the required amount of fossil fuels to provide this energy. According to Khater (2010), the production of 1,000 m^3 of freshwater per day requires about 27.4 tonnes of oil, which equates to nearly 10,000 tonnes of oil consumed in a single year. As a result of this large demand in energy, Jordan has to pay around $330 million per year on imported oil and gas, and yet there still remains a significant gap between water supply and demand (Shaqour, 2010). While it is obvious that non-oil rich countries in need of desalination plants would highly benefit from renewable energy supply, even oil rich countries realise that they are vulnerable to future energy crises. For example, Saudi Arabia has targeted 23% of its energy supply to be produced by solar power in 2030, steadily increasing this goal to 39% by 2050 (Goosen et al., 2016).

Fossil fuels are finite and cannot be replenished, thus they are even more limited in availability than groundwater aquifers. Although technology continuously advances to find new methods of detecting and extracting oil reserves, it is widely assumed that fossil fuels will no longer be available by the end of the 22nd century, and some predict as early as 2025 (Senior, 2016). With increasing population growth and energy demand, alternative forms of energy need to be considered for the future sustainability of desalination.

In addition to threatening energy source availability, fossil fuels endanger the surrounding environment through their carbon dioxide emissions. Bi-products from fossil fuel burning are known to be major contributors to global climate change, and have adversely affected the health of living organisms on both small and large scales. Desalination is one of the major constituents of CO_2 emissions due to its high energy requirements and dependence on fossil fuels, but this can easily be changed with the implementation of renewable energies. According to the World Bank (2012), generating a gigawatt hour (GWh) of electricity using oil produces 700 tons of CO_2, while concentrated solar power (CSP) generates only 17 tons of CO_2, an incredible 97.5% decrease in CO_2 emissions.

However, CO_2 emissions are not the only desalination bi-products threatening the environment. According to Cotruvo et al. (2010), wastes from desalination plants include concentrated brines, backwash liquids containing corrosion salts and antifouling chemicals, and pretreatment chemicals in filter waste sludge. Depending on the location of the plant and local practices of the area, these wastes are commonly discharged back to the sea, polluting the marine environment. The general public often believes that disposal of brine into the sea is not affecting marine life since the sea is already saline (Ahmad and Baddour, 2014), however brine concentration is often 1.3-1.7 times stronger than that of the original seawater, and could pose a threat to ocean wildlife in the long term. Ahmad and Baddour (2014) continue by stating that increases of salinity can disturb the osmotic balance of marine species, resulting in dehydration of cells, decreases of turgor pressure, and eventual death in some cases. It should also be noted that brine disposal is usually warmer than seawater by a few degrees Celsius, and this change of temperature can result in lower levels of dissolved oxygen, as well as increased toxicity of metals and chemicals (Ahmad and Baddour, 2014). Therefore, in order to conserve the health and well-being of marine and inland environments, greater effort needs to be invested in finding effective brine disposal solutions.

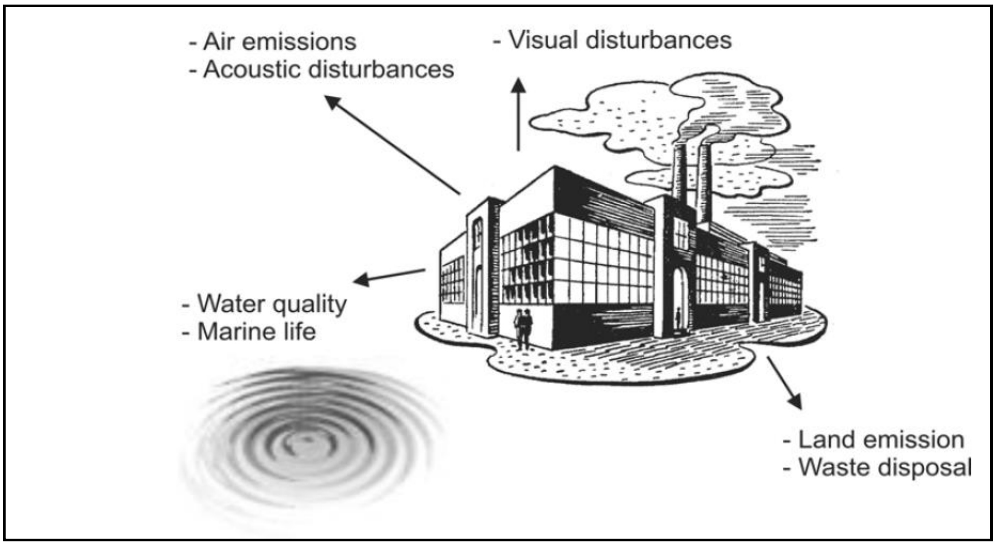

Figure 7: Environmental impacts of desalination
Source: Fritzmann et al., (2007)

Chapter 2: Methodology

2.1 Introduction

In an effort to answer the research questions outlined in section 1.2, an appropriate research methodology needs to be implemented, aimed to collect accurate information with as little bias or error as possible. Data collection will primarily stem from literature found in books, articles, and websites, as this paper is a desk-based study and time limitations prevent further detailed investigation. Information from the literature review and case study analysis will then be evaluated by scoring matrices and decision trees to rate the performance of desalination methods, energies, and brine disposal methods.

2.2 Literature Review

In order to grasp a wide perspective on desalination, comprehending its past progression and potential growth for the future, a wide variety of sources were investigated, from historic physical books to new scientific journals. Research in the field of desalination is deep and widespread, as thousands of articles, books, and reports can be found on the subject. In opposition to the snowball effect, whereby one interesting article can help generate hundreds more through the list of references, strict decision-making had to be enforced to filter relevant articles from the database. If the literature did not answer at least one of the research questions listed in section 1.2, it was considered irrelevant.

Before carrying out the research, it was essential to keep note of the literature being read and evaluate its importance to the topic. When evaluating the literature, it was important to answer questions such as:

- Does the article make good arguments? What evidence is being made for its claims?
- When was the article written? What was the context for its work? Is it outdated?
- Is the author's methodology appropriate for the study?
- Is the author reputable and trustworthy? What is his/her background? Could the author be biased because of his/her affiliation with a certain institution?
- What has been left out of the writing? Have certain concepts/methods/concerns been neglected?

The last question was particularly difficult to criticise since most articles are written with a specific focus, intending to answer questions in a distinct area. However, if the author made conclusions in their research area that appeared to neglect important factors, it was important to identify these flaws.

2.2.1 Literature Review strategy

In order to work efficiently and collect the necessary information, a search strategy was undertaken to cover a wide variety of sources at certain points in time. Table 6 below outlines this search strategy, listing the sources and their order in the process. However, it should be noted that due to time constraints, professional contacts were unable to provide any information, as nearly all professors and engineers contacted were either busy attending conferences or on summer holiday. Table 6 also lists the search terms used in the research process, justifying why these terms were used at certain points in the process. Throughout the literature search, it was important to find articles and books written within the last five years to ensure that the literature review was up to date in its findings.

Table 6: Literature Review Strategy

Sources		
Order	Source	Justification
1	WEDC Resources Centre / Library	Best to start with the library/resources centre when searching for physical materials (books, conference papers, dissertations, etc.). Otherwise any interesting material relative to the subject may already be gone if discovered too late. Also, relevant books that cannot be found in the library can be loaned out from other libraries if requested ahead of time.
2	Google Scholar	After searching the library for all available physical references, it is time to browse the internet for more recent relevant information. Scholarly articles that are peer-reviewed and cited by other researchers can be found on google scholar, which is a reliable source of information for accurate/truthful information.
3	Google	For information on specific companies or developing projects found in the previous literature, google search engine can be utilised to find news articles, blogs, or websites specifically dedicated to the company or project in question.
4	Websites	From the google search above, websites can provide more specific data about the searched term. However, unless it is an official company website, caution has to be taken to ensure the information is accurate and unbiased. Websites are also a good source for pictures and diagrams to further explain certain concepts.
5	News articles	News articles from the google search can also provide the most current information available on technology advancements and research findings. Generally, these sources are not incredibly detailed, and can often be biased, depending on the author of the article.
6	Professional contacts	After careful reading of the literature above, questions can be asked to professional contacts (i.e. university professors and engineers) about the desalination methods, renewable energies, or brine disposal methods in their field. If a piece of literature is more than 20 years old, sometimes it is best to contact the author to verify if their conclusions still hold true or have changed due to new research.

Search Terms		
Order	Search term	Justification
Early	Desalination + renewable energy	Resulted in comprehensive reviews about desalination methods and their potential link to renewable energies. Aided in understanding basics of most desalination methods, and also narrowed which renewable energies were most relevant to the application of desalination
Early	Desalination + brine disposal	Resulted in environmental assessment reports of desalination brine disposal on the local environment. Aided in understanding the harmful effects of desalination on the environment as well as existing methods that can remediate these effects.
Later	Specific terms i.e. “electrodialysis” or “wind desalination” or “zero liquid discharge desalination”	After discovering the available and potential desalination methods, renewable energies, and brine disposal methods, specific search terms can be used to obtain information regarding only one method or energy. This will help to grasp a better understanding of the method/energy, and compare it among its competitors.

2.3 Case Study Analysis

The methodology for the case study analysis is very similar to the literature review in that the data collected will be primarily from internet searches on google scholar and company websites. However, the case study analysis will focus only on information available about renewable energy – desalination systems in order to illustrate the potential sustainability of RE-fuelled plants in the future. In each RE-desalination case study analysis, a brine disposal method will be suggested as an appropriate compliment to that system for environmental sustainability. This suggestion will be based on the size, geographic constraints, and socio-economic conditions that are associated with the RE-desalination system.

Although there are technically 100 different combinations of renewable energies and desalination methods (10 desalination methods x 10 renewable energies), only 11 will be investigated. This is because only a handful of RE-powered desalination systems have been tested and commercialised, as research in the field has been very limited. Although it may be possible that other RE – desalination systems exist, this paper covers the most popular and promising combinations, as validated by figures 8 and 9 below.

T = Thermal energy, E = Electric energy and M = Mechanical energy.

	Solar		Wind		Geothermal		Ocean		
	T	E	M	E	T	E	E	M	T
SD	•								
MEH	•				•				•
MD	•				•				•
TVC	•				•				•
MSF	✓				•				
MED	✓	•		•	•	•	•		•
ED		✓	•	•		•	•	•	
MVC		•	•	•		•	•	•	
RO		✓	•	✓		•	•		

Figure 8: Promising RE-desalination combinations (highlighted with tick)
Source: Fernandez-Gonzalez et al., (2015)

Renewable energy-desalination system combination	Installed capacity (%)
Photovoltaic–reverse osmosis (PV–RO)	32
Photovoltaic–electrodialysis (PV–ED)	6
Solar–multiple-effect distillation (solar–MED)	13
Solar–multi-stage flash (solar–MSF)	6
Wind–reverse osmosis (wind–RO)	19
Wind–vapor compression (wind–VC)	5
Others	19
Total	100

Figure 9: Distribution of RE-desalination combinations across the world
Source: Ghaffour et al., (2015)

Throughout the case study analysis, both quantitative and qualitative data will be collected in order to effectively compare the performance of each RE-desalination combination and their potential application in the future. Each RE-Desal combination will be evaluated based on the following factors:

- Capacity (current and potential)
- Population served (current and potential)
- Cost (current and potential)
- Energy consumption
- Distillate production efficiency
- Geographic constraints
- Operation and Maintenance (skills, lifetime cycle)
- Additional pre/post treatment
- Most appropriate brine disposal method

2.4 Data Evaluation

From the information provided by the literature review and case study analysis, data will be evaluated through two main methods: selection matrices and decision trees. The purpose of the selection matrices is to quantitatively evaluate the sustainability performance of each desalination, renewable energy, and brine disposal method, providing a general overview of which system is the most sustainable for the future of desalination. Each selection matrix will consist of certain characteristics (ex: capacity, cost, environmental impact) scored on a scale of 1 to 10, with 1 being the least favourable and 10 being the most favourable score. After each method has been evaluated against the listed characteristics, the method with the highest total score is deemed to be the most "sustainable" option for the future of desalination. For example, Desal tech #3 from the sample selection matrix below is calculated to be the most "sustainable" option for desalination moving forward.

Table 7: Sample selection matrix

Desalination technology	Desal tech #1	Desal tech #2	Desal tech #3
Characteristic #1	8	4	9
Characteristic #2	2	7	5
Characteristic #3	4	5	7
Total	14	16	21

However, a certain method gaining the highest score on the selection matrix does not automatically guarantee that it is the most suitable for all circumstances. In fact, it is probably favourable for *most* areas of the world, but not all. This is the reason why a decision tree analysis is made – to additionally show which circumstances are best suited for each desalination, renewable energy, or brine disposal method. A decision tree analysis can help decision-makers choose the right option according to their present geographic and socio-economic conditions. A sample decision tree is shown in Figure 10 below.

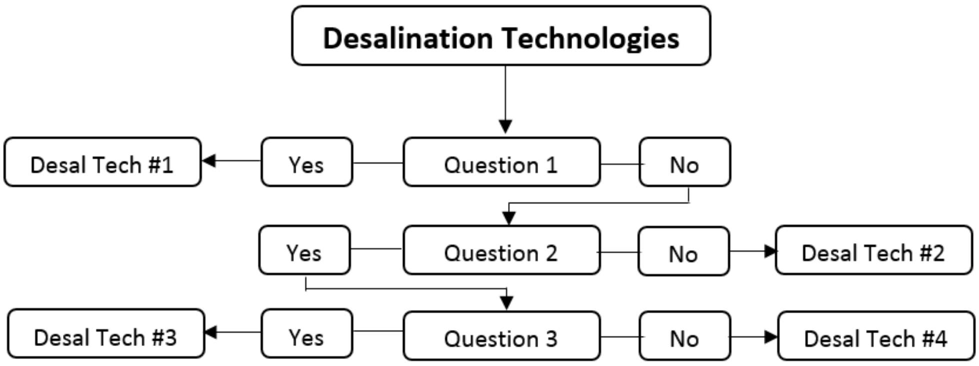

Figure 10: Sample decision tree

After the selection matrices and decision trees have been configured, a table outlining the most suitable RE-desalination and brine disposal combinations for various populations can be made. These populations will be sorted on a scale of 1 to 5, from small developing communities to large-scale developed cities. Each population will be assigned a desalination – renewable energy – brine disposal system that best suits their needs with additional considerations for alternative solutions.

2.5 Validity and Limitations

Confirming the validity of certain sources can be done through triangulation or cross-referencing, and is important when collecting and evaluating data. While most of the information gathered came from academic sources of the library and internet, data that fell outside the expected range (i.e. outliers) had to be examined carefully. While outliers were not eliminated, they were marked as points that needed cautious evaluation.

As a desk-based study, the main limitation of this paper was time. The material covered in this paper demanded an incredible amount of research which could be covered in tens of thousands of articles. Because of the amount of time assigned to write this dissertation, there remains a good amount of literature that can answer the research questions, but unfortunately are not included in this paper. Additionally, all literature used in this paper are written in English and published in an academic source. Thus, there remains the possibility that other unpublished literature, and sources that have not been translated to English, contain information that is valuable to answering the proposed research questions. Also, contacting professional experts to validate findings and offer opinions was scheduled to occur as the last step in the research process. However, due to time constraints and conflicting schedules, this could not be done.

Chapter 3: Literature Review

The amount of literature written about desalination is overwhelmingly abundant, as engineers and researchers are constantly publishing new literature to improve the performance and outlook of desalination. Due to its ability to produce new drinking water, desalination has been scrutinised over many decades as an answer to end water scarcity, although major factors such as cost and operation complexity have hindered its growth in many areas, especially developing countries. While most of the literature available has been focused on the current use and performance of desalination technologies, fewer articles have been written about the integration of renewable energies, and even less information about brine disposal solutions.

3.1 Desalination Methods

This section of the literature review describes the different methods of desalination currently available, whether it has been practiced over many decades on a large-scale market, or simply been tested multiple times in a university laboratory. The section begins with a brief introduction about desalination growth in the last 100 years, and the various water quality factors that each technology must consider when desalinating its source. The most popular thermal desalination methods will be described first, followed by the most prominent membrane desalination processes. Minor processes, which are available on a much smaller scale and are mainly at the research stage, are described at the end. The performance characteristics of each technology are then summarised, integrating the information collected from previous sub-sections into the overall framework.

3.1.1 Introduction

Over the last century, desalination has rapidly developed in response to economic growth and freshwater scarcity. According to Buros and SWCC (n.d.), a major step in development occurred during World War II when various military establishments in arid areas needed water to supply their troops. In response to these conditions, the American government spent over $300 million in the research and development of desalting seawater, seizing the opportunity to invent a large-scale solution that could benefit millions, if not billions, of consumers. This research soon turned to profit in the early 1970s when countries in the Middle East discovered large oil reserves, and were able to invest their revenue into large scale desalination plants (World Bank, 2012).

The development of desalination technology has made remarkable strides over the last half-century, notably reducing cost while increasing energy efficiency. Although many different methods have been invented to desalt water, these variations can ultimately be classified in two categories: thermal and membrane processes. Methods such as Multi-Stage Flash (MSF) and Multiple Effect Distillation (MED) are considered thermal processes because they utilize heat to evaporate clean water from the saline source, and then re-condense these water molecules (from steam to liquid) by means of cooling and pressure. On the other hand, membrane processes do not rely on heat to desalinate feed water. Rather, they separate fresh and saline water by utilising a semi-permeable membrane, which selectively allows desirable particles (e.g. pure water) to pass through while retaining non-desirables (salt). Reverse Osmosis (RO) and Electrodialysis (ED) are popular examples of membrane processes.

At its origins, desalination was primarily conducted by thermal technologies, since this was one of mankind's earliest forms of water treatment (Rasool Qtaishat and Banat, 2013), and was simple to operate. However, membranes have recently become a more cost-effective alternative, as technology has advanced the development of polymeric materials to increase production on a large, economic scale. In fact, according to the World Bank (2007), these advances in membrane technologies have driven prices of desalinated water from an average of $1.0/m^3 in 1999 to $0.50/m^3 in 2004, and the following literature in section 3.1.3 supports this. As shown by Figures 11, 12, and 13 below, the growth of membrane technology over the last decade alone has made reverse osmosis a universal favourite among desalination consumers. However, it should be noted that there is still potential for other technologies to overcome the weaknesses of RO, and change the market outlook.

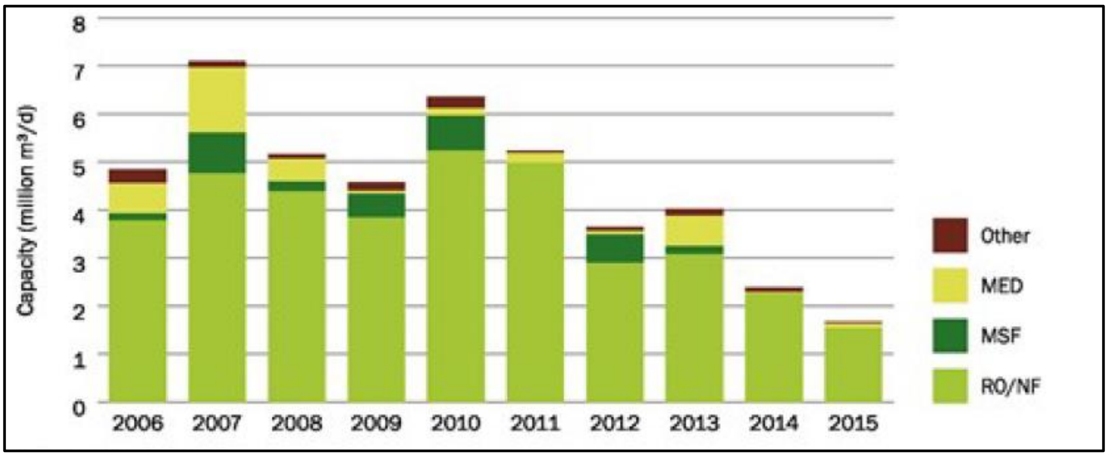

Figure 11: Annual new contracted capacity by technology, 2006-2015
Source: IDA, (2016)

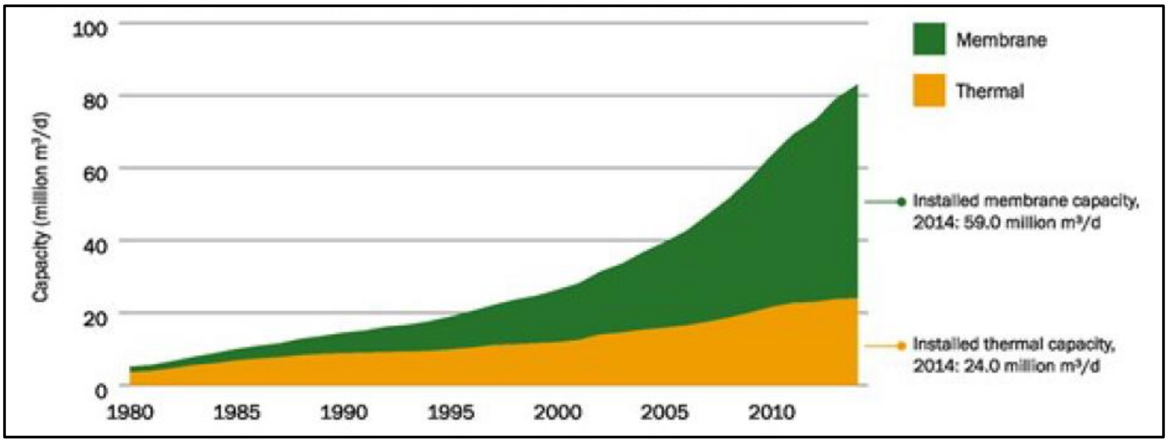

Figure 12: Cumulative installed membrane and thermal capacity, 1980-2014
Source: IDA, (2016)

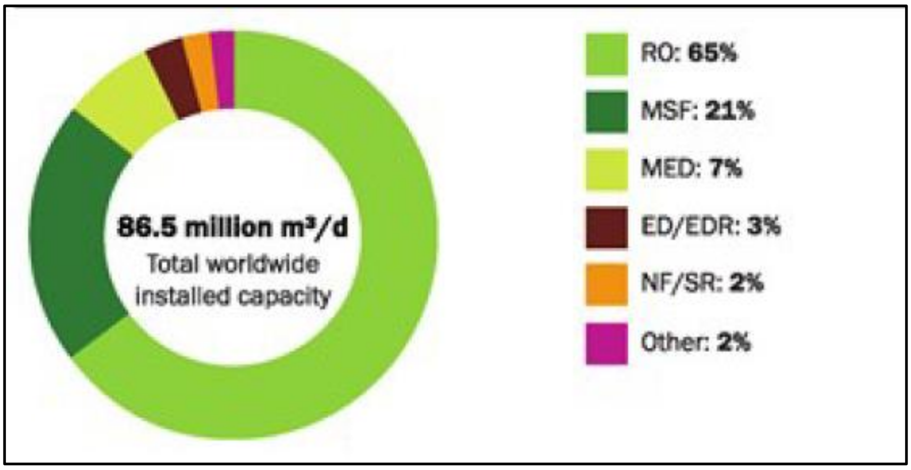

Figure 13: Total worldwide installed capacity by technology
Source: IDA, (2016)

3.1.1.1 Water Quality Considerations

In addition to the salinity levels of different source waters (Table 1), there are other notable characteristics of feedwater and product water that all desalination technologies should consider. First, while the survival of many microbial pathogens is significantly reduced in saline water, some pathogens, such as *Vibrio cholarae*, survive well in these conditions (World Health Organization et al., 2011). While most plants add chemical constituents to combat this issue, some estuarine-based desalination facilities abstract water at a particular tide level where concentrations of salt and contaminants are further reduced. According to the World Health Organization et al. (2011), desalinated water is initially more corrosive than other drinking water sources, giving rise to metal concentrations that create unacceptable appearance, taste, and consequent rejection.

3.1.2 Thermal Distillation Processes

As mentioned before, thermal distillation processes rely on heat as a means of separating salt from freshwater, and this can be applied in a myriad of different ways. As Buros and SWCC (n.d.) explain, the boiling temperature of water tends to decrease as one moves from sea level to a higher elevation, due to the reduced atmospheric pressure on the water. Therefore, in an attempt to produce more water vapour with the same amount of heat, thermal processes often control the boiling point needed for evaporation by adjusting the ambient pressure above the water. Reducing this pressure not only creates multiple boiling effects, it also helps to reduce scaling.

One of the most stubborn scale bi-products of thermal distillation is calcium sulphate ($CaSO_4$), which begins to leave the solution when seawater reaches 115°C (Buros and SWCC, n.d.). This hard scale coats any tubes or surfaces in its presence, and is often difficult to remove once it is formed. Scale deposits such as $CaSO_4$ can often lead to blockages, corrosion, and reduced lifespans of mechanical equipment. However, Buros and SWCC (n.d.) note that scale formation can be decreased through means of reducing pressure, since the solubility of such deposits increases with decreasing temperature, avoiding a change to solid state. This presents a much cheaper and easier means of scale control, as opposed to reducing feedwater salt concentration; although Thomas (1997) postulates that adding a locally available acid such as vinegar could also produce the same effect. While reducing the ambient pressure helps to decrease the energy demand of the system, Cotruvo et al. (2010) notes that there is a risk that certain pathogens and viruses cannot be killed in these cooler termperatures (50-60°C), thus a balance needs to be reached between energy efficiency and water quality.

All thermal distillation plants are known to produce very pure water (1-50 mg/L TDS) due to their evaporation-condensation techniques, although this distilled water is usually produced from less than half the incoming saline flow. Despite these low production efficiency figures, thermal technologies dominated the world market in the 1980s and 90s, particularly in the Middle East where energy costs from fossil fuels remained relatively low. In addition, operation and maintenance procedures for thermal distillation plants are often similar to those required for power plants, which is why many distillation plants are coupled to thermal power stations, and finding personnel for O&M is relatively easy (World Bank, 2012). According to Cotruvo et al. (2010), the main thermal distillation technologies on the market are multistage flash distillation (MSF), multi-effect distillation (MED), and vapour compression (VC), which will be studied in greater detail in the following sub-sections.

3.1.2.1 Multi-Stage Flash Distillation (MSF)

Multi-stage flash distillation has dominated the thermal distillation market since its inception in the 1950s, and will most likely continue to outnumber MED and VC installations due to its overall simplicity and longevity. The MSF process can best be summarized in Table 8, which describes the step-by-step process, and Figure 14 illustrates the path of incoming seawater as it is distilled through MSF.

Table 8: Step by step process of MSF scheme
Source: Adapted from Buros and SWCC, (n.d.)

Step	Description
1	Incoming seawater is heated in a vessel called the brine heater, but generally not at boiling point.
2	This heated seawater then flows into another vessel, called a stage, where the ambient pressure is lower, causing the water to immediately boil.
3	The sudden introduction of the heated water into the chamber causes it to boil rapidly, almost exploding or “flashing” into steam.
4	The steam, or water vapour, condenses on the cooler walls of the chamber (and tube of cool incoming seawater as shown in Figure 14) and is collected as fresh distilled water.

5	Generally, only a small percentage of this water is converted into vapour and collected in the distillate stream, depending on the pressure maintained in the stage. Therefore, the heated seawater will continue to flow into another stage where the pressure is even lower in an attempt to convert more water to steam. Generally, an MSF plant will contain 15 to 25 stages.
6	The process is finished when the seawater has passed through the last stage, and 25-50% of the original seawater has been converted to distillate fresh water. The fresh water continues to post-treatment, while the rest of the seawater, or brine discharge, is disposed of separately.

It should be noted that while Buros and SWCC (n.d.) state that an MSF plant will contain 15 to 25 stages, Ettouney and Wilf (2009) postulate that some old units can contain up to 50 stages, though in general, most MSF plants will have 20-25 flashing stages. There is also some speculation about the production capacity of MSF plants, as Buros and SWCC (n.d.) claim that MSF plants are generally built in the range of 4,000 - 57,000 m^3/day, while Ettouney and Wilf (2009) argue this range should be expanded to 5,000 – 75,000 m^3/day. Other authors are similarly uncertain about this figure, as the World Bank (2012) writes that the modular capacity of MSF plants is around 90,000 m^3/day, while Thomas (1997) increases this capacity up to 100,000 m^3/day. Although the figures may not be identical, the general consensus is that MSF plants are capable of producing the highest amount of water among most desalination methods, and are preferable on a grand scale.

