

UNIVERSIDADE DE LISBOA  
FACULDADE DE CIÊNCIAS  
DEPARTAMENTO DE ENGENHARIA GEOGRÁFICA, GEOFÍSICA E ENERGIA



# Renewable Energy Powered Desalination Systems: Technologies and Market Analysis

Francisco Diogo Abreu Santos Moniz Azevedo

**Dissertação de Mestrado Integrado em Engenharia da Energia e do Ambiente**

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**Orientador: Prof. Doutor Jorge Maia Alves**

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## **Abstract**

Water desalination is becoming a cost-effective solution to combat water scarcity in various areas of the planet. However, desalination is an energy-intensive process and most of the world's plants are currently powered by conventional energy production. As the costs of fossil fuels increase, their operation becomes increasingly expensive and with the additional costs of pollution and greenhouse gas emissions. Hence, the integration of renewable energy production with desalination is increasingly attractive. This thesis explores renewable energy-powered desalination technologies and how they can represent a sustainable solution to resolve water scarcity in diverse areas of the planet.

**Keywords:** Desalination; Renewable Energy; Water Scarcity;

## **Resumo**

A dessalinização de água está a tornar-se uma solução economicamente viável para combater a escassez de água em várias regiões do planeta. No entanto, este processo consome bastante energia e a maioria das centrais mundiais são atualmente alimentadas por fontes de energia convencional. Com o custo dos combustíveis fósseis a aumentar, a sua operação torna-se cada vez mais onerosa e com as dificuldades adicionais da poluição e das emissões de gases de efeito estufa. Assim, a integração da produção de energias renováveis com a dessalinização é cada vez mais atraente. Este trabalho explora tecnologias de dessalinização alimentadas por energias renováveis e como estas podem representar uma solução sustentável para resolver a escassez de água em diversas regiões do planeta.

**Palavras-Chave:** dessalinização; energias renováveis; escassez de água;

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## List of Acronyms

AC-DC	Alternating Current To Direct Current
BW	Brackish Water
BWRO	Brackish Water Reverse Osmosis
CPV	Concentrated Photovoltaic
CSP	Concentrated Solar Power
DC	Direct Current
DC-AC	Direct Current To Alternating Current
ED	Electrodialysis
FCUL	Faculty of Sciences University of Lisbon
FO	Forward Osmosis
IFPRI	International Food Policy Research Institute
IRENA	International Renewable Energy Agency
IWMI	International Water Management Institute
KACST	King Abdulaziz City For Science And Technology
MD	Membrane Distillation
MED	Multi Effect Distillation
MENA	Middle East And North Africa
MIEEA	Mestrado Integrado em Engenharia da Energia e do Ambiente
MSF	Multi-Stage Flash Distillation
MVC	Mechanical Vapour Compression
LCOE	Levelized Cost of Electricity
OECD	Organization For Economic Cooperation And Development
PV	Photovoltaic
RE	Renewable Energy
RECs	Renewable Energy Certificates
RO	Reverse Osmosis

SDAWES	Sea Desalination Autonomous Wind Energy System
SW	Seawater
SWRO	Seawater Reverse Osmosis
TBT	Top Brine Temperature
TFC	Thin Film Composite
TVC	Thermal Vapour Compression
TWC	Total Water Cost
UAE	United Arab Emirates
UK	United Kingdom
UN	United Nations
UNESCO	United Nations Educational Scientific And Cultural Organization
US	United States
USA	United States Of America
VC	Vapour Compression

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## 1. Introduction

Water is an abundant natural resource, as approximately three-quarters of the planet is covered by it. However, 97.5% of this resource is comprised by saline water, leaving only 2.5% of fresh water [1]. Moreover, almost two-thirds of this freshwater is inaccessible, since it's in the form of ice and snow in the Antarctic, arctic islands and mountainous regions. This results in less than 1% of the global water resource being accessible freshwater.

Recognizing the importance of water for sustainable development, the United Nations declared 2005-2015 the "Water for Life" decade. This year water crises ranked as third on the world's top ten risks, according to a report from the World Economic Forum based on concern, likelihood, impact and interconnections [2]. Indeed, water is crucial for social and economic development. Yet evidence points to the fact that the current use of water is unsustainable [3]. Growing demand for water resources due to population growth and evolving consumption patterns has increased water scarcity, amplifying the pressure on the natural resource and the ecosystem. The global population is expected to reach 9.3 billion by 2050 [4]. This growth will increase the urban areas of the planet and the need for drinking water, health and sanitation, as well as energy, food and other goods and services that require water for their production and delivery. Agricultural water consumption, which is a significant cause of water scarcity, is expected to increase 20% by 2050 [4]. This increase in demand will occur particularly in countries undergoing accelerated economic growth and social development. Domestic and industrial water demands are also expected to increase. A *Mckinsey & Company* Report (2009) estimated a 40% disparity, by 2030, between demand of water and a supply that is accessible, reliable and sustainable, if there are no efficiency gains until then [5]. This water scarce future represents a critical challenge to civilization.

Desalination of salt water and brackish water is a solution that can help reduce current and future water scarcity. However, desalination is an energy-intensive process. Diverse desalination technologies require different amounts of energy. Fossil fuels are currently utilized to supply most of the energy requirements. However, this leaves the desalination process vulnerable to global market prices and logistical supply issues. Furthermore, utilizing fossil fuels represents an unsustainable solution that increases environmental harm. This work will attempt to ascertain if powering desalination systems with renewable energy sources represents a viable solution. To achieve this, the various desalination technologies powered by renewable energy systems will be explored through literature review. Furthermore, the markets for RE-powered water desalination will also be evaluated through various secondary data sources.

## 1.1 Water Scarcity

Water scarcity is an issue that currently affects every continent on the planet. Water scarcity occurs when, in a particular time period, water demand nears or exceeds water availability. As stated, water scarcity depends, among other factors, on the requirements of the local population. Yet demand varies widely depending on the area of the globe: the average individual from Europe or the United States requires between 200 and 600 litres while an individual from the African continent only uses 30 to 40 litres per day.

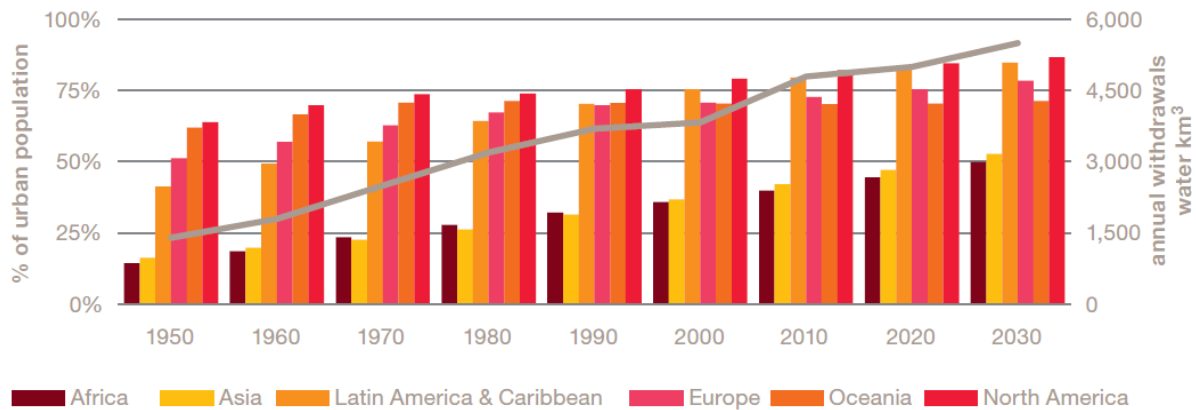


Figure 1: Trend in population density and water consumption [6]

Data on water withdrawal and consumption is frequently based on estimates rather than actual measurements. Water withdrawal is the total amount of water taken from a lake, river or aquifer for any purpose. Water consumption is the fraction of withdrawn water that is lost in transmission, evaporation, absorption or chemical transformation, or otherwise made unavailable for other purposes as a result of human use [4]. At present agriculture represents approximately 70% of total freshwater withdrawals globally, with the industrial sector representing 20% and the domestic sector 10%. Furthermore, the energy sector is responsible for 75% of the freshwater withdrawal in the industrial sector. More-developed countries tend to have a much larger proportion of freshwater withdrawals for industry, while in less-developed countries agriculture leads the consumption of water, more. In the latter, agriculture can account for more than 90% of freshwater withdrawals [4]. According to the Organisation for Economic Co-operation and Development (OECD), global water withdrawals are expected to increase by 55%, caused by increases in demand from manufacturing (400% growth), thermal electricity generation (140%) and domestic use (130%). This increase in demand will occur particularly in countries undergoing accelerated economic growth and social development such as Brazil, Russia, India, Indonesia, China and South Africa. Demand from the energy sector is expected to increase (as energy demand is expected to increase) with 90% of this demand again coming from countries outside the OECD. According to the same source, freshwater availability will be increasingly strained through 2050, if no new policies are introduced, with an increase of 2.3 billion people living in areas subjected to severe water stress, especially North and South Africa and South and Central Asia.

Currently, about 2.8 billion people live in areas that face water scarcity. Of these, 1.2 billion live in areas that suffer from physical water scarcity, while 500 million are approaching this state. Physical water scarcity occurs when the water resource in a given location is insufficient to meet the demand. Arid regions are frequently characterized by this type of water scarcity. Other regions are currently seeing artificially created physical water scarcity due to overdevelopment of water withdrawal, which leads to environmental degradation: river desiccation and declining groundwater tables. The other 1.6 billion facing water scarcity suffer from economic water scarcity. They live in areas where water is accessible in nature but distribution infrastructure, institutional or financial issues limit access to it, although the water resource available is enough to meet human demand. This is the case of, for example, Sub-Saharan Africa [7]. Different models attempt to evaluate water scarcity quantitatively. The main types of models consider the relation between water availability to human requirements or the amounts withdrawn to the renewable water supply. A model that shows areas of the planet that suffer from water scarcity can be observed in figure 2. This model, *Watersim*, was produced by the International Water Management Institute (IWMI) and the International Food Policy Research Institute (IFPRI), on a joint modelling exercise.

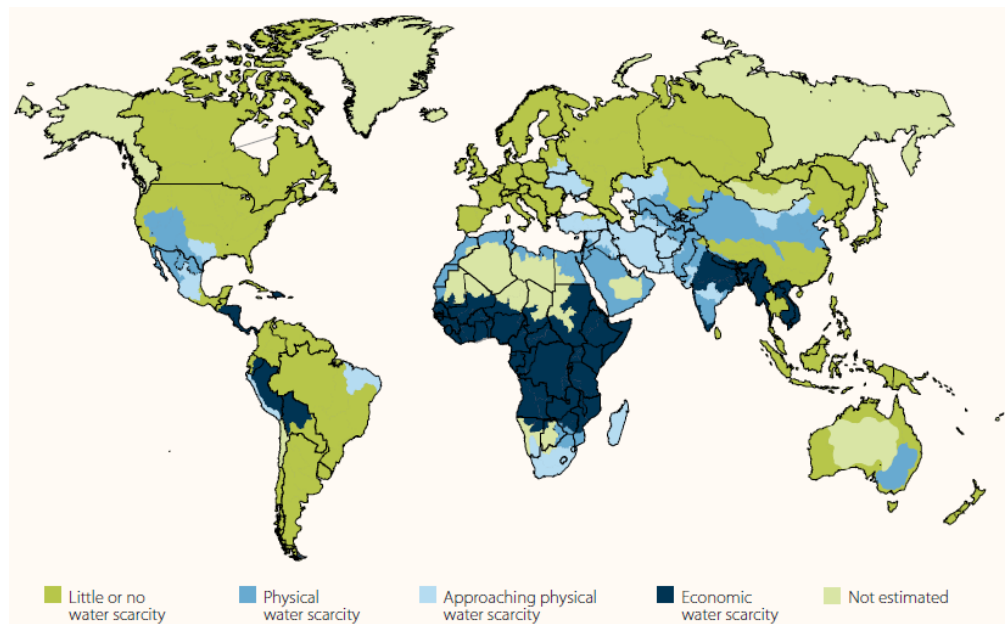


Figure 2: Physical and Economic surface water scarcity (2007); [7] as in [4]

In this model the areas with little or no water scarcity were considered as utilizing less than 25% of the water runoff from rivers. The areas that were approaching water scarcity utilize more than 60% of the river flows and were expected to experience physical water scarcity in the near future. The areas that suffered from physical water scarcity used more than 75% of the river flows for agriculture, industry and domestic use. Finally, the areas that endured economic water scarcity also utilized less than 25% of the water available in river flows. As the figure indicates, almost every continent is affected by water scarcity. The most affected areas of the globe are the Middle East and North Africa (MENA), while continents such as America, Asia and Australia also suffer to a lesser degree.

A different study by *Rost et al* considered the percentage of the population that will be water stressed in the future [8]. The outcome, which can be observed in the next figure, again suggests that the MENA region is the most affected, along with other areas such as Asia and Central America.

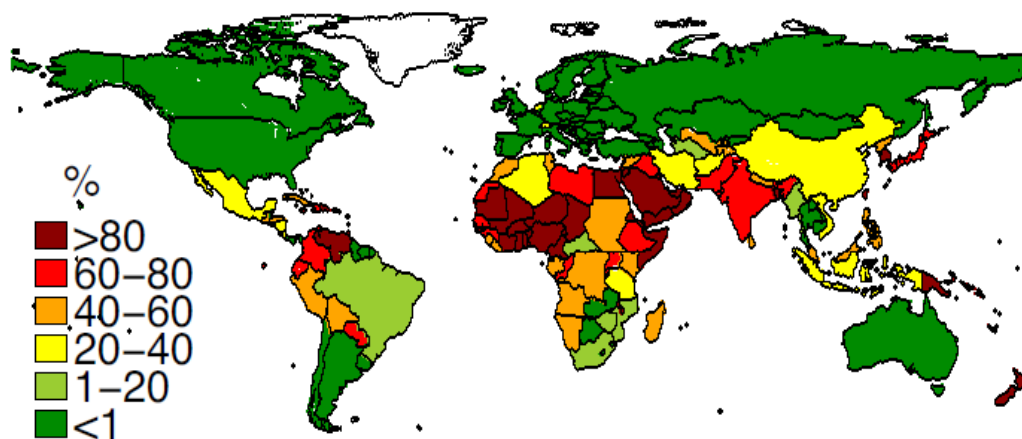


Figure 3: Percentage of country populations that will be water stressed in the future [8]

Regarding water availability, while data on precipitation is generally available, river runoff and groundwater levels are more difficult and costly to monitor. In Figure 4 the actual state of renewable water resources in 2011 can be perceived. Renewable water is the total amount of a country's water resources (internal and external resources), both surface water and groundwater, which is generated through the hydrological cycle. Non-renewable water resources are deep aquifers that have a negligible rate of recharge on the human time-scale. This data was collected from AQUASTAT - water information system, developed by the Land and Water Division of the United Nations.

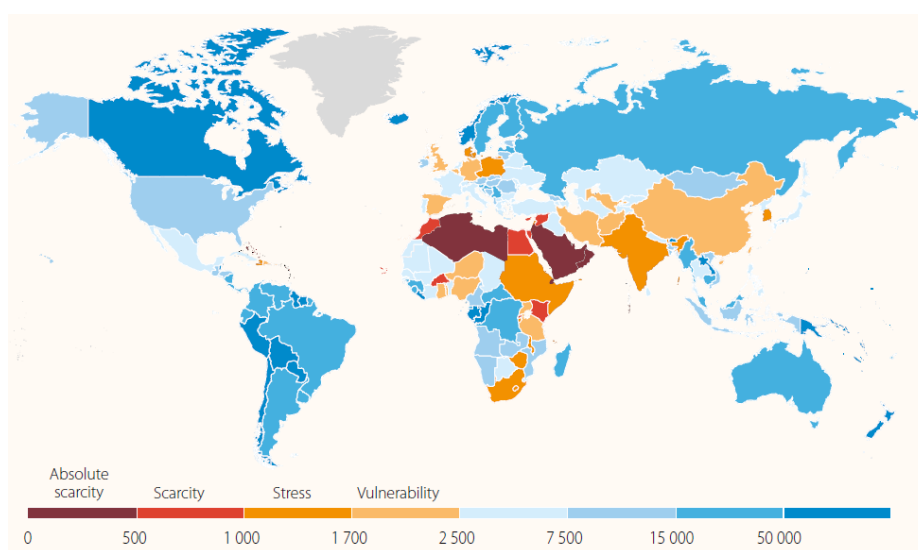


Figure 4: Actual renewable water resources (in m3) per capita and per year, in 2011 [4]

Furthermore, according to the latest World Water Development Report, until 2050 the majority of the globe will see their renewable water resources decrease, with particular concern to the already low resources of Africa and Asia. (Figure 5).

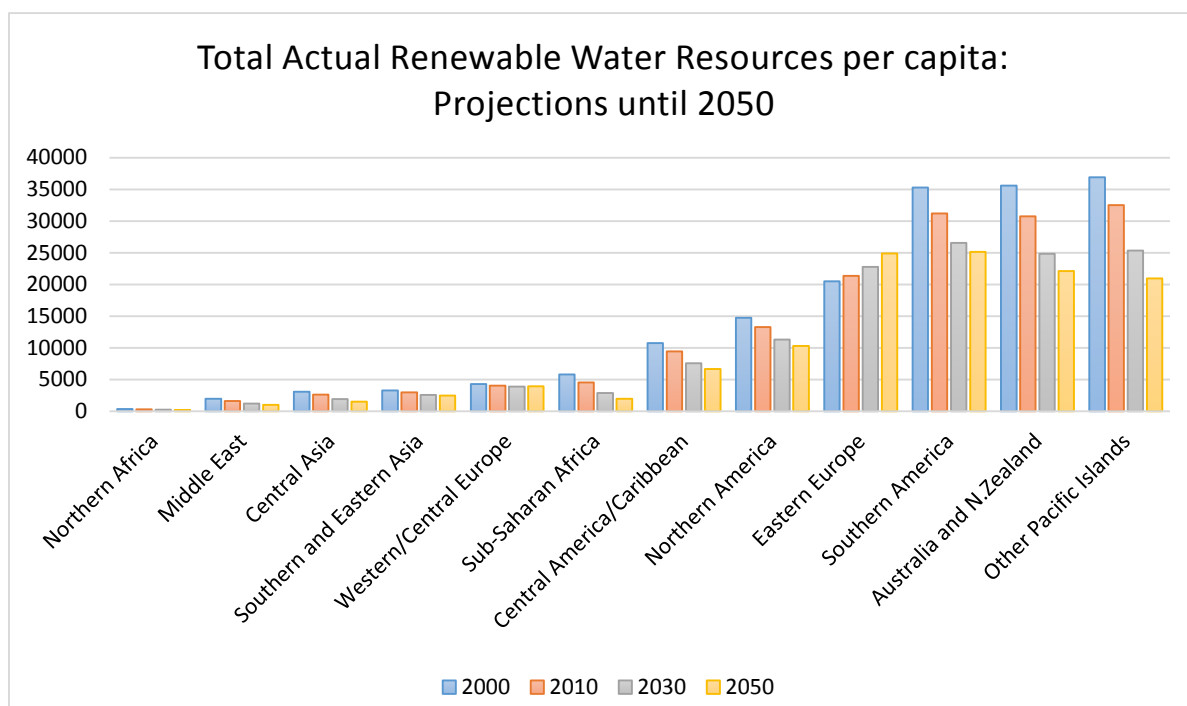


Figure 5: Total Renewable Water Resources (m3 per capita): Projections until 2050 [4]

As a final point, decline in groundwater levels is also a symptom of water scarcity. In various areas of the world groundwater is an important source of water. According to the UN, groundwater withdrawals have increased 300% in the last 50 years. In some areas, groundwater extraction already exceeds natural recharge rates. A recent study by *Wada et al* showed that groundwater depletion rates have more than doubled between 1960 and 2000 in sub-humid and arid areas, particularly in parts of China, India and the United States of America [9]. In some areas of the planet, like the coastal areas of Bangladesh, even these freshwater resources are not available at suitable depths, due to high salinity in groundwater resources [10].



