PhD dissertation

ANALYSIS OF SOLAR ENERGY IN DESALINATION PLANTS IN SAUDI ARABIA

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Abstract

Water scarcity is an issue in a number of countries, especially in semi-arid and arid areas. One of the most promising applications of solar energy is water desalination, especially in regions where fresh water is scarce, and sunlight is abundant. Desalination is a growing and necessary source of fresh water, but it is highly energy-intensive. Conventional desalination is currently supported by fossil fuels, and it is critical to explore renewable options to reduce pollution. The most important of these options is solar power. In the Middle East and North Africa (MENA), seawater desalination has been among the key sources of potable water. In the Gulf region, and especially in some of the Gulf Cooperation Council (GCC) countries, desalination has been estimated to reach 90%. Saudi Arabia is among the countries facing significant challenges due to insufficient natural water resources. This research analyses the viability of coupling the already established thermal and membrane desalination plants in Saudi Arabia with different solar energy technologies, concentrated solar power and photovoltaic (CSP and PV) to produce potable water and to be economically viable as well.

The study begins by using the analytical hierarchy process to select adequate desalination technologies for Spain and the GCC countries by considering the results obtained from a survey of experts in the field for all these counties. This study found that the most suitable technologies for Spain and the GCC countries are reverse osmosis and multi-stage flash (RO and MSF), respectively. A techno-economic and Levelised Cost of Water (LCOW) analysis are discussed. Case studies, including a standalone CSP assisted MED-TVC using Parabolic Trough (PT), a Linear Fresnel Reflector (LFR), and a Central Receiver Tower (CRT) with different storage options are analysed and discussed. Conclusions and recommendations are also presented. The application of concentrated solar thermal energy using PT, CRT, and LFR for small scale desalination plants that use fossil fuel is also investigated. The amount of fuel that can be saved by getting the necessary thermal energy from solar energy is estimated. It is found that LFR technology is the most cost-competitive, and PT technology is the best when opting for more fuel savings.

The research was followed by practical international cooperation with the Japanese company Hitachi through the construction of a CSP pilot plant using an improved Fresnel solar collector (LFR) developed by the Hitachi Company in Japan at the premises of the desalination Technologies Research Institute in Al Jubail, Saudi Arabia. Extensive studies involving pilot plant experiments were conducted for one year to assess the effects of climate conditions. The optimum operating conditions of the hybrid system that combines the use of fossil fuel and solar energy in an alternating operation mode were determined (i.e., the identification of the optimum fossil fuel (back-up)/solar combination). A comprehensive economic analysis of the obtained results from the pilot plants was carried out. The thermal collector efficiency, which is between 60% and 80%, depends on a number of climatic conditions, which include ambient temperature, heat losses, solar insolation and receiver temperature. In order to compare the cost-effectiveness, a commercial thermal desalination plant that utilised an LFR with multiple solar values of 1.0 for day time operations were compared to a conventional fossil fuel driven desalination plant. With an equal levelised cost of water for both cases, the fuel breakeven cost is attained at the cost of $92 per barrel. However, the breakeven value drops to $52 per barrel when the tested (LFR) system is operated in a different location that has a higher yearly Direct Normal Irradiance (DNI) level of approximately 1937 kWh/m^2. The study revealed that under specific climatic conditions, combining a MED thermal desalination plant with (LFR) technology and operating them without thermal energy storage proved to be more cost-effective.

Finally, one of the membrane desalination plants in Saudi Arabia has been selected to determine the design of PV-RO solar-powered seawater desalination system that yields optimum results without storage. At midday, the electrical power generated by the photovoltaic solar plant lies within the range of 9.15 MWh to 17.95 MWh. Among the designs of the solar plant capacities ranges from 1 MW to 100 MW and the plant performance factor is between 80 and 100%. The optimal results were obtained when the plant capacity reached 20 megawatts, corresponding to wasted energy of about 20%. In this case, the price of production cost for the solar plant is 0.025 euros per kWh. This price is less than the current tariff price of the kilowatt of electricity in Saudi Arabia, which is estimated to be 0.036 euros. This study confirms that the higher design capacity of the solar power plant increases the associated waste of energy. This surplus energy cannot be used by the RO plant in Ras Al-Kkhair, effectively leading to wastage and an increased operation cost.

For a capacity greater than 60 megawatts, the price of kilowatts per hour will exceed the tariff of electricity consumption in Saudi Arabia. This study is based on conducting theoretical and practical studies, considering real technical data in order to prove the possibility of integrating various desalination and solar energy technologies in different ways. It contributes to the understanding of low-temperature solar-thermal desalination systems performance under different conditions, as well as PV-Solar-reverse osmosis, and contributes to the advancement of the existing knowledge in this area, in general.

"*I would put my money on the sun and Solar energy. What a source of power!*
I hope we do not have to wait till oil and coal run out before we tackle that."

Thomas Edison

Resumen

La escasez de agua se ha convertido en un problema importante, en numerosos países, y especialmente en aquellos situados en zonas semiáridas y áridas. Una de las soluciones más prometedoras, para resolver este problema, es el uso de la energía solar para la desalinización del agua; especialmente, en regiones donde el agua dulce es escasa y la luz solar es abundante. La desalinización permite obtener cantidades importantes de agua dulce, pero es muy intensiva en energía. La desalinización convencional se apoya actualmente en los combustibles fósiles. Es fundamental explorar otras opciones que se basen en energías renovables con el objetivo, entre otros, de reducir la contaminación. Entre estas opciones, se encuentra la energía solar.

En Oriente Medio y África del Norte (MENA), la desalinización del agua de mar, ha sido una de las principales fuentes de agua potable. En la región del Golfo, se ha estimado, que la desalinización, en algunos de los países del *Consejo de Cooperación del Golfo* (CCG), ha alcanzado el 90%. Arabia Saudita se encuentra entre los países que se enfrentan a importantes desafíos debido a la carencia de recursos hídricos naturales. Esta investigación analiza la viabilidad económica para suministrar energía, a las plantas de desalinización térmica y de membrana que se encuentran en funcionamiento en la actualidad en Arabia Saudita, utilizando diferentes tecnologías como sería el caso de la energía termosolar (por concentración) y la energía solar fotovoltaica (CSP and PV) para producir agua potable.

La investigación se inicia utilizando, como metodología, el proceso de jerarquía analítica para seleccionar las tecnologías de desalinización adecuadas para España y los países del CCG a partir de los resultados obtenidos de una encuesta que fue respondida por expertos en la materia de estos países. Se obtuvo que las tecnologías más adecuadas, para España y los países del CCG, son la ósmosis inversa y la Destilación Instantánea de Multietapa (RO y MSF), respectivamente. Se lleva a cabo el análisis de viabilidad técnico-económico para obtener el coste del agua desalada, mediante el estudio de casos, que incluyen distintas tecnologías como serían: concentradores solares parabólicos (PT), reflector lineal de Fresnel (LFR) y una torre receptora central (CRT) con diferentes opciones de almacenamiento y se presentan conclusiones y recomendaciones. También se investiga la aplicación de la energía térmica solar concentrada utilizando PT, CRT y LFR para plantas de desalinización en pequeña escala que utilizan combustibles fósiles. Se estima la cantidad

de combustible que se puede ahorrar, para obtener la energía térmica necesaria, a partir de la energía solar. Se ha comprobado que la tecnología LFR es más competitiva, en relación con los costes, y la tecnología PT es mejor opción cuando se opta por un mayor ahorro de combustible.

La investigación se completa con los resultados obtenidos a partir de la construcción de una planta piloto (en cooperación con la empresa japonesa Hitachi) que utilizó un colector solar Fresnel mejorado (LFR), desarrollado por la empresa Hitachi en Japón, en el Instituto de Investigación de Tecnologías de Desalinización en Al Jubail (Arabia Saudita). Durante un año se llevaron a cabo una serie de estudios, con la planta piloto para evaluar los efectos de las condiciones climáticas. Se determinaron las condiciones óptimas de funcionamiento del sistema híbrido, que combina el uso de combustible fósil y energía solar, en un modo de funcionamiento alternado (es decir, la identificación de la combinación óptima de la relación combustible fósil (como combustible de reserva) y energía solar. Se llevó a cabo el análisis económico de los resultados obtenidos de la planta piloto.

La eficiencia de los colectores térmicos, que se sitúa entre el 60% y el 80%, depende de una serie de condiciones climáticas que incluyen: la temperatura ambiente, las pérdidas de calor, la insolación solar y la temperatura del receptor. Con el objetivo de analizar la rentabilidad se comparó una planta comercial, de desalinización térmica que utilizaba un LFR con un valor múltiple solar de 1,0 para operaciones diurnas, con una planta de desalinización convencional impulsada por combustibles fósiles. Para el mismo coste del m^3 de agua desalada, en ambos casos, el coste de equilibrio de combustible se alcanza a un coste de 92 dólares por barril. Sin embargo, el valor de equilibrio baja a 52 dólares por barril cuando el sistema probado (LFR) se ubica en un lugar diferente y que tiene un nivel de irradiación normal directa (DNI) anual más alto (aproximadamente 1937 kWh/m^2). El estudio reveló que, en condiciones climáticas específicas, la combinación de una planta de desalinización térmica MED con una tecnología (LFR) y su funcionamiento, sin almacenamiento de energía térmica, resultó ser más rentable.

Por último, se ha seleccionado una de las plantas de desalinización por membrana de Arabia Saudita para determinar el diseño de un sistema de desalinización de agua de mar alimentado por energía solar fotovoltaica PV-RO. Al mediodía, la energía eléctrica generada por la planta solar fotovoltaica se encuentra dentro del rango de 9,15 MWh a 17,95 MWh. Se dimensionaron diferentes instalaciones solares fotovoltaicas para un rango de potencias pico que varían de 1 MWp a 100 MWp y un coeficiente de rendimiento de la planta entre el 80 y el 100 % Los resultados óptimos, para el caso de la planta, objeto de estudio en condiciones de funcionamiento real, se obtuvieron cuando la capacidad de la planta fue de 20 megavatios. En este caso se obtiene que un 20 % de la energía generada, por la instalación solar, no podría aprovecharse y podría suministrarse a la red. El coste de producción de la electricidad generado por la planta solar es de 0,025 euros por kWh. Este precio es inferior al precio actual de la tarifa del kilovatio de electricidad en Arabia Saudita, que se estima en 0,036 euros.

Para una instalación que estuviera sobredimensionada (eg. Planta de 60 MWp), el precio de los kilovatios por hora superará la tarifa de consumo de electricidad en Arabia Saudita. Destacar que el estudio se ha realizado, a partir de datos reales y que tenía como objetivo analizar la posibilidad de integrar diversas tecnologías de desalinización y de energía solar.

El autor considera que la tesis contribuye a la comprensión del rendimiento de los sistemas de desalinización térmica solar de baja temperatura en diferentes condiciones, así como de la ósmosis inversa solar fotovoltaica, así como al avance de los conocimientos existentes en esta área en general.

Acknowledgements

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I would especially like to thank my supervisors, Dr. Javier Ordóñez, and Dr. Mohamed Khayet, for their guidance, encouraging me to explore something in which I have a great interest and guiding me toward its completion.

I could not have accomplished this research without the unforgotten support of my family despite the illness that I suffered during this study.

This thesis is dedicated to my parents, Abdulaziz and Naialah, and my brothers, especially my big brother Nasir, who have given me their unequivocal support.

Lastly, I would like to thank my wife for her endless support.

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List of Abbreviations

NGOs	Nongovernmental Organisations
UN	The United Nations
OECD	Organisation for Economic Co-operation and Development
ppm	Parts per million
TDS	Total dissolved solids
WHO	World Health Organisation
GHG	Greenhouse Gas
CO2	Carbon dioxide
FW	Freshwater
GWI	Global Water Intelligence
KSA	Kingdom of Saudi Arabia
IDA	International Desalination Association
ASEAN	Association of Southeast Asian Nations
WW II	World War II
MSF	Multi-Stage Distillation
VDC	Vapor Compression Distillation
MED	Multi-Effect Distillation
RO	Reverse Osmosis Desalination Process
ED	Electrodialysis
DC	Direct Current
CAPEX	Capital Expenditure
MEMA	Middle East and North Africa
OPEX	Operating Expenses
ERD	Energy recovery devices
SWRO	Seawater Reverse Osmosis Desalination
pH	Potential of Hydrogen
BOOT	Build-Own-Operate-Transfer
GCC	Gulf Cooperation Council countries
UAE	United Arab Emirates
AHP	Analytical Hierarchy Process
AGUA	Water in Spinach language
USA	The United States of America
PHN	National Hydrological Plan
CEOs	Chief Executive Officer
EU	European Union
GDPR	General Data Protection Regulation
PT	Parabolic Trough
CRT	Central Receiver Tower
LFR	Linear Fresnel Reflector
NREL	National Renewable Energy Laboratory
SAM	System Advisor Model

Chapter 1 – Introduction

1.1 Problem statement

1.1.1 Water Problems and Scarcity

In the era of the development of the 21st century, many countries are still facing World 'water scarcity' [1]. Different Nongovernment Organisations (NGOs) and media groups, and organisations, such as the United Nations (UN) and the Organisation for Economic Co-operation and Development (OECD), are focusing on the serious and fast-growing matter of water scarcity. According to the UN [2], 1.2 billion people lack access to necessary supplies of water. The problem of water scarcity is expected to increase over time, and it will affect a greater portion of the environment and increased amounts of people. In this research, the focal point is the use of desalinated seawater as an available source of fresh water [3]. Water plays an important role, whether it's in the context of agriculture or food security, or in pursuit of survival or wealth. Water demand is increasing day by day, and its availability is reducing, giving birth to water scarcity issues. When the annual supply of water drops below 1,700 m^3 per head, water stress is the result. When it falls below 1,000 m^3 per head in a region, that region faces 'water scarcity,' and at levels below 500 m^3 per head per year, it faces 'absolute scarcity.' Figure 1.1 depicts the intense level of water scarcity prevalent across the globe [4]. The map estimates the countries that may have to import at least 10% of their water in the next few years [5].

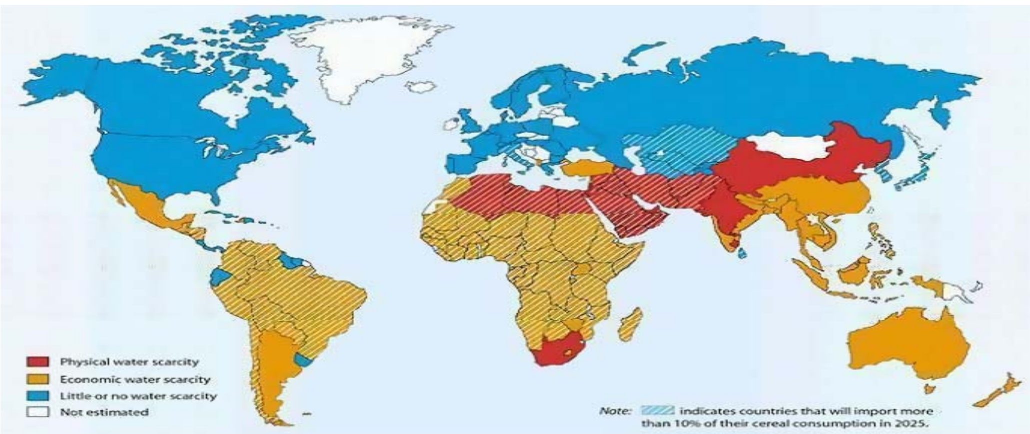


Figure 1.1. Global physical and economic water scarcity

Water scarcity has been further classified as 'physical' and 'economic' scarcity. Regions facing physical water scarcity are defined as those where further use of water is no longer possible as physical limits have been reached. On the other hand, economic water scarcity occurs where the development of capital and infrastructure has placed limits on access to water, though it is naturally available in sufficient quantities to satisfy local requirements [6]. While physical scarcity is present in places where the sources of water are not sufficient to meet pertinent demands, economic scarcity of water arises from a lack of investment or planning. It is characterised by inadequate infrastructure or a disparity in the distribution of water. Physical water scarcity is very often seen in dry and arid regions like the Middle East and countries in Africa and South America. Both economic and physical water scarcities are considered to be one of the toughest challenges facing society today [7,8].