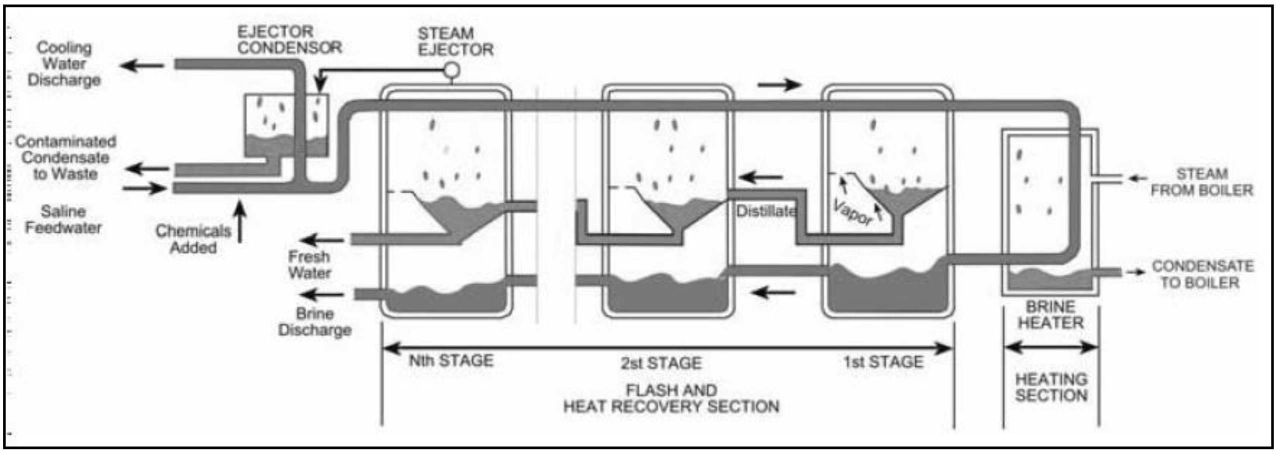

Figure 14: Simple MSF process scheme
Source: Fritzmann et al., (2007)

Though the operational efficiency of an MSF plant is best suited around 110°C or higher, the potential for scale formation and accelerated corrosion also increases around this temperature (Buros and SWCC, n.d.). This is why according to Groves (2012), MSF plants call for large amounts of treatment chemicals to remedy these scale deposits, in order to maintain reasonable production efficiency at high temperatures. The World Bank (2012) also notes that MSF plants are generally advantageous for demonstrating long economic lives (approx. 25 years) greater than anticipated at construction (15 years). According to ETSU et al. (1996), MSF is best suited for areas that prefer reliability and simplicity over thermal efficiency, especially in countries where fuel is a cheap commodity. However, the size and complexity of the MSF plant (especially one that contains many stages) makes it unfavourable for small-scale communities, where water demand is less than 4,000 m^3/day. Table 9 summarises the advantages and disadvantages of multi-stage flash distillation.

Table 9: Advantages and Disadvantages of MSF
Source: Author (based on works cited in text)

Advantages	Disadvantages
Large capacity design. Suitable for large-scale communities	Large environmental footprint
Can treat very salty water up to 100,000 mg/L	Requires large amounts of treatment chemicals to remedy scale deposits
Reliable and proven technology with long operating life	Low thermal and production efficiency
Easy to manage and operate	Large capital investment required
High quality product water	Cannot operate below 60% capacity

3.1.2.2 Multiple-Effect Distillation (MED)

MED is almost exactly identical to MSF, except that it is less energy-intensive because of one principle difference: the distribution of water in each stage. According to Buros and SWCC (n.d.), after the feedwater has been heated in the brine heater, it is sprayed or otherwise distributed in a thin film to promote rapid boiling and evaporation once it enters the flashing stage. Spraying the saline water in this manner increases the water surface area exposed to the heat and vacuum air, accelerating the vaporisation effect.

However, rather than spraying the feedwater onto the walls of the stage chamber, the saline water is distributed over the outer surface of heated tube bundles (Cotruvo et al., 2010). Each stage contains a bundle of heated tubes with steam flowing through provided by a separate boiler. According to Cotruvo et al. (2010), once the seawater is sprayed onto the tubes, the saline water film boils as it absorbs heat from the steam, and the resulting vapour passes through mist eliminators where it is introduced into the tubes of the next stage. The steam that was originally in the tube bundles is cooled by the sprayed seawater, and condenses to liquid form where it is collected as freshwater distillate. Table 10 below lists the step by step procedure of the MED process, and Figure 15 illustrates a simple MED scheme.

Table 10: Step by step process of MED scheme
Source: Adapted from Cotruvo et al., (2010) and Buros and SWCC, (n.d.)

Step	Description
1	Incoming seawater is heated in a vessel called the brine heater. Any vapour produced is separated and passed on to the next stage in a series of tubes.
2	The liquid seawater and vapour steam then flow into another vessel, called a stage, where the ambient pressure is lower due to a vacuum system.
3	The heated seawater is then sprayed onto a bundle of heated tubes inside the stage, where it quickly evaporates due to the heat and decreased pressure.

4	The vapour from this seawater is then collected and passed on to the bundle of heated tubes in the next stage.
5	Meanwhile, a portion of steam from inside the heated tubes condenses as a result of its contact with the cooler seawater, and forms distilled water. This distilled water is then passed on to post-treatment.
6	Any liquid seawater that has not converted to steam is similarly passed on to the next stage. This continues until the water has passed through all the stages of the plant.

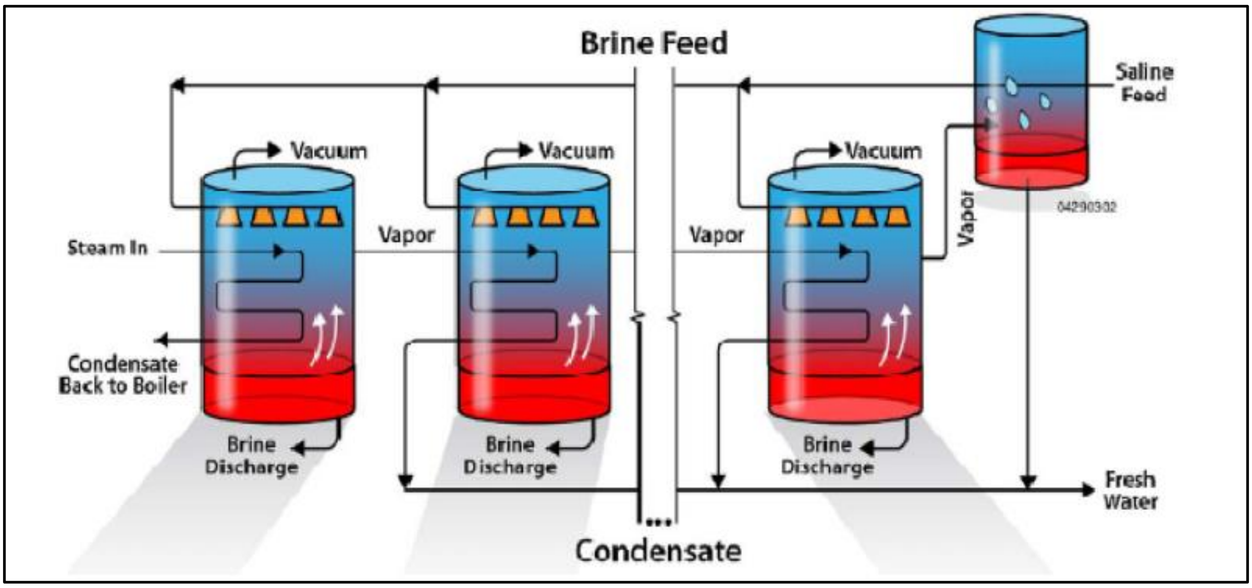

Figure 15: Simple MED scheme
Source: Al-Karaghouli, (2009)

Similar to MSF, only a small percentage of steam in the tube bundles condenses into freshwater, thus an MED plant will contain 8 to 16 stages (Buros and SWCC, n.d.), repeating the process until 25-50% of incoming feedwater has been converted to fresh water. Because of the difference in water distribution and heat application, MED plants typically operate at a maximum temperature of 70°C, reducing the scaling problem and the amount of heat energy required (Khater, 2010). There is some debate about whether MED does produce less scale deposits, as authors such as Groves (2012) and Cotruvo et al. (2010) claim that MSF is preferable over MED because of its lower potential for scale formation, however, there is no further evidence to support these claims.

MED plants will generally operate at a lower production capacity (2,000-30,000 m^3/day) than MSF plants, but are more flexible to operate at partial loads (Ghaffour et al., 2015). While MED still remains limited in its production efficiency, its ability to desalinate water at a reduced energy consumption rate makes it likely that will become more widespread than MSF, if countries choose to install thermal distillation plants. Table 11 on the next page summarises the advantages and disadvantages of multiple effect distillation.

Table 11: Advantages and Disadvantages of MED process
Source: Author (based on works cited in text)

Advantages	Disadvantages
Flexible to operate at partial loads for small scale communities	Smaller capacity design than MSF
Cost is independent of water salinity. Can treat high salinity water at same cost as low salinity	Large environmental footprint
Operates at lower temperature than MSF, producing less scale formation	Larger capital and operating expenditure than MSF due to added sprinklers and tubes
Lower energy consumption than MSF	Low production efficiency

3.1.2.3 Vapour Compression (VC)

Similar to MSF and MED, vapour compression utilises heat as a means to separate salt from freshwater. However, there are many differences between VC and MSF/MED that offer certain advantages, primarily the principle of compression.

According to Buros and SWCC (n.d.), the vapour compression distillation process is generally used in combination with other processes (mainly MED) because the heat for evaporating saline water comes from the compression of vapour rather than the direct exchange of heat from a boiler. According to the ideal gas law (PV=nRT), as the pressure of the water vapour increases, the temperature proportionally rises. Compression acts as a means to reduce the volume and increase the pressure of the water vapour within the chamber, thereby increasing the temperature.

Vapour compression is mostly available in mechanical form (MVC), though thermal compressors (TVC) also exist. MVC units typically produce small capacities of 1 – 5,000 m^3/day when operated independently, and is best utilized for small/medium scale desalting in resorts, industries and drilling sites where fresh water is not readily available (Buros and SWCC, n.d.). On the other hand, TVC units are capable of producing water at a much higher capacity (up to 36,000 m^3/day), although they are best utilised with MED plants to improve process efficiency (Khater, 2010). There is also a difference in energy consumption, as MVC units are primarily run by electricity, and TVC units rely on thermal heat. Figure 13 illustrates the difference in the two units side by side, and notes that VC units typically contain less stages (1-4) than MED or MSF plants.

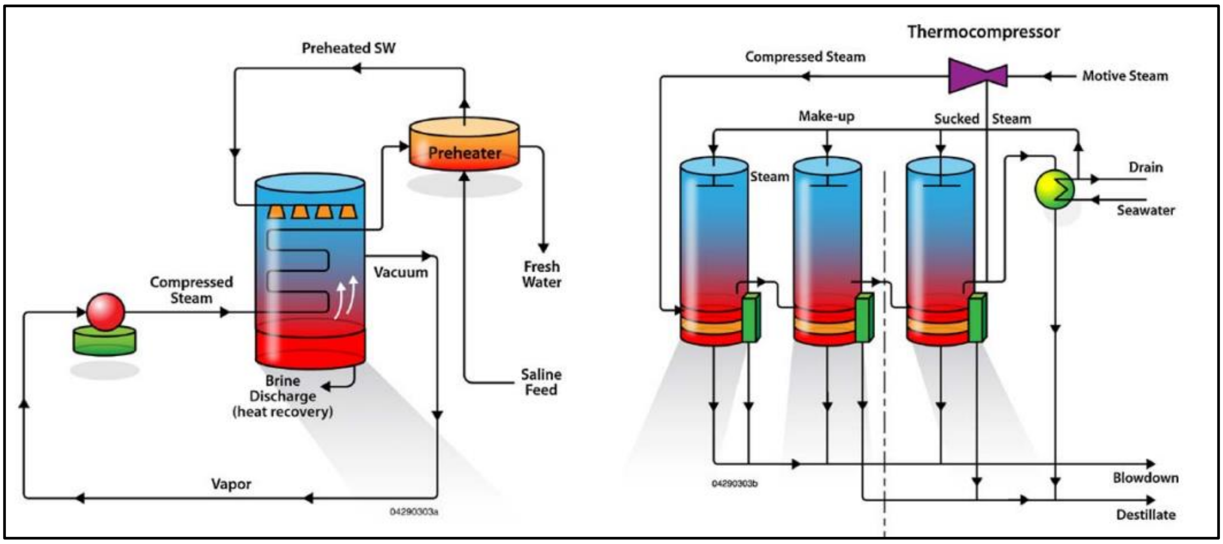

Figure 16: Diagrams of MVC (left) and TVC (right)
Source: Al-Karaghouli, (2009)

The simplicity and reliability of VC units makes vapour compression an attractive option for small installations (Buros and SWCC, n.d.), as Thomas (1997) agrees that skilled operators are generally not required for daily operation. However, periodic maintenance of the mechanical/thermal compressors should still be attended by skilled technicians. Table 12 bleow summarizes the advantages and disadvantages of VC systems.

Table 12: Advantages and disadvantages of VC
Source: Adapted from works cited in text

Advantages	Disadvantages
Operation is simple, straightforward, and reliable. Generally does not require skilled technicians	Periodic maintenance and cleaning of compressors requires technical skill
Suited for small to medium-scale desalination. TVC usually produces more water than MVC	Generally has lower capacity than MSF or MED units
Increases production efficiency when used in conjunction with MSF or MED	Cannot operate below 60% capacity
Helps reduce number of effects/stages	
Operates at low temp (<70°C) to avoid corrosion and scaling	

3.1.3 Membrane Processes

As mentioned earlier in section 3.1.1, membrane technology is dominating the world desalination market, overtaking thermal distillation as the favourite choice for desalination. This growth can be attributed to technological advances which have made membranes more effective and affordable, and projections indicate that membrane technology is the best desalination solution moving forward. However, there are still weaknesses and flaws presented by these membranes that restrict reverse osmosis and electrodialysis from becoming universal solutions for everyone.

One major flaw that is shared by all membrane processes is the inability to remove bacteria from water. Thermal processes produce distilled water with as little as 1 mg/L TDS, but membrane processes generally produce freshwater with up to 500 mg/L. Although this falls within WHO guideline limits, the absence of heat in the process does not kill as many bacteria as MSF, thus additional treatment chemicals are required to ensure pathogen-free water is distributed. Additional pre-treatment is also required to remove solid matters that would clog up membranes, or else production efficiency and membrane lifespan would be reduced (Ruskulis, 2002).

Maintenance is also a difficult task that needs sufficient attention, as membranes are generally sensitive to metals, suspended solids, and other contaminants found in feedwater (Thomas, 1997), though pre-treatment for RO or ED is generally on the same scale as freshwater treatment from a river or lake. Cotruvo et al. (2010) state that membranes are generally 0.05 – 1.0 mm thick, and operate at feed pressures of 70 – 700 kPa which can put enormous strain on the material. However, while membranes are frowned upon for their added complexity and fragile nature, they nonetheless are critical to reverse osmosis and electrodialysis, which offer particular advantages over thermal distillation systems.

3.1.3.1 Reverse Osmosis (RO)

At present, reverse osmosis is the most energy-efficient technology for seawater desalination, as it has made massive improvements in the last few decades, and is the benchmark for comparison with any new desalination technology (Elimelech and Phillip, 2011). RO is the most popular desalination method on the market, with over 65% of the world's installed capacity, and this can be attributed to its remarkably low energy consumption which has decreased costs. Initially, RO was far behind MSF in the desalination market because membranes were expensive, pretreatment was misunderstood, and energy consumption was high (World Bank, 2012). Since then, technological advances have made membranes more affordable and effective, pretreatment better understood, and decreased energy consumption to its present day benchmark status.

Although the operation and maintenance of RO systems is regarded as complex in comparison to thermal distillation, the concept of reverse osmosis is fairly simple. The most important part of the process is the semi-permeable membrane, which acts as a barrier to selectively allow water molecules to pass while retaining undesirables (i.e. salt compounds). According to the principle of osmosis, if two neighbouring water chambers were separated by this semi-permeable membrane, water would move across this membrane until the concentration of solids on both sides were equal (refer to Figure 17 below). However, the goal of desalination is not to create more water with saline compounds, rather it is the opposite. Therefore, in order to *reverse* the osmosis process, additional pressure is applied to the saline water chamber, forcing all the water molecules to move in one direction across the membrane. As a result, pure freshwater is produced and saline compounds are retained (Figure 18).

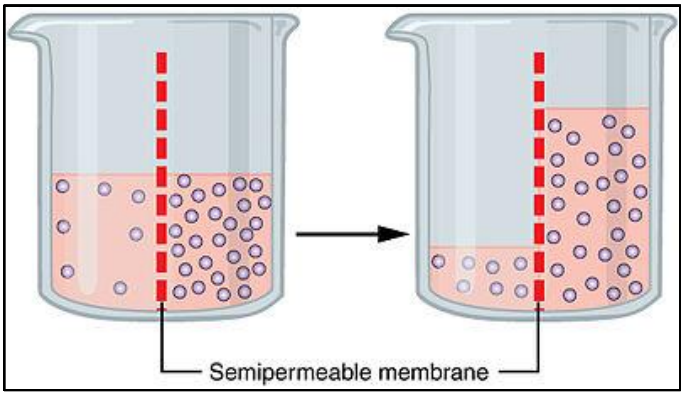

Figure 17: Principle of Osmosis
Source: OpenStax College, (2013)

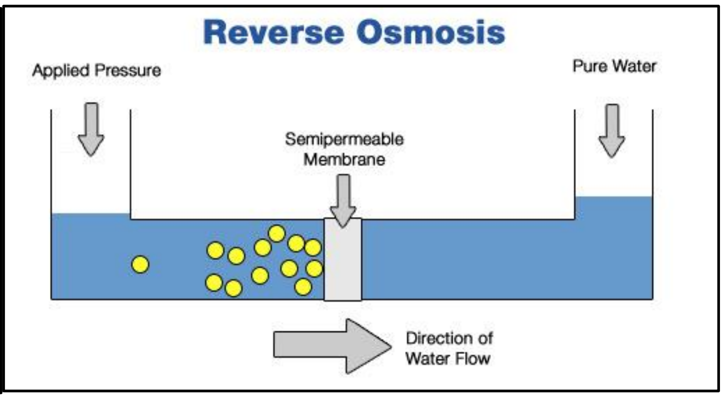

Figure 18: Simple RO scheme
Source: Armstrong et al., (2013)

The simplicity of the process allows reverse osmosis to produce more freshwater, as there is no need to capture water vapour and condense it back to liquid form. However, the product water from reverse osmosis typically contains 200-500 mg/L TDS, as opposed to the low (1-50 mg/L) TDS levels recorded in thermal distillate. Nonetheless, RO product water is still within WHO drinking water guidelines in terms of salinity. Table 13 below compares the freshwater conversion rate of reverse osmosis to thermal distillation, which is considerably higher for both brackish and seawater sources.

Table 13: Efficiency of Converting Saline to Fresh Water
Source: World Bank, (2012)

	Distillation		Reverse Osmosis	
	MSF	MED	Seawater	Brackish water
Volume of feed water (m^3)	4.0	3.0	2.0-2.5	1.3-1.4
Volume of brine effluent (m^3)	3.0	2.0	1.0-1.5	0.3-0.4
Volume of fresh water (m^3)	1.0	1.0	1.0	1.0
Efficiency (%)	**25**	**33**	**50**	**77**

As noted in Table 13, RO technology is much more efficient than distillation in terms of production, but there still remains room for improvement, beginning with the membrane. According to Elimelech and Phillip (2011), the first commercially viable membranes were asymmetric cellulose acetate membranes, developed in the 1960s. However, 20 years later, robust thin-film composite membranes were created with the ability to remain stable over a greater pH range than cellulose-based membranes, and could exhibit much higher water permeability because of its extremely thin (~100nm) polyamide-selective layers. Today, RO desalination plants continue to use these thin-film composite membranes, which have vastly improved in the last few decades, and can reject up to 99.8% of dissolved salts (Elimelech and Phillip, 2011). However, in order for the membranes to be effective, they must remain clean.

According to Groves (2012), RO membranes are subject to a number of threats, including surface fouling and scaling, which interfere with the separation process. Fouling of the RO membrane can be colloidal (accumulation of solids), biological (growth of biofilm), or organic (adsorption of humic substances and oil). Therefore, pretreatment is required to remove as many of these foulants as possible in order to maintain production efficiency and extend the lifespan of the membrane. Buros and SWCC (n.d.) note that pretreatment usually consists of fine filtration and the addition of chemicals to inhibit precipitation and growth of microorganisms. Despite these extra measures, boron is a chemical that is poorly removed by reverse osmosis (World Health Organization et al., 2011), and requires post-treatment for additional safety.

The development of fouling-resistant membranes would improve the energy usage, reliability, and environmental impact of RO technology; however, despite extensive research efforts, no such membranes have been developed that are suitable for desalination applications (Elimelech and Phillip, 2011). Developing more selective membranes to reduce boron levels could also present some difficulty, as increasing selectivity will substantially reduce membrane permeability, thereby increasing energy consumption. However, despite these drawbacks, researchers are hopeful that technological advances will be able to develop anti-fouling membranes in the near future, which could eliminate pretreatment and substantially reduce energy consumption, capital cost, and environmental impact (Elimelech and Phillip, 2011).

Another important aspect of RO desalination is the difference in efficiency between brackish and seawater sources, illustrated in Table 13. As Grubert, Stillwell and Webber (2014) explain, the osmotic pressure for brackish waters is lower than for seawater, due to the reduced concentration of salts. As a result, it is easier for the membrane to selectively allow water molecules to pass, due to the reduced interference of salt compounds. Therefore, when the same pressure is applied to a seawater chamber and a brackish water chamber, there will be more freshwater produced from the brackish water chamber. Thus, regions with low ocean salinity are often identified as naturally favourable for RO desalination (Grubert, Stillwell and Webber, 2014). Alternatively, desalination plants may choose to reduce the applied pressure when abstracting brackish sources, as this will reduce energy consumption but consequently reduce production efficiency. Table 14 below lists the RO pressures typically applied in desalination plants that abstract feedwater from different sources. It is assumed that the production efficiency in each case remains the same (around 50-75%).

Table 14: RO pressures of different sources
Source: Adapted from Fritzmann et al., (2007) and Buros and SWCC, (n.d.)

Source	Pressure (bar)
Brackish water	15-25
Seawater	50-80
Landfill leachate treatment	200

Although brackish water sources require less energy for desalination, it is imperative to identify the operation skills of the targeted area before installing a RO plant. For example, in a rural area of India where water demand was fairly small (10-300 m^3/day), a cluster of villages was given a small-scale RO plant to desalinate water from a local brackish source (Ruskulis, 2002). Local people had been had been trained in the day-to-day operation of the plant, while more extensive repairs required an engineer or skilled technician from a private company. This often caused delays and temporary closures of the plant, as a shortage of spare parts, equipment, and skilled labour disabled smooth operation (Ruskulis, 2002). The plant was eventually closed down soon after its erection.

Despite these shortcomings, reverse osmosis is still one of the most favourable desalination technologies on the market today. As mentioned before, reverse osmosis requires no additional heat energy and is purely electrical in demand (for pumping purposes). As a result, a typical seawater reverse osmosis (SWRO) facility consumes 3-6 kWh of energy to produce one m^3 of distillate, while thermal facilities generally demand 15-58 kWh for the same amount of water (Grubert, Stillwell and Webber, 2014). This energy demand can be further reduced when abstracting water from brackish sources, or through continuous innovations in membrane design and energy recovery. In fact, the World Bank (2012) reports current RO energy consumption to be as low as 1.8 kWh/m^3, approaching the theoretical minimum to separate pure water from seawater (1.06 kWh/m^3). However, it should be noted that this theoretical minimum may never be achieved due to additional energy required for intake, pretreatment, post-treatment and brine discharge. As a result of this decreased energy consumption, reverse osmosis is able to produce pure water at a much cheaper cost than most thermal distillation plants.

In the past, most authors argued that large-scale seawater desalination was best suited for thermal distillation plants, since higher salinity required greater energy consumption for RO. However, in November 2013, the Israeli company IDE technologies began operating a 624,000 m^3/day SWRO plant just 15 km south of Tel Aviv (Freyberg, 2013). In addition to serving over 3.5 million people, the SWRO plant (named Sorek) incorporates a vertical membrane arrangement, as opposed to the traditional horizontal array, which produces higher production efficiency and reduced footprint (due to decreased construction area). Continuous innovations such as Sorek are reasons why reverse osmosis provide so much hope for the future. As technology advances, the cost and performance of RO membranes are predicted to improve, and the desalination process may become cheaper and easier to operate. Table 15 below summarizes the advantages and disadvantages of reverse osmosis.

Table 15: Advantages and disadvantages of RO
Source: Author (based on works cited in text)

Advantages	Disadvantages
Much lower energy consumption than thermal distillation	Fouling of membranes leads to increased pre and post-treatment
Flexible to operate at low and high capacity; expanding incrementally as needed	Complex configuration - requires skilled personnel for O&M

Higher conversion rate of feedwater to fresh water	Lower quality product water than thermal distillation
Energy usage is proportional to feedwater salinity (cheap for brackish waters)	Difficulty removing boron and other harmful chemicals
Capital cost approximately 25% less than thermal options	

3.1.3.2 Electrodialysis (ED)

Similar to reverse osmosis, electrodialysis requires membranes as a means to separate salt from water. However, it is the salt ions, not the water molecules, which are deliberately carried through the membrane. The principles of operation are that most salts dissolved in water are naturally charged (e.g. Na^+ and Cl^-) and will be attracted to objects carrying the opposite charge (Khater, 2010). Therefore, two types of membranes are installed in an ED system: one that lets anions through but not cations, and another that does the opposite. Two electrodes are subsequently installed in the system connected to DC electricity to produce a current causing the salt ions to migrate to the electrode possessing an opposite charge. These membranes are stacked alternately and held apart by spacers (Thomson, 2003), where the freshwater is produced as a result of the ions being pulled through the anion/cation membranes. Figure 19 below illustrates this principle, where a cathode is placed on the right and an anode on the left with selective membranes in the middle.

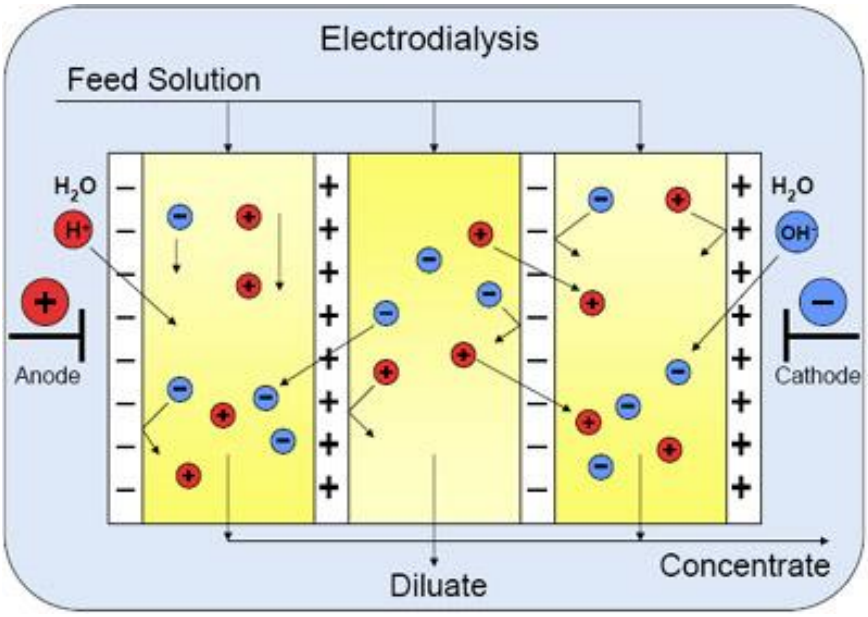

Figure 19: Electrodialysis simple diagram
Source: Fumatech, (2016)

In order to periodically clean the membranes, the polarity of the applied voltage is reversed in the electrodes, and the flows are simultaneously switched (Buros and SWCC, n.d.). This reversal process is useful in breaking up and flushing out scales, slimes, and other deposits in the cells, and is termed *electrodialysis reversal*. As a result of electrodialysis reversal (EDR), membranes are prone to less fouling and scaling, resulting in a longer useful life. In addition, these ion-exchange membranes are also able to tolerate higher levels of chlorine and extreme pH-values (Strathmann,

2004) due to their thicker, more robust structure. For this reason, EDR is used instead of RO if higher recoveries are needed and the source water contains large amounts of scaling compounds and high biofouling potential (Cotruvo et al., 2010).