## 1.2 The Energy-Water Nexus

Water and energy have a mutually dependent relationship. While conventional energy production (coal, natural gas and nuclear power plants) processes require noteworthy amounts of water, it is also true that obtaining water, transporting and treating it requires significant amounts of energy. This interdependency leads to choices in one domain affecting direct and indirectly the other.

Water requires energy for two reasons: pumping and treatment. The energy needed for pumping is determined by the elevation change that is required and also by the distance, diameter and friction of the pipe. As for the energy required for treatment, it varies depending on the type and quality of the source of water, the nature of the contaminant, the intended use for that water and consequently the types of treatment utilized. Therefore, depending on the source of water, the energy required to deliver 1m<sup>3</sup> of water for human consumption varies as is presented in table 1. Surface water is usually the least energy-intensive, if it is close to delivery point. Groundwater requires more energy since it has to be pumped to the surface. If the groundwater is brackish it will also require energy for treatment, depending on the level of total dissolved solids in the water. Finally, seawater desalination is the more energy intensive in this scale, with the energy required being a function of the temperature and salinity of the water [4].

Table 1: Energy required to deliver 1m<sup>3</sup> of water for human consumption from various water sources [3]

Source	Energy required (kWh/m <sup>3</sup> )
Lake or River	0,37
Groundwater	0,48
Wastewater treatment	0,62 - 0,87
Wastewater Reuse	1 – 2,5
Seawater Desalination	2,5 – 8,5

Furthermore, while water treatment processes such as ultraviolet light require little energy (0.01-0.04 kWh/m<sup>3</sup>), other more complex techniques such as reverse osmosis require higher amounts of energy (1.5-4 kWh/m<sup>3</sup>). In contrast, water for agriculture generally requires little or no treatment, since in this situation pumping is the major energy requirement [4]. In terms of costs, electricity costs represent 5 to 40% of the total operating costs of water and wastewater utilities, depending on the location [4]. This costs will tend to increase, as cities expand further and their water needs increase. Consequently, energy will have direct influence on availability and affordability of water.

Looking at the Energy-Water nexus from the other perspective, the International Energy Agency estimated global water withdrawals for energy production in 2010 at 583 billion m<sup>3</sup> (15% of total world withdrawals). The quantity of water required for energy production is determined by the energy production method. Figure 6 depicts typical ranges for water withdrawal and consumption by fuel source (on the right) and the water usage of different energy production technologies (left) during operation phase.



Figure 6: Water footprint of energy generation by fuel; Water use for electricity generation by cooling technology [4]

From the ranges provided by the previous figure, it can be concluded that renewable energy sources typically have a smaller water footprint compared to conventional fuel sources, but also a wider range for possible water footprint, while the water footprint of conventional fossil fuel plants is well defined within a small range. Wind energy water consumption is the lowest, using virtually no water in its process. Solar photovoltaic water footprint crucially depends on the cleaning method that is utilized, thus it presents a wide range for possible water footprint.

As for the water consumption of concentrated solar power (CSP), it is higher than that of solar PV, and the water footprint range is also wider. This fact is problematic because CSP plant locations typically coincide with regions that are water scarce. The wide range of water consumption in CSP is due to different reasons. There are four primary CSP plant designs: parabolic trough; linear Fresnel, power tower and dish/Stirling. All designs need a small quantity of water for mirror washing. The first three of them utilize a Rankine steam cycle and thus require water to operate, for steam and cooling, similarly to water-cooled fossil and nuclear power plants. However, the cooling can also be provided via air

cooling, greatly reducing the water consumption, although this option is less efficient and it requires more capital investment. Lastly, the Stirling dish only requires water for mirror washing [11]. In the table below typical water consumptions for solar CSP and solar PV are presented.

Table 2: Typical water consumption of Solar CSP and Solar PV [11]

Technology	Liters/MWh
Estimate for Ivanpah solar-thermal (air cooled)	60
Solar parabolic trough (air cooled)	295
Solar power tower (evaporative)	2270
Solar parabolic trough (evaporative)	3028
Dish Stirling	75
Solar photovoltaic with water panel washing / dry cleaning	115 / 0

The water consumption required for cleaning, both in PV and CSP, can be diminished if the maintenance procedure of cleaning the panels is accomplished without water. While eliminating the water footprint of PV power plants is crucial, the cleaning process must be assured, since the accumulation of dust particles has been shown to greatly affect the performance of the solar photovoltaic panels [12]. In order to achieve this goal companies began implementing automated, waterless cleaning processes. The *Ketura Sun* PV power plant, from *Arava Power*, is an example of this current effort. The 4,95MW power plant (the first in Israel) was originally cleaned manually, consuming water in the process. However, since March of 2014, the company decided to fully automate the cleaning process by using a robot that requires no water. The robot, developed by Israeli start-up *Ecoppia*, performs the cleaning process during the night, charging itself during the day. At this particular power plant, comprised of 18,200 panels, this cleaning process is performed under 60 minutes. According to *Arava Power's* CEO Jon Cohen, the new process is more cost effective, comparing to the previous cleaning method [13].

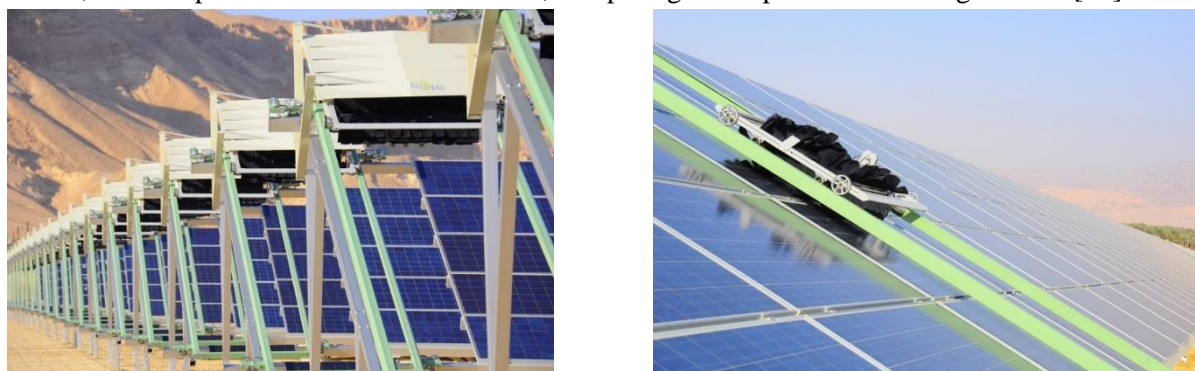


Figure 7: Dry and automated cleaning at *Ketura Sun* [13]

In contrast, the water consumption utilized in conventional fossil fuel power plants is far higher. This poses a challenge in many countries, especially in water scarce regions. A recent set of studies conducted by a group of researchers from Aarhus University in Denmark, Vermont Law School and CNA Corporation concluded that by 2040 countries such as India, China or France will not have enough freshwater resources for conventional electricity generation to meet electricity demand [14].

## 2. Desalination Technologies

Desalination refers to the wide range of processes that effectively separate dissolved minerals, including but not limited to salts, from seawater or brackish water and, by doing so, produce potable water with low percentage of total dissolved solids. The idea of separating salt from water is ancient, dating from the time where salt was a precious commodity, and when distillation of seawater during sea voyages was needed. The first location to see a major commitment to desalination was the island of Curaçao, the Netherlands Antilles, in 1928. In 1938, the first large-scale desalination plant was built in Saudi Arabia. Later, during World War II, considerable research was conducted by the USA and other countries to meet military needs for fresh water in water scarce regions. During the 60's and 70's this effort was kept by the US and other countries like Japan, that dedicated research funds to achieve advances in membrane technologies such as Electrodialysis (ED) and Reverse Osmosis (RO). In 1963 Loeb and Sourirajan from the University of California developed the first synthetic reverse osmosis membranes. At this time, and throughout the 60's, most of the world's seawater desalination capacity was in the Middle East and being met with multistage flash (MSF) technology. However, during the next decade, larger commercial RO and ED systems began to be utilized. During the last 20 years investment in the desalination sector has increased, as countries needed to enhance natural water supplies in response to growing demand. According to the International Desalination Association (IDA) plant inventory, in 1992 worldwide desalination capacity was about 16.5 million m<sup>3</sup>/day and in 2007 this number had grown to 47.6 million m<sup>3</sup>/day. Currently there are more than 15000 desalination plants worldwide, guaranteeing a total capacity of 74.8 million m<sup>3</sup>/day and nearly 60% of the water used in these plants is seawater.

Desalination technologies can be divided in two main categories: thermal desalination and membrane desalination. For thermal desalination there are three key commercial technologies: multi-stage flash distillation, multiple-effect distillation and vapour compression. For membrane desalination there are three main technologies: Electrodialysis (ED), Reverse Osmosis (RO) and Membrane Distillation (MD), although MD is not commercially available. Table 3 summarizes these desalination technologies. In addition there are other emerging technologies such as forward osmosis, which are still in research and development stage. Others with less production capacity, such as solar stills, will be reviewed in the next chapter.

Table 3: Main commercial desalination technologies

Thermal Desalination	Membrane Desalination
Multi-stage flash	Electrodialysis
Multiple-effect distillation	Reverse Osmosis
Vapour Compression	Membrane Distillation

## 2.1 Thermal Desalination

Thermal desalination, also known as thermal distillation, is based on the processes of evaporation and condensation: distillation processes where saline water is heated to vaporize, causing fresh water to evaporate and leaving a saline solution as by-product, brine. The vapour is then cooled and condensates in a different heat exchanger, hence creating freshwater. As previously stated, there are three leading thermal desalination technologies: multi stage flash (MSF), Multi Effect Distillation (MED) and Vapour Compression (VC). Furthermore, VC encompasses two types: mechanical (MVC) and thermal (TVC).

Thermal desalination processes require two forms of energy for operating: heat, which represents the highest share of the energy input, and electricity. The exception is MVC which only requires electricity.

### 2.1.1 Multi-Stage Flash

MSF requires thermal energy in the form of low-pressure bleed steam for feed-brine heating and also medium-pressure steam for ejectors that generate vacuum in different sections of the unit. Electricity is also required by the various pumps.

The process is comprised by different stages: saline water is heated between 90-110 C° and the pressure is decreased in stages. Throughout the stages (4 to 40), with successively lower temperature and pressure, part of the seawater quickly vaporizes (flashes) while the remaining continues to the following stages. The vapour then condenses as fresh water. The flashing process forms scales and deposits on the tubes, requiring periodic cleaning. Since the intake seawater can be heated by by-product heat or waste heat, it is often used in conjunction with energy sources such as fossil-fuel boilers and back-pressure steam from turbines in power stations, making it cost effective and energy efficient [15].

Currently MSF is the second most installed desalination process worldwide, after reverse osmosis, with production capacity typically ranging between 10.000 and 35.000 m<sup>3</sup>/day [16].

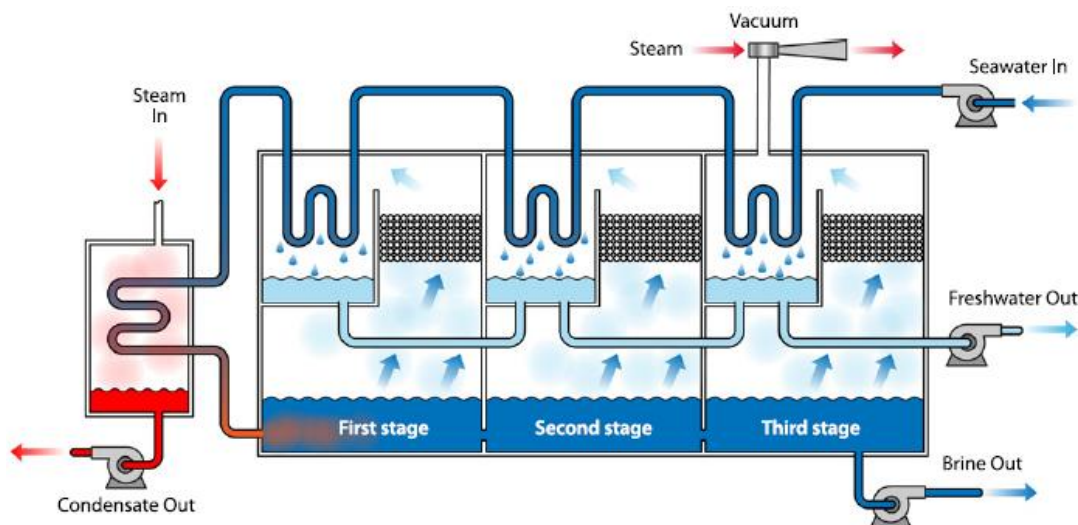


Figure 8: Diagram of MSF process [16]

### 2.1.2 Multi Effect Distillation

MED is also a multi-stage process in which vapour from each vessel is condensed in the following vessel and vaporized again at reduced ambient pressure. At the first stage, that is kept at low temperature, external heat is supplied to increase the brine temperature to around 70° C. The vapour is then transferred through a tube to the second stage vessel and the process repeats itself in series. The horizontal tube where the seawater is sprayed (on the outer surface of the tube) has vapour flowing inside, where it condensed.

MED production capacity typical range is between 600 and 30.000 m<sup>3</sup>/day. MED was employed prior to MSF, however MSF became the preferred technology because it can use low-quality steam rejected from power cycles of large scale cogeneration power plants [17]. Some researchers claim that MSF is not as thermally efficient as MED, while others do not see clear advantages of MED over MSF, other than the thermal losses that are lower in MED due to its lower operating temperature [17]. Furthermore, MED systems are more flexible and inexpensive, and less sensitive to scaling [18].

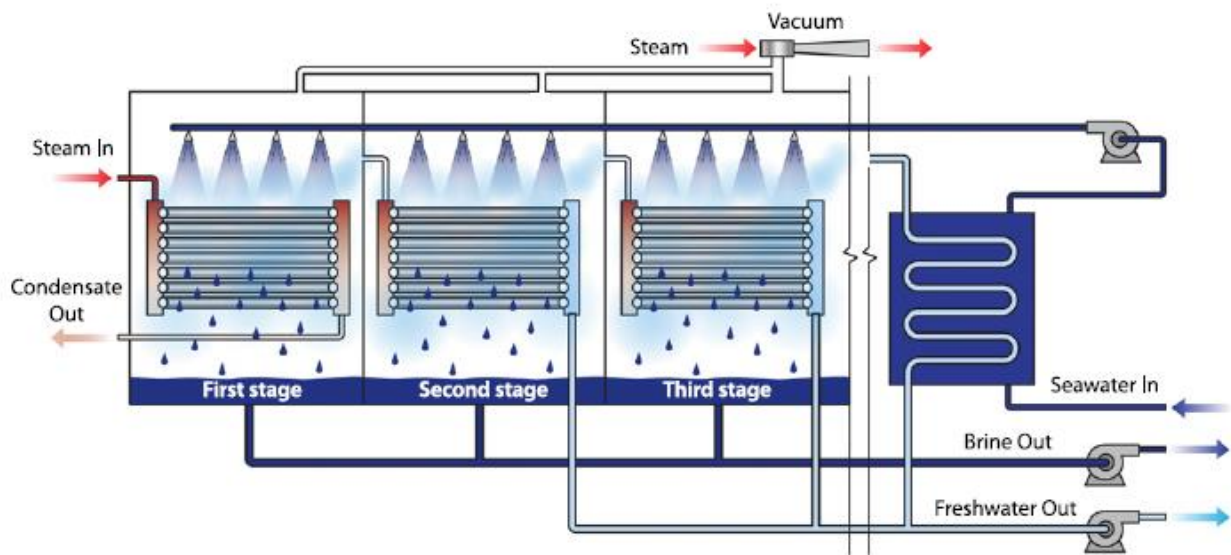


Figure 9: Diagram of MED process [16]

MED is believed to be a superior option over MSF. The reason is that MSF uses seawater feed as the coolant, meaning it uses sensible heat to recover the latent heat from the distilled water. Consequently MSF requires large amounts of seawater recirculating within the system and consumes more electricity than MED [17]. This way, MED has higher overall efficiency and less water recycling. Moreover, the lower operating temperature of MED reduces scale formation and corrosion and does not require water pre-treatment. On the other hand, research indicates that MED consumes more energy than MSF when high-pressure steam is utilized [17].



Figure 10: Fujairah F2 MED plant in United Arab Emirates

### 2.1.3 Vapour Compression

VC is a process in which the heat for water evaporation is derived from compression (instead of direct heating). The feed water enters through a heat exchanger and vapour is generated in the evaporator. Subsequently, the vapour is compressed, either by mechanical (MVC) or thermal means (TVC). The compression increases the vapour's temperature so that it serves as the heat source for the evaporator. The brine flow is also split, with a portion being mixed with the incoming feed water.

VC production capacity typical range is between 100 and 3000 m<sup>3</sup>/day for MVC and 10,000 and 30,000 m<sup>3</sup>/day for TVC. VC is often used in combination with other processes such as MED to improve overall efficiency.