About two billion people around the world are affected by water stress issues. With this figure expected to increase, it affects countries in every continent and puts a question mark on the future availability of natural resources, along with economic and social progress. The scarcity of water is also very much linked to climate change. According to the World Commission on Environment and Development, about 80 countries with nearly half the world's population are suffering from acute water shortage [9]. Water is perhaps the essential natural resource on the planet. It is necessary for human survival, serving as a critical component of our food, industry, and infrastructure. It also sustains the ecosystems and climate on which both the human species and natural world rely on. Today, we are putting more and more pressure on freshwater resources than ever before. Caught between a rapidly growing population, a developing economy and a shifting climate, water stress and, therefore, water scarcity are raising serious concerns on the existence of the human race and life around the world.

1.1.2 Fresh water availability and demand

The global water crises have been assessed based on the availability, consumption and growing scarcity of water, while its possible solutions are discussed and compared with one another. In this perspective, an appraisal of desalination technologies as a potential solution to the looming crisis of one of nature's most abundant resources has emerged as an utter necessity of the day. Water is truly considered one of the essential prerequisites to the existence of life on Earth.

Though we find 70% of the surface of the earth is covered with water, almost 97% of the water mass is found in the oceans, where salinity may range to 30,000 ppm TDS. Of the remaining 3%, approximately 2% is found in glaciers or icebergs, with less than 1% of the total earth's water in the form of fresh groundwater [10]. A freshwater body, such as a lake or river, contains very little amount of salts or other solids dissolved in it. According to (WHO), 'fresh water' may be defined as water having less than 500 ppm TDS. The fresh water that we use mostly comes from surface water bodies like rivers, lakes, reservoirs, or from groundwater sources like wells. The eventual source of all fresh water is natural precipitation in the form of rain and snow. Distribution of different forms of earth's water is presented in Figure 1.2.

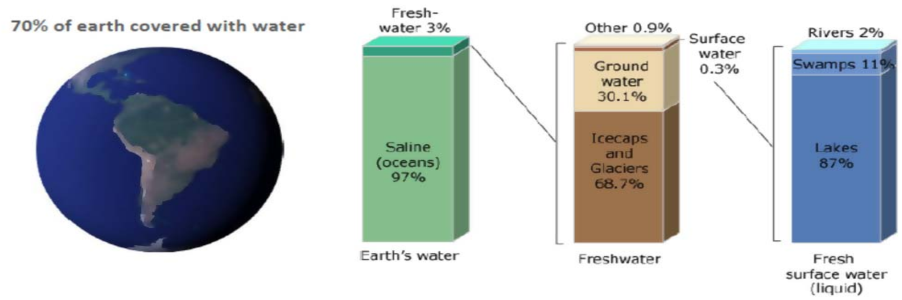


Figure 1.2. Graphical distribution of the water on Earth [10]

The present demand for water in all countries is around 4 trillion m³ per year. The withdrawal of water on a global scale has been anticipated to grow by about 10-12% every ten years to about 5 trillion m³ per year by 2050 [11]. Figure 1.3 presents the growth patterns of population and water mutually compared, where water withdrawal has roughly grown twice the rate of the population growth since the last few decades [12].

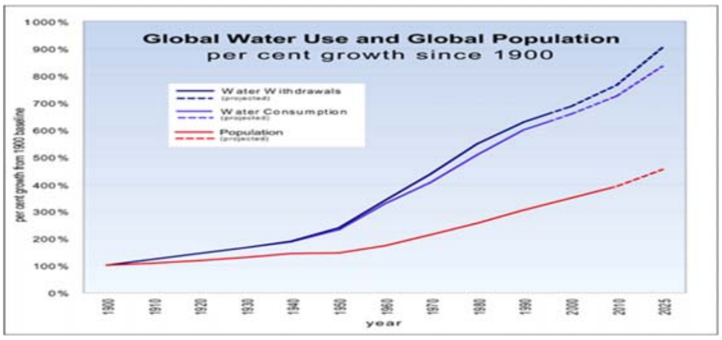


Figure 1.3. The withdrawal or consumption of freshwater has been growing at twice the rate at which the population grows [12]

According to a report issued by the United Nations [13], it is envisioned that the present population of 7.6 billion will exceed 8.6 billion by 2030 and will overreach 9.8 billion by 2050. With the world's population increasing every year and increasing stress on freshwater supply, severe water stress may be anticipated to affect an additional 2.3 billion people by 2050, especially in Africa and the South Asian and Central Asian countries. Another report estimates that by 2030, the world could confront a global water crisis to the range of 40% of its normal demands with the present business trends continuing [13]. Nearly half of the land area of the globe is swept by rivers that flow through two or more countries, with many countries receiving a good portion of their water from outside their political borders.

Water has historically been the subject of controversy in many instances, which never reached the level of conflict within countries. Rather, water shortage has often impelled cooperative arrangements to share this essential resource. However, as countries continue to push against the resources of water availability, the possibility of conflict might well increase. For example, Turkey is constructing dams and planning projects for its irrigation around the Euphrates and Tigris, which is bound to regulate the water flowing into Iraq or Syria. Egypt is also planning to manipulate the flow of the Nile, which will definitely affect Sudan or Ethiopia, countries that will need more water in the coming years for their own development [14]. The use of water on a global scale has increased by around six times over the last 100 years [15] and continues to increase at a steady rate of around 1% per year [16].

Water utilisation is expected to increase, influenced by the growth of population, the development of the economy and changing patterns of consumption, among other factors. For the protection of human health and global water security in undeveloped countries, international, multidisciplinary partnership and assistance is the need of the hour. Saudi Arabia leads the U.S. and Canada and stands as the largest water consumer, with 250 liters per capita of daily water utilisation. It is also serving as the largest producer of desalinated water and desalinated plants in the world, and it alone accounts for about 18% of the world's daily desalination capacity [17].

1.1.3 Energy costs and environmental issues in desalination

In this era of modern societies, fresh water is still one of the major warnings towards development. This problem can be resolved by indicating the new commercial technologies without even considering the need for transferring water over regions if sources for salty water are available. But it should be kept in mind that all processes are not technically strong and economically good for all the regions of the world. Desalinated water is a feasible solution that can resolve water scarcity issues. Most desalination plants operate by using fossil fuels, which contribute to greenhouse gas (GHG) emissions. There are considerable concerns regarding the environmental impacts of desalination technologies. These are directly related to the energy generation process required to drive the desalination plant as well as the design and management of the desalination process. To face the problem of climate change, many countries are developing policies that promote renewable energy for power production. These policies might impact desalination costs.

From the sustainability of systems to conferring energy and minimizing coupled greenhouse gas (GHG) discharges, the water-energy nexus ensures all these aspects by planning, calculating and operating the water supply system. About 2 to 3% of energy utilisation is done by water industries [18]. Chemical changes in the environment are encroached by each desalination process for energy requirements. The amalgam of desalination technologies and new energies can be of help in upgrading the satisfaction of desalinated water in comparison with different freshwater (FW) causes. Worldwide, energy systems are characterised by the intensive use of fossil fuels to respond to ever-increasing demand. Various environmental impacts are generated by assembling desalinated water. Energy consumption does the major harm, mostly when the origin of the energy used lies in fossil fuels.

Despite having inflated environmental and economic costs, water desalination that uses fossil fuel-based energy has become a deliberate solution worldwide, and a basic pillar of hydrological design since it is feasible to procure different nature and uses of water controlled on the basics of methods and techniques used [19]. In order to solve water scarcity problems, the main focus is on the costs and price of desalinated water in terms of its comparison with other compatible technologies [20]. Analysis governed by Pinto and Marques [21] disclose the fact that prices of desalinated water fluctuate between 0.46/m^3 USD to 160/m^3 USD.

Water and energy sources systems, the volume of desalination plants, different accounting standards for cost study, and the year of its construction matters a lot in this great difference in prices [22,23]. These limitations can be demolished by applying two different options: feeding the energy to the grid using new energy resources, and then using the same energy or storing the energy to help out the energy-storing phenomena so that stored energy can be used later [24]. The following chart concisely presents the problem statement related to water scarcity and the increasing water demand, the available desalination technologies and tools for decision-makers as well as the forms in which solar energy can be used for desalination to reduce production cost.

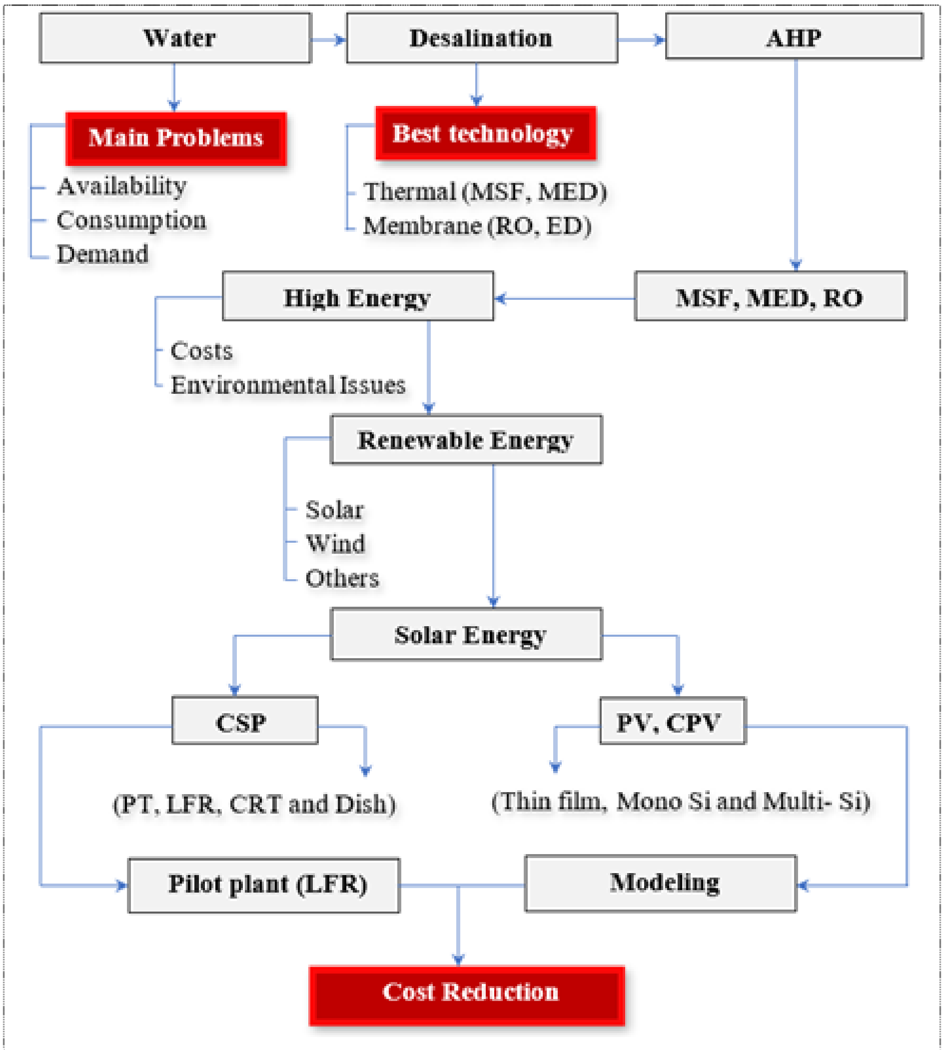


Figure 1.4. Chart for the problem statement and thesis motivation

1.2 Water Desalination Technologies (State-of-the-art)

1.2.1 Introduction

Water is an essential resource for humans on the planet. From infrastructure to food and industries to households, it is vital for human survival. According to the reports of the World Commission on Environment and Development, around 80 countries in the world are facing an acute water shortage issue [25]. This rapid consumption of freshwater resources has triggered the research to find out alternate options. One such research is seawater or brackish water, which will serve the purpose of fresh water after the removal of salts. Desalination is the process used for purifying the water by removal of salty content. In order to find good quality drinking water, desalination has emerged as a potential technique. As per the reports of Global Water Intelligence (GWI), the installed production capacity of commercial desalination units on the global scale was increased by 55% in 2012 [26].

Another study concluded that in 2013, a total of 150 countries opted for desalination to decrease the load on freshwater resources [27]. Along with water conservation strategies, it is vital to get an alternate source to fulfil the ever-growing water demands of the population. The KSA (Kingdom of Saudi Arabia) is among those countries facing water shortages and has opted for desalination since the 1970s. According to (IDA, 2017) Figure 1.5 shows that the global installed capacity of desalination plants would be doubled by 2030, reaching the number 200 million m^3 per year. This means that in 2030, desalination capacity throughout the world would most probably contribute twice more than it does now. The desalination plants in KSA has the largest purification capacities in the world. This increase is attributed to the readily available cheap fossil fuel. Moreover, the industrial and domestic sectors of the Arab Gulf States are also mainly dependent on the water purified by desalination [28].

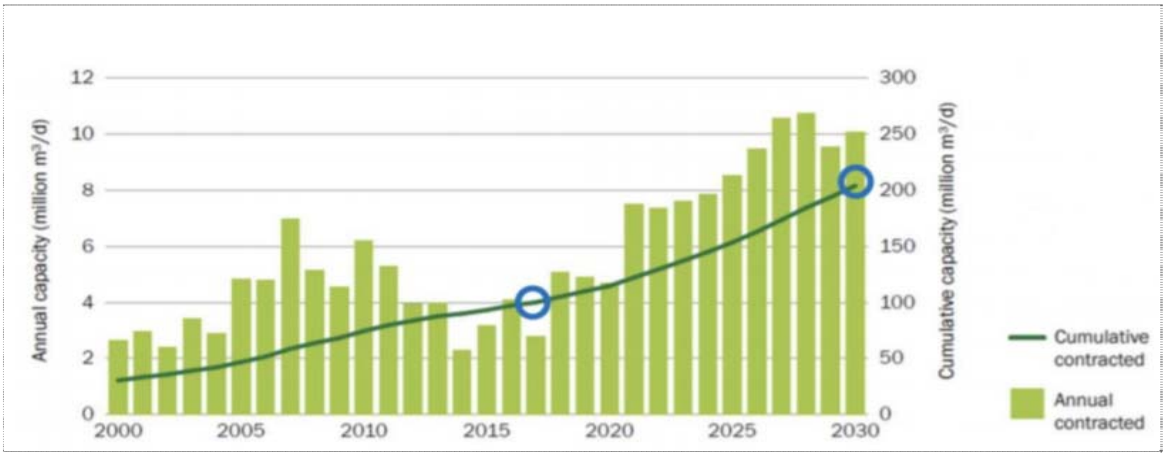


Figure 1.5. Installed capacities of desalination worldwide (2000–2030)

1.2.2 History of desalination

Desalination techniques were prevalent among the sailors for the last four hundred years. However, the first desalination plant reported to produce fresh water on a commercial basis is believed to be built during World War II. In spite of the early inception, the desalination of seawater was one of the costliest types of potable water for commercial purposes due to its intense capital requirement and prohibitive energy costs [29-31]. Since the earliest commercial desalination plants of the Second World War, the capacity of the world's contracted desalination plants has almost reached 100 million m^3/day in 2017 [32].