However, ED-based systems do not provide any barrier against pathogens (World Health Organization et al., 2011), since bacteria do not carry a charge, and ED is found to be cost competitive with RO only when brackish water sources are below 10,000 mg/L TDS (Turek, 2002). When water sources have higher salinity, RO and other desalination methods are generally cheaper. For these reasons, ED is used mainly for brackish water desalination and wastewater reuse for irrigation (Cotruvo et al., 2010), ranging in capacity from a few hundred litres per day to more than 20,000 m^3/day (Strathmann, 2004).

Despite these shortcomings, researchers continue to investigate new and improved ways of reducing the cost of ED systems, as the additional lifespan and simplicity of these ionic membranes prove to be desirable features of sustainability. Table 16 summarizes the advantages and disadvantages of electrodialysis.

Table 16: Advantages and Disadvantages of ED
Source: Author (based on works cited in text)

Advantages	Disadvantages
Long useful life of membranes with higher chemical and mechanical stability	Unable to remove harmful pathogens – requires additional post treatment
Less membrane fouling and scaling due to process reversal – less raw water pretreatment	Cost competitive only with brackish waters below 10,000 mg/L TDS
Ability to treat feedwater with high amounts of suspended solids and scaling compounds	Operates at smaller capacity than RO and MSF
High product recovery ratio	Capital costs can be high compared to RO

3.1.4 Minor Processes

Although minor processes make up less than 4% of the world's current desalination capacity, they are nonetheless important to study when considering the future of desalination. According to Ghaffour, Missimer and Amy (2013), the development of new low-cost technologies will take time to compete with the main thermal and membrane processes, but can offer solutions to problems that previously hindered pre-existing methods. Therefore, the following subsections will investigate processes that are currently under research or have just begun commercialisation (e.g. membrane distillation, forward osmosis, freezing and boiling), or have existed for long periods of time but never gained popularity (solar stills).

3.1.4.1 Membrane Distillation (MD)

As the name suggests, MD is a membrane centred process, but unlike RO and ED, the membranes used are hydrophobic, meaning they resist getting wet. Therefore, these membranes block the passage of both water and dissolved salts, but are permeable to water vapour (Thomson, 2003). Thus, MD is a thermally-driven separation process, induced by the temperature difference across the hydrophobic membrane (Alkhudhiri, Darwish and Hilal, 2012), and the product obtained is theoretically 100% pure from solid or non-volatile contaminants – similar to MSF or MED. According to Thomson (2003), the process can achieve the recycling of latent heat of evaporation without the added complexity of multiple effects or vapour compressors. Table 17 below describes the step-by-step process of membrane distillation and Figure 20 illustrates a simplified concept of membrane distillation.

Table 17: Step-by-step process of MD
Source: Adapted from Rasool Qtaishat and Banat, (2013), Mendez, (2014), and Buros and SWCC (n.d.)

Step	Description
1	Incoming seawater is heated on the warm feed side of the membrane at a low temperature heat (70-90°C) and reduced pressure which creates water vapour.
2	The water vapour migrates across the membrane through the non-wetted pores
3	The vapour subsequently condenses on a cooler surface (usually a thin plastic foil) to form pure distillate
4	Heat from the distillate is carried on to the next stage to create more water vapour from the liquid feedwater that has not evaporated. The process is repeated until the feedwater has passed through all the stages and there are two clear streams of distillate and brine discharge.

The main advantages of MD lie in its simplicity and the need for only small temperature differentials to operate. However, the recovery rate is still dependent on the temperature differential, thus if the process is run with very low temperature differentials, large amounts of water must be used to achieve adequate distillate production (Buros and SWCC, n.d.). Thomson (2003) adds that because the membrane does not have to be selective between water and salt ions, the pore size can be 1000 times larger than for RO, and there is no fouling that occurs since the membrane does not get wet. As a result of these decreasing demands, MD membranes can be made from less expensive materials such as plastic (Alkhudhiri, Darwish and Hilal, 2012).

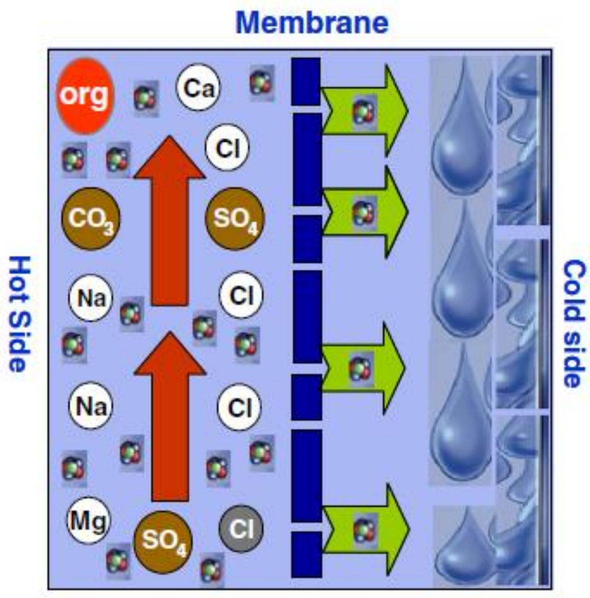

Figure 20: Membrane Distillation Scheme
Source: Adham et al., (2013)

As a result of its thermal recycling and use of low grade waste heat, membrane distillation is able to work at lower temperatures than MSF, and hydrostatic pressures that are less demanding than RO. According to Adham et al. (2013), MD results in lower operating and capital costs than RO, due to its simplicity of operation and membrane material. Similarly, Rasool Qtaishat and Banat (2013) report that MD provides lower costs than MSF and MED because of its significantly smaller vapour space. As a result, MD process equipment can be much smaller, and operating temperatures as low as 30°C can be utilized since it is not necessary to heat liquids above their boiling points (Rasool Qtaishat and Banat, 2013).

Despite these attractive advantages, MD has not yet been commercialized for large-scale desalination for two big reasons: 1) low permeate flux; and 2) technical problems such as membrane wetting. Membrane wetting occurs when the hydraulic pressure of the feedwater exceeds the liquid entry pressure of the membrane (Drioli, Ali and Macedonio, 2015). As a result, this can lead to severe fouling inside the pores caused by the precipitated/adsorbed materials, leading to decreased performance and shorter lifespan. Other technical problems include high variability in permeate flux due to concentration and temperature conditions, and trapped air within membranes which decrease water vapour migration. Despite these shortcomings, researchers are determined to develop new membranes for MD that can overcome these design drawbacks.

Recently, Aquaver commissioned the world's first seawater MD desalination plant in the Maldives, utilizing waste grade heat from a local power plant, with a production capacity of about 10 m^3/day (Drioli, Ali and Macedonio, 2015). The marketing director of Aquaver, Dr. Enrique Mendez (2014), reports that the electrical consumption of the system is less than 2 kWh/m^3, with a recovery ratio of 90%. However, it should be noted that while these results are astoundingly impressive, they were still produced from very low feedwater flow rates. Nonetheless, as a result of their work, Aquaver has received numerous awards, such as the 2013 Water Innovator of the Year award, and presently serve companies in the pharmaceutical, food and beverage, and landfill leachate industries (Mendez, 2014). In addition to these sectors, Adham et al. (2013) have tried applying MD as a complimentary process to pre-existing thermal facilities, employing MD as a means of brine disposal treatment for environmental safety. Despite its great potential, membrane distillation is still far from fulfilling all expectations, as it has much work to do in improving its membranes and permeate flux capacity to compete with pre-existing facilities.

Table 18: Advantages and Disadvantages of MD
Source: Author (adapted from works cited in text)

Advantages	Disadvantages
High quality product water	Low permeate flux
Lower operating temperatures than conventional distillation	Membrane wetting leads to severe fouling
Lower operating pressures than conventional membrane processes	Trapped air in membrane decreases desalination production
Less demanding membrane mechanical properties	Has not been commercialised yet on large scale
Reduced vapour space leads to smaller footprint	

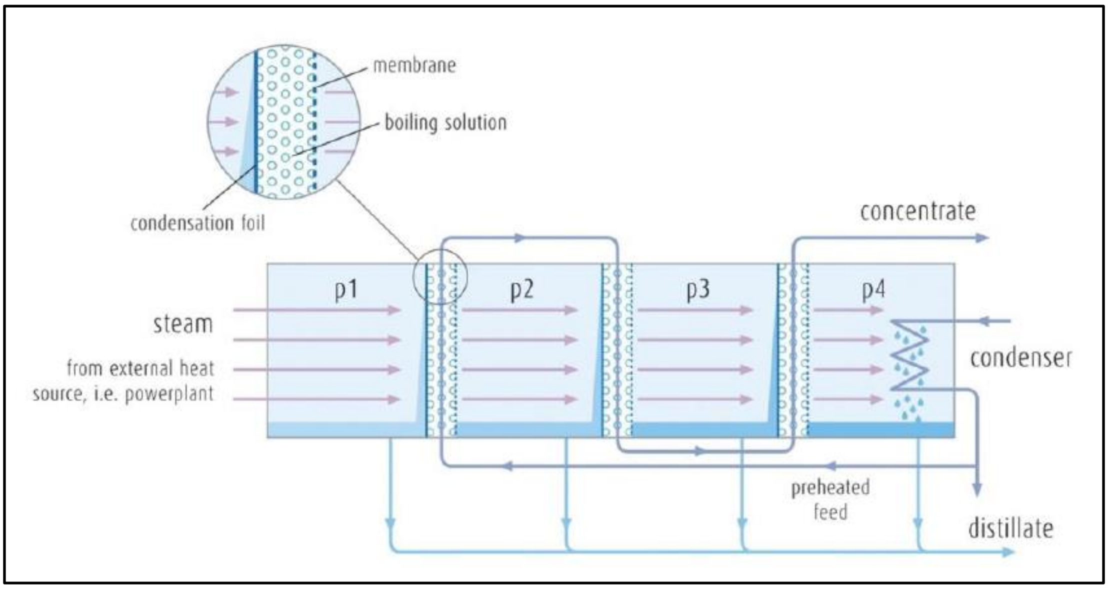

Figure 21: Schematic of Aquaver MD system
Source: Mendez, (2014)

3.1.4.2 Solar Stills (SS)

Solar stills operate on the same principle as thermal distillation plants, in that feedwater is heated and evaporated, then condensed into liquid form as fresh water distillate. However, the process is much simpler as there are no vacuum pressure pumps or multi-effect stages. Table 19 below lists the general procedure of a conventional solar still process, and Figure 22 illustrates a schematic diagram of the process:

Table 19: Step by step process of Solar Stills
Source: Adapted from (Khater, 2010)

Step	Description
1	Feedwater enters the basin of the solar still
2	Radiation from the sun enters the solar still via a transparent glass rooftop. The enclosure creates a greenhouse effect, increasing heat which causes the water to evaporate.
3	The water vapour subsequently condenses on the inside surface of the roof, flowing down the slanted surface to be collected in storage tanks

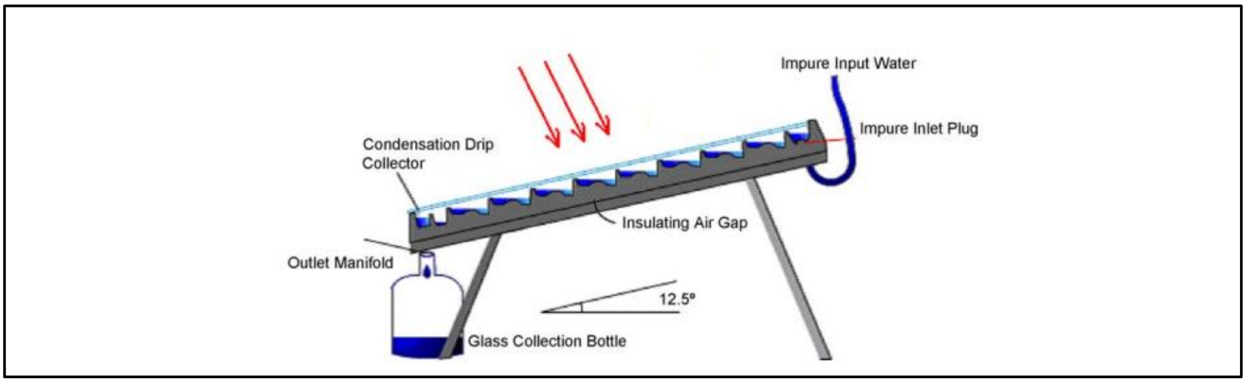

Figure 22: Schematic diagram of simple solar stills
Source: Al-Karaghouli, (2009)

Solar stills are extremely simple and require very little skill to operate. They can be constructed from simple materials and are perfect for small communities where electrical energy is scarce (Xiao et al., 2013).

However, there are many reasons why solar stills are almost non-existent in the desalination market, primarily because it is unable to produce large volumes of water in a small area of land. According to Buros and SWCC (n.d.), one square meter of solar still generally equates to 4 litres of water per day. Therefore, in order to build a 4,000 m^3/day facility, a minimum land area of 100 hectares would be needed. For this reason alone, solar stills are unable to compete with MSF and RO, as land availability begins to decrease in many countries due to ongoing economic development. In addition, the efficiency of a solar still can be affected by a myriad of factors, listed below from Ruskulis (2002):

- Poor fitting and joints, which increase colder air flow from outside into the still
- Cracking, breakages, or scratches on glass, reducing solar transmission
- Growth of algae and deposition of dust, bird droppings, etc.
- Damage over time to the blackened absorbing surface
- Accumulation of salt on the bottom, which needs to be removed periodically

Though the concept and application of solar stills may be simple, if careful attention is not given to its proper construction and maintenance, it will fail.

Despite these significant drawbacks, there is still a niche for solar stills, as thousands are still used worldwide. According to Thomas (1997), some stills have been built to thousands of square meters in size, although most solar stills are used for village level communities who are dependent on brackish waters, and have no power source. Researchers postulate that adding heat recovery mechanisms or condensers can help make solar stills more efficient and productive; however, installing these complex systems could take away the simplicity of operation that is the main advantage of solar stills.

Table 20: Advantages and Disadvantages of SS
Source: Author (based on works cited in text)

Advantages	Disadvantages
Suitable for small villages where water demand is low and electrical energy is scarce	Very low water production
Suitable for areas where plenty of solar energy is available (over 6,000 $MJ/m^2/year$)	Limited to specific geographic and social areas
Suitable for areas where large areas of land are available and cheap	Prone to many mistakes in operation and construction which can lead to ineffectiveness
Easy and cheap to build and operate	

3.1.4.3 Forward Osmosis (FO)

As opposed to reverse osmosis, forward osmosis (FO) attempts to desalinate water by drawing water across a membrane to create *equal* concentrations. According to Cotruvo et al. (2010), ammonia and carbon dioxide are added to freshwater on the opposite side of the membrane from saline water to increase the ionic ammonium carbonate concentration. This increase in concentration causes the water to naturally migrate from the salt solution, through the membrane, to the ammonium carbonate “draw” solution. Once the water has traversed and both sides have equal concentrations, the diluted “draw” solution is then heated to drive off the ammonia and carbon dioxide which are captured and reused. Thus the “draw” solution is left with pure water.

Potential advantages of FO include the fact that no external pressure is required, low heat energy is needed (temperatures are usually around 60°C), and high recovery efficiency is produced. The requirements placed on membranes for the FO process are different than those used in RO, and are predicted to be more robust and less selective to suit the lower energy consumption (Elimelech and Phillip, 2011).

As promising as FO may sound, additional research is required to determine its viability, especially because it may face the same technical membrane issues as reverse osmosis. The additional need for chemicals such as ammonia and carbon dioxide could also present a problem for many regions who have limited access to these chemicals, and additional pre/post-treatment of the water will have to be investigated.

3.1.4.4 Freezing (FR)

As opposed to heating water to a gaseous state to separate it from salt, freezing attempts to create the separation by reverting water to a solid state. According to Khawaji et al. (2008), the freezing process works by cooling the seawater until ice crystals begin to form. These crystals are then collected and melted, forming pure distillate. Theoretically, when saltwater is frozen, the ice that forms is nearly pure and the salt is left in the remaining liquid (Thomson, 2003).

Theoretically, freezing has some advantages over distillation, including lower energy requirements for single stage operation, reduced potential for corrosion, and little scaling or precipitation problems (Buros and SWCC, n.d.). The major disadvantage to freezing is the complicated handling of the ice and water, which have often required expensive machinery at a larger and more difficult scale to operate than thermal distillation. Khawaji et al. (2008) report that a small number of plants have been built in the past 40 years, but none have been successfully commercialized to produce fresh water for municipal purposes.

3.1.4.5 Nanofiltration (NF)

Nanofiltration (NF) is a relatively new technology that first found use in water treatment applications as part of the pre-treatment for standard RO systems. According to Groves (2012), NF membranes use similar materials to RO but with looser transportation properties, allowing processes to operate at lower pressures with less fouling and scaling than RO. Although there has been speculation that nanofiltration can desalinate water at the same level as reverse osmosis, Figure 23 below illustrates why this might not be the case.

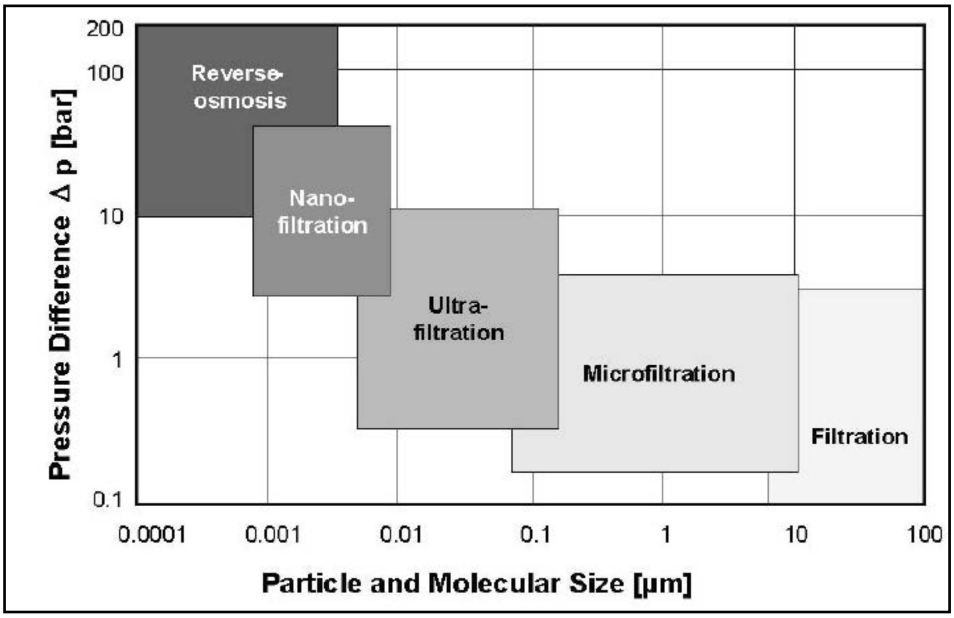

Figure 23: Separation capabilities of pressure driven membrane separation processes
Source: Fritzmann et al., (2007)

The reason why NF membranes have looser transportation properties than RO membranes is because they exhibit a larger pore size. Though this increase in permeability can increase flux and decrease scaling, it also allows larger particles to pass through, including salt molecules. Table 21 on the following page describes what constituents can be removed by each membrane, further signalling why nanofiltration may not be appropriate for desalination.

Table 21: Comparison of Membrane Process Performance Characteristics
Source: Cotruvo et al., (2010)

Membrane Type	Nominal Pore Size (μm)	Constituents Removed
Microfiltration	0.1-1	Particulates, bacteria, protozoa
Ultrafiltration	0.001-0.1	Viruses, large and high-molecular-weight organics (e.g. pyrogens)
Nanofiltration	0.001	Multivalent metal ions, some organics
Reverse Osmosis	0.0001-0.001	Seawater and brackish water desalination, salts and organics larger than about 100-300 Da

From this literature, it is evident that nanofiltration should be used for the same purpose as micro- and ultrafiltration, to remove fine particles at pre or post-treatment stage. Nanofiltration is only effective as a desalination measure for waters with extremely low salinities (2,000 mg/L or less), and can most likely be eliminated as a desalination method moving forward.

3.1.5 Summary of Desalination Technologies

Table 22 on the next page summarises the characteristics of each desalination method, inputting information that has been listed above along with other facts and figures from the World Bank (2012), Ruskulis (2002), Thomas (1997), and Fritzmann et al. (2007). Some categories are marked "unknown" as information about a specific desalination method and its corresponding characteristic could not be found in the referenced literature. If the missing information is not currently published or researched, it is the author's hope that future literature can discover these missing data points, in order to create a fair and equal comparison to assess all available desalination technologies.

Table 22: Summary characteristics of desalination methods
Source: Author (based on works cited in text)

Desalination Method	MSF	MED	VC	RO	ED	MD	SS	FO	FR	NF
Primary Energy Source	Thermal	Thermal	Thermal or Electric	Electric	Electric	Thermal and Electric	Thermal	Electric	Thermal or Electric	Electric
Typical energy consumption (kWh/m^3)	3-5 (electric) 48-80 (thermal)	1.0-2.5 (electric) 32-70 (thermal)	1.0-3.0 (electric) 10-70 (thermal)	1.8-15 (electric)	1-10 (electric)	<2.0 (electric) unknown (thermal)	600 (thermal)	Unknown	10-100 (total)	3-5 (electric)
Typical salt content of feedwater (mg/L TDS)	30,000 - 100,000	30,000 - 70,000	30,000 - 70,000	1,000 - 45,000	100 – 10,000	1,000 - 45,000	10,000 - 70,000	Unknown	30,000 - 70,000	<2,000
Product water quality (mg/L TDS)	<10	<10	<10	200-500	500	<10	<10	Unknown	<10	Unknown
Distillate production efficiency (%)	25-40	33-50	33-75	50-90	50-95	90	Unknown	Unknown	Unknown	Unknown
Typical Production Capacity (m^3/day)	4,000 - 100,000	1,000 - 38,000	0.1 - 36,000	0.5 - 100,000	0.1 - 35,000	0.1 - 10.0	0.005 – 5.0	Unknown	Unknown	10,000
Approximate operating costs ($/$m^3$)	0.70-1.50	0.75-1.50	0.85-1.50	0.30-0.95	0.25-0.90	unknown	25.00	Unknown	unknown	Unknown
Approximate capital costs ($/$m^3$/day)	800 - 15,000	950 - 12,000	1,100 - 4,200	1,000 - 2,000	260 - 300	unknown	9,000- 66,000	Unknown	2,400	Unknown
Operation and Maintenance requirements	Filtration, scale control, pump care, operate above 60% capacity	Filtration, scale control, pump care	Filtration, scale control, pump care, cleaning of compressor operate above 60% capacity	Filtration, chemical treatment, pump care, membrane cleaning, requires skilled personnel	Filtration, chemical treatment, pump care, membrane cleaning, requires skilled personnel	Filtration, careful to avoid membrane wetting, pump care, requires skilled personnel	Inspection and repair of leaks, dust and salt removal	Filtration, chemical treatment, membrane cleaning, requires skilled personnel	Unknown treatment, requires machinery for effective ice removal	Filtration, heavy chemical treatment, may require skilled personnel
Small/ Medium/ Large scale	Large	Small-Large	Small-Medium	Small-Large	Small-Medium	Unknown	Small	Unknown	Unknown	Unknown
Proven technology	Yes	Yes	Yes	Yes	Yes	Research / Marketing	Yes	Research stage	Research stage	Pre-treatment

3.1.6 Choice of Desalination Technology

There is no "best" method of desalination that is universally applicable to all situations. Some desalination methods cost less and perform better than others, but only under specific circumstances. It is the consumer's responsibility to choose which desalination technology is most appropriate for their needs, based on geographic and socio-economic issues. According to Fritzmann et al. (2007) and Ruskulis (2002), the decision for a certain desalination technology is influenced by the following factors:

- Source water salinity – brackish or seawater?
- Required product quality – does the water need to be distilled or abide by WHO guidelines?
- Water demand quantity – small or large scale demand?
- Availability of skills to operate and maintain plant – can the local labour support the plant?
- Available land area
- Available power sources
- Capital and Operating costs

Figure 24 illustrates a schematic process for choosing an appropriate desalination process based on the factors mentioned above, excluding cost and quantity. Often times, the choice comes down to a group of two or three options which can technically provide the service at the same high quality level, but cost becomes the final deciding factor. Ultimately, cost can change drastically in different areas, as site-specific elements such as local materials, labour, and engineering practices can heavily affect the final price.

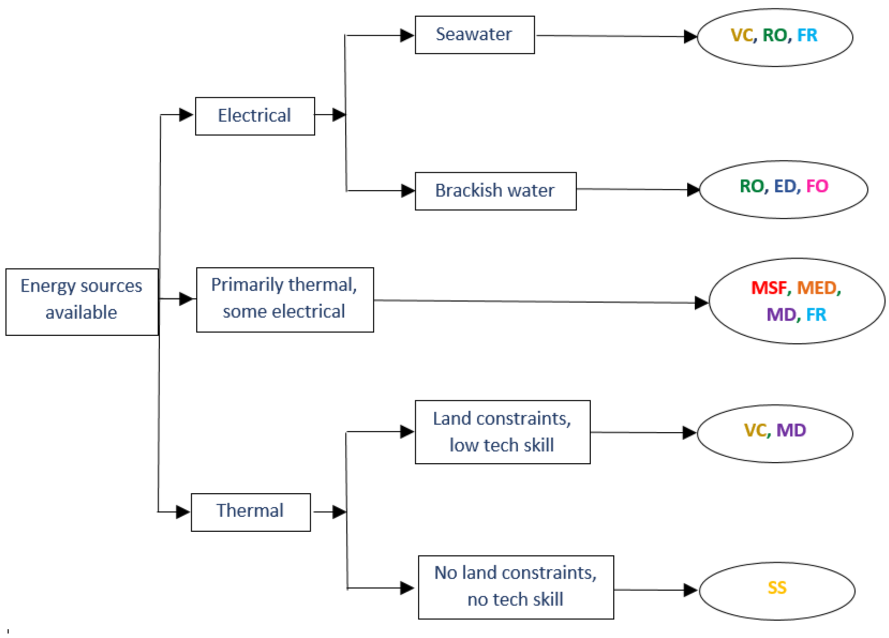

Figure 24: Selecting a desalination technology
Source: Adapted from Thomas, (1997)

When evaluating desalination systems based on feedwater salinity, most experts immediately choose thermal distillation and RO for seawater desalting, while brackish waters are typically desalted by ED and RO (Buros and SWCC, n.d.). In fact, over 20 years ago, WEDC (1994) provided some guidelines on matching desalination technologies with different salinities, summarised in Table 23 below:

Table 23: WEDC (1994) guidelines for desalination methods and TDS values
Source: WEDC, (1994)

Desalination Method	TDS values (mg/L)
Electrodialysis	500 – 3,000
Reverse Osmosis (standard membranes)	500 – 5,000
Reverse Osmosis (high resistance membranes)	Over 5,000
Thermal Distillation	1,000 – 100,000 esp. over 30,000

However, these guidelines are noticeably outdated and extremely generalised, as many of the desalination options listed in section 3.1 have been overlooked. While some researchers and engineers continue to choose desalination methods based on outdated traditional guidelines, technology has advanced tremendously over the past two decades to provide more solutions with increased performance results. For example, RO plants are now able to treat seawater at the same capacity as thermal distillation plants, but with reduced energy demands and lower costs. Although ED is technically able to treat saline water at a level of 70,000 mg/L, it requires a tremendous amount of energy to do so, leading to decreased production rates and increased costs. The same can be true for RO and other membrane technologies, as Figure 25 illustrates below. It should be noted that Figure 25 is drawn in a very broad manner only to illustrate the concept, and is not completely accurate.