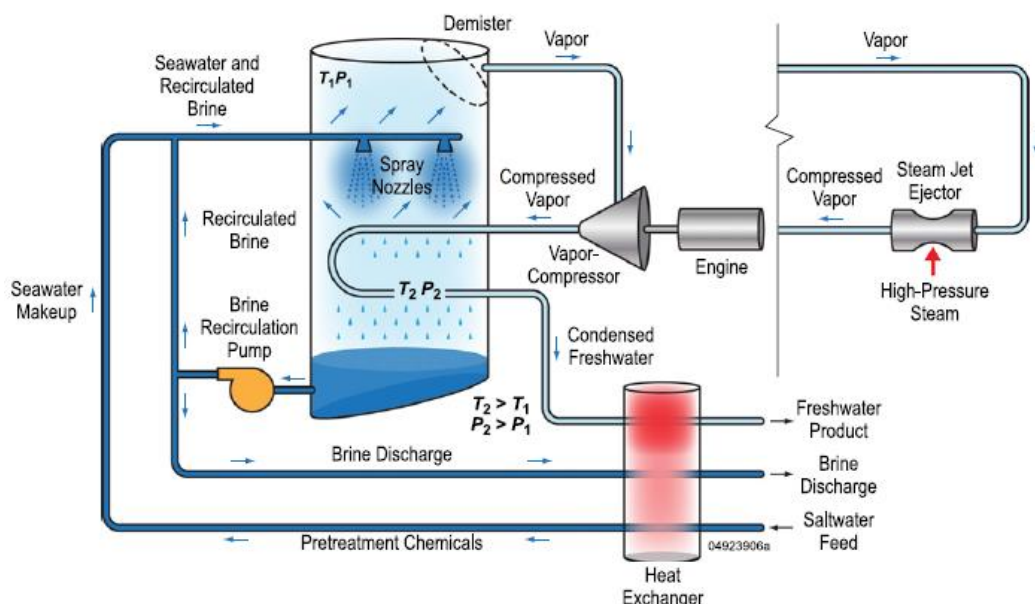


Figure 11: Diagram of VC process [16]

## 2.2 Membrane Desalination

There are three main membrane technologies utilized for desalination: Electrodialysis (ED), Reverse Osmosis (RO) and Membrane Distillation (MD). Diverse kinds of membranes exist, the principal difference between them being the size of the particles that are retained or allowed to pass through. Typically, membranes that allow bigger particles to pass through are utilized during pre-treatment. The next figure shows the effective range of membrane processes and applications.

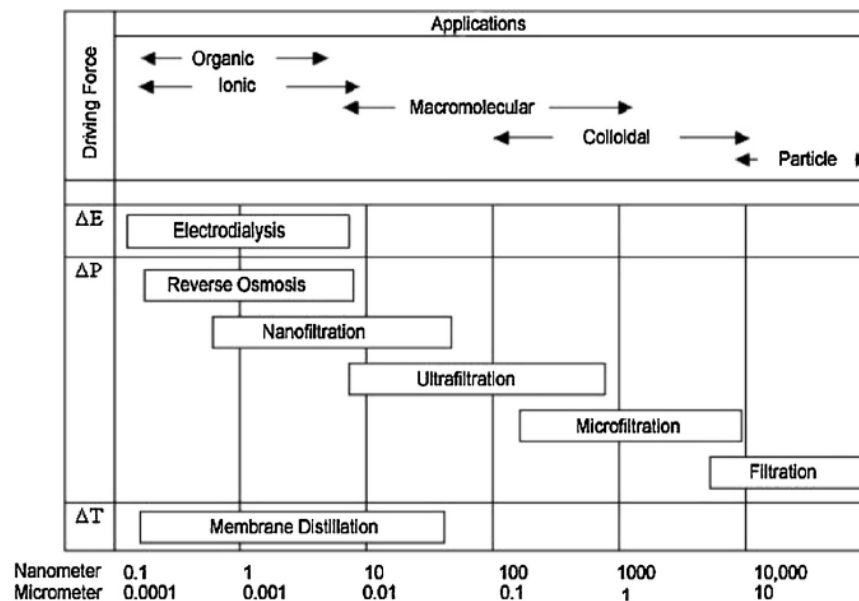


Figure 12: Effective range of membrane processes and applications [49]

### 2.2.1 Electrodialysis

Electrodialysis (ED) is an electrochemical separation process that operates at atmospheric pressure and uses the electrical potential to move salt through an ion-selective membrane by means of direct electrical current, leaving freshwater behind. This process is different from all the other main desalination processes, in the sense that in ED the dissolved salts are moved away from the feed seawater, instead of the reverse. When feed water flows the positive salt ions travel through the cation-permeable membrane toward negative electrodes, while the negative salt ions travel towards the anion-permeable membrane to the positive electrode.

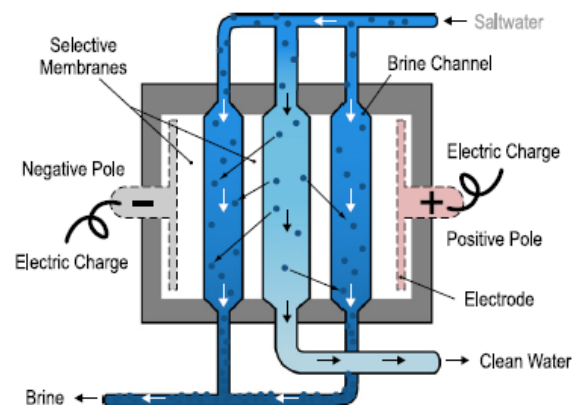


Figure 13: Scheme of ED process

An ED system consists of several systems: pre-treatment system, membrane stack, low-pressure circulation pump, direct-current power supply and post-treatment system. ED's production capacity varies between 2 and 145.000 m<sup>3</sup>/day [16]. This technology is widely used to desalinate brackish water



and is considered economically competitive for seawater application due to its energy consumption that is highly dependent on salt concentration [15] and the ion exchange membranes that are expensive and have a relatively short lifetime when working in a high-density electric field [19] [20].

Finally, ED systems can periodically reverse the direction of ion flow by reversing the polarity of the applied electric current in order to preserve the condition of the system. In this case it is named Reverse Electrodialysis.

### 2.2.1 Membrane Distillation

Membrane distillation is an evaporative process in which water vapour, driven by a difference in pressure (temperature), permeates through a hydrophobic membrane, thus separating it from the feed water phase. MD is a hybrid of thermal distillation and membrane desalination. The separation effect is based on the hydrophobicity of the polymer material that constitutes the membrane. Molecular water in the form of steam can pass through the membrane, from the higher compartment with higher vapour pressure to the warmer compartment. Furthermore, there are different methods to recover the vapour: having a liquid phase in direct contact with both sides of the membrane; an additional air gap between the membrane and the condensation surface; with an inert gas stream that passes on the permeate side.

MD has several advantages over other processes: theoretical 100% rejection of salts and other non-volatiles; lower operating temperatures than conventional distillation (60 to 90°C); lower operating pressures when compared to other membrane processes; less space and equipment required compared to other thermal processes; does not require pre-treatment; intermittent operation of the module is possible, there is no danger of membrane damage if the membrane becomes dry; theoretical system efficiency and water quality and high product are independent from the salinity of feed water.

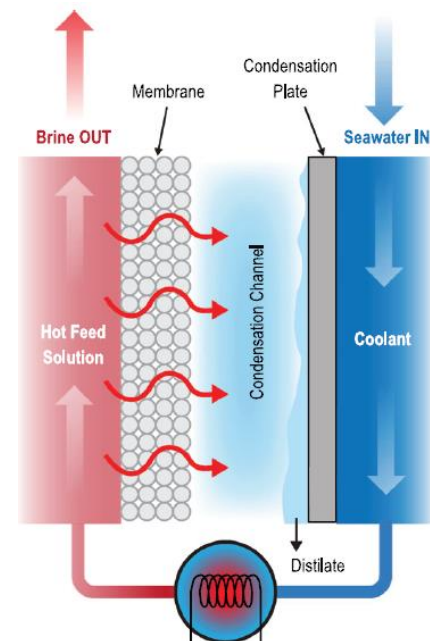


Figure 14: principle of membrane distillation

Oppositely, MD also has disadvantages: membrane wetting that leads to poor quality water, the lack of specific membranes design (MD experiments utilized microfiltration membranes) and lower flow when compared to other desalination technologies [16]. Moreover, in contrast with other membrane technologies, MD requires both thermal energy and electricity. The main energy requirement for membrane distillation is thermal energy, while electricity demand is low and is needed for auxiliary services such as pumps, sensors and controllers.

MD was introduced in the late 1960s [18] but failed to compete with other alternatives due to the impossibility of producing membranes with identical efficiencies. Currently this technology is still under development and research phase, although being considered an energy saving alternative to other desalination processes. It's still not commercially applied due to its shortcomings.

### 2.2.2 Reverse Osmosis

Reverse osmosis (RO) utilizes a permeable membrane to separate a solvent, in the case water, from a solution, by leaving a concentrated solution behind. The seawater (feed water) pressure is increased above the osmotic pressure, allowing the desalinated water to pass through semi-permeable membranes, leaving solid salt particles behind. The amount of pressure that can be applied has a limit, since the membrane can become fouled by precipitated salts and other material. Therefore, there is a limit to the fraction of feed water which can be recovered as pure water. The RO units are operated so that only a portion of the feed water passes through the membrane. The RO process is controlled and evaluated by two main parameters: rejection rate, which measures the efficiency of the membrane to remove salts from the feed water, and recovery rate, which indicates the amount of feed water that is converted into freshwater. Seawater pressure must be higher than the natural osmotic pressure, typically 2500 kPa, and is kept below the membrane tolerance pressure, typically between 6000 and 8000 kPa.

RO plants are sensitive to feed-water quality (salinity, turbidity and temperature): high salinity or high temperature affects the osmotic pressure, requiring more energy. RO systems are suited for seawater salinity around 35000 ppm of dissolved solids. In regions where the total dissolved solids content is higher (such as the Arabian Gulf) or there's high surface temperature, a pre-treatment of the feed-water is required [15]. The pre-treatment can be achieved by physical or chemical filtration and clarification of the seawater, with coagulation chambers, flocculation chambers or dissolved air flotation chambers. The filtration and clarification can be achieved with membrane filtration such as ultrafiltration and microfiltration that remove larger particles and colloids. These membrane methods may reduce the need for chemical pre-treatment.

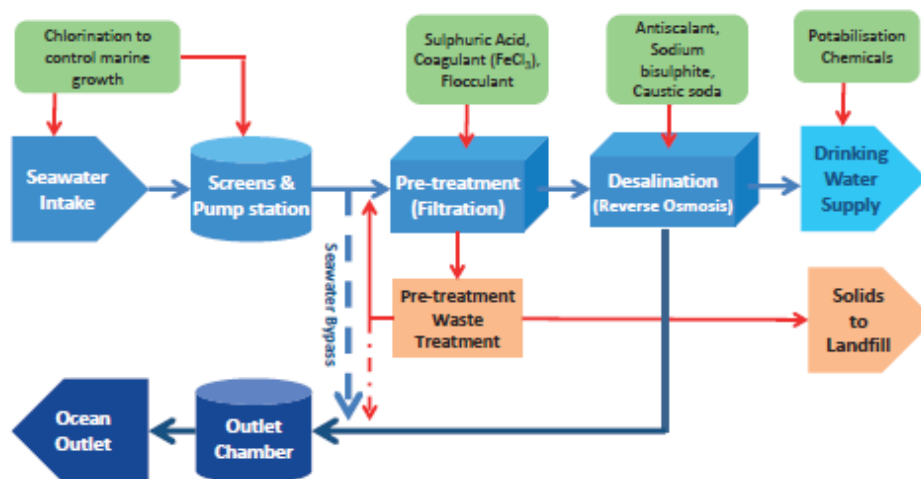


Figure 15: Schematic of Reverse Osmosis Desalination process [15]



Figure 16: Pressure Vessels at RO Desalination plant in Jordan

The pump station will then pressure the incoming water. The pressure level required will depend on the quality of the feed water, typically between 17 to 27 bars for brackish water and 55 to 82 bars for seawater [16].

For the main desalination process RO utilizes membranes to separate freshwater from saline or brackish feed-water. There are three major types of RO membranes: cellulosic, fully aromatic polyamide and thin-film composite. Since the 70's and until the early 90's most membrane modules utilized in desalination had a hollow fibre configuration and were made from cellulose tri-acetate fibre, a technology developed by Dow Chemical Company [21]. In the 90's this configuration started to be disfavoured over a different configuration: polyamide spiral wound modules. The spiral wound module is manufactured with a thin film composite made from polyamide, polysulphone or polyuria polymers [22] and is comprised by different elements such as permeate spacer, feed (brine) spacer, permeate tube and seal carrier between modules. All of these elements have improved over the last twenty years, allowing for increases in active area of membrane and higher operating pressures that led to increased recovery and improved rejection.

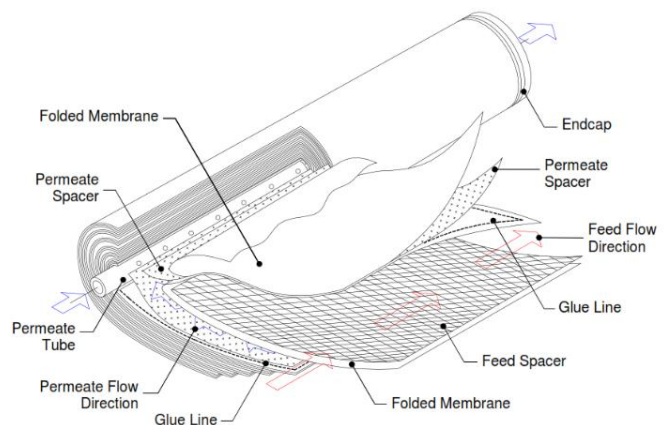


Figure 17: Spiral Wound membrane [45]

The feed-spacer offers an open channel for flowing feed water by preserving separation between the membrane sheets. It also provides mixing of the rejected substances away from the membrane surface. The most common feed spacer configuration in RO modules is biplanar extruded net. Most feed-spacers are made from polypropylene, designed for low cost (typically below \$1 per square meter), chemical

inertness and extrudability, with typical thicknesses between 0.6 and 0.9 mm [21]. The side effect of the mechanical support is feed channel pressure drop, which impacts overall system performance by reducing trans-membrane pressure and consequently permeate production. Moreover, imperfect mixing reduces salt rejection and increases fouling [21]. The permeate spacer offers a canal, between two sheets of membrane, for collection and transport of permeate from the membrane to the permeate tube. The permeate spacer plays a crucial role in element efficiency. The most common material used for permeate spacer is woven polyester. The permeate tube collects the permeate, from the permeate spacer, serving as a conduit for the transport of permeate towards external collection. This tube can also be utilized for diagnostic access during operation, by the use of conductivity sensors and sampling probes. Finally, the endcap plays an important role as it allows the load transmission while preventing bypassing of feed water and relative movements between membrane leaves.

The growth of membrane desalination technology in the early 90's can in part be explained by the advance in standardisation of the spiral wound membrane module. The standardisation resulted in reduced costs due to increased competition amongst suppliers. The low production cost, combined with high packing density, was crucial to the implementation of the technology. This led to the loss of appeal and consequent decline of the hollow fibre membrane. In most of the world, plants were converted from hollow fibre module to spiral wound modules, achieving substantial cost savings with the retrofit [21]. Currently the majority of membrane desalination installations utilize modules with spiral wound membrane configuration, although there are still large old plants using hollow fine fibre modules in Saudi Arabia. The hollow fibre modules are currently produced by just one supplier, Toyobo. Also, the adoption of thin film composite membranes (TFC) to replace cellulose acetate greatly improved membrane technology by allowing lower operating pressures, higher fluxes and higher salt rejection, leading to lower energy consumption. Besides working to achieve membranes that require low energy and deliver higher productivity, manufacturers are currently developing membranes with high boron rejection (close to 90%) in order to comply with new legislation for freshwater supply.

Presently RO is the most implemented desalination technology worldwide, representing about 60% of installed capacity. RO production capacity varies between 0.1 m<sup>3</sup>/day in marine and household applications to 395.000 m<sup>3</sup>/day in commercial applications. The main cause for its high implementation is the low energy required by the process when compared to thermal processes, achieved through improvements such as the development of efficient membranes, system design improvements such as utilizing one pass and an increased number of elements per pressure vessel (8 instead of 7) and the use of isobaric chambers for energy recovery. Although RO requires extensive water pre-treatment, all of the former features allowed for a drastic reduction of specific energy consumption in desalination, as low as 1.5 kWh/m<sup>3</sup> in small to medium capacity plants [18]. Moreover, RO only requires electrical energy, contrasting with thermal desalination that requires both thermal and electrical energy.

A novel concept that also utilizes the principle of osmosis is forward osmosis (FO). FO utilizes natural osmosis to dilute seawater feed stream by using a draw solution with higher osmotic pressure than the seawater feed, which pulls water across a semipermeable membrane from the feed solution. The draw solutes are then separated from the diluted draw solution by utilizing a low heat source (40°C) and recycled. The solutes used are typically a mixture of ammonia and carbon dioxide gas. Specific energy consumption of less than 0.25 kWh/m<sup>3</sup> have been reported for the membrane portion of the process. When considering the thermal energy required for regeneration of the draw solution FO is not considered more efficient than RO [23]. But it has the advantage of lower fouling propensity since it does not require high hydraulic pressure.

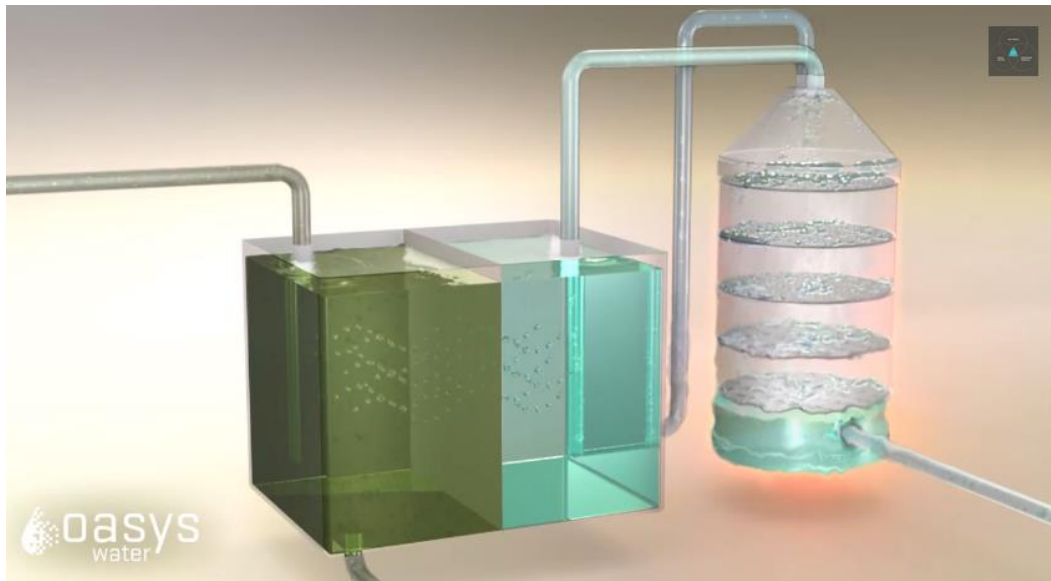


Figure 18: Schematic of FO process [52]

### 2.3 Energy Requirements

Desalination is an energy-intensive process, one that consumes more energy per liter than other water supply and treatment options. The energy required depends on several factors such as technology employed, design of the plant, quality and temperature of the feed water, the application of energy recovery devices or the intended quality of the produced water. Furthermore, the energy requirement of desalination processes is a crucial issue as it is one of the main variables affecting the cost of produced water.