1.2.3 Market forecast of desalination

The global market for desalination is estimated at USD 15 billion in 2017. It is expected to undergo steady growth with an annual growth rate of 7.8% over the next eight years. Figure 1.6 shows the current and projected global market for desalination.

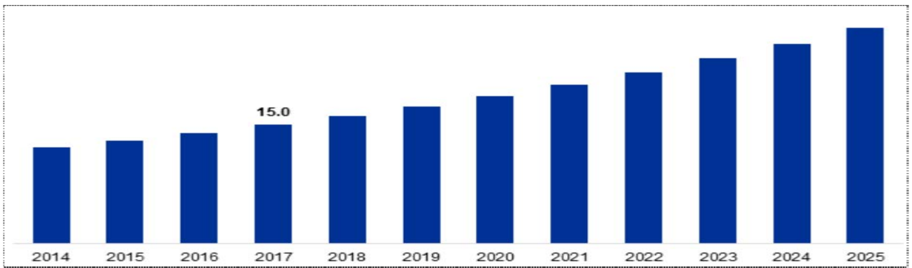


Figure 1.6. Market revenue (in billion USD) from desalination for all countries current and projected, 2014-2025 [33]

Over the last few years, desalination technologies have provided only a small share (around 1%) of the drinking water globally. Water scarcity is in one way met by reusing water through various technologies, desalination being among the foremost of them. However, the share of desalination in the total water supply chain will definitely increase in the coming years due to the rising demand for water for household needs, as well as in different agricultural and industrial sectors. Shrinking resources of fresh water, adverse changes in the environment and growing population are believed to contribute towards the market growth in water desalination [34].

In respect to technologies used, membrane technology (particularly reverse osmosis) is presently the most popular kind of technology used for the desalination of water. In 2017, more than 2 million m^3/day of fresh water were produced using different membrane technologies. The other major category of desalination technology used is thermal desalination (such as Multi-Stage Flash). Figure 1.7 presents the share of different technologies in the global production of desalinated water. The following subsections discuss commonly used technologies in more detail. The Asia Pacific is likely to experience an exponential growth of the water utilisation market, particularly in the industrial sector. The huge growth of manufacturing and processing activities in the region, such as metallurgy, chemicals or oil and gas, require plenty of water supply, which is likely to create an increasing market demand for desalinated water in the region.

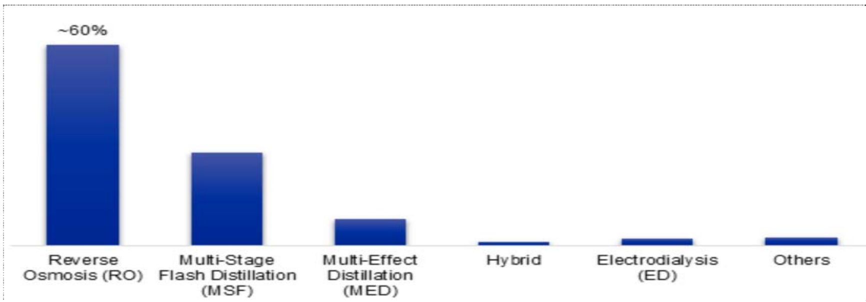


Figure 1.7. Share of different technologies prevalent in the global desalination market as of 2017 (in billion US) [33]

The significant development of industries in the ASEAN countries (including Malaysia, Vietnam, Indonesia, Thailand, and the Philippines) is likely to provide further expansion of the desalination market by 2025. The dynamics of the market in the Middle East vary greatly from the rest of the world due to several aspects.

In this region, water desalination technology is quite mature, typically driven by consistent water requirements in the oil and natural gas industry. Moreover, the region is characterised by low political resistance in the oil and gas sector, which is, of course, an important factor responsible for the growth of the market. Presently, more than half of the water supply in Saudi Arabia comes from desalination. The scenario for the rest of the world is quite different, where desalination is still an emerging technology with socio-economic conditions varying across countries. However, the level of awareness about the scarcity of water gradually rising has resulted in several countries taking up initiatives to meet the growing requirement.

An investment of around USD 10 billion is estimated to increase the world's desalination capacity by two-fold in the next five years. The two principal sources that form the source of desalination technology are seawater and brackish water. The global industry is dominated by seawater desalination sector, mainly due to the huge presence of saltwater resources. The increasing number of projects in the service sector will possibly boost the seawater desalination market in the coming future. There has been a growth from 95.6 million m^3/day in 2016 to 99.8 million m^3/day in 2017 in the worldwide contracted capacity of desalination plants (including plants that have been undertaken or are being constructed). This growth of 4.4% was reflected in both the industrial and utility sectors. While growth in the utility sector may be primarily attributed to new awards in the Arabian Gulf, the use of desalinated water in the industrial sector was due to stable prices of oil and gas, which has resulted in new projects.

The total worldwide installed capacity has grown from 88.6 million m^3/day in 2016 to 92.5 million m^3/day in 2017, showing a similar growth of 4.4%. The total number of desalination plants worldwide has increased from 18,983 in 2016 to 19,372 in 2017, showing around 2% growth. The anomaly in the growth rates of the number and capacity of desalinated plants is an important indicator that the new plants that are being constructed are of a larger capacity than the existing ones. The contracted and online capacities of desalinated water for the last 50 years is shown in Figure 1.8.

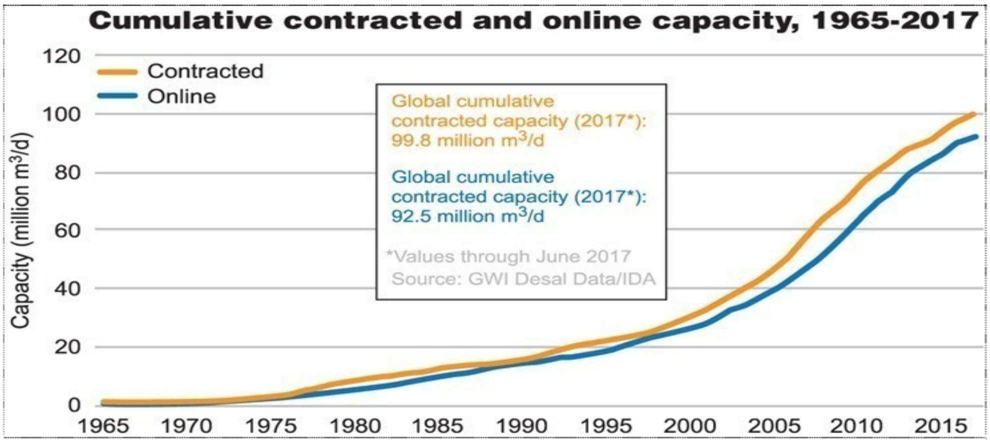


Figure 1.8. Growth of the global desalination market in the last fifty years [35]

The desalination market is growing continuously. An estimation shows that around 23 kg of oil is needed to desalinate 1 m^3 of water. This amounts to an annual requirement of more than 200 million tons of fuel annually for the current capacity of thermal plants [36], suggesting that alternative energy resources are urgently demanded for desalination systems. The Gulf countries, in particular, the United Arab Emirates and Saudi Arabia, produce more than 50% of the total desalinated water in the world (see Figure 1.9). This lion's share has essentially continued since the 1980s, when desalination started becoming the principal source of fresh water for agricultural, industrial or domestic use in the Middle East countries. The U.S. holds the next major share of 18% in the water desalination market. It should be mentioned that most of the supply for U.S. desalination plants come from low salinity water, especially rivers. In the global production of desalinated water, the other substantial contributors are Spain, Korea and Japan [29].

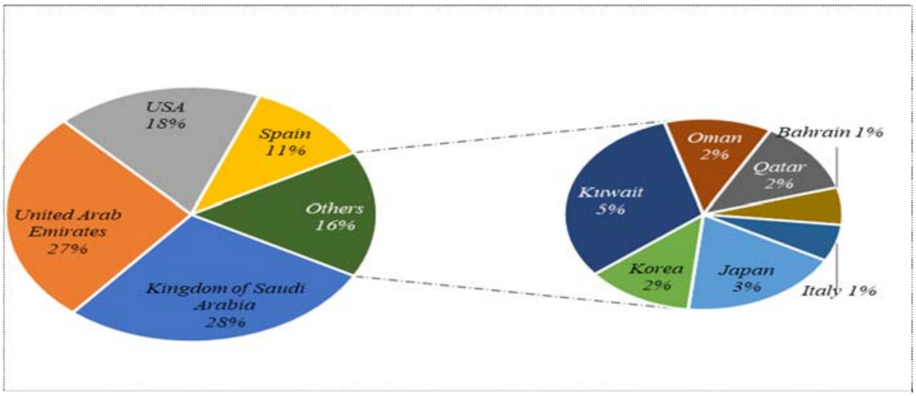


Figure 1.9. Desalination market shares of major producing countries

Desalination is a process in which water rich in salinity is fed to the unit, utilizing a form of either electrical or thermal energy to generate two product streams, one with less concentration (freshwater stream) and the other with more concentration of salt. Both seawater and brackish water can be converted into fresh water by this method. The desalination techniques can be categorized into the following main types:

- Thermal desalination techniques
- Membrane-based desalination techniques
- Hybrid desalination techniques

Thermal and membrane-based categories can be further categorized as follows:

- **Thermal technologies:**
    - Multi-stage flash distillation (MSF)
    - Vapor compression distillation (VCD)
    - Multi-Effect distillation (MED)
- **Membrane technologies:**
    - Reverse Osmosis (RO)
    - Electrodialysis (ED)

The state-of-the-art with regard to the two main categories (thermal and membrane-based) is provided in the two following subsections.

1.2.4 Thermal technologies

Thermal technology involves the evaporation of water, leaving behind the salt content, which upon condensation, gives salt-free drinkable water. The different techniques that are commonly employed are further described in detail in what follows.

1.2.4.1 Multi-Stage Flash Distillation (MSF)

Multi-stage flash (MSF) is one of the oldest desalination techniques, being in use since the 1960s. In Figure 1.10, the working principle of an MSF unit is presented. The unit is comprised of a brine heater with several stages (as per design) in which feed water is heated up to 90-115 ºC.

Then the water enters the ejector chamber with a high velocity creating vacuum, which further drives the rest of the fluid to come inside.

Then, the water is introduced into the first stage, where a pressure slightly less than the saturation vapor pressure is maintained, causing it to be converted into steam. Every stage is connected with a condenser unit to condense steam, resulting in a purified water stream. A tray collector is used to collect condensed liquid from each stage, which is then pumped to the storage tank. To further reduce the heating load of the system, latent heat removed in the condenser is used to preheat the feed stream. This will, in turn, reduce the load on the evaporator. Mist eliminators are also installed at the exit of steam to reduce the entrainment of salted water droplets. The same process is repeated several times as the water enters a series of stages. The pressure reduces in each upcoming stage compared to the previous one. The part of the brine in the last stage is recycled, and the other part is disposed of. The average recovery achieved in MSF is around 19 to 28%, with each stage producing around 1% of the total recovery [37].

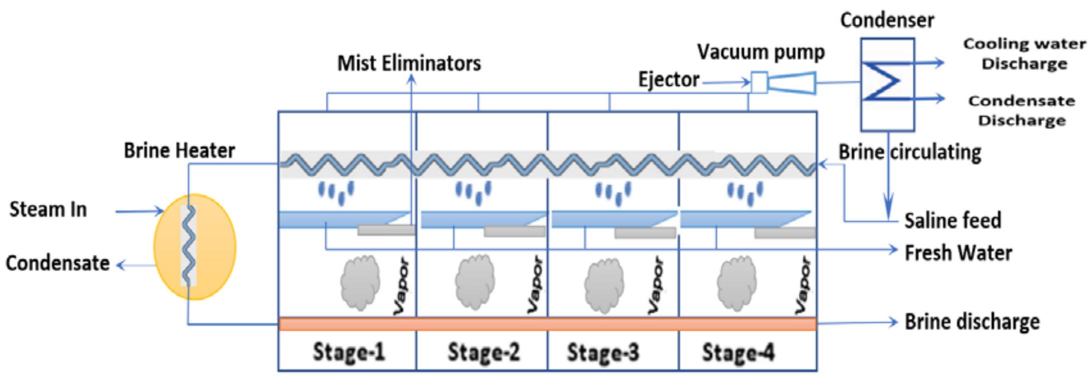


Figure 1.10. How multi-stage flash desalination works [38]

1.2.4.2 Multiple Effect Distillation (MED)

Multiple effect distillation (MED) is another thermal desalination technique in which feed water is sprayed onto a heat exchanger for the purpose of evaporation, resulting in steam production. As shown in Figure 1.11, feed water is sprayed using multiple nozzles. The resulting droplets then fall on the heat exchanger, which transforms them into steam. The resultant steam then moves to the next stage. The heat of condensation of steam coming from the first effect stage is utilized to heat the feed water sprayed in the next stage. This process is repeated in all the upcoming stages. This, in turn, reduces the thermal heat content of the whole unit. The condensed water is collected and sent to a subsequent storage tank while the brine is disposed into the sea. The average temperature on which they operate is around 62 to 75°C [37].

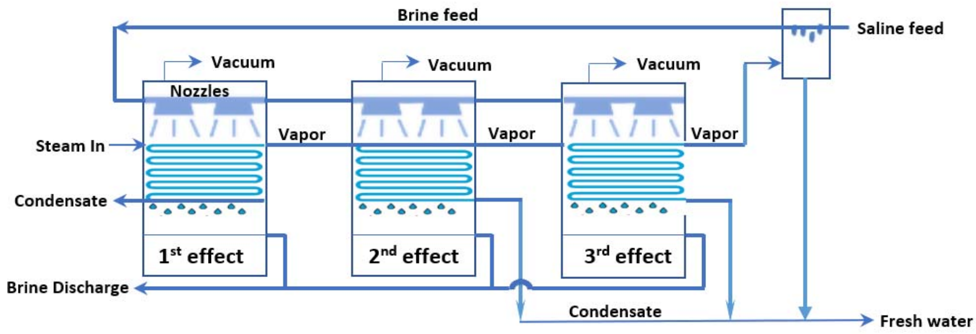


Figure 1.11. How a multi-effect distillation unit works [38]

1.2.4.3 Vapour Compression Distillation (VCD) Desalination

Vapor compression distillation (VCD) is commonly used in either medium or small-scale desalination units along with any other technique, such as MED. Instead of directly using a heat exchanger, VCD produces the necessary heat to evaporate the feed water. The operating pressure inside the unit is kept lower, resulting in less heat content requirement for evaporation. The cycle uses thermal vapor compression or mechanical vapor compression to execute the process. Thermal vapor compression units have several stages that are capable of producing 20,000 cubic meters per day of purified water, whereas mechanical vapor compression units can generate around 3,000 cubic meters per day using only one stage. Moreover, mechanical vapor compression units take up the same power per cubic meter of purified water irrespective of the number of stages being used. On the other hand, the cost of thermal vapor compression units increases as additional stages are included [39]. Figure 1.12 represents an overview of the working of a mechanical vapor compression process. They are usually operated by either power generated from diesel or electricity.