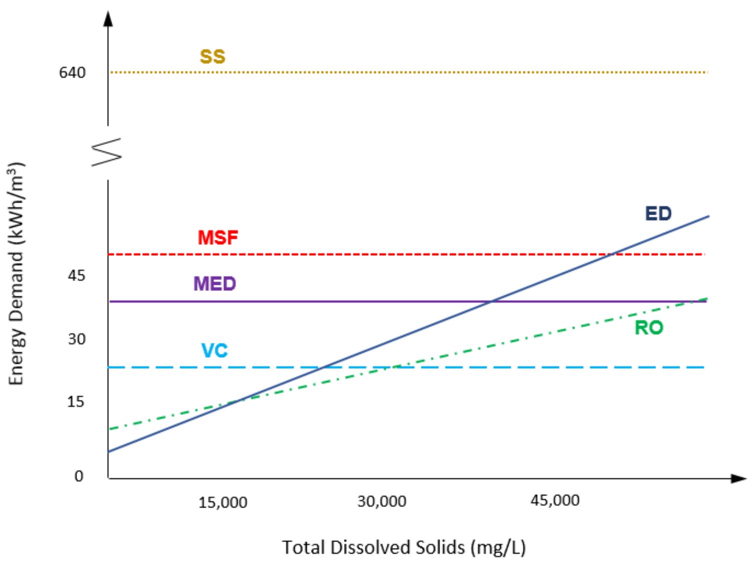

Figure 25: Salinity vs. Energy Demand for various Desalination methods
Source: Adapted from Thomas, (1997)

3.2 Renewable Energies

This section of the literature review will focus on the various types of renewable energies currently available, describing the overall concept and framework of each technology. In general, the literature available on renewable energies is vast and large, as research into RE technologies has stretched over many decades for different applications (i.e. aeronautics, robotics, etc.). Due to time constraints, this paper will focus on literature available on renewable energies AND their application to desalination. Therefore, the amount of information available is further reduced, and more specifically relevant to the project's overall objectives.

3.2.1 Introduction

One of the key factors influencing desalination growth is energy cost. According to the World Bank (2012), energy comprises almost 50 percent of total annual costs for MSF and MED, and a little under 33 percent for RO units. Thus, improving energy efficiency and using a cheaper energy source would be among the most effective ways of reducing the cost of desalinated water for the future. While most desalination plants currently run on fossil fuels, considerable attention has been given to renewable energies including solar, wind and geothermal sources, as an effort to improve the economic viability of desalination plants (Rasool Qtaishat and Banat, 2013).

While renewable energies present an attractive potential for desalination, they also possess inherent weaknesses. For example, wind and solar energy have the biggest immediate potential for powering desalination, but are only available during certain hours of the day. Therefore, in order to combat this fluctuating availability, a method of storing excess renewable energy has to be applied. Otherwise fossil fuels will need to fill in the energy gaps or the plant will be run intermittently (Thomson, 2003). Furthermore, solar energy plants tend to cover large areas which can pose a problem for small islands and regions where land cost is high (ETSU et al., 1996). Other RE sources such as hydropower and biomass can be suitable for certain areas, but may not be available in regions that require desalination.

Fossil fuels are currently cheaper than most renewable energies, and will most likely continue to be practised unless governments are prepared to take action to adopt RE for the sake of energy security, carbon footprint reduction, and "green" energy trading opportunities (World Bank, 2012). Table 24 compares the levelised cost of electricity (LCOE) among different sources, which illustrates how expensive RE sources are in comparison to coal and nuclear sources. LCOE is frequently quoted as a suitable measure for energy producing technologies, as it includes capital, fuel, fixed and variable O&M, financing and assumed utilisation rate costs of each plant type (Goosen et al., 2016). It should be noted that the table does not include all the RE sources discussed in this literature review.

Table 24: Estimates of LCOE by source
Source: Adapted from Goosen et al., (2016)

Average LCOE ($/MWh)	Coal	Nuclear	Wind	Geo-thermal	Solar PV	Solar Thermal
	79	84	112	99	491	225

While fossil fuels may be generally cheaper than RE sources on a global scale, they are still extremely expensive in certain isolated areas, including those that lack a developed electrical grid. Renewable energy sources can be especially advantageous in these targeted areas, as they would provide a cheaper alternative to fossil fuels, and a more sustainable supply of energy. Desalination processes are constantly improving in energy efficiency, and costs associated with renewable energy are decreasing at a rapid rate. Therefore, in an effort to preserve the world's environment and decrease water scarcity, greater effort needs to be invested in RE-powered desalination plants, which will quickly become more affordable than traditional fossil fuels in upcoming years.

3.2.2 Human Power

Technically considered to be a source of renewable energy, humans can provide mechanical power to pressurise pumps or create electricity. Many hand-powered boreholes are present in today's society, although generally these structures only provide enough water for drinking. When poor, isolated communities begin to rely on saline sources, sometimes the most immediate measure is to apply RO membranes to a hand-powered pump. Timmermans (2008) states that 15 bars of pressure can be created by applying 60 kg of a person's weight to a piston with a 4 cm^2 area. This can provide enough pressure to desalinate brackish water at a low flow rate, although water sources higher in salinity will require much greater pressure (refer to Table 14).

In terms of sustainability, human power may not seem like an ideal choice for energy, as the output gained from a hand-powered or bicycle-powered pump would be quite small. However, in relief situations where immediate action has to be taken to provide water at the drinking level, human power can be seen as a viable option. Once a community decides to grow and increase its water demand for agricultural and economic purposes, alternative energy sources can be proposed.

3.2.3 Hydro/Wave/Tidal Power

In terms of global energy sources, hydropower ranks at the top, providing electricity via the force of flowing water (World Bank, 2012). The most common type of hydro power plant uses a dam on a river to store water in a reservoir, releasing this water in a controlled manner to spin a turbine, generating electricity (Bennett, 2011). However, regions that are most in need of desalination are usually the ones which lack freshwater sources, such as a river. Therefore, the potential for hydropower is extremely low in these areas. While most desalination consumers, such as the Middle East, have very limited hydropower potential, other areas such as Egypt or Iran can utilise their rivers for electricity. However, if an area already possesses a river – a freshwater source – there may be very little need for desalination in the first place.

Water power can also be harnessed in the form of waves and tides. Utilising the same concept of force flow from rivers, wave energy from oceans can also be captured and converted to electricity. The advantage in utilising wave energy is the fact that oceans are often present as a water source for desalination, therefore the ocean can also be used as a source of energy to fuel the plant. However, very little research has been conducted in linking wave energy and desalination, as initial costs have been far greater than the rest of the competition, but with the advancement of technology, wave energy remains an extremely attractive and sustainable source of power.

3.2.4 Combustion

Heat is a form of energy that can best be utilised for thermal distillation plants, since they directly use thermal energy to desalinate source water. However, heat can also be used to produce steam, which effectively spins turbines to produce electricity. Today, many chemical processes produce large quantities of waste heat, usually discarded in cooling towers and other devices. However, depending upon the temperature and form of the waste heat, it may be possible to reuse this heat for desalination (ETSU et al., 1996). In some places, major desalination plants already recycle waste heat from power generators, as large-scale distillation facilities are often coupled with nuclear/coal-burning power plants.

Another method of gathering heat can be acquired through incineration, specifically waste burning. According to ETSU et al. (1996), Gibraltar is known to have their solid waste incinerated since there are no landfill sites, and they utilise this waste heat to power a six-effect MED plant to produce potable water. The incinerator and its coupling desalination plant produce nearly 1,800 m^3/day of freshwater, or about 2/3 of Gibralter's water demand (ETSU et al., 1996). Gibraltar's success can be set as an example for many other island nations who face similar circumstances.

Heat can also be acquired through geothermal power, which utilises temperature differentials between the earth's surface and subsurface to turn water into steam, again generating electricity. Temperature differentials exceeding 180°C are usually required to produce the necessary steam. According to the World Bank (2012), these dramatic temperature differences can be found just a few hundred meters below the earth's surface in geologically active areas such as the Rift Valley in eastern Africa or the "Ring of Fire" around the Pacific region. Other less active sites may require drilling as deep as 5,000 meters in order to find sufficient temperature differentials. Although geothermal heat is associated with high exploration and installation costs, it also provides a constant source of energy that is not always guaranteed with solar or wind power (Ghaffour et al., 2015). As of now, there does not exist any industrial scale geothermal desalination plants, although many test units on low to medium scale have been built. The potential for geothermal energy is very high in places with favourable geological conditions, although research related to the environmental effects of geothermal drilling need to be investigated.

3.2.5 Wind Power

According to Bennett (2011), wind power is the conversion of wind energy into electricity, pumping, or mechanical power. Electricity is the most popular converted output, with wind generators ranging in capacity from a few kW to MW. Good wind energy is often available on an intermittent basis in arid areas, particularly on islands, and is recommended for areas with mean annual wind speeds in excess of 8 m/s (ETSU et al., 1996). Greater interest in harnessing wind energy and the availability of advanced technology has resulted in exponential commercial growth of wind farms, which will usually consist of several hundred individual wind turbines connected to an electric power transmission network. Although the construction of wind farms is not universally welcomed because of their visual impact, the overall environmental effects are typically less problematic than those produced by other power sources.

The intermittency of wind seldom creates problems when using wind power to supply up to 20% of total electricity demands, as upgrades to the electric distribution network need to be implemented to mitigate these fluctuations (Bennett, 2011). However, wind power is already competitive against fossil and nuclear power in many developed countries (Kalogirou, 2005), and as wind exploration becomes more widespread, the technology will only continue to improve, harnessing power at lower wind speeds.

3.2.6 Solar Power

Solar energy can be used for desalination by either producing the thermal energy required to drive distillation processes, or by producing the electricity needed to operate membrane processes (Rasool Qtaishat and Banat, 2013). Thermal energy is usually acquired from concentrated solar power (CSP) stations, while electricity is converted from photovoltaic (PV) arrays. Solar stills (discussed earlier in section 3.1.4.2) are also considered a direct form of capturing solar energy for thermal distillation, while solar ponds are an indirect means of harnessing the sun's energy to create thermal differences (Bennett, 2011). CSP, PV, and solar ponds will be covered in greater detail in the following subsections.

Overall, every country in the world is exposed to the sun's energy at various degrees. Areas near the north and south poles experience longer or shorter daylight hours depending on the season, and countries near the equator receive the sun's strongest rays. According to the World Bank (2012), between 22 and 26 percent of the total solar energy striking the earth's land mass is estimated to fall in the MENA region, with most areas experiencing over 2,000 kWh/m^2 per year (see Figure 26 below), translating to an average of 5.5 kWh/m^2 per day. In the BCS region of Mexico, annual solar irradiance averages vary between 5 and 6 $kWh/m^2/day$, with lows of 3 $kWh/m^2/day$ in winter and highs of 7 $kWh/m^2/day$ in summer (Bermudez-Contreras, Thomson and Infield, 2008). Brauns (2008) adds that if a region were to receive a minimum of 1,000 W/m^2 (or 1 kW/m^2) during the day, then a small land area of only 1 km^2 could already produce over 1,000 MW of solar power, which would be equivalent to the electrical output of a standard nuclear power plant. This is why areas such as BCS already utilise solar energy in rural towns and fishing camps away from electricity networks, because the radiation alone is able to power most water pumping and lighting systems (Bermudez-Contreras, Thomson and Infield, 2008).

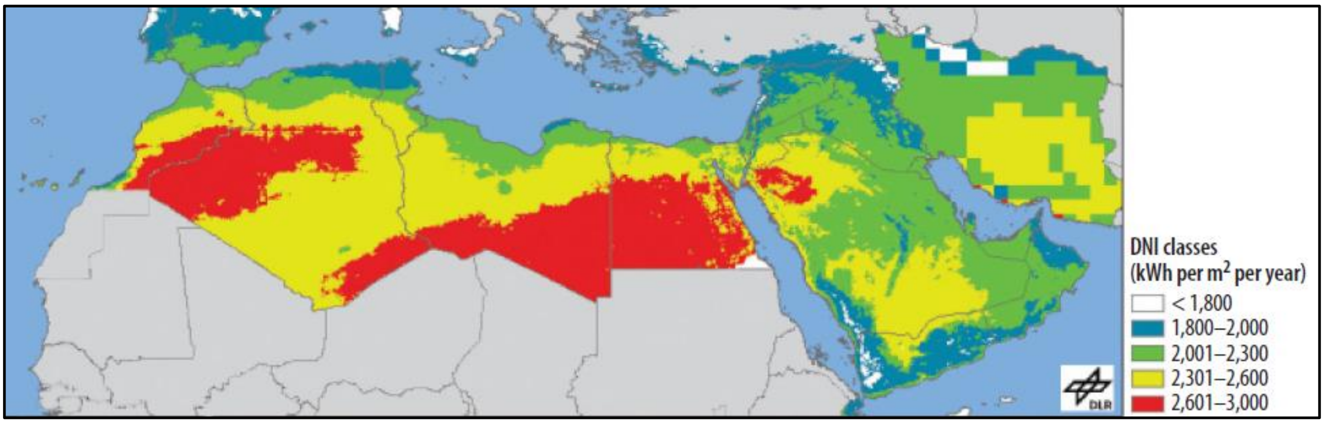

Figure 26: Annual Direct Normal Irradation in MENA region
Source: World Bank, (2012)

Although the potential of solar energy is high, there are still certain disadvantages associated with the system that need to be addressed. First and foremost, solar radiation is an intermittent source that is only available for certain hours of the day. Therefore, energy storage is necessary to provide continuous operation of the desalination plant when the sun is not available. Thermal energy can be easily stored in the form of heat fluids throughout the day, while PV systems rely on batteries. However, batteries are notoriously problematic in practice, especially in hot countries, and are best avoided whenever possible (Thomson, 2003). In practice, if a system relies on PV solar power, it is best to design the system so the pump runs only during the day, and excess water is stored in a tank for night use. Other disadvantages with solar appliances include O&M complexity (Groves, 2012), sand storms and other meteorological issues (Khater, 2010), and of course the expensive cost.

Despite these drawbacks, solar energy is rapidly developing, inching closer to achieving its potential. For example, between 1995 and 2005, photovoltaic modules improved from 12% to 15% efficiency, while decreasing in cost ($12/Wp to $8/Wp) and increasing in lifespan (15 to 25 years) (Helal, Al-Malek and Al-Katheeri, 2008). According to Thomson (2003), PV is highly reliable and often chosen because it offers the lowest life-cycle cost, and with the continuing advancement of technology, will only keep decreasing in price while increasing in capacity.

3.2.6.1 Concentrated Solar Power (CSP)

CSP is both a thermal and electrical generation technology that uses heat provided by solar irradiation concentrated on a small area (Ghaffour et al., 2015). Using mirrors and lenses, sunlight is reflected onto a receiver where heat is stored in a collection fluid (e.g. molten salt). This heat can be used directly in thermal distillation plants, or subsequently transferred to a steam turbine to generate electricity (Ghaffour et al., 2015). A CSP power plant generally consists of three parts: a solar field, thermal energy storage, and power (block) system that can produce electricity, heat, or both (World Bank, 2012).

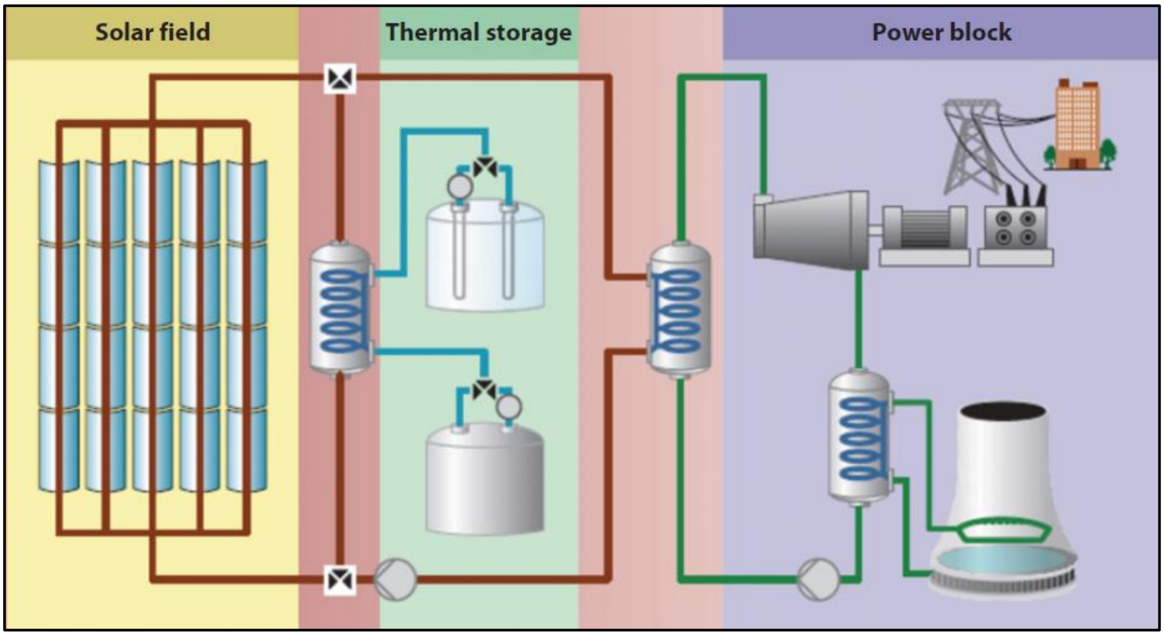

Figure 27: CSP power plant configuration
Source: World Bank, (2012)

At present, there are four available CSP technologies, differentiated mostly by their solar collection fields. These are: solar power tower (SPT), parabolic trough collector (PTC), linear Fresnel reflector (LFR) and parabolic dish collector (PDC) (Ghaffour et al., 2015).

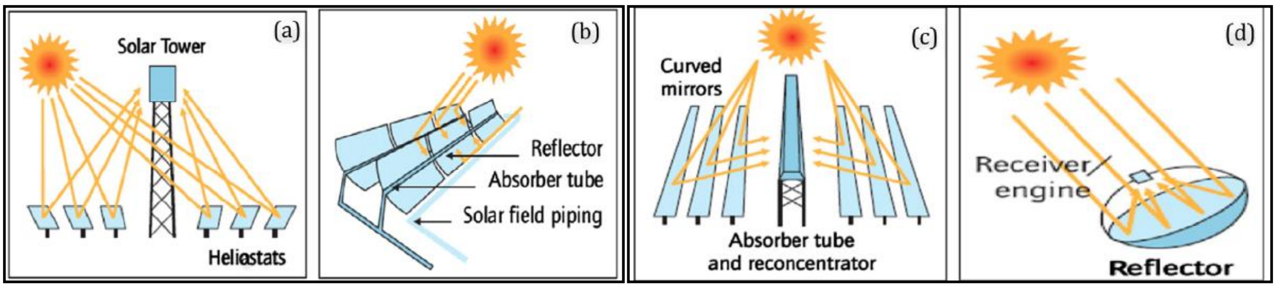

Figure 28: CSP technologies - a) SPT b) PTC c) LFR d) PDC
Source: Ghaffour et al., (2015)

Solar power towers (SPT) are large-scale power plants in which sunlight tracking mirrors, or heliostats, reflect direct solar radiation onto a receiver located at the top of a solar tower (World Bank, 2012). Heat is absorbed by a heat transfer fluid (HTF), which then transfers the heat to heat exchangers for direct application in thermal distillation plants, or to generate electrical power in steam turbines. SPTs are known to achieve very high temperatures, increasing the efficiency at which heat can be produced for thermal and electrical power, as well as reducing the cost of thermal storage for night time use (Ghaffour et al., 2015). SPTs are also known to be extremely delicate, as each heliostat must be cleaned regularly and set up vertically during strong winds to avoid structural damage (World Bank, 2012).

PTC systems use parabolic mirrors to concentrate solar radiation onto a linear absorber tube that is mounted along the focal axis of the parabolic structure (Ghaffour et al., 2015). This absorber usually consists of a special coated steel tube and a glass envelope to minimize heat losses (World Bank, 2012). Both the mirrors and absorber tube move in tandem with the sun, each with a solar-tracking device. The collected heat is transferred to a HTF – usually synthetic oil or water/steam – that flows through the absorber tube and is fed to either a steam generator or directly to thermal storage (World Bank, 2012).

Similar to PTCs, LFR uses long rows of neighbouring mirrors to concentrate the sun's energy, however these mirrors are flat or slightly curved to reflect the sunlight to a downward facing linear receiver. The mirrors are connected at different angles to a rod-bar that moves simultaneously to track the sun and move the mirrors. The linear receiver/absorber tube is fixed above the mirrors in the centre of the solar field, and contains water which is directly converted to superheated steam (up to 450°C), driving the turbine to produce electricity (World Bank, 2012). LFR has several advantages over other CSP technologies, in that the design is very light and simple, weighing less than 25 percent of other PTC systems, reducing capital and O&M cost. The World Bank (2012) continues by noting that the flat design structure of Fresnel segments can be easily integrated for industrial or agricultural uses, as these collectors could cover all types of buildings and fields. Additionally, due to its ability to generate steam directly, there is no need to incorporate a heat transfer fluid or heat exchanger in an LFR system, further reducing costs (Ghaffour et al., 2015). LFR also requires less land than PTC and SPT since the distance between mirrors is much smaller, as PTC requires more space to avoid mirror shading. However, the efficiency and capacity of LFR systems is much less than that of PTC and SPT.

Similar to PTCs, PDCs are composed of an entire system of parabolic collectors and receivers, moving together with the sun. PDCs are the newest form of CSP technology to reach the market, and are currently very expensive (Ghaffour et al., 2015). However, parabolic dish collectors have the smallest land requirement, and a high efficiency rate which could make it very favourable in the future. Ghaffour et al. (2015) notes that with mass production growth, PDCs could compete with larger solar thermal systems. Table 25 below summarises the operational characteristics of each CSP technology for comparison.

Table 25: Comparison between CSP technologies
Source: Ghaffour et al., (2015)

CSP technology	Relative Cost	Land occupancy	Cooling water (L/MWh)	Thermo-dynamic efficiency	Operating T range (°C)	Solar conc. ratio	Outlook for improvements
PTC	Low	Large	3000 or dry	Low	20-400	15-45	Limited
LFR	Very low	Medium	3000 or dry	Low	50-300	10-40	Significant
SPT	High	Medium	1500 or dry	High	300-565	150-1500	Very significant
PDC	Very high	Small	None	High	120-1500	100-1000	High potential through mass production

Although CSPs are able to produce both thermal and electrical energy from heat, Zheng et al. (2014) notes that the current cost of thermo-electric materials is relatively expensive, and can hamper the widespread use of CSPs for electric desalination processes. There is also the issue of water required for cooling and steam generation, as this is absent in PV and wind technologies, and could be a limiting factor in many countries where water in general is very scarce (World Bank, 2012).

However, CSP is still a heavily favoured source of energy due to its enormous potential. According to Goswami (2007), if only 1 percent of the Saudi Arabian desert was used for CSP, the electricity gained would be enough to provide Europe and Arab countries with electrical power and water. The World Bank (2012) estimates that MENA's total CSP potential could be over 462,000 TWh per year, exceeding its current annual energy consumption by a factor of 350, and over 20 times the energy utilised by the entire world. If a 10 km x 10 km CSP thermal collector were constructed in MENA, this would produce up to 1 km^3 of desalinated water per year, or 2.7 million m^3 per day (World Bank, 2012).

Many CSP plant development projects are currently under preparation, following the example of the Shams 1 solar power station in the United Arab Emirates. The Shams 1 CSP plant contains 768 parabolic trough collectors, covering 627,840 m^2, with a power output of 100 MW (Shams Power, 2013). Completed in 2012, Shams 1 is the first solar farm in the Middle East and the largest CSP plant in the world, costing an approximate $600 million – the world's largest financing transaction for a solar plant project. Shams Power (2013) also boasts that the plant can provide power to 20,000 homes in the U.A.E, while saving 175,000 tons of CO_2 emissions per year.

Figure 29: Shams 1 CSP power plant
Source: Shams Power, (2013)

3.2.6.2 Photovoltaic Cells (PV)

Solar PV is a method of generating electrical power by converting solar radiation into direct current (DC) electricity. For utilisation of electricity, the DC current produced is transformed into alternating current (AC) using inverters. PV cells convert solar energy into electricity through the transfer of electrons by the photovoltaic effect (Bennett, 2011), and the current produced is directly proportion to the solar intensity. Solar panels consisting of numerous solar cells are usually joined together, and are most commonly found to be static, through tracking panels can also be used to capture more sunlight in a day (ETSU et al., 1996). Rasool Qtaishat and Banat (2013) state that an increase of about 30-45% in power output was found in solar-tracking PV panels as opposed to fixed devices. Furthermore, PV electricity generation costs currently lie between \$0.24 and \$0.72/kWh, but such costs are expected to be cut in half to \$0.13 – \$0.31/kWh, due to technological wire innovations, advanced metallisation solutions, and increased automation (Goosen et al., 2016).

Figure 30: Photovoltaic cells
Source: Bennett (2011)

However, the performance of solar cells also depends on the cell temperature, as material properties dictate that solar cells work better at low temperatures (Rasool Qtaishat and Banat, 2013). Solar PV panels typically consist of crystalline silicon cells, an aluminium frame and a sheet of glass on the side facing the sun (Bennett, 2011). Although arid areas may receive high intensity solar rays, the increase in temperature can reduce cell efficiency and have a negative effect on the electrical output of the PV module, especially silicon based cells, where the conversion efficiency decreases by about 0.5% per degree rise in temperature (Rasool Qtaishat and Banat, 2013). Therefore, extra cooling methods must also be considered to keep cells at an optimum temperature. As mentioned above in section 2.3.6, solar PV also faces the difficulty of storing electrical energy when the sun is not present. For these reasons, the World Bank (2012) states that the energy potential of photovoltaic cells is much lower than CSP, as it would only cover 356 TWh per year, or less than 31 percent of MENA's current energy use.

Nevertheless, PV is still a favourable technology that has several advantages over CSP. As mentioned earlier, PV can produce electricity on a small scale at a cheaper rate than CSP without the need for a heat exchanger or steam turbine. The direct conversion of sunlight to electricity makes the PV panel easier to transport and apply to different environments. However, PV shares similar O&M procedures to CSP, in that regular cleaning of the panels must be done to ensure maximum efficiency. Ghaffour et al. (2015) also mentions the development of concentrating photovoltaics (CPV), which acts as a hybrid between photovoltaics and CSP. In CPV, additional optics with solar trackers are installed to concentrate the sun's rays on the panels, increasing PV efficiency and delivering higher energy production than both PV or CSP in some cases.

3.2.6.3 Solar Ponds

A solar pond is a body of liquid which collects solar energy by absorbing direct and diffuse sunlight, storing the solar energy as heat. Solar ponds are typically made with a salt gradient to suppress natural convention, as warm concentrated brine at the bottom of the pond is prevented from rising to the surface and losing its heat (Rasool Qtaishat and Banat, 2013). This is due to the fact that the upper, freshwater layer is less dense than the lower, salty layer, and so the warm concentrated brine remains at the bottom. Temperature differences between the bottom and top layers of the pond are adequate to drive a generator, as heat from the bottom layer is extracted through an external heat exchanger and can be utilised to power a steam turbine or remain as thermal energy (Gude, 2015).