Energy requirements for desalination have declined dramatically over the last 40 years, due to technological improvements and are expected to keep decreasing. Many factors that can minimize the energy required in desalination: enhanced system design, high efficiency pumping, energy recovery, advanced membrane materials and innovative technologies.

Thermal desalination requires both electricity and thermal energy, with the exception of mechanical vapour compression. In thermal desalination processes, the low temperature heat represents the main

percentage of the energy input while the electricity is needed for the pumps. In MSF the process operates at a top brine temperature (TBT) between 90 and 110°C. An increase in TBT increases the production rate and improves performance, however, TBT is limited due to scaling effects. The total electrical equivalent energy required by MSF varies between 19.58 and 27.25 kWh/m<sup>3</sup>. In the case of MED, the brine temperatures range between 64 and 70°C. The total electrical equivalent consumption, considering a power-plant efficiency of 30% varies between 14.45 and 21.35 kWh/m<sup>3</sup>. In the case of MVC, the electrical energy consumption varies between 7 and 12 kWh/m<sup>3</sup>, while in TVC the energy consumption is about 16.26 kWh/m<sup>3</sup> [16].

In the case of membrane desalination processes, the energy consumption depends mainly on the salinity of the feed water and the recovery rate. In RO the major energy requirement is pressuring the feed water. The average energy consumption of RO ranges from 3,7 to 8 kWh/m<sup>3</sup> for seawater, depending also on the size of the facility. For a typical SWRO unit of 24.000 m<sup>3</sup>/day the consumption varies between 4 and 6 kWh/m<sup>3</sup>, with energy recovery devices. For brackish water (BW), a BWRO unit's consumption ranges between 1.5 and 2.5 kWh/m<sup>3</sup> [16]. In the case of ED, the electrical consumption varies between 0.7 and 2.5 kWh/m<sup>3</sup> for low salinity feed water and 2.64 and 5.5 kWh/m<sup>3</sup> for salinity between 2500 and 5000 ppm [16]. RO is preferable to ED when salinity is higher than 2000ppm. In case of brackish water, ED is more energy efficient than RO. As high-salinity water requires higher amounts of energy, due to higher osmotic pressure requirements, ED is not considered a good option for seawater desalination.

Table 4: Energy Consumption of main commercial Desalination technologies [16] [24]

	MSF	MED	MVC	TVC	SWRO	BWRO	ED
Electrical Energy consumption (kWh/m <sup>3</sup> )	2.5 - 5	2 – 2.5	7 – 12	1.8 – 1.6	3 - 6	1.5 – 2.5	0.8 – 5.5
Thermal Energy consumption (MJ/m <sup>3</sup> )	190 - 282	145-230	-	227	-	-	-
Equivalent electrical to thermal energy (kWh/m <sup>3</sup> )	15.83 - 23.5	12.2 - 19.1	-	14.5	-	-	-
Total energy consumption (kWh/m <sup>3</sup> )	19.58- 27.25	14.45-21.35	7-12	16.26	3 - 6	1.5 – 2.5	0.8 – 5.5

## 2.4 Environmental Impact

Desalination entails environmental impacts that must be understood and mitigated. To begin with, the greenhouse gas emissions associated with utilizing fossil fuel energy sources for desalination must be mitigated. In the MENA region alone, the projected required desalinated water for 2050 would produce, in a similar technological scenario as today, the CO<sub>2</sub> equivalent emissions of 270 to 360 million tons per year [25]. This effect can be highly diminished by utilizing renewable energy sources such as solar PV, solar thermal, wind or geothermal energy sources and also by reducing the total energy requirement of the process [26].

Moreover, the process extracts vast quantities of water from the ocean by means of an intake. Seawater intakes have two main categories: direct intake also known as open water intake, and indirect intake, also referred as subsurface intake. A direct intake may be located at the surface, in deep water or in a flotation plant. The majority of desalination plants extract water directly from the ocean through open water intakes which have a direct impact on marine life: marine life is killed on the intake screens and organisms that are small enough to pass through the screens such as plankton are killed during the process [27]. A number of technologies are available to reduce the environmental impact of seawater intake: physical barriers (such as barrier nets, travelling screens, Ristroph screens or wedgewire screens) and behavioural deterrents (such as air bubble curtains, strobe lights, sound generators or velocity caps). Alternatively, a small number of desalination plants presently start to use indirect intakes. These have the advantages of eliminating the impact on marine life while also reducing pre-treatment requirements. This type of intake extracts seawater beneath the seafloor or beach, either off-shore or on-shore. There are different designs for indirect intake: vertical wells, angle wells, horizontal wells, infiltration galleries. However, indirect intakes may not be appropriate in all locations, being dependent on geology and sediment characteristics. Furthermore, indirect intakes have disadvantages: higher construction cost and complex survey methods.

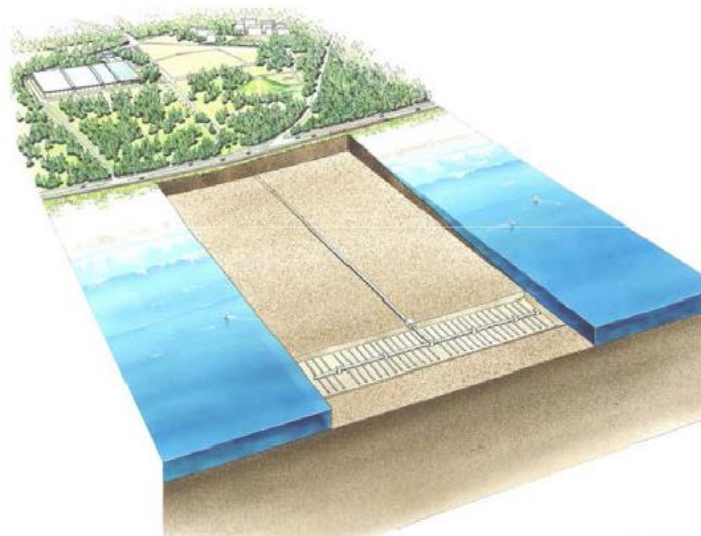


Figure 19: Infiltration gallery design at Fukuoka district waterworks [48]

In addition, the desalination process produces high salinity water (concentrate or brine), which is comprised of salts and chemicals utilized during the desalination process, mainly during pre-treatment. The brine's concentration depends on the type of desalination process used. Also, the temperature of the brine is warmer than the original feed water, in the case of thermal desalination. In membrane desalination this difference is usually within 1°C [27]. There are six options to dispose of the concentrate: surface/submerged discharge; sewer system blending at a waste treatment process; land application; deep well injection in non-drinking aquifers; evaporation ponds and finally zero liquid discharge which is a technique to solidify liquid concentrate and put it in a landfill [28]. To select the method, 8 factors must be considered: volume of concentrate; quality of concentrate constituents; geographical location of discharge point; availability of receiving site; permissibility of the option; public acceptance; capital and operating costs; and expandability capacity. However, over 90% of large plants currently in operation dispose of brine through ocean discharge. There are several methods to disperse concentrated brine, such as multi-port diffusers placed on the discharge pipe to promote mixing. Also, plants typically dilute the brine by increasing the intake of sea water or by mixing it with other sources such as cooling water from an adjacent power plant or a wastewater effluent. Currently there is a lack of comprehensive studies and monitoring data to aid in quantifying the ecological impacts of brine discharge. The few studies available indicate that the impact varies widely and is a function of factors such as the discharge method, the rate of dispersal or the sensitivity of the organisms [27].

Finally, the salt and chemicals contained by the brine could potentially be utilized to manufacture products such as: paper; ink; plastics; fertilizers, soil conditioners; fillers for lightweight; chemical agents for water treatment; or dust suppressants. The technical and economic feasibility of such solutions remains to be demonstrated [29], but if feasible, it could be the best available solution.

In conclusion, the environmental impacts of desalination plants, even when coupled with renewable energy sources, should be properly evaluated and mitigated. At present there seems to be a lack of data concerning the environmental impact of commercial plants.





### 3. Renewable Energy-Powered Desalination

Around the world communities depend on desalination for potable water supplies. Remote locations in developing countries and small islands frequently lack access to potable water and often to the electric grid. Also, in order to lower its environmental impact, desalination plants require an energy source that has low emissions and at the same time is affordable. Renewable energy sources such as solar photovoltaic and thermal, wind or geothermal energy can be utilized to solve both issues, as using locally available renewable resources is likely to be cost-effective.

As desalination worldwide capacity currently surpasses 70 million m<sup>3</sup>/day, this solution can result in noteworthy cuts in greenhouse gases. Moreover, as the costs of renewable energy solutions are expected to decline further, these will become more attractive, especially in remote regions with low population density and poor infrastructure for fresh water and electricity transmission and distribution [15].

Currently, renewable-powered desalination capacity represents less than 1% of the world's desalination capacity [22]. Most of the existing renewable-powered desalination plants are based on RO technology (62%), followed by MSF and MED. The dominant renewable energy source for water desalination is solar photovoltaic (PV), used in 43% of the existing RE desalination plants, followed by solar thermal and wind energy.

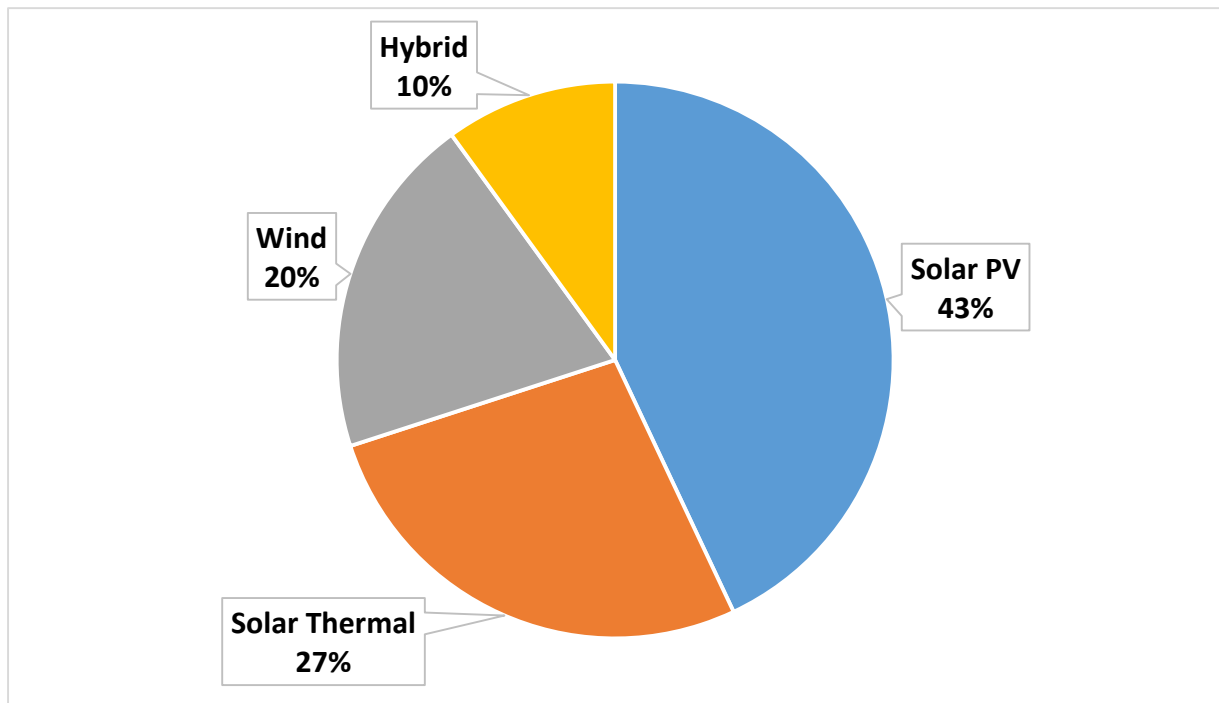


Figure 20: Renewable energy sources currently utilized for Desalination [30]

The combination energy source/desalination technology is crucial in order to match energy and water demand economically and with the lowest environmental impact possible. The feasibility of a RE plant will depend on a variety of factors such as: location, salinity of feed-water, available RE sources, plant capacity or availability of grid electricity. The possible combinations can be observed in the table below.

Table 5: Possible combinations of renewable energy and desalination technologies

	MSF	MED	VC	RO	ED	MD
Solar PV				○	○	○
Wind				○	○	○
Solar thermal	○	○	○	○	○	○
Geothermal	○	○	○	○	○	○

### 3.1 Solar-Powered Desalination

The notion of solar desalination has existed for centuries. The first documented use of solar stills was in the 16<sup>th</sup> century. Also, in 1872 Carlos Wilson, a Swedish Engineer, built a large-scale solar still that supplied drinking water to a mining community in Chile [22].

Solar thermal energy can be converted to thermal energy or electrical energy. Thermal energy can be collected directly to the water, as solar stills, or by using solar thermal collection systems, to be utilized in thermal desalination processes such as MSF, VC, MED and MD. Electrical energy can be collected by means of solar photovoltaic energy and utilized in RO and ED and by thermal processes that also consume electricity in auxiliary systems.

#### 3.1.1 Solar Stills

Solar stills are mainly suited for small production systems, where the water demand is less than 200 m<sup>3</sup>/day. The solar still works as a greenhouse, capturing the incoming solar irradiance that passes through a transparent cover and reaches a basin with salt water. With the rise in temperature the water at the surface is evaporated. The vapour rises and condensates at the transparent cover. This cover consists of glass or plastic panels with a slope that leads the condensate to a collection point. Solar stills can produce 3-4 l/day/m<sup>2</sup> daily. Due to the low production rate, and the requirement of a large area for solar collection, solar stills are not considered a viable option for large-scale production, the comparative installation costs tend to be higher than other desalination systems [22]. However, solar stills become economically viable for small-scale production for many remote and rural regions, especially for small water requirements [16].

Various researchers have attempted to increase the efficiency of solar stills by modifying the design. For example, solar stills can be coupled with solar collectors in order to increase productivity [22].

Since solar stills have a production of 3 to 5 l/day/m<sup>2</sup>, a 120-200 m<sup>2</sup> land area would be needed to supply a family that consumes 0.6 m<sup>3</sup>/day. This implies that it may not be a convincing option [17].

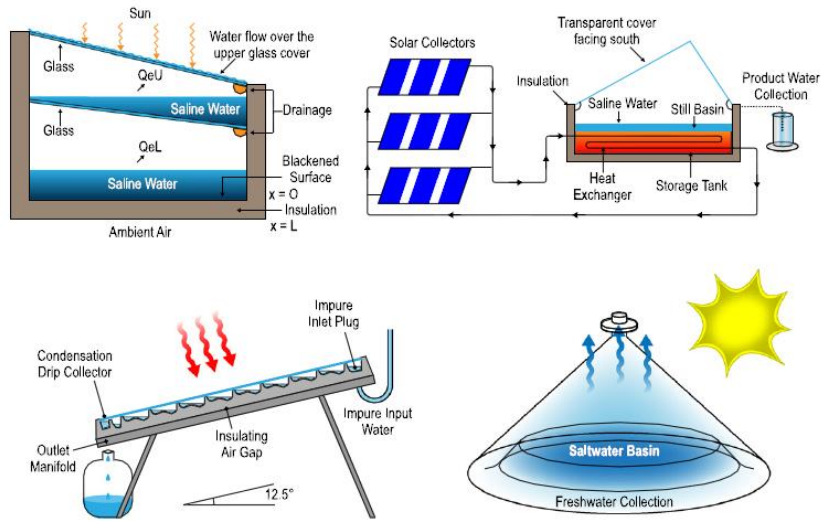


Figure 21: Diverse types of Solar Stills [16]

### 3.1.2 Solar Ponds

Solar ponds are another kind of system where thermal energy is collected and stored. Solar ponds are able to store heat due to their chemically stratified nature. Three layers compose a solar pond: the upper layer (upper convection zone), the middle layer (non-convection zone or salinity gradient zone) and the lower layer (storage zone or lower convection zone). Salinity is relatively constant in the upper and lower layers, while it increases with depth in the middle layer. The bottom of the pond can reach temperatures of 90°C. The large storage capacity of solar ponds can be useful for the continuous operation of MED, TVC and MSF desalination plants. Due to MED's lower temperature needs, the solar pond operation in MED is relatively easier than in MSF. Research has shown that for MED system the optimal thicknesses of the three zones of the solar pond are 0.3 m, 1.1 m and 4 m, for the upper, medium and lower zones of the pond, respectively [17].

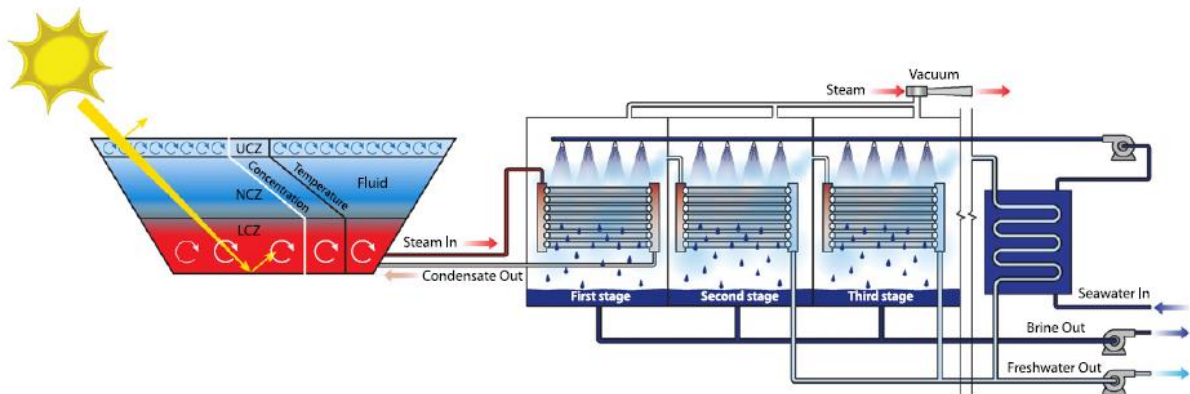


Figure 22: Solar Pond with MED desalination

Furthermore, solar ponds offer two strong advantages to desalination: large storage capacity and the possibility to re-use brine to build the solar pond. This capacity to store heat allows seasonal as well as

diurnal thermal energy storage, allowing continuous operation of the desalination plant. It has been reported that, compared with other solar technologies, solar ponds provide the most convenient and least expensive option for heat storage for daily and seasonal cycles

Examples that utilize solar ponds to power MSF plants include: Margarita de Savoya in Italy (50-60 m<sup>3</sup>/day), Islands of Cape Verde (300 m<sup>3</sup>/day) and El Paso in Texas (19 m<sup>3</sup>/day) [16].