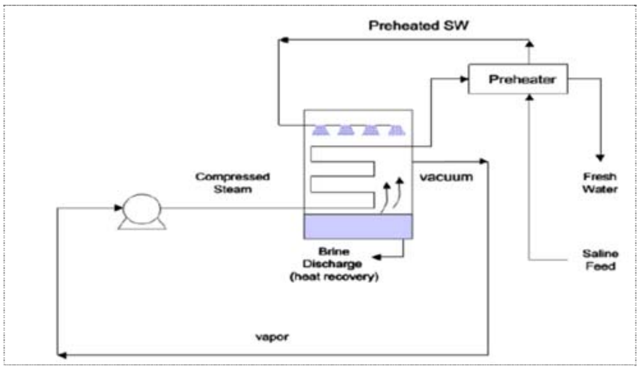


Figure 1.12. How a single effect mechanical vapor compression distillation (VCD) unit works [38]

1.2.5 Membrane technologies

1.2.5.1 Electrodialysis (ED)

Electrodialysis is a mature membrane-based technology capable of producing drinkable water on an industrial level for several years [40]. Electrical energy, in the form of direct current (DC), is used to separated pure water from a brine solution, as shown in Figure 1.13. The water ions move via a membrane wall from a diluted solution towards a concentrated solution as the DC energy flows. In the process, cationic and anionic membranes are placed between two negative and positive electrodes. As a result, ions move towards the electrode, having an opposite charge. In this way, the dissolved solid content is eliminated by its movement through the membrane.

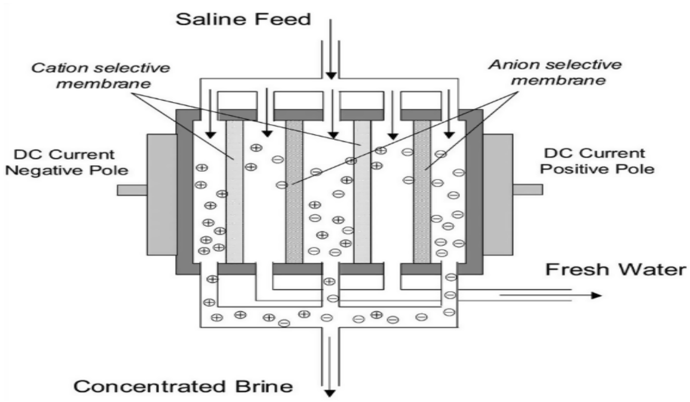


Figure 1.13. Working principle of an electrodialysis desalination unit

1.2.5.2 Reverse Osmosis (RO)

Water in reverse osmosis, a reversed effect is obtained than the natural osmotic process in which a water selective membrane is used to separate water. The movement of water from a solution that has higher salt concentration toward the solution that has less salt concentration takes place under the influence of the difference in water chemical potential on both sides. The process continues till the osmotic pressure is achieved. The working setup of RO is shown in Figure 1.14. A pressure higher than the respective osmotic pressure is applied to force the water to move from the feed side towards the freshwater side through a semipermeable membrane. Thus, water moves to the permeate, leaving behind all salts in the feed side, resulting in a highly concentrated brine.

The membrane either blocks or allows the movement of solute particles, depending on the charge and size. The dissolved salts, along with other impurities, can be removed through this process. However, the larger particles slowly deposit on the surface of the membrane, which, in turn, results in fouling. This is why a pre-treatment step is included to separate suspended solid content in order to avoid membrane fouling. Moreover, based on the end usage of purified water, a post-treatment step may also be employed, e.g., mineralisation stage in case of drinking water [37].

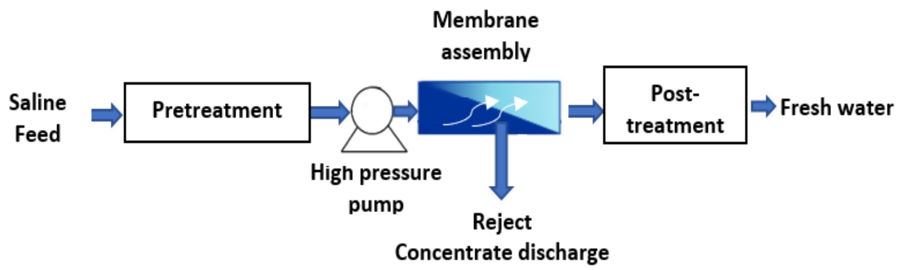


Figure 1.14. Diagram showing the main components of a typical RO plant

1.2.6 Key players in desalination technology

Desalination has always remained a much-studied and researched area with successful commercial implementations. This is one of the reasons behind the existence of successful companies and corporations that operate in the market, like VA Tech Wabag, Veolia, Toray, Dow Chemical Company and Doosan [41]. Many research institutions have employed researchers in this field, for example, the Atomic Energy Commission, the Spanish Plateforme Solar de Almería, the French Alternative Energies, etc.

1.2.7 Hybrid processes

A hybrid process integrates two or more individual desalination techniques to reduce the cost of purified water, along with better environmental operations as compared to operating the process separately. A typical scheme used for seawater desalination is the incorporation of any membrane technology into a thermal desalination unit along with power plants for the generation of electricity.

The core purpose of integration is to enhance the efficiency of the overall plant by utilising waste heat content. Further, this combination is also capable of reducing the carbon footprints (emissions) and is reported to provide energy savings of around $400 million/year [42]. A hybrid plant consumes thermal energy in the form of low-pressure steam emitted by the power plant in the thermal desalination step, whereas the electricity is used in the respective RO or VCD unit. Figure 1.15 shows a hybrid desalination unit consisting of reverse osmosis, nano-filtration, and MSF. Years ago, a final stream of better quality water coming from the MSF was used to be mixed with the first pass stream coming from an RO unit, which had a moderate salinity level. This, in turn, resulted in an increase in production capacity while meeting the quality constraints. This is one of the simplest and oldest forms of hybridisation in the field of desalination. However, these days, various hybrid schemes have been proposed in academic literature and subsequently applied in industrial zones.

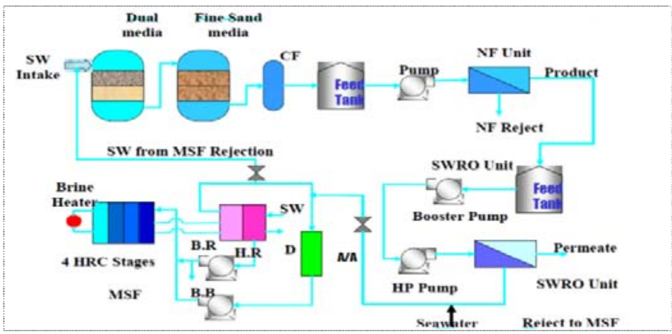


Figure 1.15. Working principle of a hybrid scheme of Nano-filtration/MSF/RO desalination unit [43]

There are a number of plants worldwide that are operated on hybrid schemes. Some of them are mentioned below:

- Fujairah I and Fujairah II (United Arab Emirates)
- Ras Al-Khair (Kingdom of Saudi Arabia)
- Az-Zour South (Kuwait)

In perspective of rising fuel prices, hybrid schemes have huge potential as they provide less energy consumption, along with reduced carbon footprints (emissions) in comparison with only thermal desalination units.

Table 1.1 shows a comparison of a hybrid scheme with a thermal scheme. For the same plant capacity, the hybrid configuration showed a decrease of 40% in the fuel consumption rate. The reduction ultimately resulted in a reduced annual cost of the purified water.

Table 1.1. Comparison of thermal techniques with hybrid configuration [42]

Desalination scheme	Capacity	Fuel consumption rate	Annual cost
MSF desalination	455,000 m^3/day	191 tons/hr	735 $million/year
60% thermal + 40% RO	455,000 m^3/day	115 tons/hr	443 $million/year

1.2.8 Alternative novel technologies

Apart from industrially prevailing technologies, researchers are working on introducing novel processes in the field of desalination. These processes include but are not limited to solar still, humid/dehumid technology, and freezing ion exchange. All these techniques are immature in terms of literature availability. Thus, in order to further reduce the production cost and energy demand, novel schemes, which have good potential in terms of industrial application, are required to be explored.

1.3 Key factors affecting Water Desalination cost

1.3.1 Introduction

Continuous research efforts in the technology of desalination make it a prime candidate for mitigating water shortage issues across the world. Further, desalination maintenance and operating costs are quite competitive with other alternatives in the water purification industry. The overall economics of this process can be split up into different cost consumption parameters, including capital investment, energy cost, operating cost, and maintenance cost. Among all, almost 50% of the total production expenditure is contributed by the energy cost. In the case of membrane-based desalination processes, i.e., ED and RO, energy is required in terms of electrical power. Whereas in thermal desalination techniques, both types of energies, i.e., the thermal part (which is used to increase the temperature of the process fluid), as well as the electrical part (to derive the process fluid), is needed.

With respect to the amount of oil that is spent on obtaining fresh water, Li et al, [44] find that it requires 8.78 million tons/year to get 1 million m^3 per day. Since the depletion of oil has become a serious global concern, it is not viable to spend such a huge amount of oil for desalination, and thus, finding alternative sources has become imperative. The main task of conducting an economic analysis is to figure out the purification cost per unit volume of water (in terms of $/$m^3$). This calculation is strongly dependent on various factors, including the site conditions, design specifications, and the processing capacity. Site conditions specify the type of pre- and post-treatment needed. The design specifications will influence energy consumption, whereas the processing capacity will define the sizes of the equipment. In the economic analysis, the unit cost of water purification is measured in terms of $ per cubic meter. Design parameters help to determine the thermal, electrical energy consumption inside the plant premises as well as the chemical dosages of the anti-fouling or anti-scalant agents. The plant production capacity determines the sizes of all equipment involved, including pumping devices, valves, boilers, and the membrane module. The site location specifies the quality of feed water on which the types of pre-treatment and post-treatment methods are selected.

This section covers the economics of desalination, specifically maintenance cost and capital cost, along with a detailed review of the components regarding their operation. In order to aid the development and conceptual planning of desalination units, the cost of different desalination processes is presented in the subsections below.

1.3.2 Total cost

The economic analysis of desalination units mentioned below is related to water purification only, whereas costs are related to the generation of electricity. Figure 1.16 illustrates the three main components on which the total cost depends.

Figure 1.16. The main components of the total cost for the desalination process

All these components are discussed in detail in the upcoming subsections [45-54].

1.3.3 Breakdown of Capital Cost (CAPEX)

The capital investment includes the expenditures involved in the construction phase till the time it operates commercially. It can be further subdivided into two categories, including direct cost and indirect cost, as depicted in Figure 1.17. Direct cost represents the cost of buildings, mechanical structures, site development, and pipelines that will be utilised after the plant becomes functional. This cost typically comes in between 50% and 85% of the cumulative capital cost. On the other hand, indirect cost includes overhead, insurance charges, and contingency expenditures.

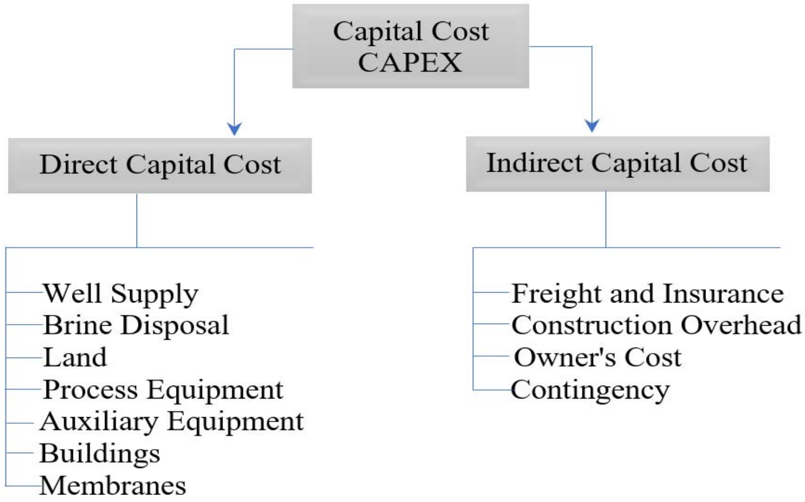


Figure 1.17. The main categories of the total capital cost

1.3.3.1 Direct Capital Cost

Direct capital cost is the most important component specifying the economics of the desalination plant for both thermal desalination and reverse osmosis technologies. The cost represents the expenditures invested during the construction phase of a unit. Therefore, the direct capital cost is the cost required to bring the plant to operational status. This cost is further subdivided into many categories discussed below.

Well supply

Well is an important part of a running plant as it fulfils the raw water demand of the process. This raw water is often used as a utility, to be either converted into steam or chilled water. It is estimated that an average well with the capacity of 500 m^3/day costs around $650/meter depth.

Brine Disposal Cost

Because of the restrictions applied by regulating authorities, the plant waste must be properly disposed of. In some cases, waste may need to be properly treated before sending it to the ecosystem. In water desalination, the cost related to disposing of the brine comes under this direct cost.

Land Cost

Land cost varies considerably from quite high to very low, depending on the location and characteristics of the site. Sites near water sources or residential areas will cost more compared to sites located far off. In short, this cost will include all expenses related to the acquisition of land on which a plant will operate, such as the purchase price, all associated encumbrances, land improvement prices, property taxes, etc. The cost of land varies from a significantly high price to even zero, as per fluctuations in the respective site location and properties. Furthermore, units operating under (build–own–operate–transfer) BOOT terms with municipalities can have subsidies, getting a further reduction in overall prices.

Process equipment cost

The process equipment cost usually contributes the major share to the direct capital investment. It includes the cost of equipment, valves, pumps, instruments, controllers, and cleaning systems. The production capacity of the plant determines the size and corresponding price. For lab scale units, the cost can be as low as $1,000. In contrast, for an industrial RO plant of 100,000 m^3/day, the capacity cost may reach up to $50 million. The thermal desalination units (MSF, MED) are comparatively expensive, with a typical cost of $40 million for 27,000 m^3/day plant capacity.

Auxiliary equipment cost

Auxiliary equipment includes those devices which do not directly take part in the production process but just help to operate the main equipment. This cost is related to equipment, such as open intakes, storage tanks, transformers, and generators.