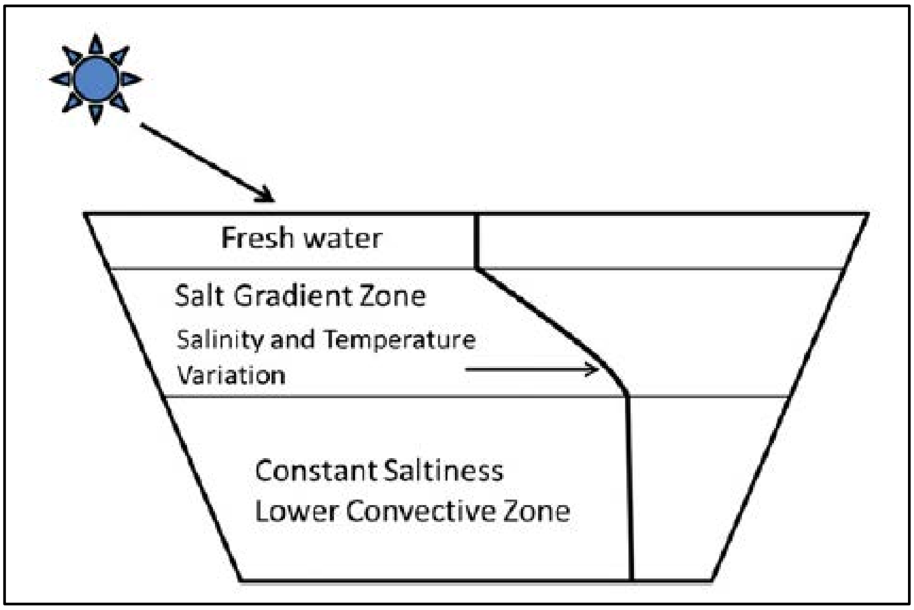

Figure 31: Typical salt gradient solar pond
Source: Rasool Qtaishat and Banat, (2013)

Solar ponds are generally considered suitable for thermal distillation processes, and may also be appropriate for membrane desalination. The annual collection efficiency of useful heat for desalination is usually around 10-15%, although larger ponds tend to be more efficient than smaller ones due to losses at the pond edge. Rasool Qtaishat and Banat (2013) add that solar ponds are particularly suitable for desalination plants, as waste brine from the plant can be used to drive the salt gradient in solar ponds, and the heat produced in solar ponds can be used to drive desalination plants. Li, Goswani and Stefanakos (2013) claim that solar ponds have a low cost per unit area of collector, with inherent storage capacity and the ability to use surface water as a cooling mechanism.

This method could be environmentally beneficial and extremely cost-effective, but the size of solar ponds for large-scale desalination could be too big for practical convenience. However, for small and medium scale communities, solar ponds can offer a source of renewable energy and environmental-friendly brine disposal for desalination.

3.2.7 Solar Collectors

According to Kalogirou (2005), solar energy collectors are a special kind of heat exchanger that transform solar radiation to thermal energy via a fluid (water or oil) flowing through the collector. The heated fluid is then carried directly for use in the desalination application or stored in a thermal tank for use at night or during cloudy days. There are basically two types of solar collectors: nonconcentrating and concentrating. CSP technologies are considered to be concentrating solar collectors, since they consist of sun-tracking reflective surfaces that intercept and focus the sun's radiation to a smaller receiving area. While CSP is a vastly popular choice for sustainable power generation, it is still important to study nonconcentrating solar collectors, which can provide cheaper thermal energy at a smaller scale. Nonconcentrating solar collectors can basically be divided into two types: flat plate collectors (FPC) and evacuated tube collectors (ETC).

3.2.7.1 Flat Plate Collectors (FPC)

Developed in the 1950s, FPCs are stationary collectors with a set collection surface area. According to Khater (2010), FPCs usually consist of the following:

- Black coated flat absorber plate – can also be corrugated or grooved to increase surface area. Made mostly from copper, aluminium, steel, glass or plastic.
- Glazing – usually a single glass cover that aids in trapping radiation
- Tubes – transport heat transfer fluid across the surface and to storage tank
- Heat transport fluid – usually water or oil
- Heat insulation – minimises heat losses

FPCs are stationary and do not track the sun's trajectory throughout the day. Therefore, they typically produce less thermal heat than CPCs, but are significantly cheaper and easier to operate. FPCs which consist of multiple glass layers for glazing and selective absorber plates will obtain higher efficiencies compared to a collector with a single glass layer and non-selective absorber (Khater, 2010). FPCs can also typically last more than 25 years if properly maintained.

3.2.7.2 Evacuated Tube Collectors (ETC)

Similar to FPCs, ETCs are stationary with a set collection surface area. However, ETC's are slightly more complicated in practice, as they are composed of multiple vacuum-pressured tubes containing a copper absorber sheet fused to a heat pipe. The transfer fluid (methanol or water) within the heat pipe is evaporated as a result of the decreased pressure and increased heat radiation, traveling through the heat pipe where it releases its heat at the manifold or heat exchanger (Khater, 2010). This released heat is then used to warm up flowing liquid from the storage tank, and the condensed transfer fluid is recycled within the heat pipe for further evaporation. A schematic of an ETC tube is shown below along with an image portraying an array of evacuated tube collectors.

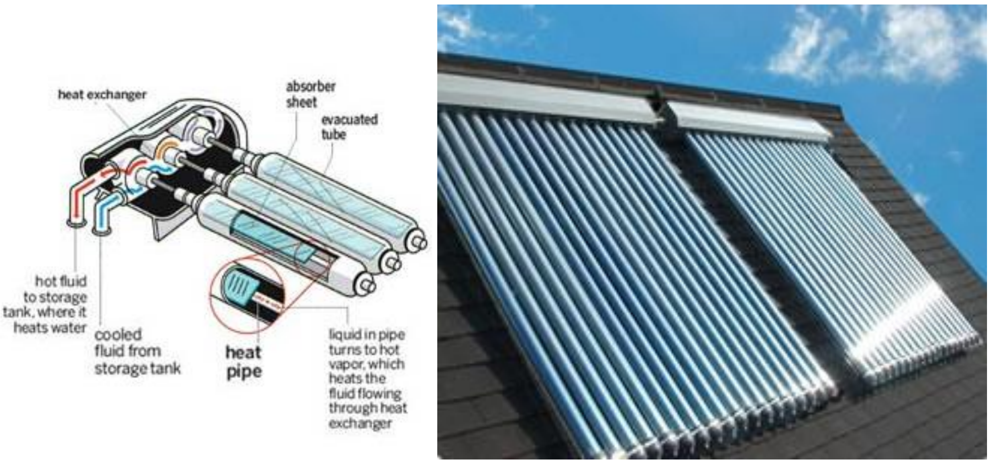

Figure 32: Evacuated Tube Collectors schematic and image
Source: Ksenya, (2011)

The vacuum within the ETC reduces heat losses from convection and conduction, which in turn increases temperature and improves efficiency performance when compared to FPCs (Khater, 2010).

3.2.8 Summary of Renewable Energies

Between 1974 and 2009, 131 renewable energy-powered desalination plants were installed worldwide, with CSP and PV being the preferred energy sources due to the sun's reliable and predictable presence (World Bank, 2012). Table 26 below summarises the advantages and disadvantages of each renewable energy and its relationship with desalination, further illustrating why solar energy is favoured above others.

Table 26: Summary of Renewable Energies
Source: Author (based on works cited in text)

Renewable Energy	Advantages	Disadvantages
Human power	People are readily available	Very small output – only for drinking purposes
	Low O&M complexity	Could be tiring and impractical
		Limited to specific consumers
Hydro power	Rivers or waterfalls are reliable source of mechanical power to spin turbines	Needs to be located close to high flow river/waterfall
	Cheap alternative to fossil fuels where available	Requires large-scale energy converters and plant
Wave power	Waves from ocean can also spin turbines and generate electricity	Needs to be located close to the ocean
	Great potential for improved wave power efficiency	Very little research conducted in wave energy and desalination
Combustion (geothermal, waste, biomass)	Waste heat from power generators can be recycled	Needs to be close to power generator

	Biomass and solid waste can be source of energy	Waste generation must be sufficient for energy demand
	Geothermal differences are constantly available	Preferable for geologically active sites, otherwise drilling costs severely increase
Wind Power	Direct generation of electricity from kW to MW	Available on intermittent basis
	Exponential growth of wind turbines over past decades	Recommended for wind speeds averaging over 8 m/s
	Already competitive in cost against fossil fuels in many developed countries	Large footprint depending on efficiency and power output
	Potential for improved performance at lower wind speeds	
Solar: CSP	Stores thermal energy and produces electricity	O&M complexity
	Can supply power to all desalination methods	High capital and O&M costs
	Very high potential to produce more energy than needed	
Solar: PV	Flexible small or large scale	O&M complexity
	Direct conversion of solar to electricity	Cannot store energy without batteries
	Costs continue to decrease at fast rate	
Solar: solar ponds	Simple and easy to maintain	May require high land area
	Can be used for brine disposal	Suitable only for small energy requirement
Solar: nonconcentrating solar collectors	Cheaper and easier to maintain compared to CSP	Suitable only for thermal energy
		Best used for small scale

Although the initial cost of renewable energies is high (Table 24), strategic support from government subsidies could reduce RE LCOE costs, perhaps as much as 46-60 percent in MENA countries over the next 15 years (World Bank, 2012). According to Ghaffour et al. (2015), government sponsorship of RE projects in Germany aided in creating new jobs (from 66,600 in 1998 to 377,800 in 2012), earning the second-highest share of employment in the country behind the automotive industry. In 2013, Germany was able to produce 25% of its electricity from renewable resources, and can only continue to increase this percentage due to decreasing RE costs. The idea of combining different RE sources is also one that should be considered, as geothermal and solar energies can be utilised on 12 hour cycles to reduce the probability of depleting heat sources within the geothermal reservoir (Ghaffour et al., 2015).

3.3 Brine Disposal

This section of the literature review will focus on brine waste disposal options for various desalination plants. Research into brine waste disposal has been very limited in comparison to desalination methods and renewable energies, as environmental awareness about brine runoff has only recently been studied.

3.3.1 Introduction

The impact of brine disposal on the marine ecosystem in near-shore environments is potentially large, as the effects of high-temperature, chemically-enhanced brine discharge from desalination plants can lead to mortality and extinction. Each stage of the desalination process either adds or concentrates chemicals, most of which are discharged along with the brine at the end of the process (World Bank, 2012). These chemicals are frequently used to control marine growth around the intake (i.e. molluscs), as well as remove suspended solids and prevent scaling/corrosion of the infrastructure. According to the World Bank (2012), the salinity of brine discharge from desalination plants can be more than twice the salinity of the source seawater, typically in the range of 46,000 to 80,000 mg/L. Aside from the increase in salinity, copper and chlorine concentrations may also be toxic to the surrounding environment, as these chemicals are frequently found in brine discharge to prevent biofouling. The combined effects of higher temperatures, salinity, and chemical additives can reduce the amount of dissolved oxygen in water, significantly harming the marine ecosystem.

For many years, researchers and engineers believed that brine discharge did not pose any threat to the environment, as salt from desalination plants was simply returned to its original location. Buros and SWCC (n.d.) state that the "major solute in concentrate stream is salt, and disposing of salt in the sea is generally not a problem," while Elimelich and Phillip (2011) concur by saying, "there is a lack of useful experimental data from laboratory tests or field monitoring to assess these impacts…published data are inadequate to establish the salinity level at which marine organisms can tolerate long-term exposure." However, the World Bank (2012) writes that Spain experienced major impacts on its seafloor communities from brine discharges that raised near-shore salinity levels to over 39,000 mg/L. Studies showed that while the worm population increased from 69 to 96 percent in a two year span, other marine species declined. In addition, sea grass habitats showed that even a brief exposure (15 days) to salinities in excess of 40,000 mg/L caused a 27 percent increase in mortality of plants. The research indicated that 38,000-40,000 mg/L TDS represented the tolerance threshold for marine organisms, which is clearly below the salinity of brine discharge from desalination plants. The salinity threshold can differ for various environments, as salt marshes and mangroves have higher sensitivity to brine disposal than oceanic coasts with strong waves and rocky shores. Thus, more research needs to be conducted to study the salinity thresholds of multiple environments.

Apart from seawater ecosystems, attention also has to be given to inland brackish waters. Care needs to be taken not to pollute any existing ground or surface water with the salts contained in brine discharge (Buros and SWCC, n.d.), as the environment in this case is much more sensitive to salinity changes. Conventional wastewater treatment can help to reduce chemical concentrations in brine, but may not be able to reduce salinity levels. Thus, the following subsections will examine the various different options for brine disposal, with most applications focused on inland treatment.

3.3.2 Coastal Seawater Brine Disposal

According to Cotruvo et al. (2010), discharge through a new ocean outfall is widely practiced all over the world, as over 90% of large seawater desalination plants in operation dispose of their concentrate in this manner. The purpose of an ocean outfall is to dispose of the plant concentrate in an environmentally safe manner, either through natural mixing in the sea tidal zone or by discharging the concentrate beyond the tidal zone with installed diffusers. Although it would seem simpler to release the brine within the tidal zone, the mixing capacity of the aquatic area may not be sufficient for wildlife stability.

Ahmad and Baddour (2014) suggest that submerged discharge would be necessary to ensure high dilution and minimize harmful impacts. A vertical riser with numerous small diameter exit nozzles would be connected at the end of a long submerged pipe line, increasing the momentum of discharge and the dilution of brine in seawater. While this technology sounds effective from a dilution perspective, it would be costly in terms of both capital and O&M, and further research would need to be conducted to study the long-term effects of such an installation.

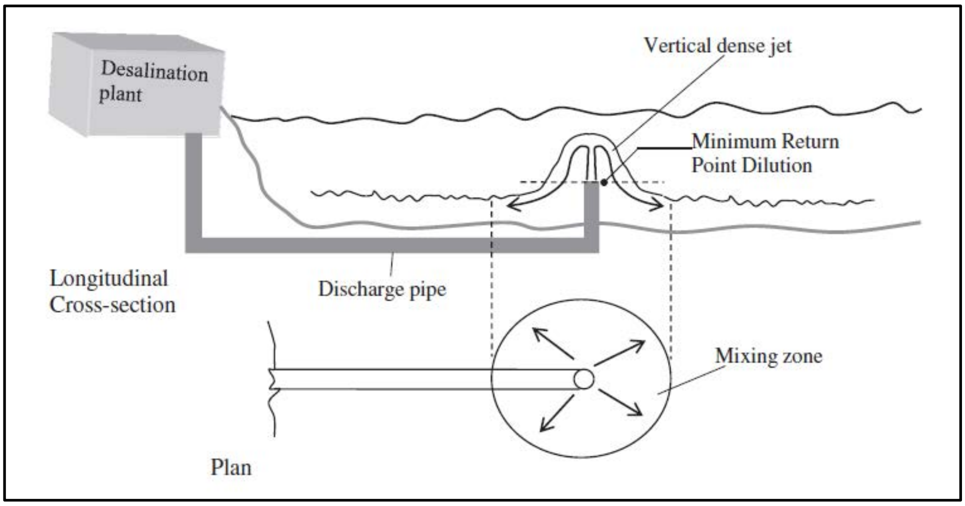

Figure 33: Simple submerged diffuser discharge
Source: Ahmad and Baddour, (2014)

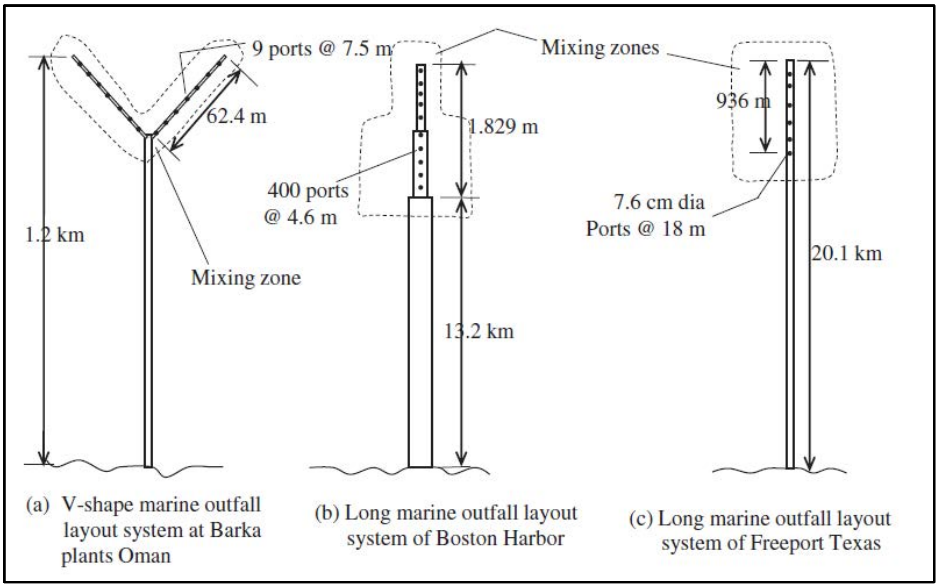

Figure 34: Various submerged outfall systems
Source: Ahmad and Baddour, (2014)

In general, coastal seawater brine disposal can be effective if the dilution product is safe for the environment. Cotruvo et al. (2010) notes that in order for seawater discharge to be acceptable it must consider the following:

- Salinity threshold of species in the area of discharge
- Concentration of metals and chemicals in the effluent
- Concentration of nutrients and organics in the effluent that can trigger changes in marine flora and fauna in the area of discharge
- Elevated temperatures from thermal desalination processes
- Disturbance of wildlife near outfall

3.3.3 Inland Brine Disposal

For desalination plants located away from seashores, the following brine disposal options are described:

3.3.3.1 Evaporation Ponds

Evaporation ponds are a zero-discharge technology based on the principles of natural solar evaporation in human-made lined earthen ponds and basins (Cotruvo et al., 2010). Holding ponds are constructed for concentrate storage, while the evaporation pond reaches the high salinity needed for normal pond operations. Similar to wastewater evaporation ponds, the solid salt waste accumulates at the bottom of the pond, and is periodically disposed of in a suitable landfill. This evaporation pond could also serve as a solar pond (described in section 3.2.6.3) as long as the salt gradient is respected. Cotruvo et al. (2010) note that the following considerations should be made with respect to evaporation ponds:

- Suitable only for disposal of concentrate from small plants in arid areas with low land costs
- Significant land requirements
- Climate dependence (must be appropriate temperature and solar radiation exposure)
- Evaporation rate decreases as solids and salinity levels in the ponds increase. Therefore, frequent cleaning must be made.
- If the evaporation ponds are not lined, a portion of the concentrate may percolate to the freshwater aquifer beneath the pond.

3.3.3.2 Concentrate Deep Well Injection

In deep well injection, brine is distributed into porous subsurface rock formations, where the effluent flows to a targeted aquifer. This aquifer can either be the original source of brackish water, or another separate aquifer with favourable soil conditions. While this method is relatively simple and promotes brackish water replenishment, it is also extremely risky, as the injected brine can harmfully affect targeted soils and contaminate neighbouring freshwater aquifers. This is why deep well injection systems also include a set of monitoring wells to confirm that the concentrate is not migrating into adjacent aquifers (Cotruvo et al., 2010). Cotruvo et al. (2010) lists the following considerations attributed to deep well injection:

- Limited to site-specific conditions of confined aquifers with large storage capacity
- Not feasible for areas with elevated seismic activity or geological faults
- Potential for contamination via brine injection flow or leakage in discharge aquifer
- Potential scaling and decrease of well discharge capacity over time
- Backup concentrate disposal methods are required for periods when injection wells are tested and maintained
- High well construction and monitoring costs

3.3.3.3 Spray Irrigation

This disposal technology uses brine concentrate for irrigation of salinity-tolerant crops or ornamental plants (lawns, parks, golf courses) which are less sensitive to saline water (Cotruvo et al., 2010). Key issues and constraints associated with spray irrigation include:

- Seasonal nature – some plants only grow during certain times of year
- Restricted to small desalination plants
- Backup disposal alternative is required when crop irrigation is not needed.
- Feasibility determined by climate, land availability, irrigation demand, and salinity tolerance of the irrigated plants.

- Possible negative impact on groundwater aquifer beneath the irrigated area; use of this method may cause significant concerns if the concentrate contains arsenic, nitrates, metals, or other contaminants

3.3.3.4 Zero Liquid Discharge (ZLD)

Zero Liquid Discharge technologies, such as brine concentrators, crystallisers and dryers, convert brine effluent into highly purified water and solid dry product which can be suitable for landfill disposal or sold for commercial use (Cotruvo et al., 2010). ZLD brine concentrators work in the same manner as vapour compressors (discussed in section 3.1.2.3), in which increased vapour pressure enables thermal evaporation, creating separation between salt and water. Vapour compressors are energy efficient and simple to use, and are suitable for small-medium scale production. On the other hand, crystallisation vessels also operate with steam and vacuum compressors to promote evaporation, but additionally rotate the brine in a centrifugal vortex (Cotruvo et al., 2010). Rather than continuously recycling heat for evaporation, the brine is dewatered to a mineral state by the centrifuge.

The energy cost for both brine concentrators and crystallisers is quite high, and the equipment costs are usually several times greater than the capital investment needed for other concentrate disposal alternatives. Due to these high costs, ZLD is impractical unless no other brine waste management alternatives are available. ZLD is justifiable for inland brackish desalination plants where site-specific constraints limit the use of natural evaporation or wastewater treatment plant disposal (Cotruvo et al., 2010). For example, in Jumilla, Spain, a centrifugal MVC plant – operating at 2.2 bar pressure and 186-190°C – utilises the salt product from ZLD as an economically valuable good for profit (Fernandez-Lopez et al., 2009).

3.3.3.5 Sewers

The last option considered for brine waste disposal is to construct a sewer line from the brackish desalination plant to the nearest coastal seawater desalination facility. Theoretically, the use of concentrate from a brackish water desalination plant as feedwater to a seawater desalination plant would be mutually beneficial for both plants. This is because the inland plant is normally limited by a lack of suitable brine discharge management, and the seawater plant exerts more energy to treat higher salinity feedwater (Cotruvo et al., 2010). Therefore, a sewer line between the two facilities would provide a solution for the inland plant's brine discharge, while decreasing the feedwater salinity for the seawater plant (in most cases).

However, constructing a sewer line could be very expensive, as it may take thousands of miles for an inland plant to reach a coastal plant, and continuous O&M would need to be applied. Also, the volume of discharge emerging from the seawater desalination plant would increase, possibly amplifying negative effects on the marine environment if the engineering design is flawed.

3.3.4 Summary of Brine Disposal Methods

In general, the hydraulic conditions at a discharge site should be able to dilute, disperse and degrade the salt and its residual pollutants without harmfully affecting the surrounding environment (World Bank, 2012). The choice of brine disposal management depends mostly on the conditions of the surrounding environment, as sensitivity to salt intrusions can have different effects for various ecosystems. Table 27 below summarises the advantages and disadvantages of each brine disposal method, and Table 28 from the U.S. National Academy of Sciences ranks the brine disposal options according to challenges each poses from a management perspective. Figure 35 also indicates the relative costs of each disposal method, illustrating how changes in concentrate volume affect the capital cost of construction for each brine disposal option. However, O&M costs are not included, which can greatly affect the project costs over its useful lifetime.

Table 27: Summary of Brine Disposal Methods
Source: Author (based on works cited in text)

Brine Disposal Method	Advantages	Disadvantages
Seawater Discharge: Surface	Low capital cost and low operation skills required	Improper wave circulation can lead to decreased dilution and increased pollution
Seawater Discharge: Submerged	High dilution capabilities from diffusers	High capital and O&M costs
	lower risk of pollution	
Evaporation Ponds	Low operation skills required	High capital costs for land acquisition
	No additional energy source required	Possible contamination of underlying aquifers
Concentrate Deep Well Injection	Ability to replenish brackish source	Possible contamination of groundwater
	Possibility to filter brine discharge from soil conditions	Limited to site-specific condition of confined aquifers with large storage capacity
		High well construction and monitoring costs
		Could trigger earthquakes
Spray Irrigation	Less freshwater production for agricultural demand	Can only be used for certain seasons of growth
		Restricted to small desalination plants
		Possible contamination of aquifers beneath irrigated area
Zero Liquid Discharge	Separation of salt into solid state for landfill disposal	Very high capital equipment costs
	Economic benefits of solid salt for commercial use	Complex O&M

	Additional freshwater created	
Sewers	Avoids local pollution around brackish source	High capital and O&M costs for large distance sewers
	Decreased feedwater salinity for seawater desalination plant	Increased coastal brine discharge could lead to pollution

Table 28: Challenges of Brine Disposal Management
Source: World Bank, (2012)

Disposal Option	Capital cost	O&M cost	Land required	Env. Impact	Energy	Public concern	Geology
Surface Water	Low	Low	-	Med - High	Low	High	-
Deep injection wells	Med - High	Med	Low	Low	Med	Low - Med	High
Evaporation ponds	High	Low	High	Med	Low	High	High
Spray Irrigation	Med	Low	High	Med - High	Low	High	High
Zero Liquid Discharge	High	High	Low	Low	Low	Low	Low
Sewers	Low	Low	-	Med	Low	Low	-

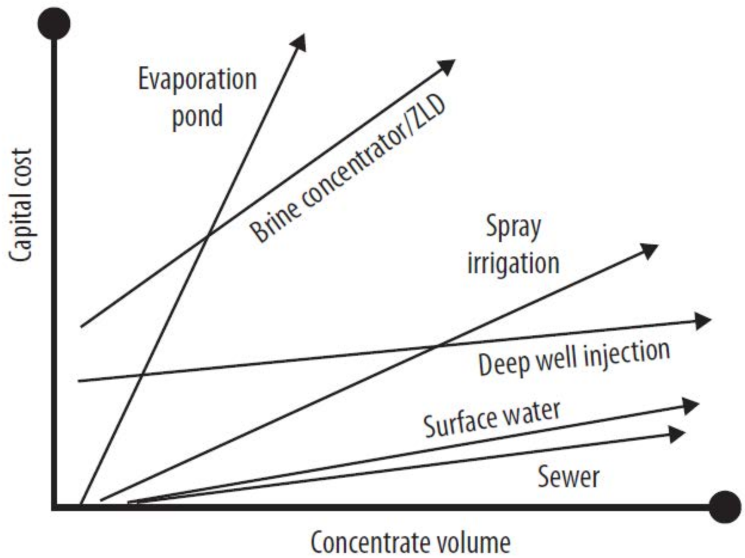

Figure 35: Cost Comparison of Brine Disposal Methods
Source: World Bank, (2012)

Chapter 4: Case Study Analysis – combining renewable energies with desalination systems

4.1 Introduction

Whereas the previous literature review considered desalination and renewable energy separately, this chapter looks at specific examples of combined systems, and evaluates appropriate brine disposal systems that can potentially be matched with these RE-fuelled desalination plants.

4.2 Solar Desalination

This section will review case studies and expert analysis about certain solar-powered desalination technologies and their potential application for the future.

4.2.1 Solar Stills (SS)

Many experiments and case studies have been investigated with regards to solar stills, dating as far back as the 1950s. As mentioned in section 3.1.4.2, solar stills are advantageous in that they are simple to build, operate, and maintain. However, solar stills produce low amounts of distilled water and require large amounts of land to operate. These advantages and disadvantages are further exemplified in the case studies below.

According to Bemudez-Contreras, Thomson and Infield (2008), solar stills were tested in Puerto Chale, Mexico in the 1980s, with sloped glass panels and ferrocemento (light mortar and steel mesh) materials. A wind pump was used to supply seawater from a beach well to the solar still, and the prototype device could produce 200 L from an active surface of 54 m^2. When the prototype was expanded to 300 m^2, it was expected that the device could produce around 1 m^3/day, enough to cover the drinking needs of the town. The plant's best recorded performance was 1.6 m^3/d, exceeding initial expectations. However, after 6 months of successful operation, a new elected government did not have the resources necessary to continue plant operation, and the solar stills were quickly abandoned (Bermudez-Contreras, Thomson and Infield, 2008). The town currently operates a reverse osmosis plant, producing 15 m^3/d of water, but it is not specified whether this plant is fuelled by renewable energies.