### 3.1.3 Indirect Solar Thermal

Desalination can be conducted in conjunction with indirect solar thermal technologies such as solar thermal collectors or concentrated solar power (CSP) power plants.

Solar thermal collectors collect heat by absorbing solar radiation. These can be connected to different desalination systems like multiple stage basin stills, multiple effect humidification or membrane distillation units.

Multiple stage basin stills have multiple compartments to recover part of the condensing heat that heats the water in an upper compartment. An example is the thermal desalination unit with a heat recovery system from the "Energy and environmental engineering office" (IBEU) and the Solar- Institut Jülich. The energy demand for the production of 1m<sup>3</sup> of fresh water is approximately 120-150 kWh due to the use of several stages in which the water is evaporated with the latent heat of each previous stage. Depending on the number of condensing stages, the production rate can be improved by a factor of 3 to 5, in comparison to a regular solar still. About 15 to 18 litres of distillate can be produced per square meter collector area per day [31].



Figure 23: Multi stage solar basin [31]

Multiple Effect Humidification units use heat from solar thermal collectors to induce multiple evaporation and condensation cycles inside thermally isolated, steam-tight containers. By solar thermally driven humidification of air, water and concentrated salt solution are separated. During re-condensation most of the energy used before for evaporation is regained and can be used in subsequent cycles of evaporation and condensation, which considerably reduces the thermal energy input required

for desalination. The thermal efficiency of the solar collector is much higher than for solar stills and the specific water production rate is in the region of 20 to 30 litres per m<sup>2</sup> of absorber. A company that develops such products is Mage Water Management GmbH [31].



Figure 24: Mage Water MidiSal 5000 Desalination System, Dubai [31]

MD units have also been investigated by Fraunhofer ISE since 2001. Since then, two systems were designed: Oryx150 with capacity for 120liters/day and Two-Loop System with capacity of 1800liters/day [31].



Figure 25: Two-Loop System, Gran Canaria [31]

CSP plants concentrate the direct solar irradiation, converting it in usable thermal energy. The conversion of heat into electricity is realized by conventional power cycles such as steam turbines (Rankine cycle) or other engines. This heat can be utilized directly to operate MSF, MED or MD plants. In addition, the produced electricity is also used for auxiliary processes and it can also be used to run an RO plant.

Solar concentration is a concept that has been researched for centuries, since the first concept developed by Archimedes to the concentrators designed by Leonardo Da Vinci. Currently there are four main types of CSP designs: parabolic trough, Linear Fresnel collector, power tower and Sterling-dish engine.



Figure 26: Power Tower CSP PS10 in Seville ; Dish Stirling prototype in Almería

Presently the parabolic through system is considered the best option for CSP/desalination coupling, in particular with MED and RO [16]. It is also the most commercially advanced of the various CSP technologies. A key test facility that studied the integration of a MED plant with a CSP plant is the *Plataforma Solar de Almería – CIEMAT* [18].



Figure 27: Parabolic through system

One main advantage of solar CSP over other renewable energy technologies such as solar PV or wind energy converters is the option of energy storage. Unlike electrical storage, thermal storage is practical and economically feasible, even for large-scale applications. This thermal energy storage consists of a concentrate of nitrate molten salts and can have a full-load storage capacity in the range of several hours. The same molten salts can also be utilized as transfer fluids, replacing synthetic oil typically used, increasing the overall efficiency of the plant.

One of the main disadvantages of solar CSP is the ground area required by the system which translates into low energy density ( $\text{kWh/m}^2$ ) when compared to other technologies such as solar PV. This means that this option requires suitable land areas, as well as high level of direct normal irradiance.

In regard to coupling CSP with desalination plants, CSP plants can deliver thermal and electrical power to MSF and MED plants. MED is generally considered a better option. After the steam passes through the steam turbine and produces electricity, it can be utilized for the MED process. This notion is comparable MED or MSF plants that utilize the heat from conventional fossil fuel plants. In addition a solar pond that functions as thermal storage can also be included. Finally, a CSP plant can also be used in conjunction with an RO plant by producing the need electricity. Internal studies from Bechtel Power Corp. concluded that CSP-RO coupling is more efficient and requires less energy than CSP-MED coupling [16].

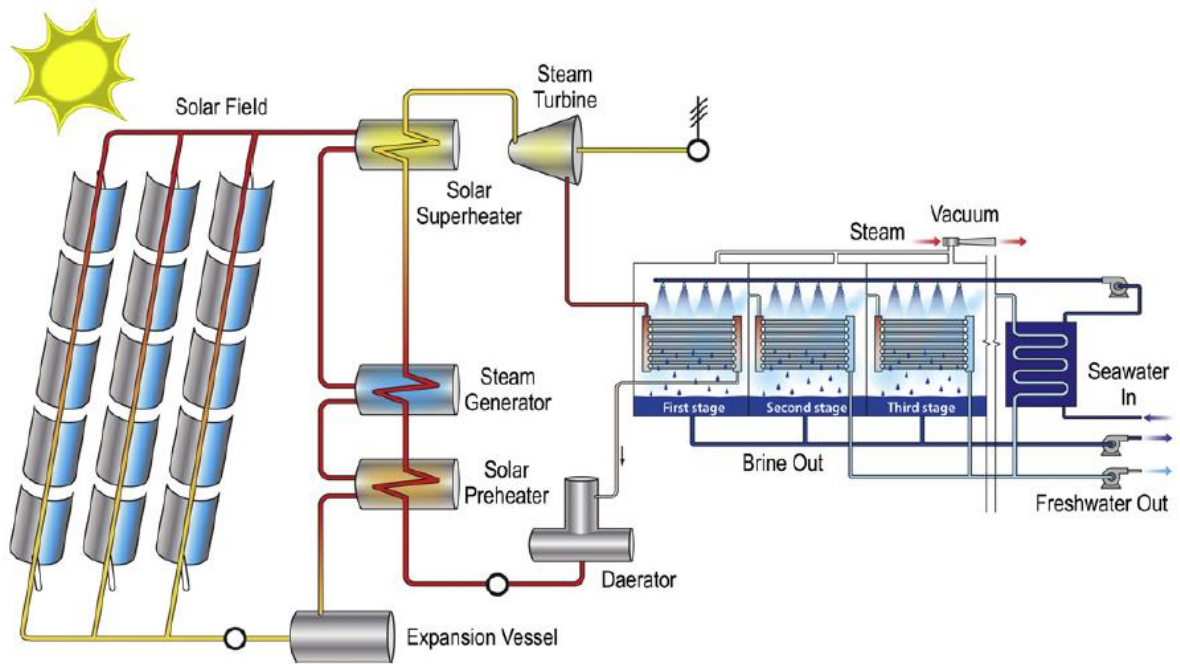


Figure 29: Schematic of CSP connected with MED [16]

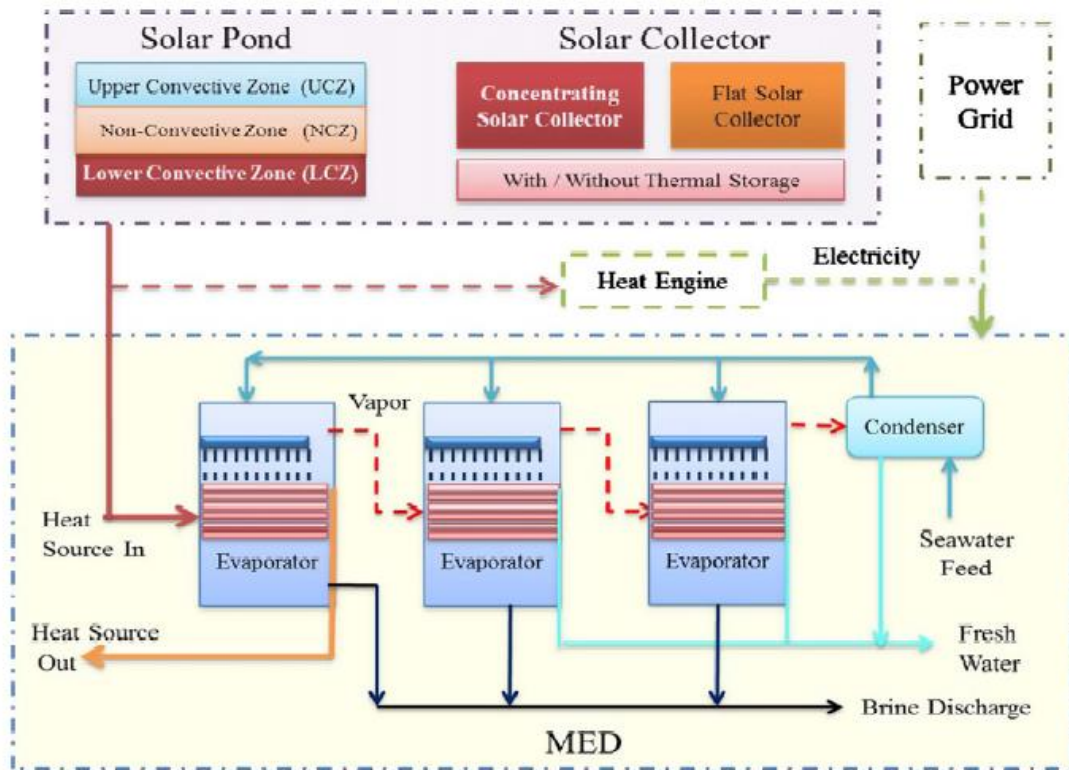


Figure 28: Schematic of MED with CSP and Solar Pond [17]



### 3.1.4 Solar Photovoltaic

Solar photovoltaic (PV) systems convert sunlight into direct current electricity by utilizing semiconductor materials that display the photovoltaic effect, PV cells. The PV cells form PV modules, which produce direct current that can be stored in batteries or directly fed to an inverter, which converts the direct current in alternating current. PV cells can be made from diverse technologies, being monocrystalline silicon and polycrystalline silicon the most common choice.



Figure 30: Solar PV plant powering Desalination plant in Yuma, Arizona [50]

Solar PV systems can be connected directly to RO or ED desalination processes as both require electrical energy for the pumping system. The system can include a set of batteries for energy storage, in order to stabilize the energy input of the RO unit, and a charge controller that regulates the charge of the batteries, avoiding deep discharges and overcharge. The set of batteries avoids variations in pressure and flow, enabling the membrane system to produce a known amount of water at the desired quality. In contrast, batteries introduces several issues. The typical charge-in/charge-out efficiency of a deep-cycle lead acid battery is 75-80%, leading to loss of system efficiency on the order of 20 to 25%. Also, batteries perform worse and degrade faster at higher temperatures, which is likely to be the case in locations where desalination systems are implemented, leading to high maintenance costs [32]. Moreover, over the lifetime of the facility, the battery bank would need to be replaced an average of 4 times.

For the above reasons, research efforts are currently being made in order to store the energy in form of the product water. This means that the system may have to be slightly oversized to account for variations in the energy resource. This can lead to lower lifecycle cost as well as a more robust system design that eases autonomous operation [32].

Another issue currently under research is the effect of large variations in solar irradiance in battery-less membrane systems. Experiments indicate that the system can still produce good quality water [32], although this capability will be dependent on the type of membrane utilized. An important issue in RO desalination is the ability to operate at variable capacities, based on available energy. ENERCON GmbH developed a RO technology in which a piston system used for energy recovery also enables variable levels of energy input. RO systems operating with this technology can range production between 12.5% and 100% of nominal capacity by adjusting the piston speed, adjusting the production for available energy input or water demand [33]. Currently other companies are developing systems that have this demand response capability, meaning that in the near future RO systems will control the production according to available energy, not requiring batteries or connection to the electric grid.

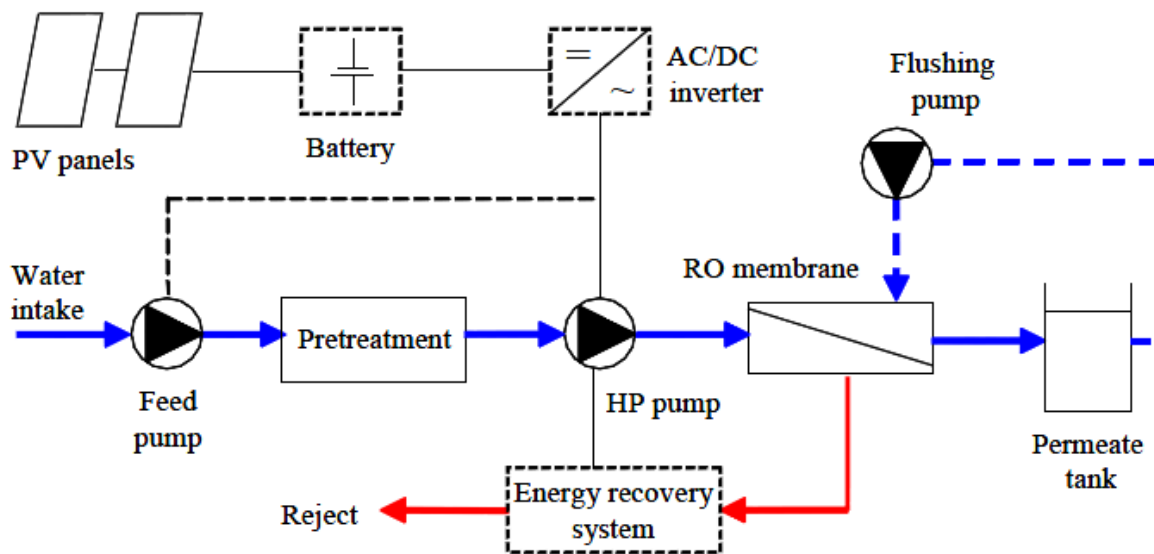


Figure 31: Schematic of PV-RO system [53]

PV-RO is considered one of the strongest options for renewable energy powered desalination, particularly for remote areas, as both PV and RO are highly modular and scalable [17]. This modularity also assists in cost reduction being achieved via economies of scale. Furthermore, this modularity allows for small-scale systems that can be realized by coupling the DC output of PV modules directly to DC pumps and electronics, increasing overall system efficiency by 5 to 10% due to the avoidance of losses in DC-AC power conversion and AC-DC rectification [32].

PV-based membrane desalination systems have been demonstrated throughout the world, particularly in remote areas or islands such as in the Canary Islands (PV-RO for brackish water, 5 m<sup>3</sup>/day), Saudi Arabia and Oshima Island (PV-ED for seawater, 10 m<sup>3</sup>/day). An example of such a system in Saudi Arabia will be reviewed as a case study in the next chapter.

Regarding PV-ED desalination, most researchers utilize this process only for brackish water and so far only a few studies have been made for this option but PV-ED is considered the most cost-competitive option at low-concentration brackish water (less than 2500 ppm) [16].

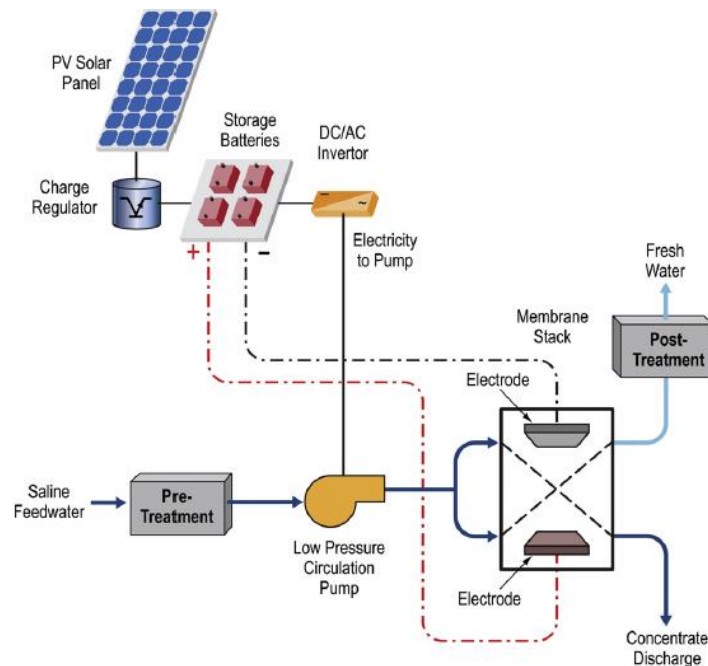


Figure 32: Schematic of PV-ED System

### 3.2 Wind-Powered Desalination

Wind turbines convert the air movement, generated by atmospheric pressure differences driven by solar radiation, into mechanical power and subsequently in electrical power by driving a generator.

The electrical and mechanical power generated by a wind turbine can be used to power desalination plants. The two can be coupled through four types of media: electricity, thermal energy, gravitational potential energy (with use of water storage) and kinematical power (direct mechanical coupling) [33].

Currently RO, ED and MVC units are coupled with wind energy generation, although most applications are Wind/RO. Wind energy can drive MVC units by utilizing directly its mechanical energy in a mechanical compressor, although few applications of this variation have been implemented [16]. One of the reasons for this is because MVC also requires an additional heat source due to operation temperature.

Several researchers have created prototypes and studies, having concluded that wind/RO systems are cost-competitive with conventional diesel-powered systems [33]. Extensive research in Wind/RO systems has been conducted by the Instituto Tecnológico de Canarias (ITC) with projects such as AERODESA and SDAWES (Sea Desalination Autonomous Wind Energy System). SDAWES project which concluded that, in RO, the product water flow and conductivity were slightly affected by the variations in frequency of the electrical grid under minimum wind speed [18]. The wind variability

usually leads to the installation of a battery system and a control system that also controls the surplus of energy, in order to smooth system operation. The coupling of a wind system to a SWRO plant can use either mechanical or electrical energy, but only the second option is viable to connect to a medium or large scale plant [18].