Building construction cost

The building construction cost is dependent on the category of building, site specifications, and volumetric capacity. It includes the construction of a laboratory, workshops, offices, and a control room.

Membrane Cost

The membrane module is the major part of RO-based desalination techniques. The water production capacity defines the membrane module cost and usually lies in the range of $500 - $1,000 per 50 to 100 m^3/day module.

1.3.3.2 Indirect Capital Cost

Indirect capital cost is another important component specifying the economics of a desalination plant, including the following subcomponents:

- Freight and insurance charges (approximately 5% × direct cost).
- Construction overhead cost (approximately 15% × direct cost, depending on the plant capacity).
- Contingency cost (approximately 10% × direct cost).
- Owner's cost (around 10% × direct cost).

Figure 1.18 represents the breakdown of the indirect capital investment components for the desalination projects in the MENA Region for both thermal and SWRO desalination projects. As depicted, SWRO has lower construction costs compared to a thermal unit.

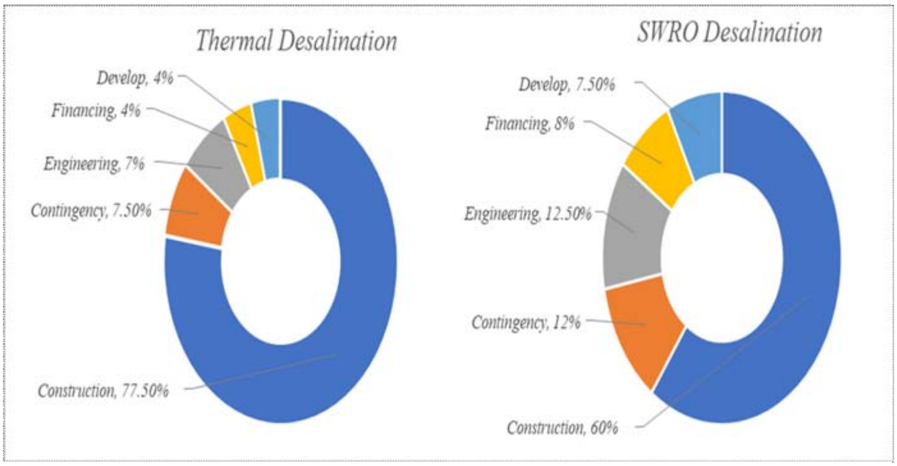


Figure 1.18. Average capital cost breakdown of desalination projects in the MENA region

Source: Water World Consultants

1.3.4 Components of Operating Cost (OPEX)

Operating cost is the next major expenditure after capital investment. The major breakdown is represented in Figure 1.19. It considers both the direct and indirect operating costs. The direct cost is the money spent directly in running a plant, for example, the cost of chemicals being dosed, the cost of operators and engineers, the cost of replacing the equipment parts, etc. On the other hand, indirect expenditures involve the cost of plant administration, insurance, utilities and general expenses.

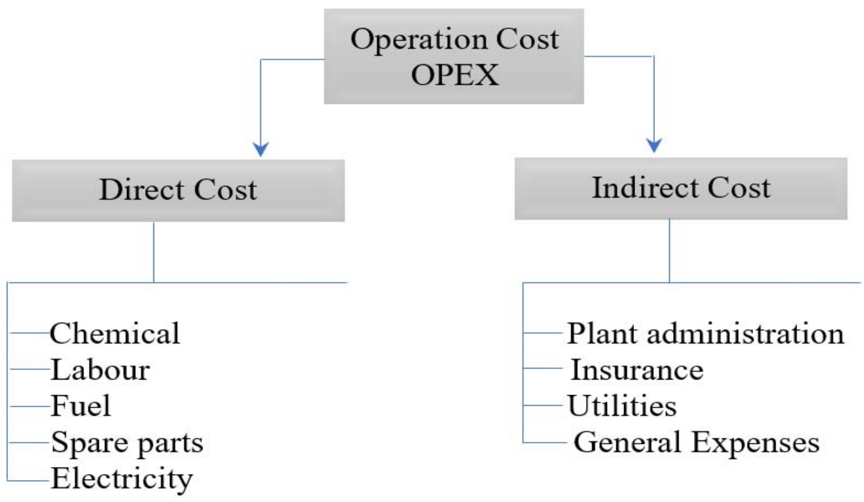


Figure 1.19. The main categories of the total operation cost

1.3.4.1 Direct Operating Cost

Direct operating cost is a recurring nature of cost and is the second major expenditure after capital investment. The major breakdown for both technologies' thermal desalination and reverse osmosis is shown in Figure 1.20. As shown, in thermal desalination, the major operating cost is attributed to thermal energy, whereas in SWRO, electrical energy consumes the largest portion of operating costs. Hence, small improvements in direct OPEX components can bring a significant reduction in overall costs. On the other hand, indirect costs represent only 10% and 8% of the total operating costs in thermal and SWRO plants, respectively.

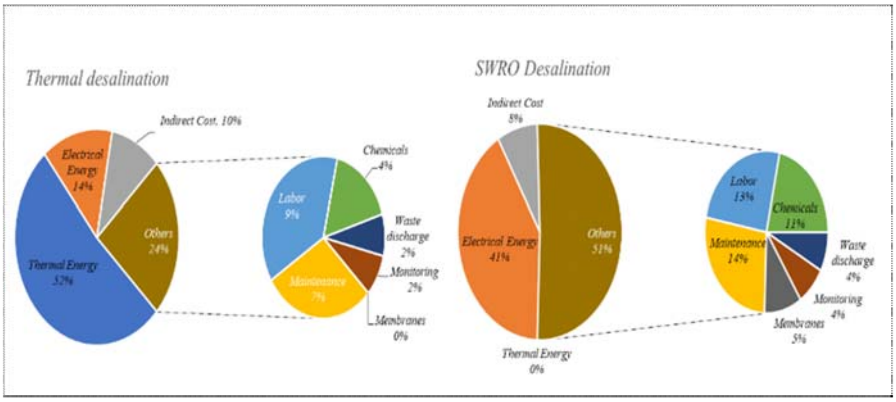


Figure 1.20. Average O & M Cost Breakdown of Desalination Projects in the MENA Region

Source: Water World Consultants

Chemical Cost

In order to avoid scale formation, chemical cleaning plays a vital role in the maintenance and smooth running of desalination plants. It requires periodic dosages of chemicals, such as caustic soda, sulfuric acid, antifoaming, agents, and anti-scalants. The corresponding price is influenced by market value and availability. Furthermore, the membrane-based process involves more chemical costs than thermal techniques due to potential fouling and choking issues in the membranes. Moreover, MED units require fewer chemical dosages compared to MSF plants as they use less seawater in the feed. Table 1.2 represents the chemical name along with the specific cost and dosing rate in the membrane and thermal desalination techniques.

Table 1.2. Unit cost, specific cost, and dosing rate of different chemicals used in desalination plants across the globe [55]

Chemical	Dosing rate	Unit cost g/m^3 of water	Specific cost g/m^3 of water
Sulfuric acid (H_2SO_3)	0.242 $/Kg	0.504	0.0122
Caustic Soda	0.140 $/Kg	0.701	0.0098
Chlorine	0.040 $/Kg	0.482	0.00193
Anti-scalant	0.050 $/Kg	1.9	0.0095

Labour cost

The labour cost includes the salaries and other facilities provided to administration staff, maintenance staff, and operating staff. The value may differ from location to location as per availability of manpower.

Fuel cost (Steam cost)

Fuel cost is one of the major contributors in the total operating cost of the desalination unit. The cost is strongly related directly to the fuel price and inversely to its efficiency. The higher the efficiency of units, the lower the steam consumption will be. The unit steam cost lies in the range of 2 to 3.5 $/ton [56] depending on the type of fuel and efficiency of the boiler.

Spare parts cost

The spare parts cost related to non-routine maintenance activities can be forecast as per the plant size, location, age, and labour experience. This is usually taken as a fixed cost, ranging from 1 to 1.5% of the total installation cost, as represented in Table 1.3.

Table 1.3. Typical maintenance cost factor for thermal [57]

Production capacity	Maintenance cost factor (% of IEC)	Installed plant cost	Annual maintenance cost
4546 m^3/day	1.5	750,000 $	11,250 $
454.6 m^3/day	4	200,000 $	8,000 $

Electrical power cost

Electrical power cost includes tariffs, connection fee, and transmission distance charges of the desalination unit. However, power usage depends on the plant's water purification production capacity. For desalination processes involving thermal unit processes, electrical power consumption is low compared to membrane desalination techniques. As a general estimation, electrical power costs can be considered to be 0.04 to 0.09 $/kWh [44] with an average value of 0.037 $/kWh [58]. Table 1.4 shows the comparison of energy consumption for MSF, MED, and RO plants.

Table 1.4. The comparison of overall energy consumption and equivalent electrical energy requirements with respect to plant capacity to the main desalination technologies

Production capacity	MSF	MED	RO
Possible desalination plant capacity	60000 m^3/day	N/A	24000 m^3/day
Energy consumption	4 to 6 kWh/m^3	1 to 2.5 kWh/m^3	5 to 7 kWh/m^3
Electrical energy equivalent to thermal energy	8 to 18 kWh/m^3	4 to 7 kWh/m^3	N/A
Overall equivalent consumed energy	12 to 24 kWh/m^3	5 to 9.5 kWh/m^3	5 to 7 kWh/m^3

1.3.4.2 Indirect Operating Cost

The indirect operating cost includes the following components:

- Plant-administrative cost: The administrative expenditures can be regarded as an indirect operating cost.
- Insurance cost: The insurance cost is calculated as 0.5 % of cumulative capital cost.
- Utilities expenses: It is difficult to estimate the utility expenses as they vary according to the energy cost and inflation rate.
- General expenses cost: This includes the cost related to stationery and other general items needed to run the operational units, such as log books, control room items, etc.

1.3.5 Factors affecting the per unit water purification cost

Thanks to the intensive research in the desalination sector, the per unit cost of water purification through this technique has reduced over the past few decades [53,59]. The integration of any energy recovery devices (ERD) in RO plants and replacement of copper nickel plates with carbon steel plates in the MSF units has improved the overall economics of the process. A comparison of distilled water prices in the past and now is shown in Table 1.5. However, this gap varies from country to country and as a function of the plant purification capacity [54], [60,61].

Table 1.5. The comparison of purified water unit rate of seawater reverse osmosis desalination and multi-stage flash desalination in the past and now

Technology	Unit rate in past	Unit rate these days
Multi-stage flash desalination	6 to 7 $/m³ in 1970	0.52/m³ to 1.75 $/m³
Sea water reverse osmosis desalination	2.5 to 3.0 $/m³ in 1975	0.5 to1.5 $/m³

Multiple factors dictate the price of water obtained through desalination. All these factors are discussed below.

1.3.5.1 Salinity along with quality of the feed water

The raw water quality has a direct influence on deciding the pre-treatment technologies required prior to the desalination stage. For operating cost calculation, the required pressure for the RO-based desalination unit is related to the salinity of the feed water, resulting in greater energy cost in the case of seawater feed (Total dissolved solid >10000 ppm) as compared to brackish water desalination (1500 ppm< Total dissolved solid <10000 ppm) [62-64]. Furthermore, the salinity content of the water depends on the water body location. For instance, the average TDS in the Baltic Sea is approximately 10,000 ppm; on the other hand, in the Arabian Gulf countries, this value is around 48,000 ppm [64,65]. Because of the higher salinity, Arabian Gulf countries are using thermal desalination despite the higher operating cost that is associated [64]. Moreover, the impurities present in the feed water to the desalination unit are important for the determination of the membrane module design and specifications [66-70].

1.3.5.2 Plant capacity

The larger the plant capacity of the desalination unit, the lower e the per unit production cost will b [71]. Also, some expenses are identical irrespective of the plant size, so capacities are increased to slow down the production cost [72]. Figure 1.21 shows the reverse osmosis desalination plant costs for units of different capacities. The cost is as low as 2.65 $/1000 gal for large plants of 325,000 m^3/day capacity and increases to 4.75 $/1000 gal for small plants of 10,000 m^3/day capacity. This implies that by increasing the plant capacity, a significant decrease can be achieved in the per unit purified water cost.

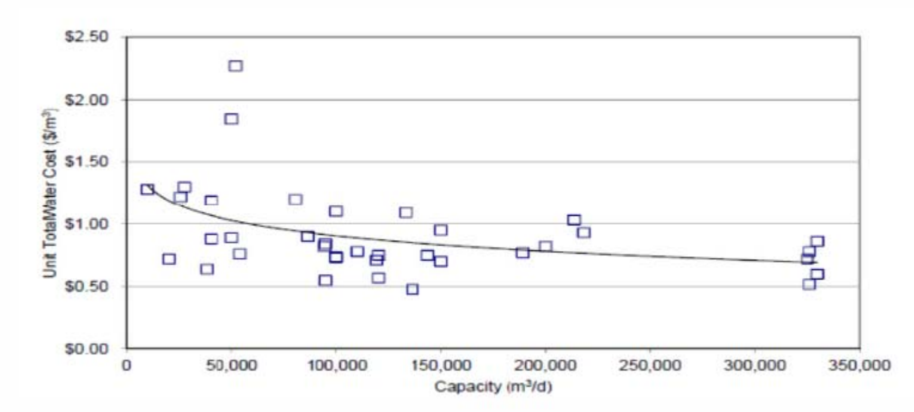


Figure 1.21. Reverse osmosis desalination plant unit production cost as a function of capacity [73]

1.3.5.3 Plant location and site conditions

The plant location affects the labour and land cost since, in some countries, the land prices and labour costs are low, while in other countries, the respective prices are high. Shipment charges also differ based on the location. The infrastructure costs, including building materials, steel, concrete, drainage, and structures, vary as per site location. However, some studies have concluded that the plant site and location have a minor impact on the total unit production cost [74,75]. But still, keen considerations are recommended while making a land choice, keeping in mind the soil conditions and close proximity to an easily available power source.

1.3.5.4 Manpower

The availability of engineers, management, and qualified operators near the plant site will result in reduced production costs by decreasing the duration of manpower's travel times. Labour costs are one of the significant parameters contributing to the operating cost in desalination units [74,76]. Hence, in the desalination sector, the in-time availability of qualified manpower is important to maintain good quality [74].

1.3.5.5 Energy cost

The availability of inexpensive energy sources results in a significant decrease in the total operating cost associated with a desalination plant.

Table 1.6 presents the forms of energy required in different processes, such as RO, ED, MSF, and MED. Electrical energy is required in the first two, while thermal energy is required for the last two techniques. More precisely, the energy consumption in MSF desalination is 15 to18 kWh/m^3, 2 to 3.5 kWh/m^3 in RO, and 5.7-15 kWh/ m^3 in MED [77,78]. At the same time, this kind of technology depends on the salt content. Figure 1.22 shows the minimum required energy for the thermal desalination of seawater. In general, for the determination of the energy consumption per m^3 of purified water produced, the following equation is introduced.

$$Ec = \frac{e}{v}$$

where,

Ec: Energy consumption per m^3 of purified water produced, (J/m^3).

e: The energy consumed during the production processes.

v: The water produced during the production processes.