Xiao et al. (2013) investigated different case studies where solar still designs were modified to increase energy efficiency and water productivity. The first of these studies involved the modification of the glass cover when it is moulded into different shapes (Figure 36 below). Tayeb (1992) found that the inclined flat glass cover (a) was the most productive (1.25 litres/m^2/d), while other glass covers produced 1.10 to 0.83 litres/m^2/d under similar conditions.

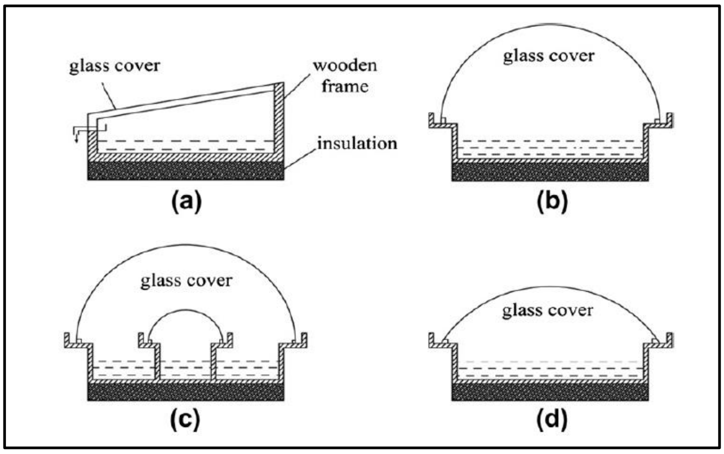

Figure 36: Basin solar stills with different glass covers
Source: Tayeb, (1992)

Xiao et al. (2013) concluded that installing reflectors, heat storage systems and extra condensers could increase productivity up to 14.4 litres/m^2/d, although this has only been proven through small-scale experiments of less than 200 litres per day production. Solar stills provide promise for fisherman and villages in remote areas, where population is small and electricity is scare, and the skills needed to construct and operate such systems are rather minimal. Prakash and Velmurugan (2015) also conducted a similar meta-study, investigating several modifications to solar stills which either increased or decreased productivity. However, they did not draw any conclusions on which consumers would benefit from solar stills in comparison to other desalination technologies.

In Kalogirou's (2005) study of seawater desalination and renewable energies, solar distillation was deemed economically beneficial in comparison to other plants when producing water on a scale of less than 200 m^3/day. This is because typical desalination plants have decreased capital costs per m^3 when capacity increases, but solar stills have a constant capital cost per unit of water produced. Thus, as the plant capacity increases, the capital cost of the solar still begins to equal that of conventional desalination plants. Kalogirou (2005) continues by adding that solar stills normally don't require extra energy (unless pumps are needed to transfer water from the sea), thus operational costs are kept to a minimum, and the major share of water cost is the amortisation of capital cost. In conclusion, Kalogirou (2005) states that solar stills are best used for remote settlements where brackish/seawater is the only source available, power is scarce, and demand is less than 200 m^3/day. Solar stills are further beneficial if freshwater transport from other locations are too expensive (via trucking or piping), and the targeted project area is arid and cheap.

While solar stills are also compatible with PV and CSP technology, it is best recommended that such complex technologies be attributed to larger scale demands. Table 29 below summarises the performance characteristics of solar stills, based on the information provided in section 3.1.4.2 and 4.2.1.

Table 29: Summary characteristics of Solar Stills
Source: Author (based on works cited in text)

Solar Stills		
Capacity (m^3/day)	Current 0.005 - 5.0	Potential < 200
Population served (assume 25 l/p/d)	Current < 200	Potential < 8,000
Cost ($/$m^3$)	Current 25.00	Potential unknown
Energy Consumption (KWh/m^3)	~ 600	
Distillate production efficiency (%)	unknown	
Geographic constraints	• Large land area must be available • Best used in remote locations • Water demand must be less than 200 m^3/d • Best used in arid areas where solar energy is plentiful (over 6,000 MJ/m^2/year)	
Operation and Maintenance (skills, lifetime cycle)	• Inspection and repair of leaks • Dust and salt flushing • Glass top cleansing	
Additional pre/post treatment	• Almost none – product water can be mixed with well water to be more potable	
Most appropriate brine disposal method	• Surface seawater discharge – if located by turbulent waters where mixing occurs • Evaporation ponds – if located inland, cheap available land and small water demand makes this choice ideal	

* Note: For population served, it is assumed that solar stills will only provide water for drinking and hygiene needs. Other industrial/agricultural needs can be met by seawater or yearly precipitation patterns

4.2.2 Solar Multi-Stage Flash (S-MSF)

Multi-Stage Flash is currently the world's largest provider of thermal desalination, having dominated the market in the 1970s and 80s before the introduction of reverse osmosis. Although MSF is considered inefficient in its energy use, it has nonetheless been investigated as a potential sustainable solution when partnered with solar energy. The following case studies describe experiences where MSF was fuelled by either CSP or PV solar technologies.

Dating back to 1980, a solar thermal MSF plant was installed in La Paz (Mexico), with a capacity of 10 m^3/day (Bermudez-Contreras, Thomson and Infield, 2008). This plant consisted of 10 stages and had a total of 518 m^2 solar flat plates for collection during night and day. The plant was designed to operate continuously 24 hours a day with an additional 160 m^2 parabolic concentrating collector field for heat storage. Similarly, in Las Barranas (Mexico), a 20 m^3/day MSF unit was installed, fuelled by a combination of PV panels and parabolic trough collectors. According to Bermudez-Contreras, Thomson and Infield (2008), both of these plants operated for some time before eventually being abandoned. The reasons are a bit unclear, although speculation has suggested that the local political climate and lack of MSF expertise led to the eventual downfall.

Li, Goswami and Stefanakos (2013) compiled a table outlining performance characteristics of some CSP-MSF plants, though these plants were built for experiment or model purposes. Although it is not explicitly stated, it is assumed that these plants were never upgraded to operational scale. A simplified version of this table is shown below:

Table 30: CSP-MSF case studies
Source: Adapted from Li, Goswami and Stefanakos, (2013)

Location	Capacity (m^3/d)	Collector type	Cost ($\$/m^3$)	No. of stages	DNI ($kWh/m^2/d$)
Tianjin, China	0.3	FPC	4.67	1	5.58
Tianjin, China	6.0	FPC	3.9	1	5.58
Gaza	0.145	FPC	n/a	3	6.98
Suez, Egypt	0.0025 - 0.0165	FPC	n/a	1	7.03
Tamilnadu, India	0.0085	FPC	9.0	1	4.97

It is also worth noting that Li, Goswami and Stefanakos (2013) compiled a similar table for case studies of solar pond assisted MSF research, since these models were able to produce water at a much larger capacity than CSP-MSF at lower prices. Solar ponds were a great subject of interest for many scientists, as its ability to collect and store heat in a simple manner made it an attractive choice for future desalination. Again, it is not specified whether these models were upgraded to operational status.

Table 31: Solar Pond-MSF case studies
Source: Adapted from Li, Goswami and Stefanakos, (2013)

Location	Capacity (m^3/d)	Pond size (m^2)	Cost ($\$/m^3$)	No. of stages	DNI ($kWh/m^2/d$)
North Africa	15	2,500	5.48	12-14	5.11 – 6.03
North Africa	300	36,000	2.39	12-14	5.11 – 6.03
Qatar	20	1,500	2.85	n/a	5.50 – 6.00
Safat, Kuwait	1.0	n/a	2.84	18	5.4-6.33
Tripoli, Libya	1,570	7,800	1.80	31	5.11 – 6.03
El Paso, US	1.6-9.0	3,000	n/a	24	7.36
El Paso, US	550	49,441	3.42	20	7.36

As observed from the table above, solar pond – MSF plants are capable of producing water at high levels, though the demand for land area is quite high. However, increasing the number of stages in an MSF plant decreases the required area needed for the solar pond. While this may lead to extra costs, it also allows the saved land to be used for future development.

An example of a solar MSF plant that has reached operational success is the CLLEEN Water and Power system. This MSF unit uses solar PV panels to capture the sun's energy during the day, storing excess energy in batteries for operation at night (Bennett, 2011). In addition to municipal use, the CLLEEN system is also advertised for treatment of mining and frac water, as well as disaster relief and military base camps (CLLEEN, 2011). According to the CLLEEN website, this water treatment system uses only 5.18 kWh per m^3 of water produced, and is able to produce 1,093 m^3 of water per day at a low price of \$0.30/m^3. While this cost figure is a bit difficult to believe (seeing as conventional water supply is more than double the price), additional benefits of CLLEEN include no need for grid electricity, liquid fuel, membranes, filters, or chemicals. The unit covers a very small footprint (around 30 m^2) and converts up to 70% of incoming feedwater into product distillate.

Figure 37: CLLEEN Water Treatment and Power System
Source: CLLEEN, (2011)

Projects such as CLLEEN offer a lot of hope for the future of solar MSF desalination, as even the power of PV panels is sufficient for thermal distillation. It is also an example of how energy efficient and cheap PV-MSF can become. However, while these pilot projects have shown how successful solar MSF can be on a small scale of less than 10,000 m^3, there is still growing concern of MSF's conventional disadvantages when expanded on a large scale, particularly scaling and intermittent operation. Table 32 summarises the characteristics of solar MSF, combining information from section 4.2.2 and the literature review.

Table 32: Summary characteristics of Solar Multi-Stage Flash
Source: Author (based on works cited in text)

Solar Multi-Stage Flash		
Capacity (m^3/day)	Current 0.0085 – 1,570	Potential 100,000
Population served (assume 150 l/p/d)	Current < 10,500	Potential 666,000
Cost (\$/m^3)	Current 0.30 – 9.0	Potential as low as 0.30
Energy Consumption (KWh/m^3)	5.18 (electrical) unknown (thermal – typically around 48-80)	
Distillate production efficiency (%)	up to 70	
Geographic constraints	• Large land area must be available for solar ponds • More land area must be available for multiple flash stages • Better suited for high salinity seawater – must be located close to sea coast • Best used where solar energy is plentiful	
Operation and Maintenance	• Filtration, pump care and scaling control • Must operate above 60% capacity • Requires some level of expertise • Cleaning and maintenance of solar technologies	
Additional pre/post treatment	• Most impurities are removed • Additional treatment may be required to remedy scale deposits	
Most appropriate brine disposal method	• Surface seawater discharge – if located by turbulent waters where mixing occurs • Evaporation ponds – especially if solar ponds are source of energy, although attention needs to be paid to amount of brine water produced	

4.2.3 Solar thermal Multiple Effect Distillation (St-MED)

As a thermal distillation process, MED is characterised by its lower energy consumption in comparison to MSF, receiving considerable attention in the Middle East (Palenzuela et al., 2014). As a result, solar thermal MED systems have been studied extensively; some combined with vapour compressors (VC) to improve cost and production. According to Li, Goswami and Stefanakos (2013), the technical feasibility and reliability of solar MED plants has been proven through two long-term experimental units: the Abu Dhabi solar desalination plant and the Solar Thermal Desalination project at the Plataforma Solar de Almeria (PSA) in Spain.

The Abu Dhabi solar desalination plant was an 18-stage MED unit, harnessing the sun's energy via evacuated tube collectors (ETC), and was operational between 1984 and 2002. Numerous experiments and model simulations of the plant showed that maintenance was pertinent, as dust deposition could cause water production to drop to 40% of the designed flow. Economic feasibility studies also showed that the plant was “not worth operating” when powered solely from solar energy, due to the high percentage of inactive time (Li, Goswami and Stefanakos, 2013).

On the other hand, the Spain PSA site has been able to demonstrate relative cost-competitiveness in the range of $\$2.52/m^3$ – $\$3.53/m^3$, due to additional vapour compressors which have decreased the number of stages needed and reduced top operating temperatures (Garcia-Rodriguez and Gomez-Camacho, 1999). The PSA plant contains 14 stages and produces 3 m^3/hr (with 5 m^3/hr brine reject), although 24-hour operation has only been utilised in summer time when maximum production can be achieved. Otherwise, production costs dramatically increase. The plant continues to operate today since its inception in 1988, although it is used mainly for research purposes.

Table 33 below lists a number of solar thermal MED projects which have been conducted in the last few decades. It is worth noting that the “model” projects are computer simulations which can indicate the potential performance of solar MED in the future. From this information and that of the literature review, Table 34 summarises the performance characteristics of solar thermal MED.

Table 33: Solar MED case studies
Source: Adapted from Li, Goswami, and Stefanakos, (2013)

Solar collector MED					
Model/Experiment	Location	Capacity (m^3/d)	Collector type	Cost ($\$/m^3$)	No. of stages
Experiment	Abu Dhabi, UAE	120	ETC	6.58 – 10.00	18
Experiment	Sydney, Australia	100	FPC	4.00	n/a
Model and Experiment	PSA, Spain	72	PTC	2.52 – 3.53	14
Model	Richmond, California	0.151	FPC/ETC	2.05 – 4.70	7 - 12
Model	Zikim, Israel	100,000	PTC	0.69	16
Solar Pond MED					
Model/Experiment	Location	Capacity (m^3/d)	Pond size (m^2)	Cost ($\$/m^3$)	No. of stages
Experiment	U. of Ancona (Italy)	30	625	3.66	4
Experiment	Bundoora, Australia	0.9 – 2.3	720	18.00 – 22.00	3
Model	Bundoora, Australia	100,000	4,200,000	0.67 – 1.44	12
Model	Athens, Greece	500	30,000	2.00	14

Table 34: Summary characteristics of solar Multiple Effect Distillation
Source: Author (based on works cited in text)

Solar Multiple-Effect Distillation		
Capacity (m^3/day)	Current 30 – 120	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 800	Potential 666,000 or higher
Cost ($/$m^3$)	Current 2.52 – 10.00	Potential as low as 0.67
Energy Consumption (KWh/m^3)	2.90 (electrical) and 36 (thermal)	
Distillate production efficiency (%)	around 40	
Geographic constraints	• Large land area must be available for solar ponds • Better suited for high salinity seawater – must be located close to sea coast • Best used where solar energy is plentiful	
Operation and Maintenance	• Filtration, pump care and scaling control • Cleaning and maintenance of solar technologies • Requires some level of expertise – esp. for added tubes, sprinklers, and vapour compressors	
Additional pre/post treatment	• Most impurities are removed • Additional treatment may be required to remedy scale deposits	
Most appropriate brine disposal method	• Surface seawater discharge – if located by turbulent waters where mixing occurs • Evaporation ponds – especially if solar ponds are source of energy, although attention needs to be paid to amount of brine water produced and salt water gradient	

4.2.4 Solar thermal Reverse-Osmosis (St-RO)

While reverse osmosis and solar thermal collectors have each gained respectable attention in the desalination industry, the combined use of both processes has been very limited in research. While RE-powered desalination typically costs more than conventional desalination, experts predict that CSP reverse osmosis plants could produce water with costs below $0.60/$m^3$ by 2030 (Grubert, Stillwell and Webber, 2014). Few case studies can be cited for investigation, although not all performance factors (i.e. cost, energy consumption, capacity, etc.) are listed for each example.

In terms of solar pond – reverse osmosis couplings, only one example could be found from Li, Goswami and Stefanakos (2013) about an experimental plant in Kuwait which produced 1 m^3/d of water at a cost of around $5.70/$m^3$. The size of the pond and the energy consumption of the system were not included.

In Delgado-Torres and Garcia-Rodriguez's paper, *Status of solar thermal-driven reverse osmosis desalination* (2007), a CSP-RO system in Saudia Arabia is described, capable of producing between 7.6 and 26.5 m^3 of desalinated water per day. Utilising parabolic trough collectors (PTC) and thermal energy storage, the solar field is designed to operate for about 8 hours on an average sunny day on the best month of the year (May). With a 75% conversion rate, the RO unit was recorded to operate in solar-only mode for 8.5 hours in one day in March, producing a total of 28.2 m^3 of desalinated water. While this exceeded initial expectations, it should be noted that the plant operated with low salinity feedwater (5,400 mg/L), which requires less energy to desalinate than typical seawater (35,000 mg/L).

In a different paper, Ibarra et al. (2013) designed and tested their own CSP-RO unit, fuelled by parabolic trough collectors and a thermal energy storage tank. While the RO unit is not described in great detail, Ibarra et al. (2013) note that the electric consumption of the system is around 4 kWh/m^3, and that water production averages 1.2 m^3/hr, or 28.8 m^3/day if radiation and thermal conditions are favourable. While summer readings in Almeria, Spain indicated that water production was stable during day and night, radiation during winter was unable to provide constant required temperature readings, thus operation was very intermittent. Ibarra et al. (2013) note that while the water production of the system seems low with regards to its complexity, it is nonetheless a favourable option for remote areas where access to electricity and freshwater is a challenge.

While the number of case studies in solar thermal RO systems is limited, the following table below summarises the current and potential performance characteristics of these systems.

Table 35: Summary characteristics of solar thermal reverse osmosis
Source: Author (based on works cited in text)

Solar thermal Reverse Osmosis		
Capacity (m^3/day)	Current 1.0 – 28.8	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 200	Potential 666,000 or higher
Cost ($/$m^3$)	Current 5.70	Potential as low as 0.60
Energy Consumption (kWh/m^3)	4.00 (electrical)	
Distillate production efficiency (%)	75	
Geographic constraints	• Large land area must be available for solar ponds • Large, flat area must be available for CSP • Best used where solar energy is plentiful throughout year	
Operation and Maintenance	• Membranes need replacement every 4-6 years • Cleaning and maintenance of solar technologies • Requires skilled personnel for complex configuration	
Additional pre/post treatment	• Chemical treatment required to reduce membrane fouling • Treatment required to remove boron and other harmful chemicals	

Most appropriate brine disposal method	• Submerged seawater discharge – high concentrated brine needs extra diffusers for sufficient mixing • Evaporation ponds – only for small scale and when utilising solar ponds as thermal source • Zero Liquid Discharge – when located far from sea and sewer transport is too expensive

4.2.5 Solar photovoltaic Reverse-Osmosis (PV-RO)

In contrast to solar thermal - reverse osmosis, engineers have heavily researched the integration of photovoltaic cells with RO units, even commercialising these desalination units on a small scale. PV-RO is the most advanced renewable energy – desalination combination on the market, with the highest potential to replace large-scale desalination plants in the near future. Tables 36 and 37 below outline various case studies selected from Thomas (1997) and Li, Goswami and Stefanakos (2013) which display the range capabilities of tested PV-RO units. With respect to the case studies selected by Thomas (1997), it can be expected that the performance levels of these desalination units have improved since the author's publication almost 20 years ago.

Table 36: Selected case studies of PV-RO – salinity and energy demand
Source: Adapted from Thomas, (1997)

Location	PV capacity (kW)	Battery	Capacity (m^3/d)	Feedwater salinity (mg/L)	Net energy demand (kWh/m^3)	Operating Conditions
Concepcion del Oro, Mexico	2.50	No	0.71	3,000	6.9	Intermittent
St. Lucie, Florida	2.70	Yes	0.64	32,000	13	Continuous
Sadous, Saudi Arabia	10.08	Yes	5.7	5,700	<18	Intermittent
Jeddah, Saudi Arabia	8.00	Yes	3.2	42,800	13	Daylight operation

Table 37: Selected case studies – cost and capacity
Source: Adapted from Li, Goswami and Stefanakos (2013)

Location	PV capacity (kW)	Battery	Capacity (m^3/d)	Cost (\$/m^3)
Abu Dhabi, UAE	22.49	No	20.00	7.30
Ras Ejder, Libya	50.00	No	300	0.90
Gran Canaria, Spain	4.80	Yes	10.0	13.16

In a PhD paper entitled *Reverse Osmosis Desalination of Seawater Powered by Photovoltaics without Batteries*, Thomson (2003) constructed an experimental PV-RO unit with the capacity to produce up to 4 m^3/day of clean water at a specific energy consumption of less than 4 kWh/m^3. When tested, Thomson found that the unit was able to produce an average of 3.3 – 3.9 m^3/day with energy consumption values ranging between 3.2 and 3.7 kWh/m^3 depending on solar irradiance and feed water temperature. Capital costs were calculated around $46,000 with operational costs predicted to be about $4.00 per m^3, but no additional fuel or battery costs were needed for such a system (Thomson, 2003). In comparison to solar stills, Thomson (2003) explained that when aiming to produce an output of 3 m^3/d, a typical solar still would require 600 m^2 of land area, while the PV-RO system needed only 20 m^2 for PV panels. While the figures produced by the PV-RO unit demonstrate success, it is still important to note that when solar power is low on a given day, the system will operate at a reduced flow and pressure, causing product concentration to rise considerably (Thomson, 2003).

As a measure of commercial success, PV-RO units have been installed in various Pacific Islands, providing clean water to hotel resorts as a result of booming tourism. In Fiji, PV-RO units produced by Citor (Australian RO membrane manufacturer) and Solar Power Indonesia have treatment capacities of 5 – 240 m^3/day, with PV panels ranging from 3.1 – 100 kW in power capacity. The cost is not mentioned, but is assumed to be reasonably affordable. According to Bennett (2011), the successful implementation of PV-RO systems requires extensive government support in the form of legislation, finance and labour, which is what has allowed these PV-RO systems to flourish.

In the BCS region of Mexico, PV-RO systems developed by Yan Kunczynski continue to operate in remote villages, producing up to 19 m^3/day of freshwater with TDS levels below 250 mg/L (Bermudez-Contreras, Thomson and Infield, 2008). Operating with battery banks and large PV arrays, the system has achieved energy consumption values as low as 2.6 kWh/m^3, with over 70,000 hours (8 years) of operation running entirely on solar energy. This is particularly impressive considering the system treats seawater. Although some authors argue against the use of batteries because of their additional maintenance demand, the continuous operation of the system from battery storage can provide longevity and stability as seen in the case of Kunczynski.

In a study conducted by Grubert, Stillwell and Webber (2014), the potential of PV-RO was put under investigation, as consumer sites were identified for future RE-desalination growth. The criteria of these consumer sites involved both geophysical and social conditions, as the target group had to be located in an area of favourable solar radiation (>5 kWh/m^2/day), high sea surface temperature (>25°C), low water salinity (<50th percentile), high water stress (>85th percentile), high water price (≥$1.50/$m^3$) and high city population (≥1 million). High solar insolation is desirable for power generation, while high feedwater temperature and low salinity are associated with lower process energy consumption for reverse osmosis. The social conditions outlined above were used to target large cities that were more likely to secure the financing needed for large water treatment infrastructure with high water prices that could potentially support PV-RO desalination. The results showed that the area which most closely met all these conditions was Southeast Asia, particularly India. However, this area did not meet the financial target, which the authors speculate could be the most decisive factor. For example, most of the world's current desalination capacity is concentrated in regions such as the Middle East and United States where freshwater is limited, but there is sufficient wealth to support desalination. Thus, geophysical conditions do not seem to be the major drivers of desalination installations, but rather play a minor role in initiating demand. Therefore, the authors admit that while a region with moderate geophysical conditions but extremely high water prices and stress would not be classified as an "excellent" site in the model, it may actually be the most suitable for PV-RO in the real world. Although in general, these types of conditions would be favourable for any type of RE-powered desalination, not only PV-RO.

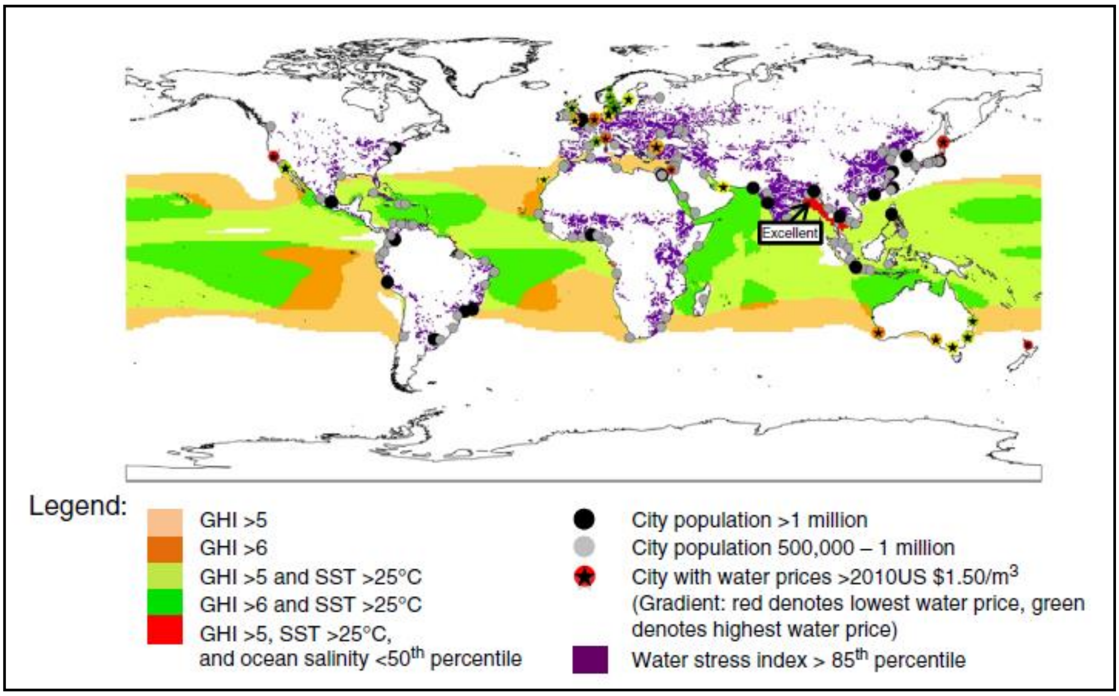

Figure 38: Grubert, Stillwell and Webber study findings
Source: Grubert, Stillwell and Webber, (2014)

Table 38: Summary characteristics of PV-RO
Source: Author (based on works cited in text)

Solar photovoltaic Reverse Osmosis		
Capacity (m^3/day)	Current 0.64 – 300	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 2,000	Potential 666,000 or higher
Cost ($/$m^3$)	Current 0.90 – 13.16	Potential lower than 0.90
Energy Consumption (kWh/m^3)	2.60 – 18.00 (electrical)	
Distillate production efficiency (%)	Unknown (usually 40-70%)	
Geographic constraints	• Best used where solar energy is plentiful throughout year • Almost none - flexible at small or large scale and mobile	

Operation and Maintenance	• Membranes need replacement every 4-6 years • Cleaning and maintenance of PV panels • Additional supply and replacement of batteries if needed • Requires skilled personnel for complex configuration
Additional pre/post treatment	• Chemical treatment required to reduce membrane fouling • Treatment required to remove boron and other harmful chemicals
Most appropriate brine disposal method	• Submerged seawater discharge – high concentrated brine needs extra diffusers for sufficient mixing • Zero Liquid Discharge – when located far from sea and sewer transport is too expensive • Evaporation ponds – when concentrate is high and water production is low

4.2.6 Solar photovoltaic Electrodialysis (PV-ED)

As mentioned in section 3.1.3.2 of the literature review, electrodialysis is best used for brackish water desalination, as the increasing cost to desalinate high salinity water makes ED more expensive than RO, MSF, and MED. As a result, nearly all research in PV-ED has been directed towards brackish water sources with TDS levels below 10,000 mg/L. Table 39 below illustrates a number of case studies from the past 30 years that have focused on PV-ED applications.

Table 39: Selected case studies of PV-RO
Source: Adapted from Fernandez-Gonzalez et al., (2015)

Location	Year	Capacity (m^3/d)	Feedwater salinity (mg/L)	Energy consumption (kWh/m^3)	Cost (\$/m^3)
Spencer Valley, USA	1986	2.8	1,000	0.82	15.97
Thar desert, India	1986	1.0	5,000	1.00	n/a
Ohsima Island, Japan	1986	10.0	30,000	n/a	5.77
Fukue, Japan	1990	200.0	700	0.60 – 1.00	n/a
New Mexico, Mexico	1996	18.0	900	0.80	n/a
Alicante, Spain	2008	13.7	4,473	1.33 – 1.47	0.19 – 0.43
Alicante, Spain	2008	< 100	3,500	4.00	5.77 – 15.97
Canary Island, Spain	2013	4.0	2,240 – 3,392	0.62	n/a

In 2015, the United States Agency for International Development (USAID) awarded its prestigious Desal Prize to a team from the Massachusetts Institute of Technology (MIT) for their invention of a photovoltaic electrodialysis desalination system. The purpose of the Desal competition was to "secure water for food" by creating cost effective and energy efficient technologies for potable water

(Restuccia, 2015). In partnership with Jain Irrigation Systems (JIS), MIT developed the PV-ED unit to treat brackish water with salinity levels up to 5,000 mg/L, removing both chemical and biological contaminants via prefiltration, electrodialysis-reversal, and post-treatment Ultra Violet (UV) radiation. The system is purely powered by photovoltaics and converts 90-95% of incoming feedwater into clean, drinking water. The brine concentrate is dried in a solar evaporation pond, which should be fairly small in size considering the amount of brine produced.