Various wind powered desalination plants have been installed throughout the planet, including for example Kwinana desalination plant in Perth, Western Australia (Wind-SWRO 140.000 m<sup>3</sup>/day), the first of its kind in Australia. To supply its energy requirements an 80MW wind farm was constructed. Another example in Australia is the Sydney (Kurnell) desalination plant (Wind-SWRO 250.000 m<sup>3</sup>/day), built in 2010 and that supplies 15% of the water supply of Sydney and purchases its energy from a 140 MW wind farm constructed near Bungendore specifically to supply the desalination plant.



Figure 33: Sydney Wind-RO plant during construction [51]

### 3.3 Geothermal-Powered Desalination

Geothermal energy can be used for heat and electricity generation, making it an option to couple with any major desalination system that requires thermal or electrical energy. Geothermal energy sources are qualified in terms of measured temperature: low (<100 °C), medium (100-150°C) and high temperature (>150°C). Thus, it is usable for a wide range of temperatures, from room temperature to over 150°C. The energy is usually extracted with ground heat exchangers and heat can be directly used for thermal desalination or indirectly by producing electricity, although the first option is preferred.

The first geothermal desalination plant was constructed in 1972 in the USA, followed by plants in Tunisia, France and Greece. Notwithstanding, using geothermal energy to power desalination is not as common as using solar or wind energy, although it is a mature technology with competitive cost. The main advantage of geothermal coupling is that no thermal storage is needed since it is continuous and predictable [34].

### 3.4 Hybrid-Powered Desalination

Hybrid renewable energy sources is the concept of combining more than one renewable energy resource. In order to deal with the intermittency of renewable energy sources such as solar and wind, the utilization of both becomes ideal since in certain locations their energy production profile does not coincide.

Several studies were conducted during the last 35 years regarding hybrid desalination systems, although none of them were large-scale applications. Throughout these, the ability to optimize hybrid configurations to maximize performance and minimize costs has been demonstrated. In a study by *Mohamed et al* a simplified method for sizing and simulating a hybrid Wind-PV-RO plant was presented, reaching a promising value for water production cost of 5.21 €/m<sup>3</sup> [33]. Another study with the same configuration, in Eritrea, East Africa determined that a system with 35 m<sup>3</sup>/day production had a specific energy consumption of about 2.33 kWh/m<sup>3</sup> [35].

A recent study by *Koutroulis et al* studied the optimization of desalination systems supplied by PV/Wind energy production, concluding that utilizing such hybrid solution results in lower overall cost compared to desalination systems powered by either only PV or Wind exclusively [36].

An even more recent study by *Hossam-Eldin et al* that analysed the techno-economic optimization of hybrid renewable energy systems for RO desalination concluded that the choice of technologies depends on a variety of factors such as availability of energy resources, specific design constraints or available components specifications and prices. For this reason, an iterative approach is most likely to be applied, one that assesses all the available energy combinations and their economic viability for a given location. It also concluded that in order to reduce the total cost of energy productions it is crucial to minimize the amount of excess energy produced. Lastly, it concluded that utilizing hybrid energy production is more appropriate for medium scale RO than for small scale RO for countries with similar conditions to Egypt [37].

## 4. Desalination Markets

Presently the majority of desalinated water comes from seawater sources, 63%, followed by brackish water with 19% and only 5% comes from wastewater sources.

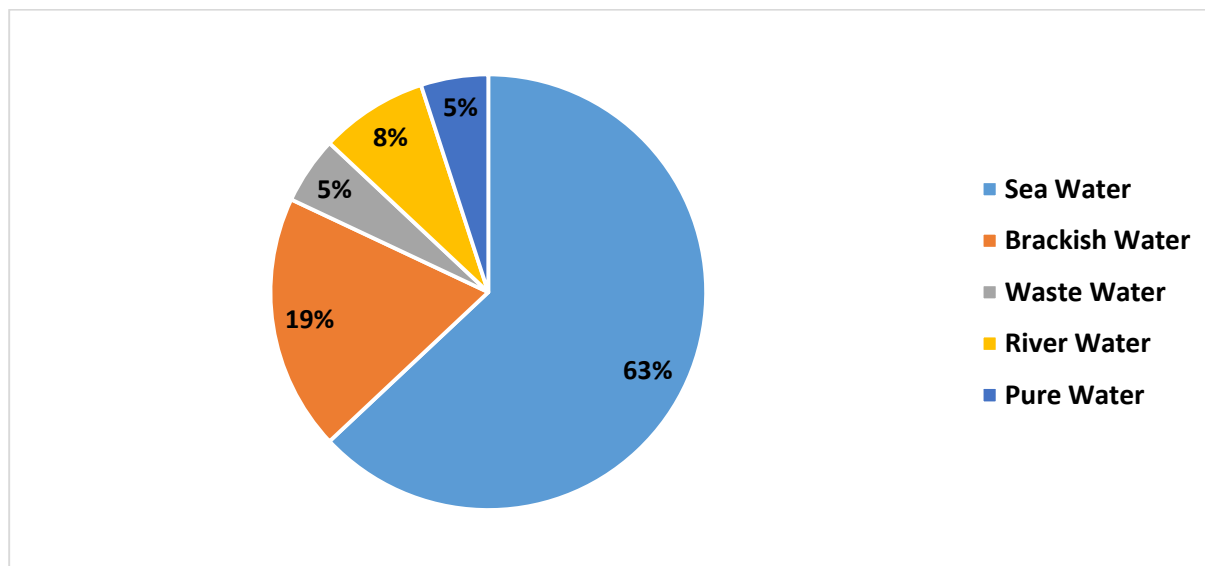


Figure 34: Sources of Feed Water for Desalination processes [38]

Desalinated water is mainly used for municipal and industrial purposes: 70% of the global desalinated water is used by municipalities and 21% by industries. Other end users include: power generation (4%); irrigation (2%); military (1%) and tourism (1%) [38]. In terms of global capacity by plant size, 49% of the desalinated water is produced in very large facilities (production above 50,000 m<sup>3</sup>/day). This percentage is even higher, 66%, if only seawater desalination is considered. When brackish water and wastewater are considered, the distribution is more homogeneous, with 24% and 27%, respectively.

Seawater desalination is the predominant process in almost all regions of the world, with the exception being North America, where brackish water desalination is the prevailing process, accounting for 36% of global brackish water desalination.

Desalination is vital for the societies of many arid regions of the world, namely the Middle East, Persian Gulf, North Africa and other locations where the availability of fresh water is insufficient to meet demand or the supply is implausible or uneconomical. The largest producers of desalinated water globally in terms of volume capacity are (in descending order): Saudi Arabia, United Arab Emirates, United States, Spain, Kuwait and Japan. Also, at the beginning of the century other countries had a significant development in desalination capacity. For example Israel opened in 2005 its first major desalination plant in the southern city of Ashkelon. Since then, four more large-scale seawater desalination plants have come online in Israel, with plans to add additional capacity due to severe droughts that have prolonged in time.

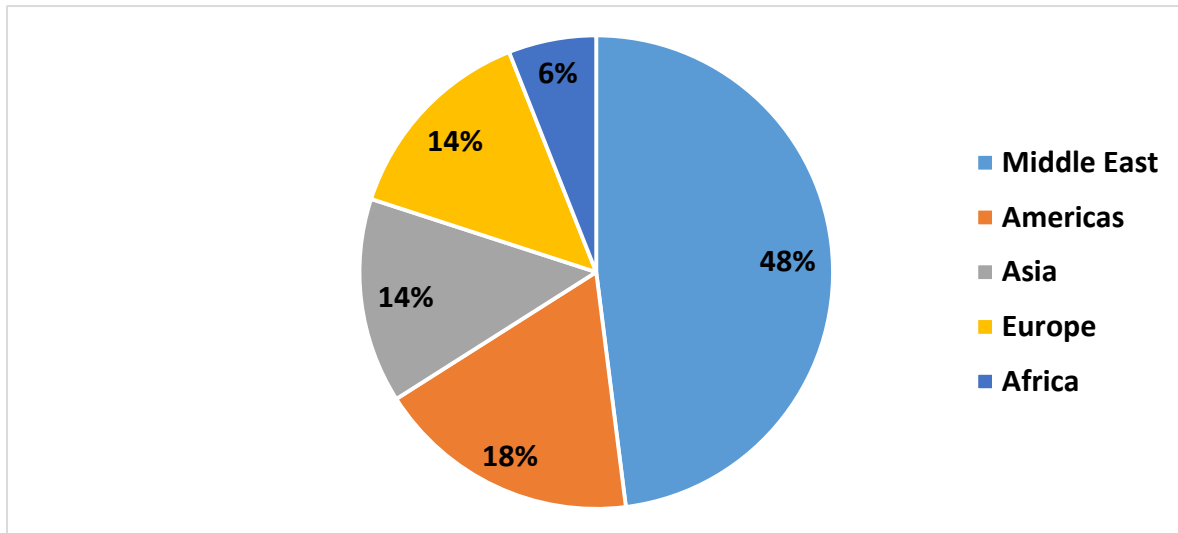


Figure 35: Worldwide Desalination Capacity [25]

In terms of technological options, currently two desalination technologies dominate the market: reverse osmosis (RO) and Multi Stage Flash (MSF), with 60% and 27% of the market, respectively. Forecasts for global desalination growth anticipate that the share of RO will increase to approximately 73% by 2016 [25].

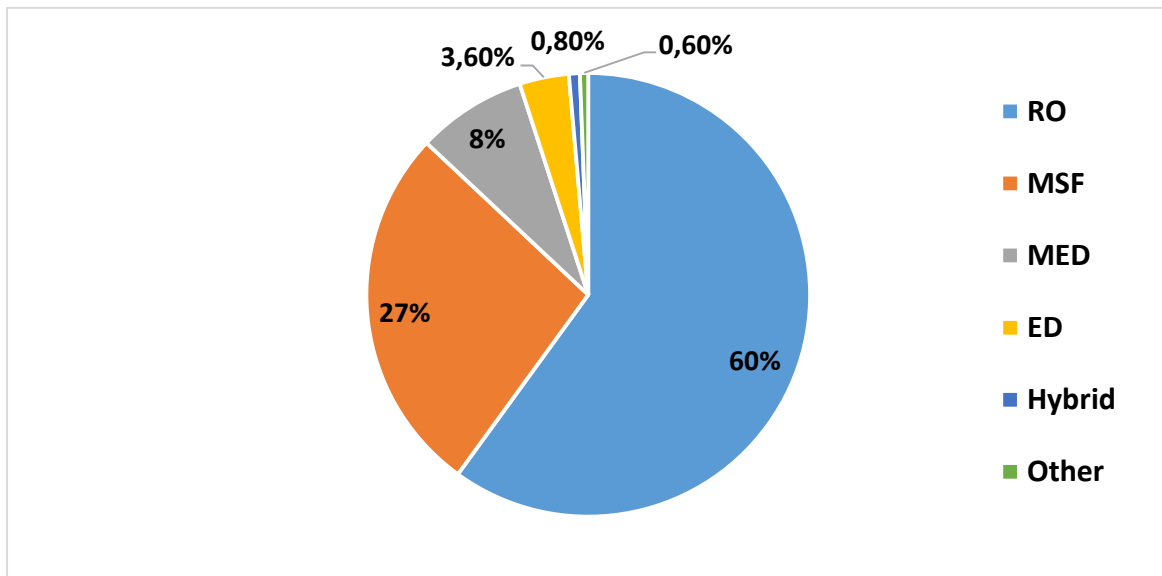


Figure 36: Desalination Technology Market [15]

The global desalination capacity is expected to grow at an annual rate superior to 9% until 2016, both in developed and emerging countries, with a continuation of the past development, meaning the future markets will not change in the near future. Close to 54% of this growth is expected to occur in the MENA region, although strong potential also exists in other areas of the planet such as remote regions and small islands [15]. From the top 15 markets investing in desalination, 9 are MENA countries. Other areas that are presently building large-scale desalination projects include Australia, China, India and the

USA. In addition, throughout the next 12 months 24 high capacity desalination plants are expected to be commissioned, totalling about 5.444.642 m<sup>3</sup>/day of production capacity [39]. The demand will come from: Saudi Arabia (8 plants), Oman (2 plants), Qatar (1 plant), Kuwait (2 plants), Nigeria (3 plants), South Africa (3 plants), India (2 plants) and Singapore (1 plant). The next figure shows the development trend for the main desalination markets.

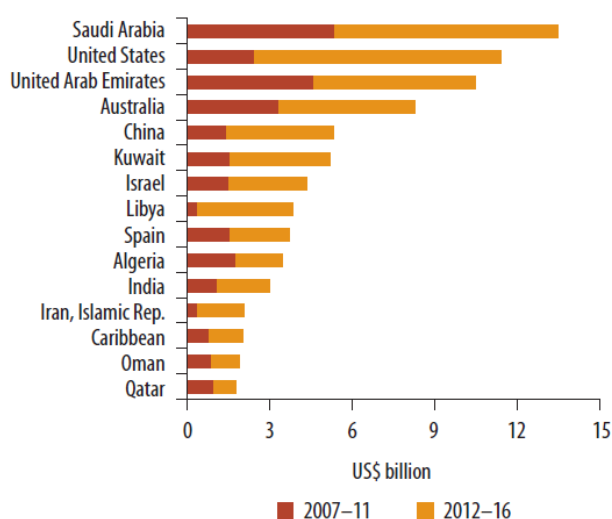


Figure 37: Top 15 world markets for desalination

It is expected that the total desalination market will reach over US\$31 billion by 2015 and that about 50% of total investment will be for SWRO projects, due to their lower investment, total water cost and footprint size.

Furthermore, according to the International Renewable Energy Agency (IRENA), desalination coupled with renewable energy can already compete cost-wise with conventional systems in remote regions where the cost of energy transmission is high. Renewable energy powered desalination is growing throughout the planet in countries such as Australia, Saudi Arabia, Egypt, Jordan, Morocco, Turkey, United Arab Emirates, Cyprus or Spain. This growth is particularly seen in arid regions with high solar energy potential such as the MENA region.

#### 4.1 Middle East and North Africa (MENA) Region

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change projects dramatic changes in climate across the region during this century: temperature increases combined with substantially decreasing precipitation, leading to severe water stress in the region.

A hydrological analysis confirms that per capita renewable water resources in MENA are among the lowest in the planet and projections indicate the situation will deteriorate. The Food and Agriculture Organization of the United Nations considers that total renewable water availability of less than 2000 m<sup>3</sup> is a potentially serious constraint and becomes a major issue in drought years while less than 1000 m<sup>3</sup> per capita indicates severe constraints to socioeconomic development and environmental protection. Considering this and examining Figure 38, it can be concluded that by 2020-2030 water availability in the MENA region will be a severe constraint to socioeconomic development and environmental protection in all the countries that are comprised in the MENA region.



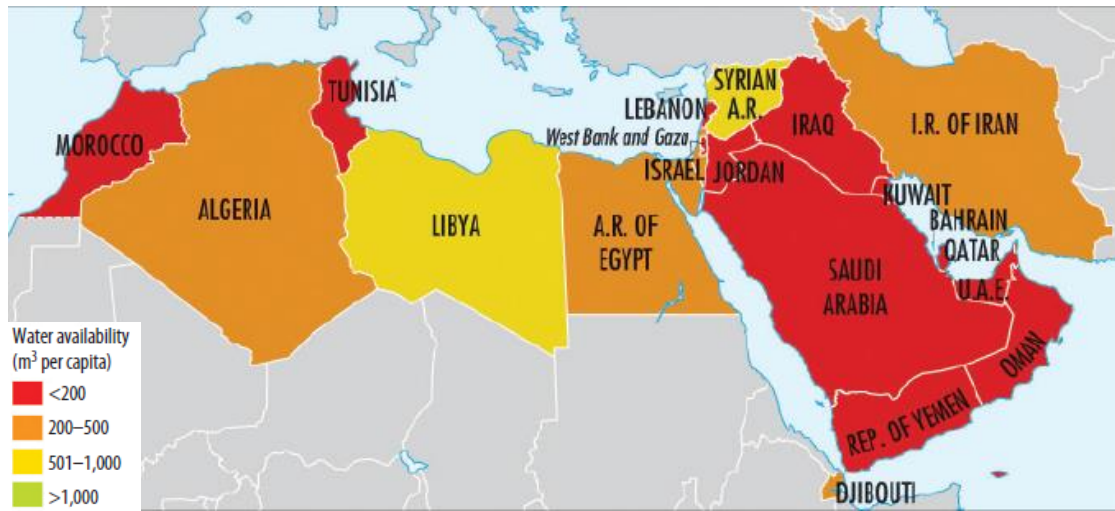


Figure 38: MENA's Water Availability by 2020-2030 [25]

Conventional supply management options in MENA are very limited. More than 80% of the region's surface freshwater resources are stored in reservoirs. MENA's rivers are the most heavily dammed in the planet. Thus, the potential to expand water supplies by building news dams is limited. This limited potential exists in more humid parts of the region such as north-western Iran and the Atlas Mountains of Algeria and Morocco. For this reason, the potential to bridge the water demand gap must come from unconventional supplies such as desalination of seawater or brackish water and wastewater reuse.

Also, future water demand in the MENA region is expected to increase while current water demand already exceeds natural available water suppliers by almost 20% Water demand is expected to increase due to population growth, which is expected to reach 697 million by 2050 from a current 381 million. Thus, the water balance gap is expected to reach 37% of total demand in 2020-2030 in an average climate scenario, reaching 51% by 2040-2050 [25].

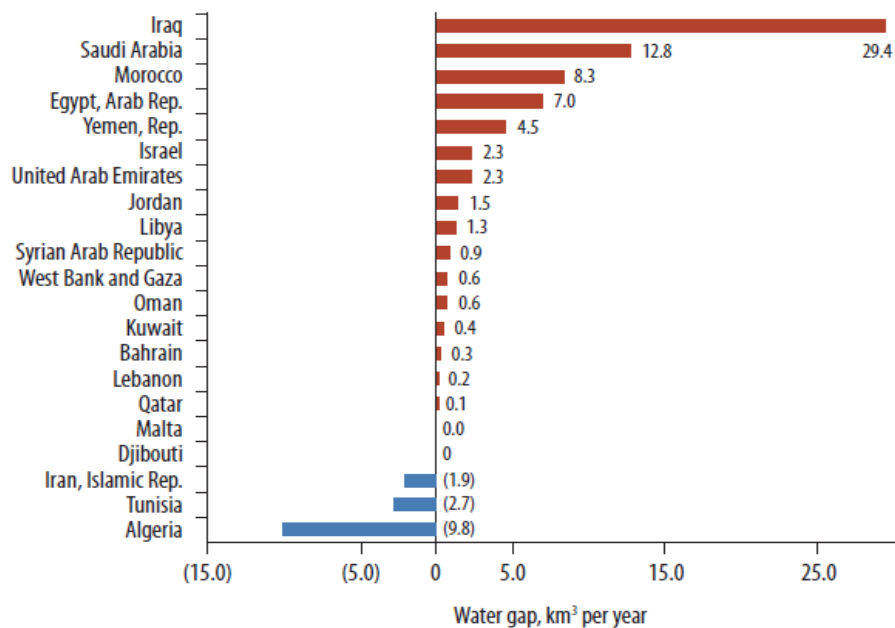


Figure 39: Demand Gap in MENA Countries by 2040-50 [25]

Desalination has proved to be a technically feasible option to supply MENA’s water gap. All MENA countries have access to seawater as a source of water for desalination and in 2012 there were approximately 2800 desalination plants in MENA that produced 27 million m<sup>3</sup> of fresh water every day [15].