Desalination researchers are committed to reducing this cost further to 1.5 to 2.0 kWh/ m^3 [79]. To reduce the energy cost, other alternatives, such as renewable sources [80,81] and nuclear sources, are being considered [82]. However, significant improvement is still required to reduce the production cost.

Table 1.6. Rate of energy consumption and corresponding driving forces for different desalination techniques, including RO, ED, MSF, and MED [83-87]

Desalination technique	Driving force for desalination	Energy consumption range (kWh/m^3)
Multi effect desalination	Latent heat	12.2 to 19.1
Multi-Stage Flash desalination	Latent heat	19.5 to 27.2
Electrodialysis desalination	Electrical potential	2.5 to 20
Reverse osmosis desalination	Pressure force	3.5 to 8

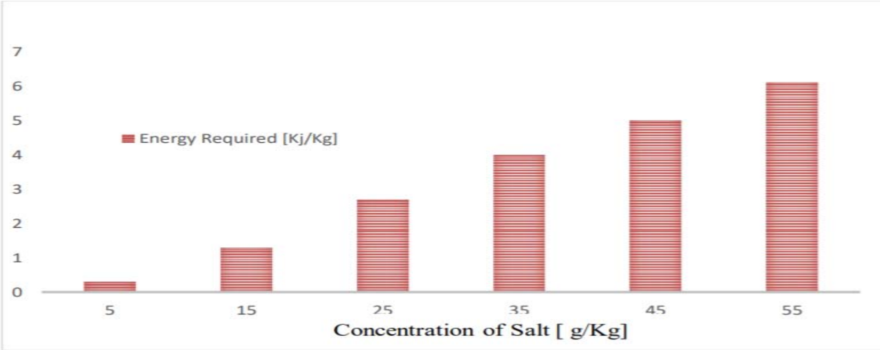


Figure 1.22. Energy Required for Desalination of Seawater [44]

1.3.5.6 Energy recovery

In a desalination plant, an enormous amount of energy is consumed at a number of stages, including pre-treatment, main process, post-treatment, waste disposal, and final distribution to consumers. However, energy is also being wasted in many locations. The recovery of this energy and then using it whenever required reduces the overall energy consumption. The theoretical value of the minimum energy required for the desalination of seawater is around 3kJ/kg water [88]. Figure 1.23 shows the relation of water recovery and minimum work required to produce desalinated water. As clearly shown, higher recovery can be achieved with a comparatively larger input of energy. After a recovery rate of 85% to 90%, the production cost increases abruptly.

Hence, an optimum value of recovery has to be selected in order to purify water at an economical cost. A tradeoff between capital investment and energy cost is necessary to find out the optimum design conditions. As shown in Figure 1.24, it is clearly shown that as the capital cost increases, the operating cost decreases. This is mainly because the capital cost increases with plant capacity. And further, plant production capacity has an inverse relation with operating expenditures. A detailed review has been published on this topic recently [89].

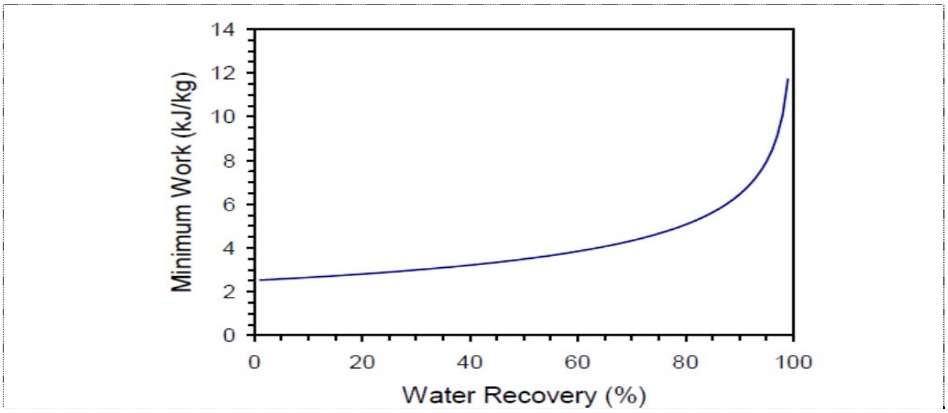


Figure 1.23. Energy requirement for desalination of seawater as a function of water recovery. Salt solubility in water precipitation of NaCl salt assumed to begin at 90% recovery [88]

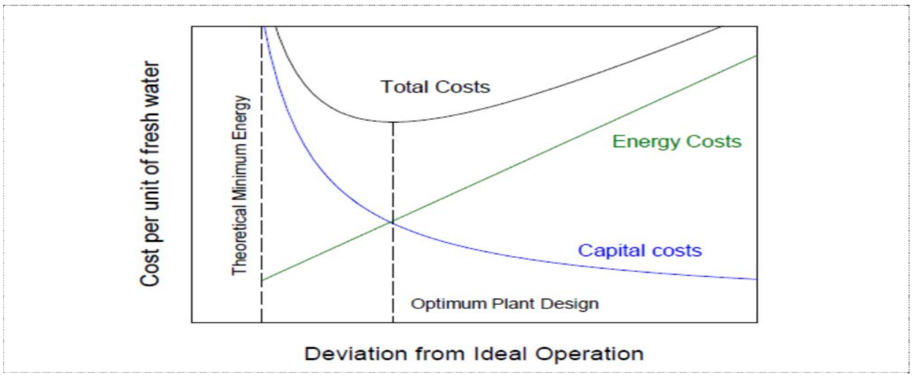


Figure 1.24. The balance between energy use and capital costs for desalination [89,90]

1.3.5.7 Plant life and amortisation

The higher the plant life of a desalination plant, the lower its operating cost will be. By opting for materials of good quality, the shelf life of a plant can be increased, resulting in better economics of the process [74,91].

1.3.5.8 Intake and outfall

Another important technical consideration is related to the choice of the intake and corresponding outfall of a desalination process.

There is a number of factors which need to be kept in mind, such as:

- The intake distance with respect to the plant.
- The screens type of intake mechanism.
- The structure type of intake mechanism.
- The pipeline types (underground or above ground).

All these factors affect the cost of operation. The intake system cost may vary from 0.13 \$MM/1000 m^3 per day for an open intake to 0.79 \$MM/1000 m^3 per day for complex intakes [92].

1.3.5.9 Brine discharge (Disposal)

Properly disposing of the desalination waste or brine is important, otherwise, it can affect the environment. Proper treatment and then disposing of it to an ecosystem requires costs, which have a significant contribution to the overall production cost. A design of a discharge mechanism or cooling assembly to reduce its temperature and a process to chemically neutralize it is required [79,93]. In the case of seawater, disposing the brine to the sea will not increase its salinity. On the other hand, in the case of a brackish desalination unit, disposing of the brine increases the corresponding cost drastically [94].

1.3.5.10 Pre-treatment

Pre-treatment steps are necessary to remove the impurities that may affect the desalination equipment.

- In the case of RO, membrane fouling has to be reduced because of slime growth. It is necessary to remove the fouling components before introducing a feed into the membrane units [95,96].

- In thermal desalination, scaling is the major issue to be tackled. By removing the scale that causes impurities in the pre-treatment step (such as chemical additives), the shelf life of the desalination unit can be increased [54].

According to [97], a published article entitled "Seawater Desalination Costs," the cost of pre-treatment would lie in the range of 0.13 $MM - 0.40 $MM per each 1000 m^3/day.

1.3.5.11 Post-treatment

After desalination, the water becomes free of salt. However, it is still not pure enough to be sent to consumers. In most cases, the hardness and the pH level of desalinated water have to be corrected for domestic usage [85]. The actual post-treatment technique selection depends on the end usage of water and the type of desalination process. In brief, the final usage will determine which type of post-treatment is required. In the case of wastewater used as feed, the cost associated with post-treatment is usually higher.

1.3.5.12 Regulations

Regulating organisations exist in all regions of the world. They have imposed certain obligations and limitations, which have to be met by industries. Moreover, in some regions, permits are required to install a plant. The cost attributed to all these tasks is another contributing factor in the economics of desalination.

1.3.5.13 Financing

In case a loan is taken from a bank in order to cover the capital investment of a plant, the interest rate will appear in the total production price of the desalinated water. The higher the interest rate, the higher the operating cost will be. Moreover, the interest rate changes each year, and the inflation rates will have a direct impact on the loan and interest to be paid back.

1.3.5.14 Hybrid desalination plant

Each type of desalination technique has its own advantages and disadvantages. A hybrid plant can be installed by using a combination of any of the two techniques. In this way, the overall efficiency of desalination can be increased. There are two primary objectives when considering options for creating a hybrid plant [85,95]:

- The reduction of production costs by decreasing the rate of scaling/fouling, which will result in reduced maintenance costs.
- Improvement of the quality of purified water when seawater is used as feed.

1.3.5.15 Co-generation

A dual-purpose plant is a plant that generates electricity and purifies the water at the same time. Saudi Arabia and some other oil-producing countries are using this co-generation principle in various plants. For example, the waste steam of a power plant is used to heat up the feed of a thermal desalination unit. In this way, not only capital costs but also energy costs can be significantly reduced. The average desalted water cost was reported to be 0.8 $\$/m^3$ for the Shuqiq co-generation unit and reached 1.71$\$/m^3$ for the Rabigh unit of the desalination unit in 2009 [96].

1.3.5.16 Types of desalination techniques

The type of desalination technique used in the process plays a vital role in the determination of the operating cost. For each type of desalination method, the energy requirements are different. Hence, by choosing an adequate technique, one can reduce the corresponding production cost. There is no general rule for the technique that is more adequate compared to others. However, generally, RO desalination units have shown lower energy consumption compared to thermal desalination plants. This lesser energy cost makes them a potential alternative in replacing the older technology.

In the study by Ghaffour et al., a comparison of desalination techniques is presented with potential improvements [54]. It is concluded that slight improvements in factors related to the used technology can significantly reduce the production cost. Reverse osmosis has shown lower purified water costs compared to MSF and MED. Furthermore, the cost related to brackish water desalination (0.2 to 0.4 $\$/m^3$) through reverse osmosis is lower when compared to seawater (0.5 to 1.2 $\$/m^3$). Moreover, the salinity level is higher in the case of seawater, which means that the cost related to managing the salinity level is higher in the latter case. It is also suggested that hybrid processes, including renewable energy sources, such as wind energy, solar energy, or geothermal energy, will further help to get purified water at an economical price. Hence, RO has already recorded reduced prices compared to non-membrane-based processes (MED, MSF), and further integration of solar energy will make a potential economic breakthrough.

1.3.6 Summary

This section presents the state-of-the-art with regard to cost analysis of desalination techniques. The main points of this review are as follows:

- Direct capital cost represents the largest portion of the total cost, followed by the direct operating cost of the desalination plant.
- The major direct operating cost for thermal desalination is associated with thermal energy, while reverse osmosis desalination is associated with electric energy.
- Reverse osmosis desalination is associated with lower maintenance and labor costs compared to thermal desalination technology.
- Site conditions related to water salinity and water quality primarily affect the operating costs of desalination plants, while land prices and labor costs mainly affect the direct capital cost.
- Increase of the plant capacity and plant life results in a significant reduction of the operating costs of the desalination process.
- The water usage after desalination will determine the required type of post-treatment, which will affect the corresponding cost, especially in cases where water after desalination should be potable.
- Environmental issues and the associated costs should be considered when planning the desalination process, especially with regard to waste and brine disposal.
- Operating cost reduction can be achieved through co-generation (i.e., simultaneous production of purified seawater and electricity) or by a combination of desalination technologies with renewable energy sources (e.g., wind, solar).

1.4 Status of Desalination as function of site conditions

1.4.1 Spain

The rapid urbanisation and development in the industrial sector have drastically increased water consumption in Spain. In this regard, desalination has emerged as a potential technique to provide an alternate source of usable water [109,110]. Numerous controversial water projects, including problems in water transportation from the river Tajo and the river Ebro diversion plan, is expected to decrease water flow from the river Júcar. For these reasons, Spain has become a country that has the fourth-highest desalination production capacity in the world [111]. The first plant was built in 1965 in the Canary Islands, as shown in Table 1.7. These units used MSF as a working technology by then. With the installation of new plants under the AGUA program, the purification capacity has crossed 3 million cubic meters per day [112].

Table 1.7 The oldest plants in Spain working on MSF (obsolete these days) and RO [113]

Plant location	Commissioning year	Capacity m^3/day	Processes
Termolariza (Lanzarote)	1965	2,000	MSF
Fuerteventura	1970	2,000	MSF
Ceuta I	1969	4,000	MSF
Las Palmas	1979	20,000	MSF
Las Palmas Island	1970	-	RO
Cabo de Gatain Almeria	1993	-	RO

Since thermal technology consumes a tremendous amount of energy, the Spanish government has taken measures to move from thermal desalination to reverse osmosis technology.

Table 1.7 shows the two earliest plants built on RO technology. In the 1930s, when the Civil War ended, the government tried to find ways to boost the falling economy of the country, and tourism was promoted in the Canary Islands. In order to meet the water demands of tourists, various desalination plants were constructed. In 2010, approximately 3% of the country's total water demand was supplied by desalination units, i.e., 1.6 million cubic meters per day. Europe's largest reverse osmosis technology operated plant was constructed in Barcelona in 2009. Again, in 2017, water levels reached the lowest value in the past two decades [114], raising serious concerns. Table 1.8 shows the seawater desalination units built under the AGUA program in the regions closest to the Mediterranean Sea.

Table 1.8 Major desalination plants (with capacity at least 20×10^3 m^3/day) around the Mediterranean Sea that are part of the AGUA program [115]

State	Plants	Capacity (m^3/day) ×10^3
	Torrevieja	230
	Alicante II	68
Alicante	Mutxamel	52
	Javea	29
	Denia	26
Almerıa	Carboneras	120
	Campo de Dalias	86
	Nijar-Rambla Morales	58
	Bajo Almanzora	58
Barcelona	El Prat de Llobregat	172
Castellona	Oropesa	52
	Moncofar	43
Gerona	Tordera II	29
Malaga	Marbella	58
	Mijas	58
Murcia	Valdelentisco-Mazarron	200
	Aguilas	172
	San Pedro del Pinatar I	68
	San Pedro del Pinatar II	68
Valencia	Sagunto	23
Total		**1,670**

Figure 1.25 shows the five areas having 90% of the total desalination capacity of Spain. These areas include the Canary Islands, Andalucía, Murcia, Valencia, an autonomous region, and the Balearic Islands [116].