According to MIT PhD student Natasha Wright (2014), the main inventor of the system, the PV-ED unit is designed to serve a village of 2,000 – 5,000 people providing drinking water at a rate of 6 -15 m^3/day (or 3 litres/cap/day). The unit was initially aimed to serve rural villages in India, where saline groundwater is present in 60% of the country, and 25% of the country's population live in villages of 2,000 – 5,000 people, many of which do not have reliable access to electricity (Wright and Winter V, 2014). When carefully examined, it was found that ED required less energy to treat the saline groundwater in these areas than RO, and was up to 50% cheaper in most cases. Due to decreasing costs of RO membranes and increased RO performance, it was found that the threshold TDS level for ED desalination is 5,000 mg/L. As a result of their work, MIT and JIS won $140,000 in prize money with an additional $150,000 to invest in further development and commercialisation, and a possible $400,000 grant to implement pilot projects in a USAID mission region (Restuccia, 2015). While the cost to operate this system is not mentioned, it is assumed to be affordably well priced, considering it won the USAID Desal award for its "cost-effectiveness" and was targeted towards rural Indian villages.

In a study conducted by Fernandez-Gonzalez et al. (2015), the reference energy consumption for ED of brackish water (2,500 – 5,000 mg/L) was found to be between 0.49 – 0.91 kWh/m^3, which is surprisingly low in comparison to other desalination methods. As a result of this low energy consumption, production costs could optimistically range from $0.20-0.54/$m^3$, although this is undoubtedly the best-case scenario. However, with increasing water scarcity and decreasing fossil fuel availability, the widespread use of ED-PV is predicted to occur between 2020 and 2050 in areas of low brackish water salinity (Fernandez-Gonzalez et al., 2015).

Table 40: Summary characteristics of PV-ED
Source: Author (based on works cited in text)

Solar Photovoltaic Electrodialysis		
Capacity (m^3/day)	Current 1.0 – 200.0	Potential 35,000 or higher
Population served (assume 150 l/p/d)	Current < 1,333	Potential 233,000 or higher
Cost ($/$m^3$)	Current 0.19 – 15.97	Potential as low as 0.19
Energy Consumption (kWh/m^3)	0.49 – 4.00 (electrical)	
Distillate production efficiency (%)	90 – 95	

Geographic constraints	• Best used where solar energy is plentiful throughout year • Water source must be 5,000 mg/L or lower
Operation and Maintenance	• Membranes need replacement every 10 years • Cleaning and maintenance of PV panels • Additional supply and replacement of batteries if needed • Requires skilled personnel for complex configuration
Additional pre/post treatment	• Filtration required to remove suspended solids and reduce membrane clogging/fouling • Post-treatment required to remove harmful bacteria and chemicals (UV radiation)
Most appropriate brine disposal method	• Evaporation ponds – suitable since water production is typically lower than other desalination methods, and salt concentration is very high • Zero Liquid Discharge – salt recovery could provide economic benefits, although costs are higher

4.2.7 Solar Membrane Distillation (S-MD)

Membrane distillation (MD) is a hybrid membrane-evaporation process which has been of interest for desalination, mainly because of its low temperature heat and electricity demands (Rasool Qtaishat and Banat, 2013). Coupling solar collectors and PV panels to the MD process has been a goal for some in the desalination industry, although MD has yet to be built on the same large-scale status as MSF or RO. Small-scale solar powered MD units have been developed and tested by a number of researchers, although the number of case studies is small in comparison to other desalination-renewable energy combinations listed above. Table 41 below lists some of these case studies.

Table 41: Selected case studies of solar MD
Source: Adapted from Li, Goswami and Stefanakos, (2013)

Project	Model / Experiment	Capacity (m^3/d)	Solar type
El Paso	Model and Experiment	0.35	Solar Pond
MEMDIS, SMADES	Experiment	0.10 – 0.50	FPC and PV
MEDINA	Model	3.36 – 14.81	Solar pond
SMDDS	Model and Experiment	0.64 – 0.71	FPC
MEDESOL	Model	0.50 – 50.00	CPC

Although the costs of these experiments and models are not outlined, an economic analysis of solar MD from Banat and Jwaied (2008) estimated water production costs to range from \$15-18/m^3. These high prices can be attributed to the fact that MD membranes have only recently been developed, and are not available at the same low price as RO and ED membranes. In addition, the combination of solar technologies and MD processes is even more recently studied. However, once the system is operational, MD is usually inexpensive to maintain, and the energy is minimal in cost (Rasool Qtaishat and Banat, 2013). Increases in membrane and plant lifetime operation can also lead to decreases in water production costs.

While initial cost estimates may be discouraging, projects such as MEDESOL (Seawater Desalination by Innovative Solar-Powered Membrane Distillation System) are supported by the European Commission to develop and assess solar multi-stage MD processes at a high efficiency and cost effective rate (Blanco Gálvez, García-Rodríguez and Martín-Mateos, 2009). The aim of the project is to construct multistage MD systems with a capacity range of 0.5 m^3/d to 50 m^3/d, while achieving technical simplicity and high-quality water output from seawater sources. It is planned that the heat source will proceed from an advanced compound parabolic solar concentrator, although cost estimates have not been drawn yet. Nevertheless, it is a good indication that MD is a viable process that could surpass RO in the future with further research and development.

Table 42: Summary characteristics of solar MD
Source: Author (based on works cited in text)

Solar Membrane Distillation		
Capacity (m^3/day)	Current 0.1 – 50.0	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 333	Potential 667,000 or higher
Cost (\$/m^3)	Current 15 – 18	Potential unknown
Energy Consumption (kWh/m^3)	Unknown (typically around 2.0 for electric)	
Distillate production efficiency (%)	Unknown (typically around 90)	
Geographic constraints	• Best used where solar energy is plentiful throughout year • Large land area must be available for solar ponds • Large, flat area must be available for CSP	
Operation and Maintenance	• Membranes need replacement every 6-10 years • Careful hydraulic pressure applied to avoid membrane wetting • Cleaning and maintenance of solar technologies • Additional supply and replacement of batteries if needed • Requires skilled personnel	
Additional pre/post treatment	• Very little pre-post treatment needed – most impurities removed • Basic filtration can be applied for better flux	
Most appropriate brine disposal method	• Submerged seawater discharge – high concentrated brine needs extra diffusers for sufficient mixing if located by sea coast • Evaporation ponds – suitable since reject salt concentration is very high; however size can be issue • Zero Liquid Discharge – salt recovery could provide economic benefits, although costs are higher	

4.3 Wind Desalination

This section will review case studies and expert analysis about wind-powered desalination technologies, specifically reverse osmosis and vapour compression, as these two methods benefit the most from wind power, from a mechanical and electrical viewpoint.

4.3.1 Wind Reverse Osmosis (Wi-RO)

Seawater desalination processes based on reverse osmosis (RO) are reported to have the lowest energy requirements (Fernandez-Lopez et al., 2009), and because most seawater desalination plants are located on the coast, wind resources are usually abundant. Studies in relation to wind-powered reverse osmosis are plentiful and proven in many parts of the world. For example, on the island of Syros (Greece), a wind RO plant could produce 60-900 m^3/day depending on wind conditions (Ruskulis, 2002). Similarly, Delgado-Torres (2007) mentions two different wind RO plants producing 18 and 20 m^3/d, at average wind speeds of 5 and 10 m/s, respectively.

In the Canary Islands, many experimental models have been built in an effort to optimize water production at a lower cost from wind power. One such system could produce 5-50 m^3/d, averaging 13 m^3/d at an annual average wind speed of 7 m/s (Kalogirou, 2005). While the capacity of many of these tests and models have been fairly small, a study by Forstmeier et al. (2007) suggests that under optimum conditions, a 1.5 MW wind turbine should be capable of producing up to 5,500 m^3/day for a RO system. If wind farms are increasingly endorsed and popularised, there is no doubt that this capacity can increase to replace conventional reverse osmosis.

In terms of energy consumption, various case studies have shown relatively similar results. According to Bennett (2011), a reverse osmosis plant in Perth, Australia requires 26 MW to run and uses an estimated 4.1 kWh/m^3, garnering this power from a nearby wind farm of 48 turbines and 80 MW total power. In a study by Gokcek and Gokcek (2016), a small scale wind-RO desalination plant of 24 m^3/day desalinates seawater with a specific energy consumption of 4.38 kWh/m^3.

In the same study by Gokcek and Gokcek (2016), it was estimated that the production costs of wind-RO plants could range from \$2.96-6.46/m^3 when wind turbines are off-grid, but dramatically decrease to \$0.87-2.87/m^3 when connected to a common power grid. In an economic evaluation of hybrid wind and solar RO systems, Mokheimer et al. (2013) estimated that the energy consumption of desalination could range between 8-20 kWh/m^3 (depending on raw water salinity) bringing costs to an estimated range of \$3.69-3.81/m^3.

Table 43: Summary characteristics of Wind RO
Source: Author (based on works cited in text)

Wind Reverse Osmosis		
Capacity (m^3/day)	Current 5 – 900	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 6,000	Potential 667,000 or higher
Cost ($/$m^3$)	Current 0.87 – 6.46	Potential as low as 0.87
Energy Consumption (kWh/m^3)	4.1 – 20.0	
Distillate production efficiency (%)	Unknown (typically around 90)	
Geographic constraints	• Best used where wind energy is plentiful throughout year (coasts and high altitudes) • Large land area must be available depending on efficiency and power output of turbines	
Operation and Maintenance	• Membranes need replacement every 4-6 years • Maintenance and repair of wind turbines • Additional supply and replacement of batteries if needed • Requires skilled personnel for complex configuration	
Additional pre/post treatment	• Chemical treatment required to reduce membrane fouling • Treatment required to remove boron and other harmful chemicals	
Most appropriate brine disposal method	• Submerged seawater discharge – high concentrated brine needs extra diffusers for sufficient mixing if located by sea coast • Zero Liquid Discharge – when located far from sea and sewer transport is too expensive	

4.3.2 Wind Mechanical Vapour Compression (Wi-MVC)

Wind turbines and mechanical vapour compressors have many similar characteristics in that they are both involved with compressible fluid flow (ETSU et al., 1996). This combination has piqued the curiosity of many researchers as a possible alternative to solar RO, in areas where radiation is insufficient and membranes are too difficult to operate. Some selected case studies are outlined below.

On the island of Reugen in Germany, a large wind-powered MVC plant with a 300 kW wind energy converter was able to produce 120-300 m^3 of freshwater per day in a successful experiment (Kalogirou, 2005). According to Karameldin and Mekhemar (2003), wind turbine diameters of 20-43 metres are able to produce 203-938 m^3/day where average wind speeds are 7 m/s, and energy is stored in a connected local grid. It was also found in the same study that along the Red Sea coast, strong mean wind speeds ranging from 6-15 m/s were observed, indicating coastal regions as potential locations for energy production. This is very interesting considering many large scale desalination plants are located by the coast, since the source of their feedwater comes from the sea.

According to Zejli et al. (2011), the MVC process is mostly competitive for production capacities of less than 5,000 m^3/d, and should only be used for greater capacities when combined with other desalination processes such as MED. For an MVC plant tested in Morocco, it was found that when operating at a capacity of 20-100 m^3/d, costs varied between $10.06 and $2.92/$m^3$, but could reach as low as $1.27/$m^3$ if operated at 500 m^3/d. This cost was deemed comparable and competitive to Morocco's current average cost of water, which averaged at about $0.91/$m^3$ during the time of the study. Forstmeier et al. (2007) also found in their study that wind-MVC plants could provide clean water from the sea at a cost of $1.10-1.50/$m^3$, provided the appropriate site is chosen and the systems are designed properly. Forstmeier et al. (2007) quote, "If it comes to stand-alone applications for remote places, MVC is a very suitable process for desalination due to its variability in operation."

Table 44: Summary characteristics of Wind MVC

Source: Author (based on works cited in text)

Wind Mechanical Vapour Compression		
Capacity (m^3/day)	Current 20 – 500	Potential 36,000 or higher
Population served (assume 150 l/p/d)	Current < 3,333	Potential 240,000 or higher
Cost ($/$m^3$)	Current 1.10 – 10.06	Potential unknown
Energy Consumption (kWh/m^3)	Unknown (typically around 1.0-3.0 electric)	
Distillate production efficiency (%)	Unknown (typically around 33-75)	
Geographic constraints	• Best used where wind energy is plentiful throughout year (coasts and high altitudes) • Large land area must be available depending on efficiency and power output of turbines	
Operation and Maintenance	• Maintenance and repair of wind turbines • Additional supply and replacement of batteries if needed • Requires technical skill for compressors	
Additional pre/post treatment	• Basic filtration for pre-treatment • Most impurities removed, scaling is rare	
Most appropriate brine disposal method	• Submerged seawater discharge – high concentrated brine needs extra diffusers for sufficient mixing if located by sea coast • Zero Liquid Discharge – when located far from sea and sewer transport is too expensive; VC is very capable of producing ZLD • Evaporation ponds – if brine concentrate and distillate recovery is high, but ZLD is too expensive	

4.4 Geothermal MED/MSF desalination (G-MED)

In some areas of the world, geothermal heat is easily accessible, and can be a source of "free" power that is both renewable and constantly available. Although geothermal heat can be utilised to generate steam for electric turbines, the only existing case studies of desalination methods coupled with geothermal combustion are thermal based (i.e. MSF and MED). The case studies presented here are cited from Ghaffour et al. (2015) in their paper, *Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems*.

- In the BCS region of Mexico, a combined MED-MSF plant was constructed and tested for a coastal site where geothermal water was constantly available at temperatures of around 80°C. It was found that the application of 118 m^3 of geothermal groundwater at 80°C was able to desalinate 20 m^3 of freshwater per day.
- SepthonWater Technology used heat from a geothermal power plant (100°C) to desalinate water from two MED units ranging in capacities of 18.9 to 79.5 m^3/day.
- Despite the richness in geothermal resources that exist around the Aegian region (Greece and Turkey), there exists very few geothermal desalination units built for testing. One pilot plant was built in Kimolos Island, producing 80 m^3/day from 1,440 m^3 of geothermal water at 60-61°C. The water source was found to be easily accessible at depths of 188 metres.
- In another feasibility study at Nysyros Island, a MED/MSF unit was found to produce up to 225 m^3/day of freshwater from low enthalpy geothermal resources. The costs of the produced freshwater, including the plant costs, ranged from \$0.65 to \$2.00/m^3. These numbers show that geothermal desalination is economically viable in some cases where geothermal energy is easily accessible and practically free.

Ghaffour et al. (2015) conclude that while there is a need to accelerate the development of geothermal desalination, future studies must be conducted to accurately assess the commercial application of such desalination technologies in these areas, including upscaling and detailed economic modelling.

Table 45: Summary characteristics of geothermal MED-MSF
Source: Author (based on works cited in text)

Geothermal MED-MSF		
Capacity (m^3/day)	Current 18.9 – 225	Potential 100,000 or higher
Population served (assume 150 l/p/d)	Current < 1,500	Potential 666,000 or higher
Cost (\$/m^3)	Current 0.65 – 2.00	Potential as low as 0.65
Energy Consumption (kWh/m^3)	Unknown (typically around 32-80 thermal)	

Distillate production efficiency (%)	Unknown (typically around 25-50)
Geographic constraints	• Best used where geothermal resources are easily accessible at shallow depths (i.e. geologically active sites) • More land area must be available for multiple flash stages
Operation and Maintenance	• Maintenance of geothermal energy storage • Filtration, pump care, and scaling control • Requires some level of expertise, esp. MED
Additional pre/post treatment	• Most impurities removed are removed • Additional treatment may be required to remedy scale deposits
Most appropriate brine disposal method	• Surface seawater discharge – if located by turbulent waters where mixing occurs • Concentrate Deep Well Injection – redirecting heated brine to geothermal source could provide added longevity

4.5 Multiple Combination: Solar and Wind MED-MVC (SW-MVC)

Although this section will only look at one example of a multiple renewable energy – desalination combination, it is still worth mentioning to illustrate the benefits that can be provided when multiple desalination methods and renewable energies are combined into one system. The integrated desalination system under investigation is a two-step process combining MED and MVC, powered by a solar field and wind farm respectively (Fernandez-Lopez et al., 2009).

According to Fernandez-Lopez et al. (2009), the seawater first enters a 14-stage MED system, powered by thermal energy from a solar field, producing 37.5 m^3/h of fresh water. The brine from this system is then passed on to the MVC distillation cycle, where 62.5 m^3/h of fresh water is obtained, and the remaining salt is crystallized in solid form. Thus, the integrated system produces 100 m^3/h of distilled water, or 2,400 m^3/d. A flow diagram of the combined system is illustrated below:

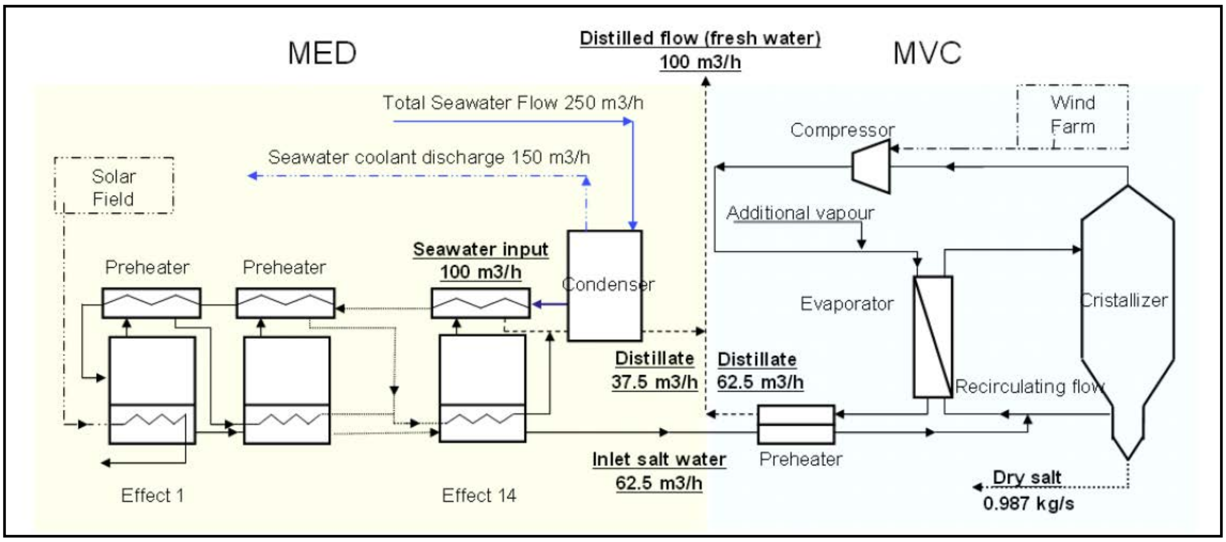

Figure 39: Flow diagram of solar and wind MED-MVC scheme
Source: Fernandez-Lopez et al., (2009)

Overall, the integrated system requires 2,362 kW-h for MED and 1,944 kW-h for MVC (Fernandez-Lopez et al., 2009), thus totalling 4,306 kWh for 100 m^3 of water produced, or 43.06 kWh/m^3. Despite this large energy consumption, the final product water is completely clean and potable, and there is no extra measure of brine disposal needed, as the MVC process completely solidifies the salt as zero liquid discharge. Thus, the distillate production efficiency is at 100%.

The total operational costs of such a system have been calculated at 2,198,732.75 € (or $3,158,479.60 according to the average exchange rate of 2009) per year, translating to $3.60/$m^3$ of freshwater produced. However, Fernandez-Lopez et al. (2009) stipulate that if the extracted salt is sold to the general market, this can bring costs down to 0.59 €/m^3, or $0.85/$m^3$. This MED-MVC process provides environmental protection through zero liquid discharge, and operates at a competitive price that could replace conventional desalination plants.

Table 46: Summary characteristics of solar wind MED-MVC
Source: Author (based on works cited in text)

Combined Solar and Wind MED-MVC		
Capacity (m^3/day)	Current 100	Potential unknown
Population served (assume 150 l/p/d)	Current < 666	Potential unknown
Cost ($/$m^3$)	Current 3.60	Potential as low as 0.85
Energy Consumption (kWh/m^3)	43.06 (23.62 thermal and 19.44 electric)	
Distillate production efficiency (%)	100	
Geographic constraints	• Best used where wind and solar energy is plentiful throughout the year • Large land area must be available depending on efficiency and power output of turbines and solar collectors	
Operation and Maintenance	• Maintenance of solar and wind technologies • Filtration, pump care, and scaling control • Requires some level of expertise, esp. MED and ZLD	
Additional pre/post treatment	• Most impurities removed are removed • Additional treatment may be required to remedy scale deposits	
Most appropriate brine disposal method	• Zero Liquid Discharge is already designed in the system	

4.6 Summary

Table 47 and Figures 40-42 below compare the current capacity, cost, and energy consumption of the renewable energy – desalination systems described above. However, it should be noted that these are not necessarily indications of which system is most capable, cheap or energy efficient. Rather, it serves to illustrate the development of each combined system and the range that has been covered through its evolution. Although the energy consumption for solar stills is around 600 kWh/m^3,

Figure 42 limits the vertical axis to 100 kWh/m3 in order to allow low energy systems (e.g. S-MD) to appear on the graph.

Table 47: Capacity, Cost, and Energy consumption of RE-Desalination systems
Source: Author (based on works cited in text)

RE-Desal Combo	SS	S-MSF	St-MED	St-RO	PV-RO	PV-ED	S-MD	Wi-RO	Wi-MVC	G-MED	SW-MVC
Capacity (m^3/d)	0.01 – 5	0.01 – 1,570	30.00 – 120	1.00 – 29	0.64 – 300	1.00 – 200	0.10 – 50	5.00 – 900	20.00 – 500	18.90 – 225	100
Cost ($\$/m^3$)	25.00	0.30 – 9.00	2.52 – 10.00	5.70	0.90 – 13.16	0.19 – 15.97	15.00 – 18.00	0.87 – 6.46	1.10 – 10.06	0.65 – 2.00	3.60
Energy Consumption (kWh/m^3)	~ 600	5.18 – 85	2.90 – 39	4.00	2.60 – 18	0.49 – 4	2.00	4.10 – 20	1.0 – 3	32.00 – 80	43.06

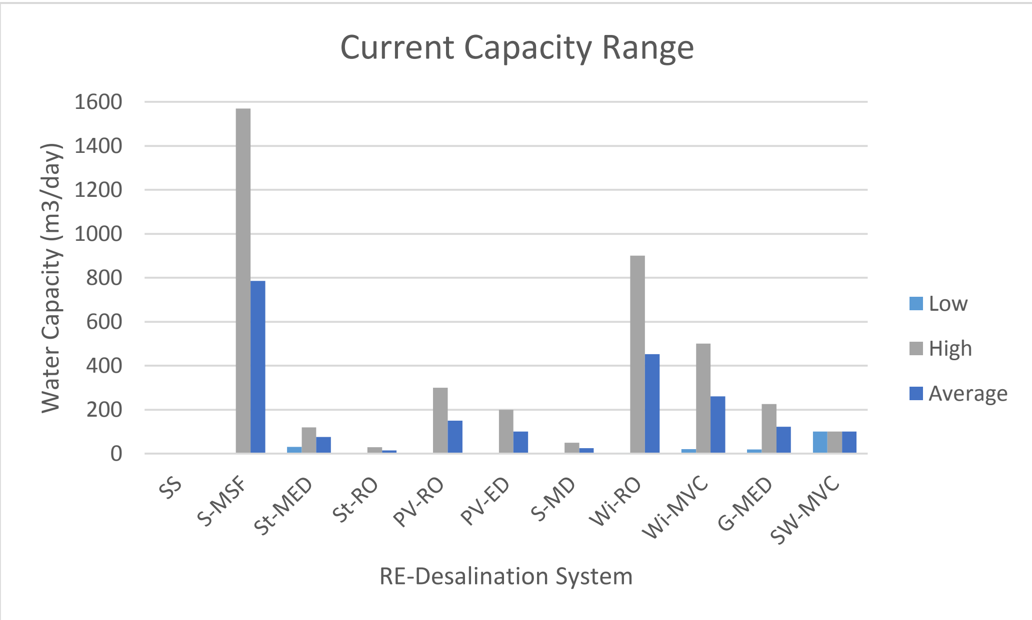

Figure 40: Current capacity range of RE-Desalination systems

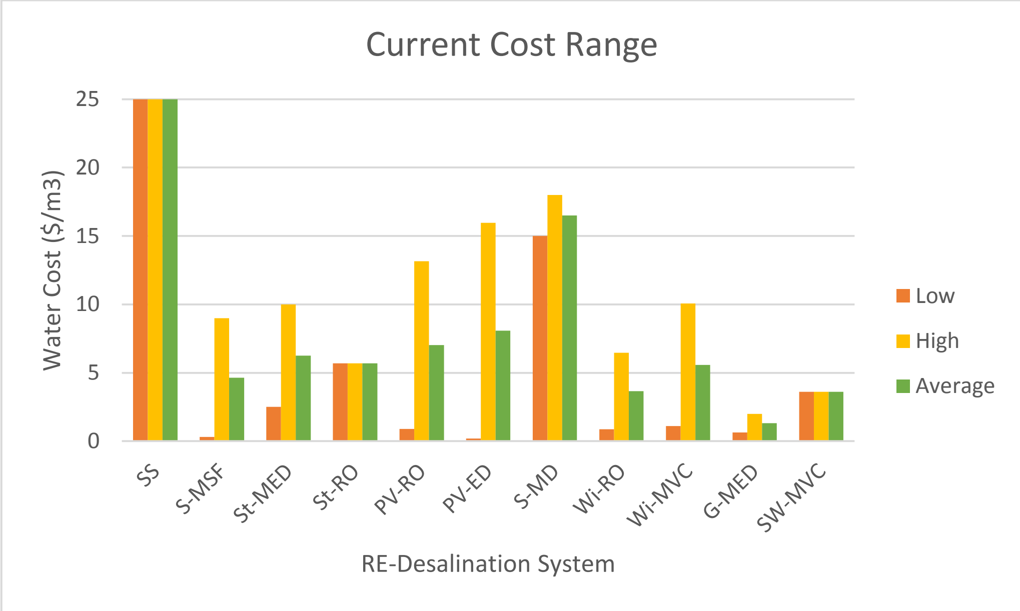

Figure 41: Current cost range of RE-Desalination systems

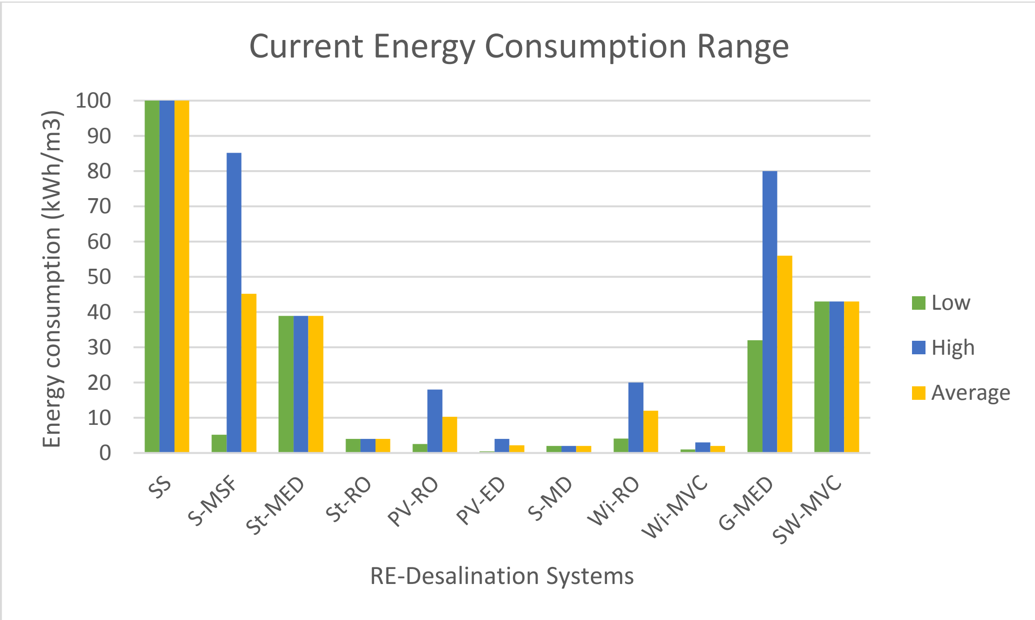

Figure 42: Current Energy Consumption range of RE-Desalination systems

Chapter 5: Results and Discussion

5.1 Introduction

Based on the information collected from the literature review and case study analysis, the following selection matrices have been configured to compare the performances of each desalination, renewable energy, and brine disposal method. The selection matrices serve to quantitatively rank the sustainability performance of each method, illustrating which systems have the best potential to reduce water scarcity moving forward.