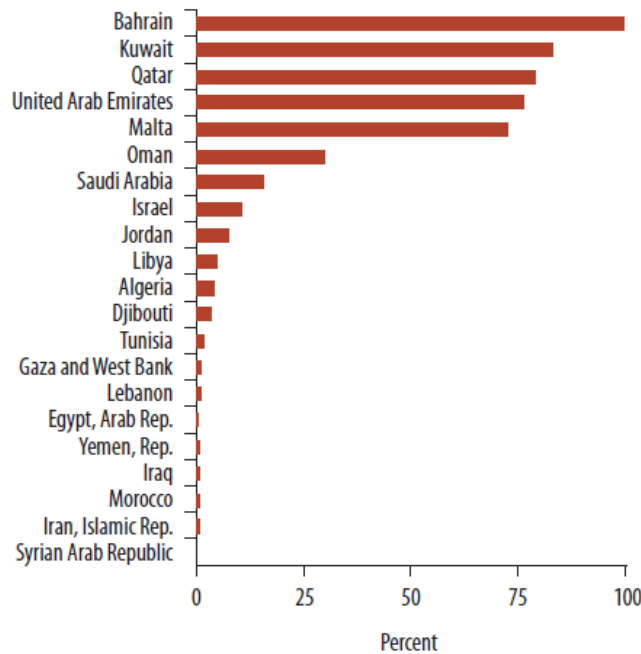


Figure 40: Share of National Water Demand in MENA met by desalination in 2010 [25]

The biggest challenges for the growth of desalination will be the reduction of the water cost and its energy demand, its reliance on fossil fuels and the reduction of its environmental impacts. Renewable energy systems can play a key role in all of the above. Currently renewable energy systems represent less than 4% of MENA’s primary energy balance, although MENA has plentiful renewable resources. Wind energy is currently explored along the coast of North Africa, particularly in Morocco, Algeria and Egypt. Also, solar energy potential in the MENA region is higher than in any other region of the world [25], with opportunity to apply CSP and PV electricity production. The solar market in the region is expected to grow substantially over the next 10 years.

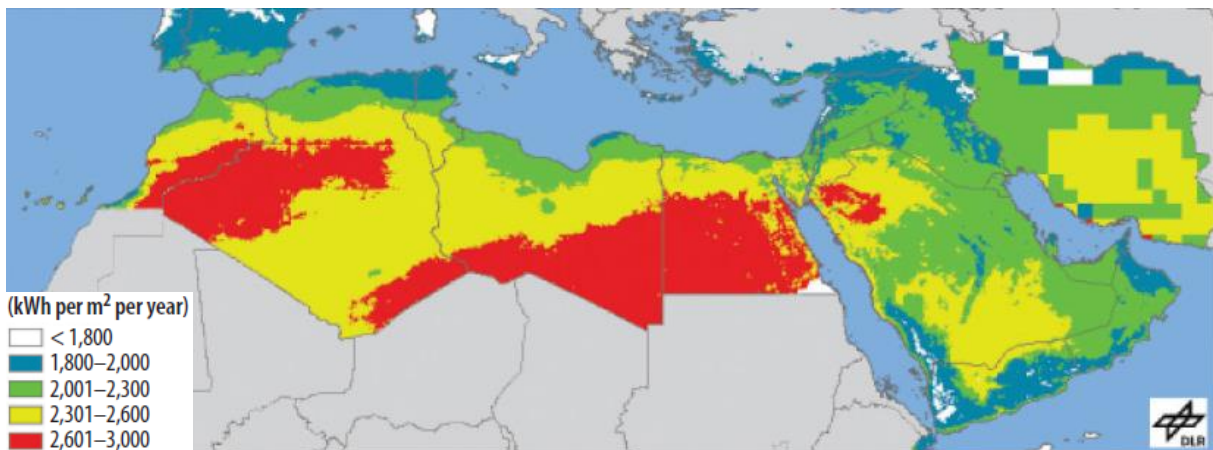


Figure 41: Annual Sum of Direct Normal Irradiation in 2011 [25]

Particularly in the Gulf Cooperation Council countries (Saudi Arabia, Qatar, United Arab Emirates, Kuwait, Oman and Bahrain) there are a number of initiatives related to the energy-water nexus and the utilization of renewable energy sources in desalination. The UAE, which produces all of the water in its distribution system through 9 desalination plants, launched in 2013 a programme for RE desalination with the main long-term goal to implement renewable energy-powered desalination plants in the country and to have a commercial scale facility by 2020. Presently the programme is being developed by *Masdar* in conjunction with 4 companies: *Abengoa*, *Degrémont*, *Sidem/Veolia* and *Trevi Systems*. Another programme, which is in a more advanced stage, is led by Saudi Arabia in an effort to power desalination through renewable energy.

#### **4.1.1 Saudi Arabia**

As previously mentioned Saudi Arabia is the largest producer of desalinated water in the planet. Saudi Arabia utilizes 1.5 million barrels of oil per day for desalination, which provides 70% of the country's drinking water [15]. With its growing population Saudi Arabia will require an additional 6 million m<sup>3</sup>/day of production capacity during the next 20 years, an investment above 200 billion dollars [28].

Aware of its future necessities, Saudi Arabia launched one of the more prominent initiatives in renewable energy desalination in the world, conducted by the Energy Research Institute at King Abdulaziz City for Science and Technology (KACST). Launched in 2010, it aims to utilize solar energy for seawater desalination at low cost, thus contributing to Saudi Arabia's water security and economy. It also sets the goal of advancing industries that can supply the development of clean energy technologies and protect the environment. The ultimate goal is to allow all seawater desalination in the country to be carried out utilizing solar energy by 2019, at a lower cost compared to current costs of thermal processes.

The implementation of this initiative was divided in four stages to be conducted over 9 years. The first phase, initially envisioned between 2010 and 2013, intends to build a solar photovoltaic powered (CPV) RO seawater desalination plant (SWRO) in Khafji, with capacity to produce 30.000 m<sup>3</sup> per day, making it the largest solar powered desalination plant in the world, the first high volume SWRO powered by solar energy. Presently this objective is near completion, with two PV power plants being constructed in Al-Khafji and Al-Oyainah solar village, with 10MW of total installed power. The next phase of the initiative intends to construct over the next three years a solar-powered SWRO plant that can produce 300.000 m<sup>3</sup>/day. Lastly, the final two phases intend to spread the initiative throughout the country.

To achieve these objectives, KACST established a joint research cooperation with IBM. Through the Centre of Excellence for Nanotechnology they are developing technologies to apply in the Initiative such as Ultra High Concentrator Photovoltaic (UHCPV) devices and nano-membranes for desalination that have anti-fouling coatings and are resistant to chlorine, salt blockage and accumulation of bacteria.

This UHCPV module, already applied at the Solar Village in Riyadh and Al-Khafji, is comprised of a triple junction solar cell capable of achieving 40% efficiency, for an overall module efficiency of 30% and a cost of \$2/watt [40].

Another good example is the recently announced SWRO plant in Ras Al Khaimah (UAE) with a production capacity of 80,000 m<sup>3</sup>/day and powered by a 20 MW PV plant.

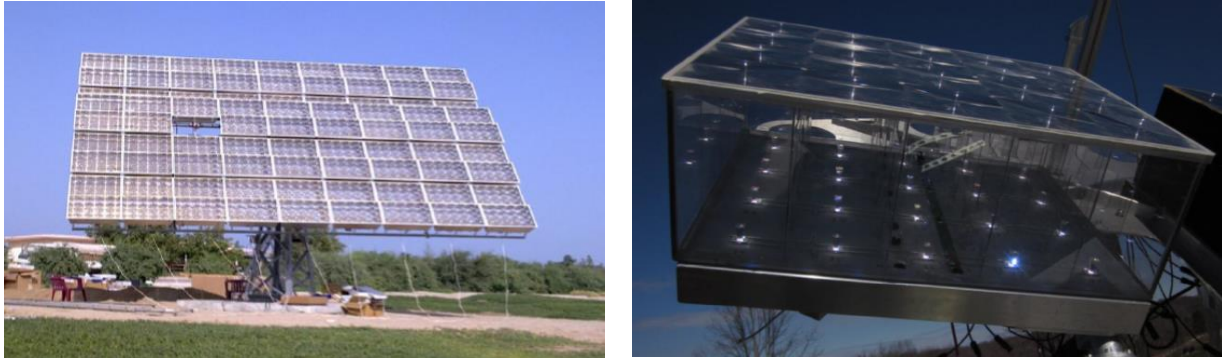


Figure 42: Ultra High Photovoltaic Concentrator with solar tracking in Al-Khafji and a UHCPV Module

#### 4.1.1.1 Case Study: Al-Khafji Solar powered SWRO Plant

The Al-Khafji SWRO plant, the world's first high volume solar powered SWRO, is currently under construction next to a previously existing MSF desalination plant.



Figure 43: Location of the Al-Khafji SWRO Plant [46]

The intake of seawater is done at 6300 meters from the plant with a deep open intake, which allows for better seawater quality and simpler pre-treatment, when compared to other water intake alternatives. The seawater quality of the area of the Arabian Gulf is characterized by challenging conditions: high salinity, high Boron content and high water temperature. According to national standards, the Boron

concentration for the desalinated water must be below 0.5 ppm, while the natural conditions offer between 5 to 6 ppm. The plant consists of different systems, as can be seen in the next figure.



Figure 44: Components of the Al-Khafji Plant [46]

The first is a pumping station for the initial attainment of water. The pre-treatment starts at the pumping station, with a coarse and fine screening to protect the plant from large objects that could block the process. Following, there's an initial physical and chemical filtration and clarification of the seawater, with a coagulation chamber, a flocculation chamber and a dissolved air flotation chamber. This pre-treatment removes between 85 and 95% of total suspended solids. The pre-treatment process ends with a two-staged closed filter process that removes particles such as sand and anthracite.

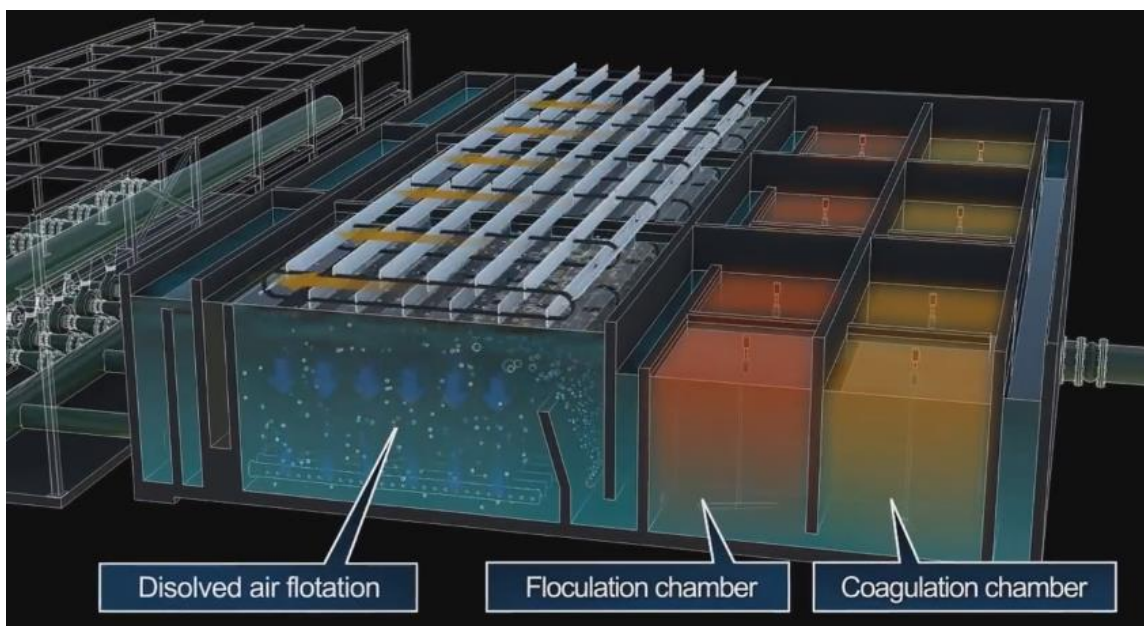


Figure 45: Pre-treatment system [46]

Subsequently, the RO process is achieved in two stages, with a new polymer nanomembrane – i-Phobe - that allows for a more energy efficient process and resists chlorine - which is used for the pre-treatment of seawater. Furthermore, an energy recovery device is utilized during the RO process, recovering energy (pressure) from the concentrate stream, pressure that is then utilized for the water approaching the RO membranes (this mechanism allows for an energy recovery of 50 to 60%). To conclude the process, a post-treatment system is required to re-mineralize the water. Potable water is attained by adding lime milk, CO<sub>2</sub> and chlorine. The potable water is then kept in the water tanks of the adjacent MSF plant. In this particular project, more than half of the capital investment was spent for the Intake and Pre-treatment systems [40].

## 4.2 Other Areas

Other countries that will require desalination in order to meet future water demands include the USA, Australia China and India.

USA is the 2<sup>nd</sup> largest market in the world, with desalination plants installed in all its states and the US government plans to invest heavily in R&D for water desalination in order to guarantee an adequate water supply. At this time the US desalination market is mostly comprised of membrane technology, RO in particular.

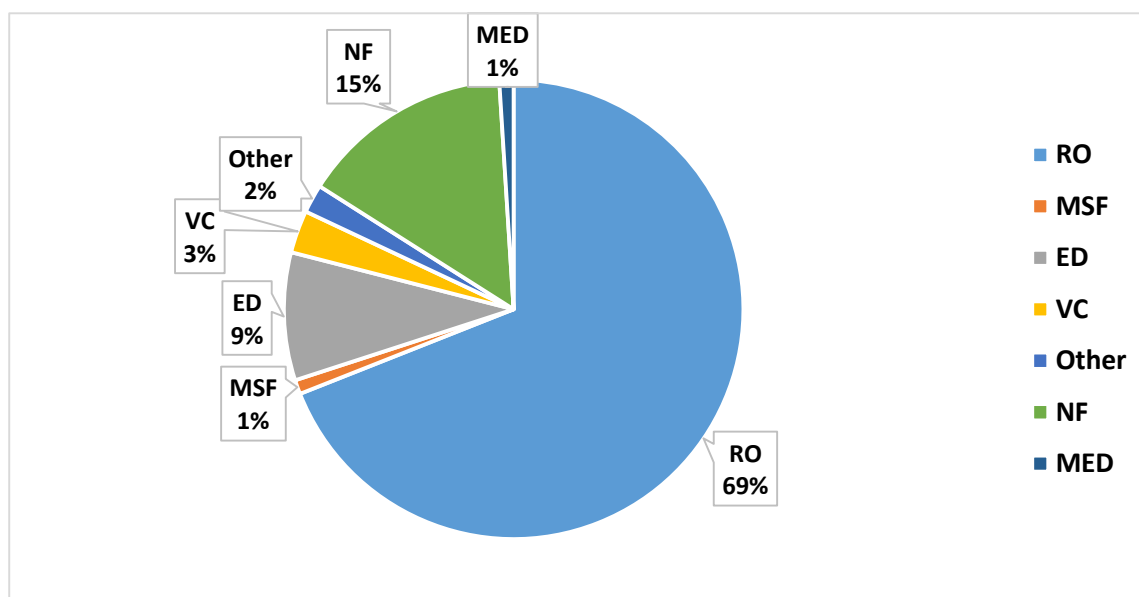


Figure 46: USA's desalination market by chosen technology

The states of Florida, California, Texas and Virginia are the largest producers of desalinated water in the US. In California alone, 15 to 20 new desalination projects are expected until 2030 [38].

Presently one of the world's largest desalination plants is under construction in California, the Carlsbad Desalination Project in San Diego County. This desalination plant will have a production capacity of 190,000 m<sup>3</sup>/day and will be constructed adjacent to a previously existing fossil fuel power plant. The

state's effort to invest in desalination is due to the chronic lack of water resources in the region. The entire state of California is currently rated as in severe drought, according to the country's Drought Monitor, with nearly 63% of the state being rated as in extreme drought. The existing drought period started 3 years ago.