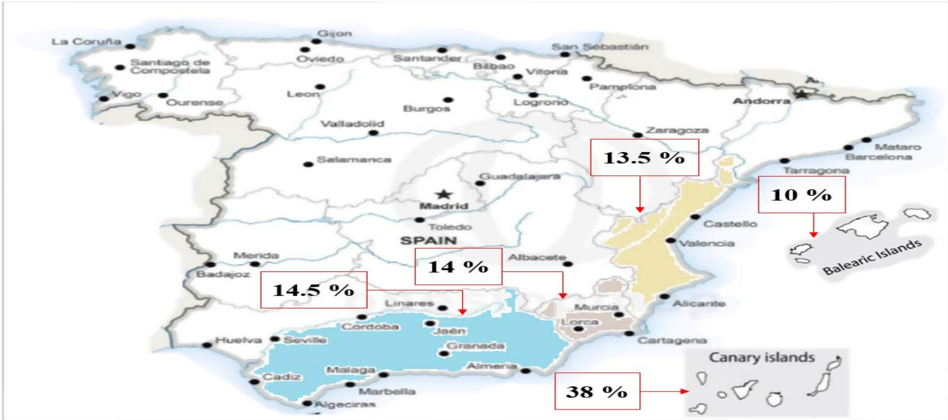


Figure 1.25 Spanish desalination units close to the Mediterranean Sea

As of November 2008, a total of 800 units were working in Spain, most of them having a production capacity of less than 10,000 cubic meters per day. The top 27 plants with a capacity of more than 50,000 cubic meters per day that were built under the AGUA program are mentioned in **Appendix I**. Some plants, which have a capacity of more than 200,000 cubic meters per day, are under construction, such as Torreviejaor Valdelentisco-Mazzaron [117]. So far, desalinated water produces around 3% of the total water usage in Spain [118]. Figure 1.26 shows the year wise trend of desalination production capacities in Spain. Since 2010, there has been an exponential increase in the country’s interest towards desalination.

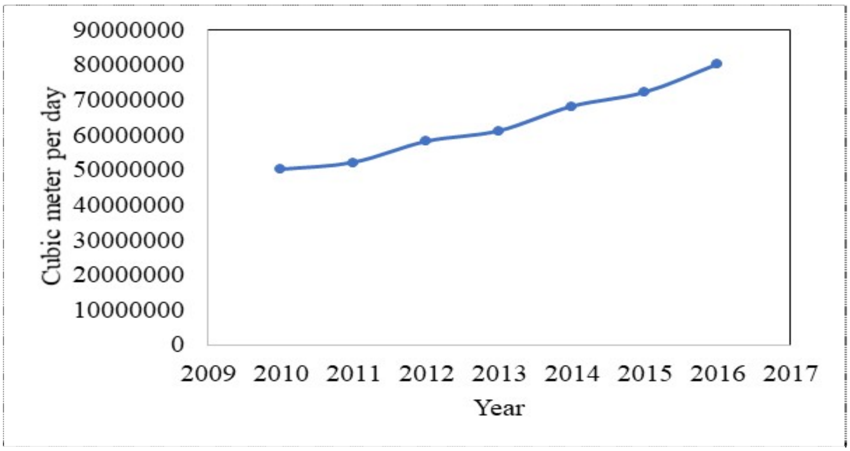


Figure 1.26. The desalination production capacities of plants in Spain (2010 – 2016) [119]

1.4.2 Gulf Cooperation Council Countries

The Gulf Cooperation Council (GCC) countries use seawater desalination to fill the gap between water demand and available freshwater supply. The freshwater shortage is attributed to higher evaporation rates, low rainfall, and insufficient freshwater resources [120-122]. Being rich in fossil fuel reserves, thermal desalination has been mainly used for around the last 50 years. Due to globalisation and rapid industrial development, it is expected that water resources will be reduced to 50% of the current available capacity. Therefore, it is vital to find ways to enhance the desalination efficiency to deal with the ever-increasing demand. In these countries, MED and MSF are used to purify water in around 80% of the desalination plants [123]. These techniques consume a tremendous amount of thermal energy. In this region, the first thermal desalination unit was installed in the 1960s. It is reported that 59% of desalinated water is produced through MSF, 12% through MED, and 29% through RO [124]. The desalination water purification capacity has increased from 72 to 98 million cubic meters per day during 2012-15 [125]. More plants with a capacity of 38 million cubic meters per day or more are expected to be installed in GCC countries, taking the total production capacity to 120 million cubic meters per day by 2020 [126]. Figure 1.27 shows the year-wise production of desalinated water in the Gulf countries.

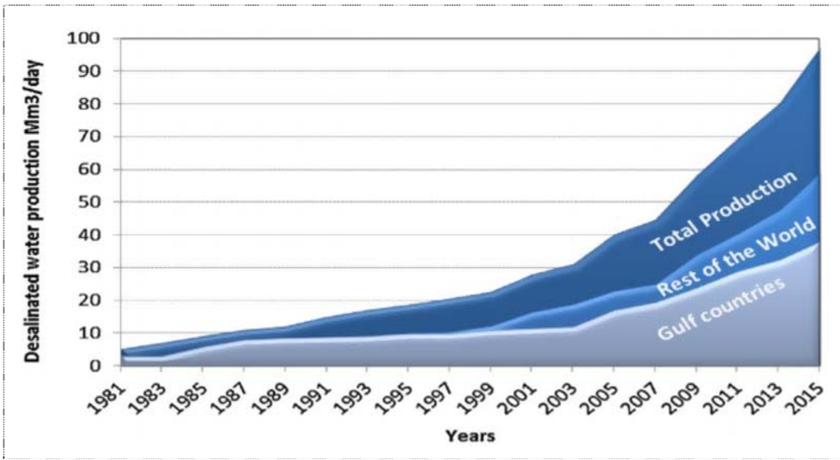


Figure 1.27 Comparison of water desalination in GCC countries in comparison with the rest of the world [127]

Figure 1.28 shows that GCC countries have the highest per capita water withdrawal, coming third after Japan and the USA [128]. In the Gulf Arabian region, freshwater production is twice that of South Africa, i.e., 634.2 m^3 per head per year. Out of all countries worldwide, KSA and UAE have the highest per capita reported value [129]. Figure 1.29 shows the breakdown of water usage in these six countries. A major portion is attributed to agriculture and the municipal sector [130]. Comparatively, a little amount is being used in the industrial sector. It emphasizes that conservation strategies should be adopted in daily practice in order to reduce the water consumption in the municipal sector.

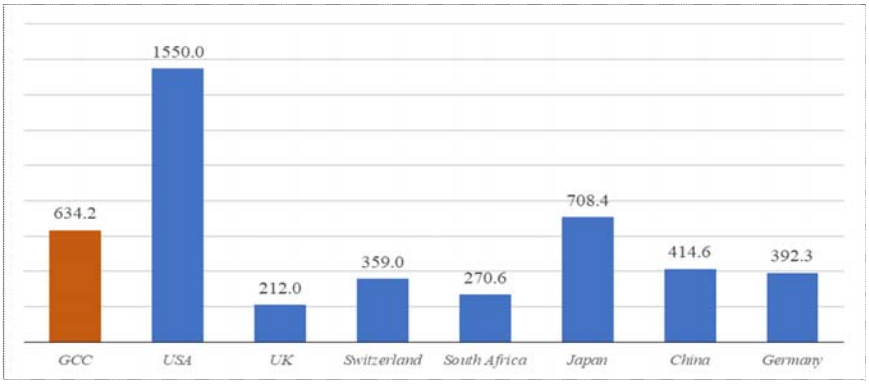


Figure 1.28. Per capita water withdrawal of different countries

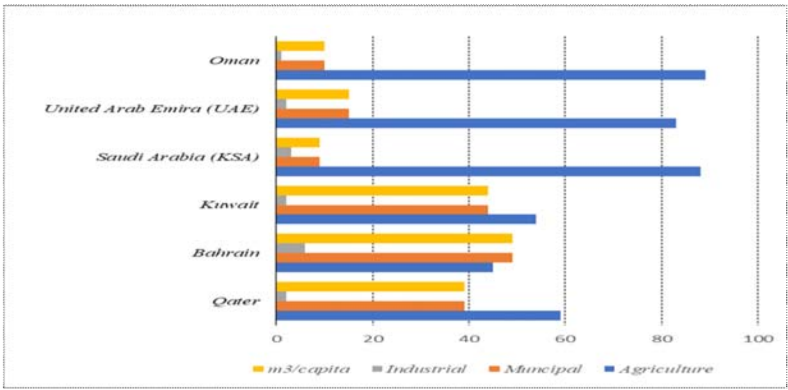


Figure 1.29. Consumption of water consumption in different sectors of the GCC countries

1.4.3 Saudi Arabia

In 1907, the first large capacity plant for water desalination was constructed in Saudi Arabia. In 1928, a multi-stage flash plant for water desalination, with the ability to produce 227 m3 per day was built in Al-wajh and Doha. In 2010, Saudi Arabia used 6% of the water needs by desalinated processed water, 2.2% through reused wastewater, and 33.5% using surface water in 2010 [257]. The situation was improved in 2014, and Saudi Arabia produced 60% of its entire water needs through desalinated water [258]. In 2016, desalinated water supplies enhanced by 827 million m^3 in 2 thousand to 1377 million m^3 and, consequently, touched the figure of 18 hundred million m^3 in 2018 [259,230]. In accordance with this situation, plants for desalination in diverse sizes and implementing different technologies were designed and developed by the corporation for saline water conversion in Saudi Arabia. These plants have a capacity of 44,000 - 947,890 m^3/day.

Table 1.9 provides data about desalination plants presently working with their starting time, the technology employed, and lifetime duration.

Table 1.9. Plants for desalination presently in service in the Kingdom of Saudi Arabia (2018) [230]

No. [a]	Service Area	Location	Technology used	Year of Commission	End of Life	Export Design[b]	Water Production[b]
1	Tabuk	**Haql-II**	**RO**	**1990** (27)	**2015** (+2)	**4954**	**5,760**
2		**Duba-III**	**RO**	**1989** (28)	**2014** (+3)	**4954**	**5,760**
3		Al-Wajih-III	MED	2009	2034	7740	9,000
4		**Umlujj-II**	**RO**	**1986** (31)	**2011** (+6)	**3784**	**4,400**
5		Umlujj-III	MED	2009	2034	7740	9,000
6	Makkah	Rabigh-II	MED	2009	2034	15480	18,000
7		Al-azizia	MED	1987 (30)	2012 (+5)	3870	4,500
8		Laith	MED	2009	2034	7740	9,000
9		Al-qunfudah	MED	2008	2033	7740	9,000
10	Jizan	Farasan-II	MED	2009	2034	7740	9,000
11	Makkah	Jeddah-IV	MSF	1982 (37)	2007 (+10)	190,555	221,575
12		Jeddah-I	RO	1989 (28)	2014 (+3)	48,848	56,800
13		Jeddah-II	RO	1994	2019	48,848	56,800
14		**Jeddah-III**	**RO**	**2013**	**2038**	**206,400**	**240,000**
15	Makkah	Shoaiba-I	MSF	1989 (28)	2014 (+3)	191,780	223,000
16	Al-baha	Shoaiba-II	MSF	2001	2026	391,300	455,000
17	Makkah	Yanbu-I	MSF	1981 (38)	2006 (+11)	86,688	100,800
18		Yanbu-II	MSF	1998	2023	123,675	143,808
19		**Yanbu**	**RO**	**1998**	**2023**	**109,908**	**127,800**
20	Al-madinah	Yanbu-Exp	MED	2013	2038	58,643	68,190
21	Asier	Shoqaiq	MSF	1989 (28)	2014 (+3)	83,432	97,014
22	Jizan						
23	Al-sharqiah	Al-Jubail-I	MSF	1982 (37)	2007 (+10)	118,447	137,729
24	Al-Riyadh	Al-Jubail-II	MSF	1983 (36)	2008 (+9)	815,185	947,890
25	Al-qasim	**Al-Jubail-III**	**RO**	**2000**	**2025**	**78,182**	**90,909**
26	Al-sharqiah	Al-Khobar-II	MSF	1983 (36)	2008 (+9)	191,780	223,000
27		Al-Khobar-III	MSF	2000	2025	240,800	280,000
28		**Ras-Al-kair**	**RO**	**2014**	**2039**	**307,500**	**310,656**
29	Al-Riyadh	Ras-Al-kair	MSF	2040	2015	717,500	740,656
30	Al-sharqiah	Al-Khfji	MSF	1986 (31)	2011 (+6)	19,682	22,886

a. 1-10 West Coast (Satellite Plant), 11-122 West Coast (Large Plant), 23-30 East Coast (Large Plant)
b. (m3/day)

It can be observed that with strict quality control and operation, and with proper maintenance, several plants exceeded their expected lifetime. The technologies used for desalination of water are subdivided into two types: phase and non-phase change processes. Multi-effect distillation (MED), Multi-stage flash (MSF), and mechanical vapor compression (MVC) are considered phase change processes, while reverse osmosis is considered a non-phase change process. The most frequently used technique for water desalination is reverse osmosis. It is used in 63% of desalination plants across the globe, while MSF is the second most used technology, and it is applied in more than 23% of desalination plants around the world [231]. MSF and MED are particularly suited for integration into cogeneration plans, where they can utilise the waste thermal energy, leaving the turbine to produce fresh water [232].

Due to its ability to integrate into cogeneration plants and their large capacities, MSF makes 87% of the total desalination plants in Saudi Arabia, as Figure 1.30 shows [230]. Water desalination is a highly energy-intensive process. Today, Saudi Arabia consumes 25% of its total gas and oil resources for desalination plants. This ratio is likely to reach a level of 50% in 2030 [257].

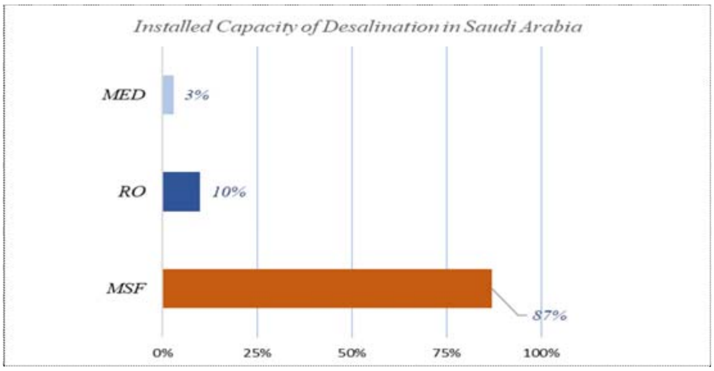


Figure 1.30. Capacity of installed desalination plants in KSA by desalination technology types

All types of desalination technologies need some form of energy. In reverse osmosis, electrical energy is utilised to keep the pressure constant at a value more than the relative osmotic pressure. On the other hand, MED and MSF, which are known as thermal desalination technologies, need thermal energy for the vaporisation of feed water. Fossil fuel is being used in the majority of the plants for desalination in the present day, and fuel cost is a major portion of the total production cost of desalination plants. 20-25% of entire energy resources are being used by plants for desalination in Saudi Arabia. This consumption has risen by eighty-four percent, starting from 1980 to 2010 [263,264]. Table 1.10 presents the consumption data of energy used by prominent technologies for water desalination [265]. The minimum energy uptake by the reverse osmosis process is observed in the form of electrical. The natural osmotic process uses a special type of membrane for separation of water, but in reverse osmosis, a totally different effect is achieved. A new type of chemical potential of water is used on both sides to convert the water with larger salt content to a solution possessing lower salt content.