A decision tree analysis has also been fabricated to illustrate what questions should be asked in choosing an appropriate desalination, renewable energy, or brine disposal method. This is because a highly ranked system on a selection matrix does not guarantee it is appropriate for all situations and circumstances. Thus, a decision tree analysis helps to filter which methods are best suited for each geographic/socio-economic location.

At the end of the chapter, a range of geographic/socio-economic conditions are listed with a recommendation of which desalination-renewable energy-brine disposal combination is best suited for that condition.

5.2 Selection Matrices

5.2.1 Desalination Methods

In terms of sustainability, the ideal desalination technology should be energy-efficient, technologically reliable, and available at a cheap price. Additionally, the ideal desalination technology should be flexible for all locations and circumstances. The selection matrix below evaluates the ideal performance of these desalination methods based on the following:

- Cost (capital and operating) — 10=low cost; 1=high cost
- Salinity of source water — 10=high salinity; 1=low salinity
- Pre and post treatment requirements — 10=no treatment required; 1=large amounts of treatment needed
- Energy consumption — 10=low energy demand; 1=high energy demand
- Distillate production efficiency — 10=high product water/feed water ratio; 1=low product water/feed water ratio
- Land area requirements — 10=small land area needed; 1=large land area
- Location requirements — 10=flexible location site; 1=specific location
- Capacity size — 10=high water capacity; 1=low water capacity
- Operation complexity — 10=low O&M skills needed; 1=expert O&M skills
- Proven technology — 10=presently operating; 1=research stage

Table 48: Desalination selection matrix

Desalination Technology	MSF	MED	VC	RO	ED	MD	SS	FO	FR	NF
Cost	5	5	5	7	7	4	8	4	4	8
Salinity	9	9	9	7	4	8	9	6	8	1
Treatment	8	7	7	4	5	7	9	4	7	5
Energy	4	6	6	8	8	7	2	8	4	8
Distillate	5	6	7	8	9	9	6	8	6	8
Land area	6	7	7	7	7	7	1	7	6	7
Location	6	7	8	9	7	8	6	8	6	8
Capacity	8	8	5	9	6	7	1	7	7	5
Operation	6	6	7	5	5	6	9	5	5	7
Proven	8	7	7	8	7	2	8	2	2	6
Total	65	68	68	72	65	65	59	59	55	63

As can be noted from the selection matrix above, reverse osmosis is considered to be the most "sustainable" desalination method because of its ability to desalinate water at a large capacity and affordable price. Reverse osmosis can additionally be applied to most circumstances, with flexible location preferences and the ability to treat different water salinities at very low energy demands. However, in areas where RO is too complex to operate, other methods such as MED-VC or ED can be sustainable alternatives. Also, if Membrane Distillation is further developed and tested on a large scale, it may quickly overtake RO as the most sustainable desalination method for the future, as its thermo-electric combination allows high quality water to be produced at extremely low energy demands and simpler operation techniques.

5.2.2 Renewable Energies

The renewable energies in question should first and foremost be compatible with the desalination technologies listed above. The purpose of this investigation is to evaluate which renewable energies are best suited to replace fossil fuels in desalination plants. Thus, it is ideal that these energies be powerful, available, and affordable. The selection matrix below evaluates the following RE characteristics:

➢ Energy production	10=high energy conversion; 1=low energy conversion
➢ Operations complexity	10=low O&M skills needed; 1=expert O&M skills
➢ Geographic availability	10=available everywhere; 1=remote locations
➢ Intermittent availability	10=available 24 hours a day; 1=only few hours
➢ Land area requirements	10=small land area needed; 1=large land area
➢ Cost (capital and operating)	10=low cost; 1=high cost
➢ Proven work with desalination	10=marketed and tested; 1=never tested

Table 49: Renewable Energies selection matrix

Renewable Energy	Human	Hydro	Wave	Geo-thermal	Waste/ Biomass	Wind	Solar CSP	Solar PV	Solar Pond	NCSC
Energy	3	9	5	8	6	7	9	7	6	5
Operations	8	5	5	7	7	7	6	7	8	7
Geography	6	3	5	4	6	7	8	8	8	8
Intermittent	5	9	9	9	7	7	7	7	7	7
Land area	8	7	7	8	7	7	5	6	2	6
Cost	8	8	5	8	7	8	6	7	8	8
Proven	5	3	3	7	7	8	6	9	9	9
Total	43	44	39	51	47	51	47	51	48	50

As can be noted from the selection matrix above, the most sustainable choice for renewable energy is tied between geothermal, wind and solar photovoltaics. The decision to couple RE with desalination is a difficult one to make, as no energy source is constantly available across all areas of the globe at a low affordable price. While combustion, wind and solar power sources have been extensively explored in the past few decades, only recently has work been conducted in acquiring energy from tidal waves. Since most desalination plants are located on the coast and pump feedwater from the sea, installing a nearby wave power plant can be ideal for its constant operation and geographic availability. However, there still remains extensive work to be done, as wave turbines are further developed and tested to meet desalination requirements. Similarly, the same can be said for most renewable energy sources, as research continues to improve the efficiency of these technologies, and large-scale production decreases unit prices.

5.2.3 Brine Disposal Methods

When evaluating brine disposal, the ideal method should be sustainable from an environmental viewpoint, creating the least amount of damage over a long period of time. Similar to RE and desalination, brine disposal methods should aim to be affordable and operational in many different parts of the world. Therefore, the following selection matrix evaluates brine disposal from these simple factors:

- Environmental impact — 10=no adverse effects; 1=high adverse effects
- Location requirements — 10=flexible location site; 1=specific location
- Operations complexity — 10=low O&M skills needed; 1=expert O&M skills
- Land area required — 10=low land area needed; 1=large land area
- Cost (capital and operating) — 10=low cost; 1=high cost

Table 50: Brine Disposal selection matrix

Brine Disposal	Surface Discharge	Submerged Discharge	Evaporation Pond	Deep well Injection	Spray Irrigation	ZLD	Sewers
Environment	3	9	7	6	4	10	7
Location	4	7	6	5	4	9	7
Operations	9	5	8	5	7	4	7
Land area	9	9	3	8	6	9	8
Cost	9	5	7	6	8	3	5
Total	34	35	31	30	29	35	34

As can be noted from the selection matrix above, the most sustainable choice for brine disposal is tied between submerged discharge and zero liquid discharge. Although these processes are the most expensive among brine disposal methods, they offer the safest solution to the environment, which is the main purpose of safe brine treatment. While surface discharge has been practiced for many years and operates simply at a low cost, it can only be the first choice for brine disposal if it does not have any harmful effects on the local environment.

5.3 Decision Tree Analysis

5.3.1 Desalination

Although RO attained the highest score among desalination methods in the selection matrix, this does not guarantee that reverse osmosis is most suitable option for all populations. When choosing an appropriate desalination method, certain questions need to be raised in order to make the right decision. The decision tree in figure 43 below illustrates the thought process that should be considered when choosing a desalination system.

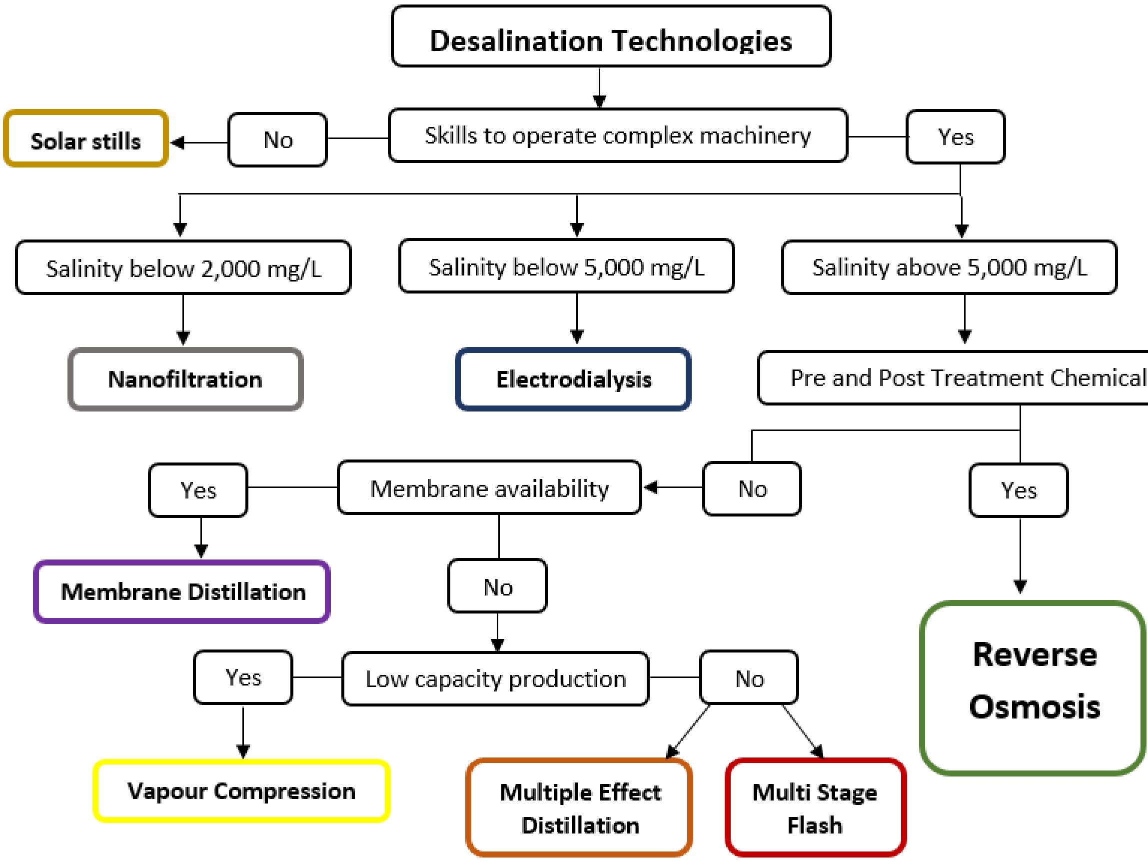

Figure 43: Desalination Decision Tree

As can be noted by the above desalination decision tree, reverse osmosis is appropriate for almost all situations where the salinity level of the source water is above 5,000 mg/L and chemicals are readily available for pre and post treatment. While this constitutes as an affirmative solution for most large-scale desalination plants located by the sea, other inland small-scale projects would benefit from other methods. While it is not marked on the decision tree, it should also be noted that consumers will often base their choice for a desalination method on familiarity. This is often the case for MSF, which has established a firm ground in many countries where it has reliably delivered clean drinking water for decades. In cases where MSF is already prominent, consumers may simply upgrade their plants to include vapour compressors or multiple effects because they are already familiar with thermal-based desalination. Although membrane-based processes (i.e. RO and MD) appear to be the most sustainable choices for desalination moving forward, many decision-makers will often choose to stay with what has worked before, adding simple upgrades rather than starting from scratch.

5.3.2 Renewable Energies

Similarly, the choice for renewable energy is outlined by the decision tree below, which is already notably more complex than the desalination decision tree due to the intermittent nature of renewable energies and their dependence on geographic location.

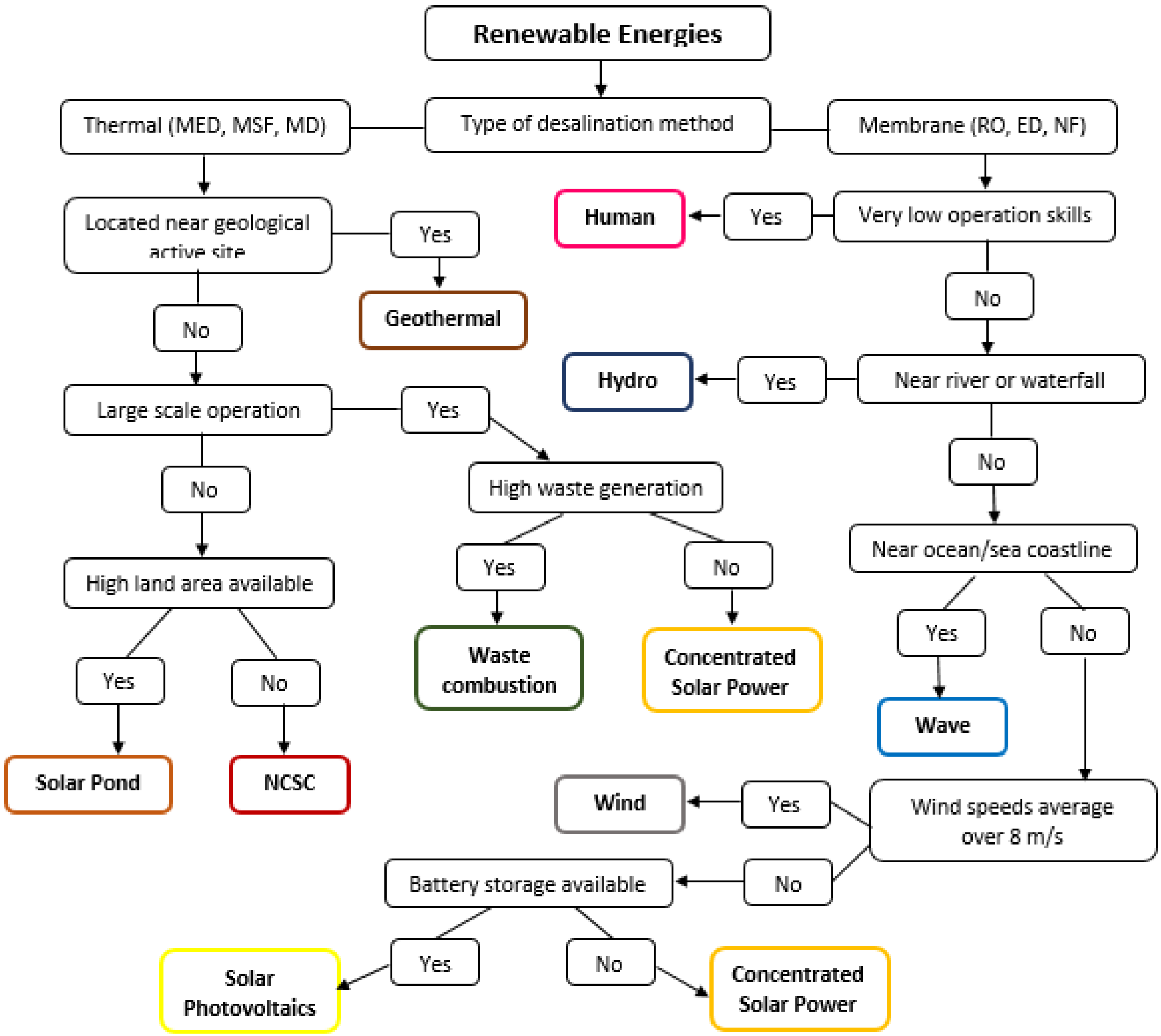

Figure 44: Renewable Energies Decision Tree

As can be seen by both the selection matrix and the decision tree, the choice for renewable energy supply is not straightforward. Solar and wind are perhaps the most commonly present form of energy present on Earth, but even these sources are only available at certain hours of the day. Constant sources such as geothermal and hydropower would be superior alternatives to fossil fuels, but are unfortunately limited to only certain geographic areas. This is why selecting an appropriate renewable energy source for a desalination plant relies primarily on the type of energy demanded by the plant, followed by the location of the plant itself. In some cases, policymakers and engineers may choose to build a renewable energy plant first, replacing fossil fuels as quick as possible and then selecting a desalination plant that caters to the energy provided by the RE plant.

5.3.3 Brine Disposal

Similar to renewable energies, the selection of brine disposal methods is heavily influenced by the location of the desalination plant and its surrounding environment.

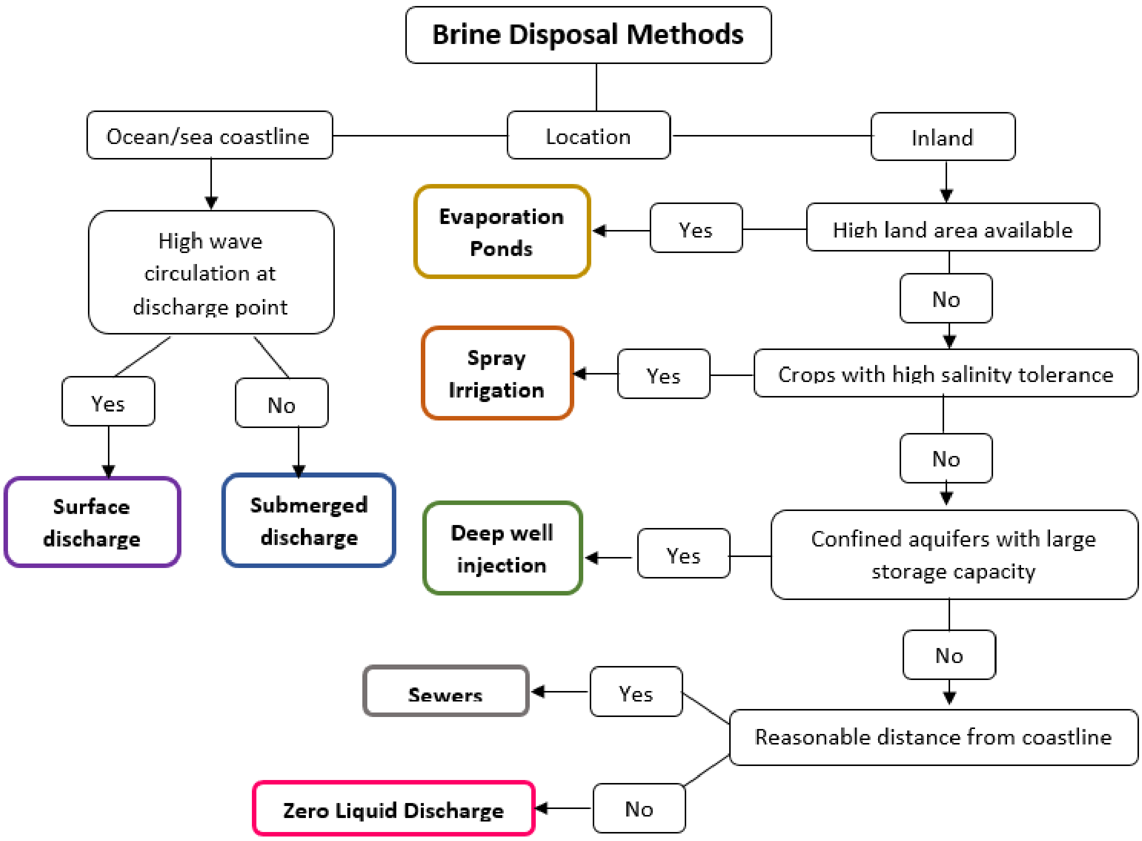

Figure 45: Brine Disposal decision tree

Most desalination plants utilise seawater as opposed to brackish water, and may only need to decide between surface discharge and submerged discharge. In some cases, it may be cheaper to apply ZLD where the capital and operating costs of submerged discharge are far too high. For inland desalination units, brine disposal is a more serious issue that needs to carefully consider the surrounding environment. Taking advantage of certain features such as high salinity crops and confined aquifers can lead to cheap alternative solutions, although most plants would likely resort to evaporation ponds, sewers, or zero liquid discharge.

5.4 Conditions for RE-Desalination and brine disposal

Based on the information gathered from chapters 3, 4 and 5, the following table has been composed, outlining a variety of consumers that can benefit from the combinations of desalination, renewable energy, and brine disposal methods.

Table 51: Conditions for RE-powered desalination and brine disposal

Socio-economic and environmental conditions		Suitable Desalination + Renewable Energy + Brine Disposal	Considerations
1	Low population Low operation skills Low capital investment	Solar Still – evaporation pond	* Surface discharge may also be considered if located close by coast * Hand-powered RO pumps may also be considered
2	Low population Brackish water source Low-medium O&M skills and capital	Solar PV – ED – evaporation pond	* Wind is also viable energy option * NF can also be considered if source is less than 2,000 mg/L * Deep well injection and spray irrigation may also be suitable
3	Low-medium population Isolated island - seawater source Low-medium O&M skills and capital	Solar NCSC – MED/VC – surface discharge	* Solar PV and Solar ponds may be suitable * Wind or Geothermal are also viable energy options * RO may also be considered * ZLD may be suitable if there is market for salt
4	Med-High population Med-High O&M Med-High capital investment	Wind – RO – submerged discharge	* MED/VC may be considered * Solar PV, Geothermal, and waste combustion can also be suitable * If inland, sewers or ZLD are also viable options
5	High population High O&M available High capital investment	Solar CSP – RO – zero liquid discharge	* Geothermal, Hydro/Wave power may also be suitable * MED/VC or MSF can also be considered * Submerged discharge may be suitable if there is no market for salt

As can be seen from the suggestions above, solar and wind are highly recommended as suitable RE sources for the future, with RO as the most popular choice for desalination and ZLD as an environmentally friendly disposal option. As discussed before, solar and wind are highly researched due to their geographic availability across all parts of the world, and although they are intermittent, they are more accessible for different populations. Similarly, RO is a dominant force in the desalination market because of its ability to treat all ranges of saline water, and is flexible on both a small and large scale. On the other hand, ZLD is not the favoured choice for brine disposal for large scale desalination plants (surface discharge is preferred), but for environmental purposes, it may be the best solution for all desalination plants, regardless of location. Once technology advances and ZLD becomes more affordable, it should be coupled with nearly every desalination plant.

Chapter 6: Conclusions and Recommendations

This paper has reviewed all the different desalination technologies, renewable energies, and brine disposal methods that currently exist at both the market and research scale. These technologies have been evaluated and compared in an effort to discover which are most sustainable for the future of desalination. Although some of these systems are currently in operation, there exists a large percentage of desalination plants that continue to operate from fossil fuels, and practice careless methods of brine disposal that harmfully affect the environment.

While the methodology applied may contain holes of information due to time constraints and limited published literature, it nonetheless provides an overview of the sustainable performances of each desalination, renewable energy, and brine disposal method available, which no literature has been able to do before.

6.1 Answering the Research Questions

In order to evaluate the work of this paper, it is best to revisit the research questions postulated from the beginning:

1) **Under what circumstances does desalination become a necessary method of water supply?**
   Section 1.6 of the Introduction covers the reasons why desalination is necessary in today's world, and what conditions merit its use. Although desalination can best be avoided by means of water transport, rainwater harvesting, or wastewater recycling, desalination can prove to be the most reliable solution to water scarcity when all other alternatives are economically unfeasible or physically inexistent.
2) **Which desalination methods are most energy-efficient, environmentally friendly, and affordable? Are there some desalination methods that we can already eliminate moving forward?**
   Table 22 in section 3.1.5 compares each of the current desalination methods to each other, listing important characteristics such as energy consumption, cost, and distillate production efficiency. Additionally, Table 48 in section 5.2.1 quantitatively ranks the performances of each desalination method, awarding reverse osmosis as the most "sustainable" desalination technology, followed by MED, VC, ED, MD, and MSF. Admittedly, it was difficult to measure environmental friendliness with desalination methods, as all desalination units produce brine at varying quantities and concentrations.
   When evaluating the future of desalination, methods such as freezing and nanofiltration can essentially be eliminated from consideration. Freezing requires complex machinery to handle ice at different scales, and nanofiltration can only be effective for a small range of saline sources (less than 2,000 mg/L), rendering it useless as a stand-alone desalination system.

Additionally, VC is suggested to be best applied as a compliment to MED or MSF, although it can still operate independently for small to medium scale populations. Forward Osmosis is at a very limited stage in its research, and while it shows some benefits when compared to RO, it also contains drawbacks that prevent FO from competing against major desalination methods in the future.

3) **Which renewable energies present the most promise for the future of desalination? Can these renewable energies be as reliable and affordable as fossil fuels?**
   While Table 26 summarises the advantages and disadvantages of each renewable energy, the selection matrix in Table 49 ranks the RE options against each other, awarding Geothermal, Wind, and Solar PV as the most "sustainable" sources of power for desalination moving forward. However, other sources of renewable energies such as Hydropower, solar CSP and waste combustion may be more appropriate for certain areas, depending on the geographic location and energy demand of the desalination plant.
   While there is no single renewable energy that can substitute fossil fuels for all desalination plants, certain RE sources can provide cheaper, more reliable power than fossil fuels according to the conditions of the desalination facility (see Figure 44 for selecting appropriate renewable energies).

4) **What are the most environmentally safe and sustainable methods of brine waste disposal moving forward?**
   Table 27 lists the advantages and disadvantages of each brine disposal method, while Table 50 ranks the brine waste disposal options, selecting ZLD and submerged discharge as the most environmentally safe and sustainable methods. Although these methods are expensive, they guarantee that the brine produced from desalination plants are dealt properly without any harmful effects.

5) **Under what socio-economic and environmental conditions does each RE-powered desalination method become an appropriate means of water supply?**
   Chapter 4 analyses current case studies of RE-powered desalination systems, with Tables 29 – 46 summarising the performance characteristics and suitable operating conditions of each combined system. Table 51 in section 5.4 also lists a variety of socio-economic and environmental conditions, from small developing rural areas to highly populated cities, matching suitable combinations of desalination, renewable energy and brine disposal methods to each condition.

6.2 Recommendations

The following lists a number of recommendations that can be made for scientists and engineers to improve the future outlook of desalination:

1) ***More research and development of wave tidal power***

Scientists have only recently begun studying the possibility of converting wave/tidal power to electricity, and thus far, very few pilot projects have been implemented. While it is important that research continues to improve the performance of solar and wind machines, attributing an equal amount of attention to wave power turbines could offer a constant source of power (24 hours a day) for many desalination facilities located close to the sea. If wave power is harnessed successfully at an affordable price, it could easily replace fossil fuels as the main source of energy for large-scale desalination plants.

2) ***More research and development of Membrane Distillation***

Researchers and engineers have given positive remarks for the initial results that Membrane Distillation has displayed. A combination of thermal distillation and membrane processes, MD has offered the benefits of both types of desalination, while minimising the weaknesses. In recent years, scientists have claimed that Membrane Distillation could surpass RO in the desalination market, but the amount of attention given to the technology has not been sufficient to increase its growth. If more R&D were assigned to help overcome the flaws of MD and improve its production costs, it could quickly overtake the desalination market, offering better performance standards than its competitors.

3) ***More research to study the harmful effects of brine disposal on the environment***

For many years, desalination experts believed that returning brine to the sea was a natural process that had no adverse effects on the environment. However, recent studies have shown decreased growth in many local species in Spain, and there remains questions about the detrimental effects that desalination has caused in other parts of the world. Therefore, more studies need to be conducted to discover what effects brine disposal has on its local environment, and research the long term effects of such reckless practices. Additional research can not only raise awareness about the harmful effects of open brine waste, but can also help engineers design appropriate methods of brine disposal that are released back to the environment in a healthy, safe manner.

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Appendix

Ethical Checklist