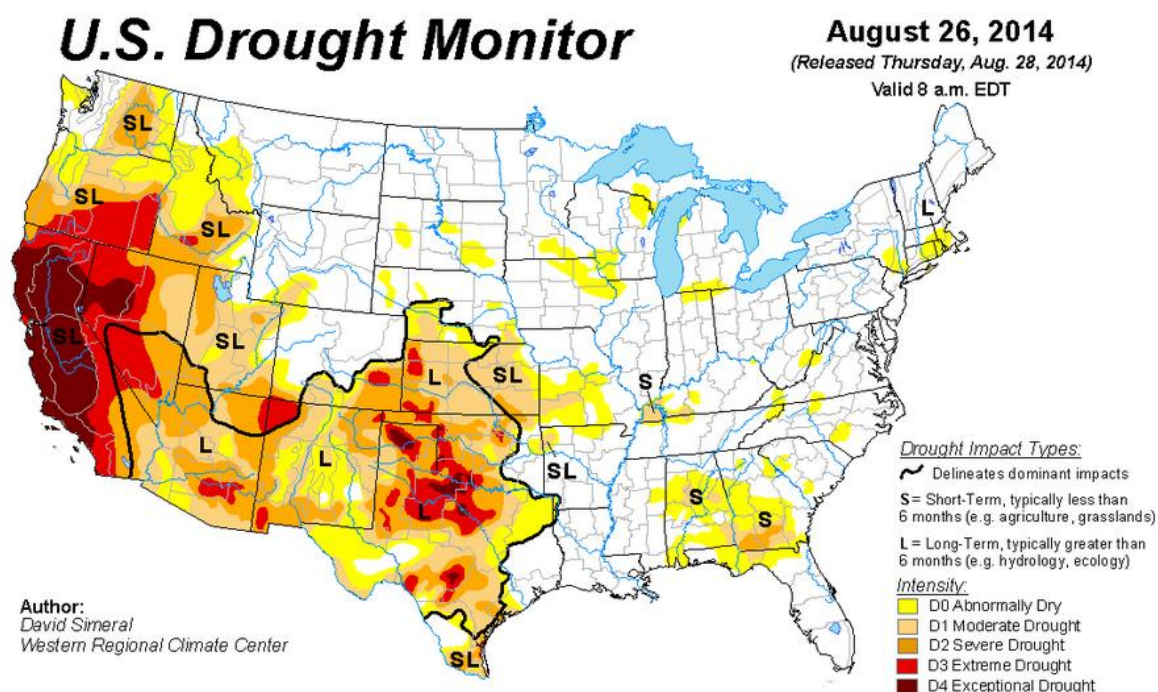


Figure 47: USA Drought Summary

Australia is also expected to endure water scarcity in the future, due to a 21% rainfall decline over the last 10 years, in an already dry continent. This decline in rainwater was connected to increased greenhouse gases and ozone levels, in southwest Australia, as is expected to continue [41]. Thus, its desalination market grew during since the beginning of the century and is expected to advance in the short and medium term. As already mentioned, the first large SWRO plant in Australia became operational in 2006 in Perth, one of the areas that is expected to suffer from rainfall decline. Perth Seawater Desalination Plant (SWRO), which buys electricity generated by a wind farm north of Perth, is designed to optimize the energy consumption and requires a total of 3.4 kwh/m<sup>3</sup>. Since then, five other were constructed, with a combined production of 1455 megaliters/day. Of the six plants, five of them are renewable energy powered RO systems, with the electricity being bought from wind farms, hydropower and solar thermal and solar photovoltaic. This is achieved by purchasing renewable energy certificates (RECs) equivalent to the amount of electricity consumed. Presently 4 of the desalination plants are in “stand-by” mode since water demand has been lower than expected.

China is also implementing desalination plants to alleviate water scarcity. The country's desalination capacity increased 4.6 times between 2005 and 2008 [28], making it the fifth highest desalination

country, and it may increase its capacity 100 times by 2020 [38]. In February 2012, China's State Council announced its 12th Five-Year Plan for desalination, establishing an expected target of 2.2 - 2.6 million m<sup>3</sup>/day of online capacity by 2015, versus less than 1 million m<sup>3</sup>/day today. It is thought that the government will extend subsidies and preferential financing policies to seawater desalination projects, support initial public offerings or bond sales by related enterprises and encourage private investment into the industry. One of the main goals is to increase domestic equipment production, to provide 70% of all equipment used in desalination plants.

Finally in the case of India, the country has over 1000 desalination plants with a total capacity close to 300,000 m<sup>3</sup>/day. Most of the current capacity is based on RO technology (63%), followed by MED (26%) and MSF (11%), although the majority of plants are MED (71%), followed by RO (22%) and MSF (7%). This market is under development stage with an expected compounded growth rate of 25% between 2010 and 2015-2017 [40].

### **4.3 Economic Assessment**

The cost of water production through desalination has declined over the years as a result of reductions in price of equipment, power consumption and advances in system design. As conventional water sources tend to become more expensive due to over-exploitation of aquifers and increased fuel prices, desalinated water is becoming a viable alternative in certain areas of the globe.

Cost estimates for desalinated water are site-specific and depend on several parameters [24]:

- Electric power availability: the desalination plant can be for example connected to an already existing conventional power plant and utilize waste thermal heat, or be connected to an energy grid and have the electricity transported a large distance;
- Chosen technology and components design: investment costs vary widely between thermal and membrane desalination plants. For similar production capacity thermal processes require larger footprint, higher specific energy (electrical and thermal) and have more expensive equipment than SWRO processes. On the other hand thermal distillate has higher quality than RO distillate and don't require pre-treatment;
- Plant size: generally the higher the plant capacity, the lower the total water cost and investment cost per volume of water;
- Geographical location and site-specific characteristics: land cost and water transmission;
- Quality of the feed water: salinity, temperature, intake arrangement and required produced water quality all influence the final cost as these parameters affect pre-treatment and post-treatment as well as operation and management costs and life-expectancy of the components;
- Energy price and availability: energy consumption has a major impact in final water cost;



- Financing specifics: amortization period, inflation;
- Operation and Management: equipment replacement (especially membranes, pumps and header pipes), skilled labour costs and training requirements.

Capital investment and total water costs are primary parameters utilized by decision makers to select appropriate desalination technology. Currently MSF plants require higher capital costs while RO requires higher operation and maintenance costs. Desalination costs have been decreasing for all technologies, with the largest cost reduction in RO technology, making RO the preferred technology. However, researchers believe these costs will not continue to decrease at the same rate in the near future, with rising costs of energy and raw materials [24].

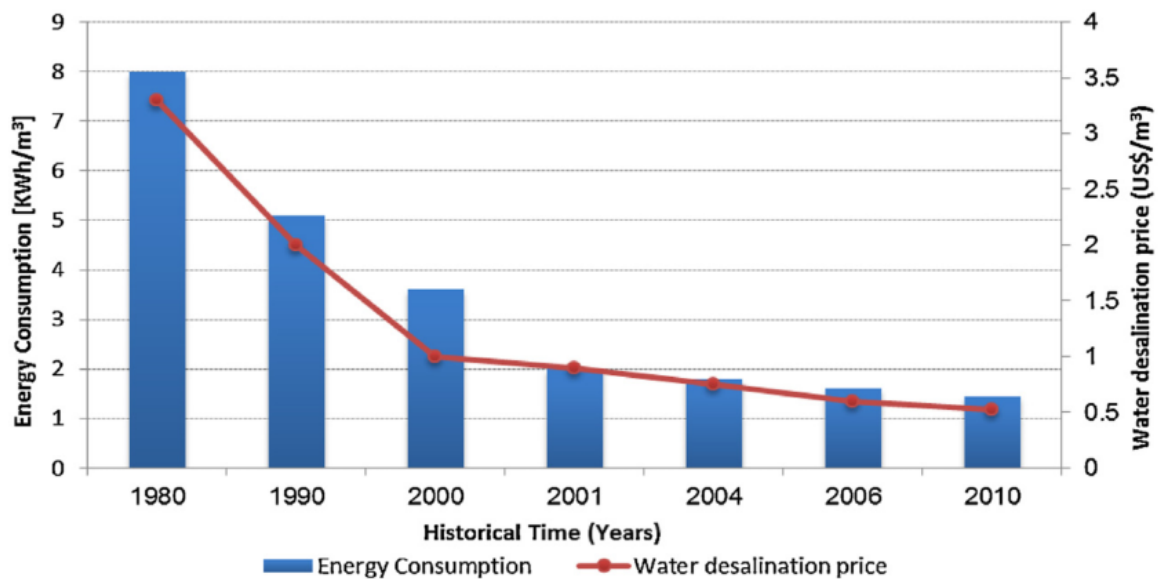


Figure 48: Development of achievable energy consumption and cost in RO desalination [22]

The cost of desalination is largely led by the energy cost. Consequently, the economic feasibility depends on local availability and cost of energy. Typically the TWC has a share of 28% for energy costs in the case of RO, and higher in the case of MSF (40%) and MED (32%) [22]. Also, electricity prices usually range at 5-6 \$/kWh [15].

The up-to-date TWC for SWRO ranges between 0.5-1.20 \$/m<sup>3</sup> [24]. In MED, the TWC for large systems with a production between 91,000 m<sup>3</sup> and 320,000 m<sup>3</sup> (per day) ranges between 0.52 \$/m<sup>3</sup> and 1.01 \$/m<sup>3</sup> [22]. In MSF the TWC ranges between 0.70-1.20\$/ m<sup>3</sup> while in VC it ranges between 0.60-1.0 \$/m<sup>3</sup> [24]. TWC is better compared when analysing total energy consumption of these processes, since thermal energy is subsidized differently by governments in energy rich countries.

Table 6: Cost of desalinated water by technology

Desalination technology	Cost (\$/m <sup>3</sup> )
SWRO	0.5 – 1.20
MED	0.52 – 1.01
MSF	0.70 – 1.20
VC	0.6 – 1.0

As for the cost of RE desalination, various literature indicates that the costs are higher than systems using conventional energy. The total solar system cost can range from 17.4% to 76.7% of total desalination system, depending on different system configurations. Studies have shown that in a PV-RO system, the desalination system alone should amount to 27-39% of total system cost [17].

Table 7: Water Cost of different RE Desalination combinations by production capacity [42]

Technology	Capacity (m <sup>3</sup> /day)	Production Cost (\$/m <sup>3</sup> )
Solar Still	0.1	1 – 5
Solar MED	1-100	2 – 5
Solar MD	0.1-10	8 – 15
CSP-MED	>5000	1.8 – 2.2
PV-RO	<100	5 – 7 (BW) 9 – 12 (SW)
PV-ED	<100	8 – 9
Wind-RO	1000	1.5 – 4
Wind-MVC	<100	4 – 6

However, in general the available costs are calculated for small or medium-scale systems within R&D environment. In commercial large-scale plants the cost should be more competitive due to economies of scale. For example at the already mentioned Australian desalination plant in Perth, Wind-RO, the cost is reported around 1.17 \$/m<sup>3</sup>. Furthermore, the levelized cost of electricity (LCOE) of renewable energy

technologies such as wind and solar PV is already cost-competitive with conventional electricity generation (coal and combined cycle gas turbines) in locations with appropriate irradiance or wind resource. A recent study from the Fraunhofer Institut for Solar Energy Systems studied the LCOE in Germany in 2013 and also predicted the future cost development through 2030 based on learning curves and market scenarios. It concludes that utility-scale PV and on-shore wind energy production are already cost-competitive with combined cycle plants and hard coal plants in Germany. In other areas of the planet with higher solar irradiance or wind resource the LCOE will be even lower, thus improving the competitiveness of the renewable energy systems and increasing the opportunity of utilizing RE to power desalination systems that require only electricity, such as RO.

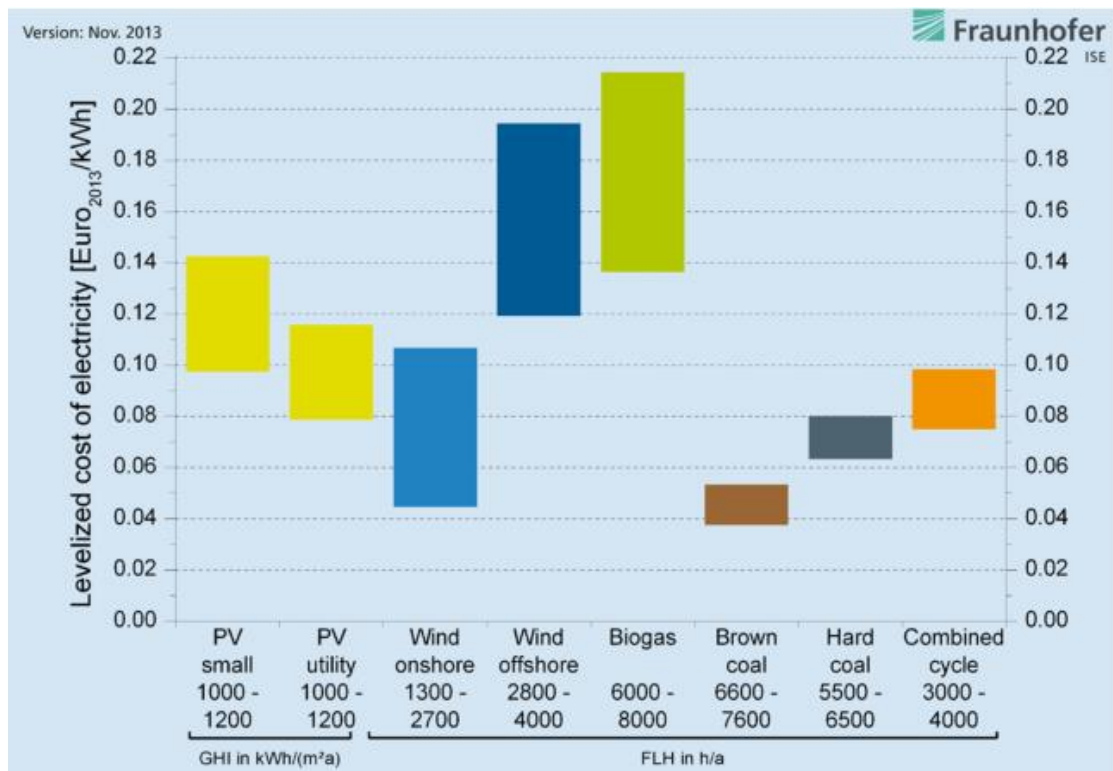


Figure 49: LCOE of renewable energy technologies and conventional power plants in Germany in 2013 [43]

In figure 49 the value under technology refers either to global horizontal irradiation (GHI) in the case of PV or to full load hours in the case of the others. The study concludes that by the end of the next decade the LCOE of small rooftop PV systems will compete with onshore wind and conventional generation and also concludes that PV utility-scale plants will be considerably below the LCOE of conventional power plants by 2030 [43].

The final cost of RE desalination will be dependent on a number of parameters. The application of a RE system will require considerations such as location, plant design, energy storage or lack thereof, the intended energy yield and its hourly distribution.

The direct connection of large scale renewable energy production systems with large desalination plants has potential and is already occurring in key markets such as Saudi Arabia and Australia. The key sources for funding such projects have been governments and public-private transaction models. However, while various countries offer financial support for electricity produced by renewable energy sources, this support is not yet common for energy displaced by renewable energy sources in desalination plants. Thus, leading corporations in the large-scale desalination industry will play a crucial role in the implementation of RE desalination. A list of these is presented in table 8.

Table 8: Leading Companies in Global Desalination Market

<b>Company</b>	<b>Country</b>	<b>Company</b>	<b>Country</b>
Abengoa S.A.	Spain	Fisia	Italy
Acciona S.A.	Spain	General Electric Water	USA
AES	USA	Hyflux	China
Aqualia	Spain	Hyunday	S.Korea
Aqualyng	China	IDE Technologies	Israel
Aquatech International Corp.	USA	Inima	Spain
Befesa	Spain	ITT	USA
Biwater	UK	Koch Membrane Systems Inc.	USA
Cadagna	Spain	Kurita	Japan
Danfoss A/S	Denmark	Mitsubishi	Japan
Degrémont - Suez Environment	France	Modern Water Plc.	UK
Desalia	Spain	Nomura	Japan
Doosan	S. Korea	Siemens	Germany
Dow Water	USA	Tedagua	Spain
Energy Recovery Inc.	USA	Veolia Water Solutions	France
FCC	Spain		

In regard to small-scale commercial systems that deliver renewable energy with desalination technology in one small packaged process, these tend to be intended for remote locations where electricity supply is unavailable and currently these applications tend to be niche and specialised. To determine the market

potential of these, different data should be considered such as: local water consumption, local energy consumption, percentage of water already derived from desalination and availability of local renewable energy resources. As commercialization of RE desalination is still a novelty, knowledge about market potential and its characteristics is minor. For this reason, evaluating investment risk and return is difficult. Also, the pricing structures and subsidies of water supplies in many countries can create scenarios in which investing in RE desalination can remain unprofitable or offer high perceived risk, although there is a growing need for desalination technologies in various regions of the globe. Access to safe drinking water is generally considered a fundamental human right and consequently the cost of water production, either by desalination or other means, is often loosely linked to the price that final consumers pay for the water. Moreover, even in cases where the water from RE desalination has lower costs than other alternatives, it might not seem attractive due to the high initial investment costs and subsequent low operational costs, dissuading users with limited financial capability.

## 5. Conclusions

Current and future water challenges will require solutions for the sustainable use of the planet's water resources. This thesis explored one of the available alternatives that can support this goal. Recent technological developments that allow for low cost desalinated water production and increased energy efficiency indicate that integrated renewable-energy powered desalination holds significant medium and long-term development potential. The reviewed renewable energy technologies are especially promising in areas where water scarcity is severe, although the application of RE desalination has so far been limited.

The main challenges for renewable energy driven desalination plants are the reduction/financing of initial capital investment for energy generation and the reduction of energy consumption of the desalination process, utilizing more robust energy recovery systems. Another challenging issue for RE desalination is the matching of the power output with the energy demand of the desalination process. Current two options to solve this issue are considered: power supply management and supply side management. In the first, a steady energy output is secured by means of for example hybrid power generation. In the second, the desalination process operates in respect to the energy output of the renewable energy source.

In reference to the environmental impacts of desalination, these require further investigation and attention in order to achieve water security without increasing environmental externalities. Renewable-energy based desalination can help eliminate the carbon emissions of conventional energy supply from the desalination process but there are still other issues such as brine disposal.

Various desalination technologies exist, as well as diverse renewable energy technologies to power them. However, there is no perfect technological solution, optimal combinations vary from region to region, RE desalination systems need to be designed iteratively. A decision on what are the best technologies to employ requires evaluating several design parameters: seawater quality, desired water quality, availability of renewable energy resources, capital cost, operation and maintenance costs, energy efficiency and environmental impacts. As both solar power systems and desalination systems can be developed separately and then coupled together, it is possible to analyse them separately, though a holistic approach should be preferred. Having said this, I consider that solar PV coupled with RO desalination stands out as the superior choice between the available. There are several reasons for this conclusion: RO is currently the most energy efficient desalination process commercially available, and one that only requires electrical energy in order to drive mechanical auxiliary systems; solar PV systems capital costs are expected to keep decreasing, making it attractive and cost-competitive with fossil fuel systems [44]; all solar thermal processes require water in their processes, even though this water footprint can be lowered, making solar PV the most attractive option in locations where water scarcity is the original parameter; the seasonal increase in available energy coincides with the increased water

demand; and finally, both PV and RO systems are highly scalable, allowing a project to be built in phases or as the need arises.

Innovative technologies such as graphene membranes and carbon nanotechnology membranes and new processes such as forward osmosis and the combination of more than one desalination technology within the same plant, will give way to new possibilities to couple with renewable energy sources and will provide interesting research possibilities.

Finally, the main world markets for desalination are the MENA region and countries such as Australia, China, India and the USA, while other areas such as islands have the potential to become significant markets. Until recently the construction of large-scale desalination plants was frequently based on the availability of conventional energy resources. However, with the ever decreasing costs of RE production, the association of RE with desalination will permit the implementation of the latter in further locations that require it, leading to the growth of RE desalination markets.

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