Table 1.10. Desalination technologies and their energy requirements

Technology	Heat utilised (KJ/Kg)	Electrical energy (KWh/m^3)
Vapor compression (VC)	-	8-15
Multiple stage flash (MSF)	250-330	3-5
Reverse Osmosis (RO)	-	2.5-7
Multi effect desalination (MSD)	145-39	1.5- 2.5

1.5 Desalination and Solar Energy (State-of-the-art)

1.5.1 Introduction

The world has already realised the dangers emerging from the high emission levels caused by the uncontrolled use of fossil fuels. Therefore, there is awareness regarding the use of alternative and renewable sources of energy, such as geothermal heat, wind, tidal, hydro, etc. Now renewable sources form an inconsequential share of the global supply of energy [155]. Renewable energy is very useful, and it plays a vital part in the area of saltwater and brine desalination in emerging countries. There are intensive activities for developing and installing desalination plants on a large scale recently, which are chiefly motorised by renewable sources of energy for locations that have low density and are deprived of electrical grid networks. With the help of solar panels and other technologies of renewable energy, we need to understand the need to use renewable energy sources in order to save our planet. Hence, this is the right time to change our energy habits for a sustainable future and to safeguard the planet for the coming generations.

Solar energy is one of the most potential renewable energy sources. Our atmosphere receives 1.7×10^5 terawatts energy in an hour, and it is remarkably greater than the yearly energy consumption globally [156]. Recent technologies, such as photovoltaic (PV) systems and solar thermal systems in this field, have led to renewed interest in generating electrical power and heat energy. Apparently, energy from the sun is the best non-conventional (renewable) energy source for water desalination. Figure 1.31 represents solar energy concentration in different parts of the globe. It is obvious that those areas have more water scarcity but more availability of energy from the sun. Therefore, a sun-powered process of water desalination may appear as a potential source and best choice for the water desalination process, 0.6 litre/m²/d of oil is equal to 6 kWh/m²/d of solar energy [157].

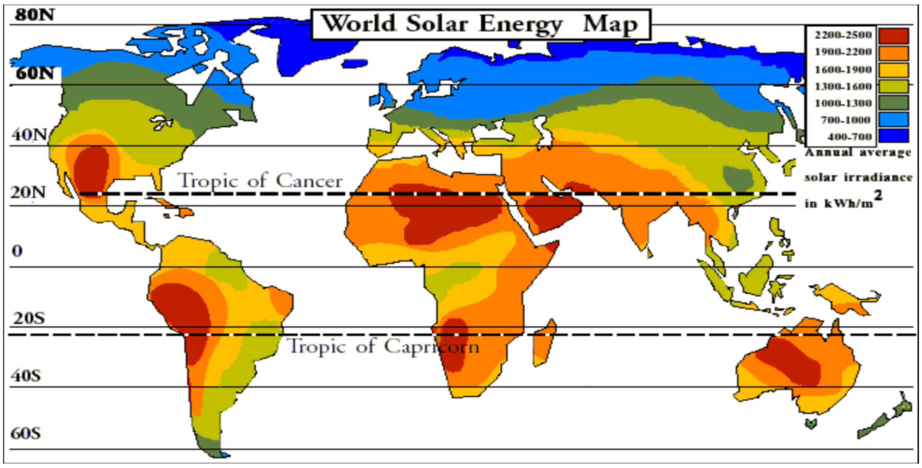


Figure 1.31. Distribution of solar intensity around the world [158]

The extensive development in fitted desalination capacity in the previous ten years is vital to investigate the amount of energy needed for the same and linked greenhouse gas discharge. Consideration is being given to the area due to inflation in the hazard of greenhouse gas discharges. Incessant development advances have made the technologies for desalination a viable substitute and competitive in contradiction of water importations or transference. Further, joining renewable sources of energy with desalination can deliver the supportable foundation for drinkable water. Furthermore, linking these technologies reduces the carbon print of desalination because of its hefty dependence on fossil fuel.

An extensive variation in possibilities is obtainable for linking non-conventional (renewable) energy resources and technologies used in the desalination process. In terms of room of water invention, every grouping of technologies has its own virtues, The twenty-four-hour accessibility of renewable energy sources for powering plants for desalination and price, whereas most desalination plants run by non-conventional (renewable) sources of energy are under observation at present, the fixed volume is above than nine thousand meters per cube/day. Worldwide desalination installations based on the process by foremost renewable sources of energy is shown in Figure 1.32.

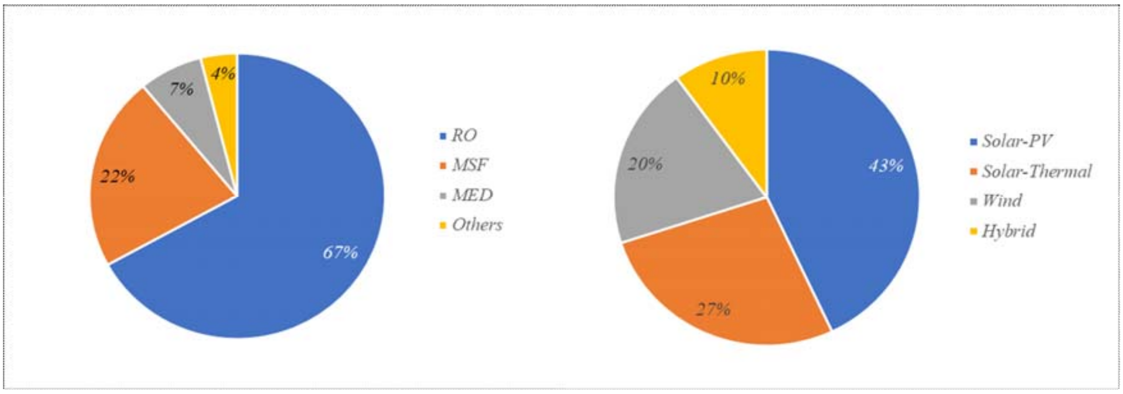


Figure. 1.32. Distribution of desalination capacity across the globe by major renewable systems of energy [159]

1.5.2 Desalination process by Solar Powered Plant

This is a form of renewable type of energy, which is abundant on the planet, which has a rate of 120 Petawatt on the earth's surface. Ultimately, the solar energy that reaches Earth per day is more than sufficient for the energy demands of the whole world for two decades [160]. Moreover, the environment-friendly nature of a solar power desalination plant makes it the most beneficial technology [161,162]. These types of desalination techniques can be grouped into I) Direct collecting process and II) Indirect collecting methods. The direct collecting process includes HD desalination and solar stills being the simplest techniques, while indirect methods are related to the commercial processes of desalination, like RO, MSF and MED [162]. The solar still method resembles the naturally occurring hydrological cycle pertaining to condensation and evaporation. This simple technique uses the evaporation of water in some containers and then the condensation process of vapours on the top lid, which is capable of producing potable water. More detail can be seen in [163,164]. The technologies for renewable energies can be linked to the purification of the membrane and heat energy for the production of electricity and heat.

The advantages of membrane procedures in comparison with thermal procedures comprise [165]:

- Less asset expenditure and power demands.
- A higher ratio for space/production and lower footprint high efficiency in recovery percentage.

- Minimum hindrance to operation during membrane replacement or repair and maintenance. Downgrade or upgrade options are allowed by modularity.
- More resistant to corrosion or scaling on account of surrounding temperature and rejection ratio of microbial contamination by membranes.

➢ **The perks of thermal processes in comparison membrane processes:**

- Tested and accomplished technique.
- Product water is of higher quality.
- Flexible monitoring and controlling for membrane procedures needed.
- High resistance to quality variations in seawater.
- Zero cost on replacement of membranes.

The comparison between indirect and direct solar desalination technologies shows that the latter needs big lands and shows relatively less protection. Although it can be compared with the indirect desalination process at lower level production because of its simplicity and lower expenditure. The present research focuses mainly on indirect solar collecting methods, especially those which could be integrated into common desalination techniques.

Figure 1.33 shows possible classifications of solar water desalination systems. While a large set of indirect methods has been proposed, the present research examines reverse osmosis (RO), thermal desalination (MED) technologies (marked with red dotted lines), as well as hybrid technologies using photovoltaic cells combined with reverse osmosis (PV + RO) and solar thermal desalination processes (CSP + MED).

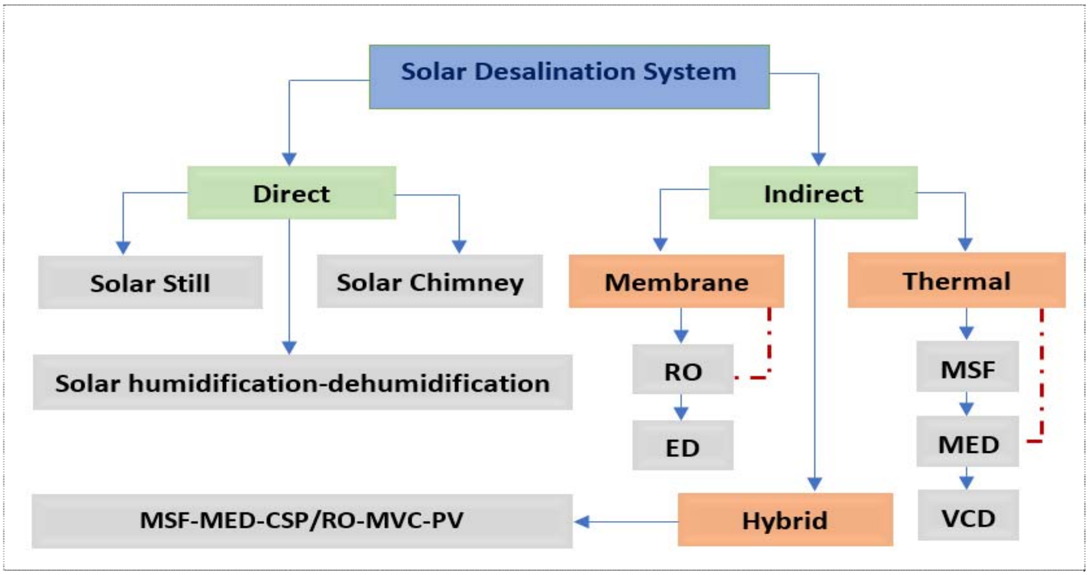


Figure 1.33. Possible classifications of sun-powered water desalination schemes (by other)

1.5.2.1 Types of direct technologies

A solar still is comprised of a darkened sink occupied with brine water up to a certain depth and protected by glass placed in an inclined position to enable the spread of radiation from the solar source and compression. The radiations from the sun ingoing to the sink warm up the darkened inside layer that sequentially warms up the water triggering evaporation. Due to the partial pressure variance and alteration in temperature, the water vapor becomes compressed end to end with the inclined cover, and this is collected by an appropriate facility at the bottom. The compressed vapours are gained, which will be top quality and a small quantity within the value of two to three litres per meter square per day [166]. Figure 1.34 shows the graphic illustration of a solar still [167].

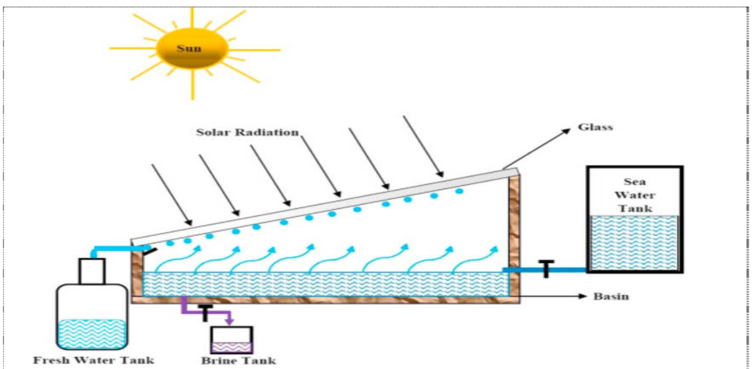


Figure 1.34. The principle of simple solar still desalination.

The second case of straight solar purification by Humidification Dehumidification (HD) is comprised of three elementary apparatus: The humidifier, the solar collector and the dehumidifier (see Figure 1.35). [168] demonstrates air movements in the shut coil from the compressor to the evaporator and so on. Water streams in an open route as follows: saltwater goes into the system as the chilling liquid at temperature (T_1) and passes over the condenser, therefore, chilling moist air and recording its enthalpy variation.

It comes out of the compressor at temperature (T_2), having improved the temperature of vanishing of water. After this, water is warmed up in the collector pitch, coming out at the maximum temperature of this system as (T_3). The warm water is at that moment dispersed over the big zone substratum in the evaporator for setting situations for evaporation. Evaporation heat energy is gained from within the system, therefore lowering its temperature at (T_4). Salt-water comes out from the system at temperature (T_4). Purified water comes out from the system at T_D. The temperature is somewhat higher compared to (T_1).

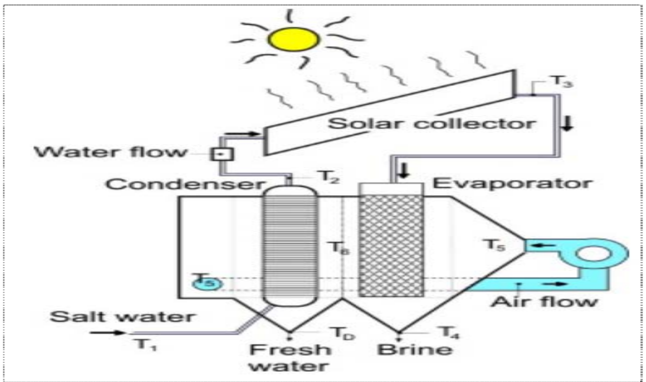


Figure 1.35. Solar humidification–dehumidification desalination system.

Essential research was performed observing the solar funnel by Schlaich in 1970. At that point, scheming and building of Schlaich was conducted as the model in Manzanares in Spain, by SC et al. [169]. There are two systems for indirect solar destination: one of them is a solar collection array and conventional desalination. Indirect solar energy is the most suitable technique for the desalination process.

1.5.2.2 Types of indirect technologies

Indirect purification procedures include the change of solar energy into heat and electric energy for running the series of thermal and membrane procedures of distillation. It can be separated into two wide-ranging procedures:

1. Harvesting energy by solar source (CSP).
2. Electricity generated by photo voltaic (PV) cells. More detail in the following section.

The similarity of every process of distillation with the technology of solar system is run by what sort of energy is desired, electrical or thermal, along with its accessibility. With fast advances in solar energy technologies, both photovoltaic and solar heat energy, there is also an increased interest in linking desalination to solar energy, focusing on refining energy efficiency in addition to reducing it. In this study, the author has researched and discusses works published in international journals and international conferences in the field of photovoltaic reverse osmosis (PV/RO) and solar thermal desalination thermal processes (CSP/MED).

1.5.3 CSP Technology Overview

There are four types of CSP technologies, which are described in detail: Solar Towers, Linear Fresnel, Parabolic troughs and dishes. These diverse CSP technologies are at various levels of growth. Many technologies related to CSP generate electrical power electricity in the same method as conservative power plants. Viebahn et al. [170] define CSP as renewable energy technology with the important potential to encounter a portion of the forthcoming energy demand. For developments custom-made in the previous 10 years, the electricity price from renewable energy technology is sustained to fall and conferring to the year 2018. The international agency of renewable energy gave a statement on the costs for generating power. Decreases in the total amount of installations are driving the decrease in the levelised cost of electricity, cost for power and solar technologies to variable degrees. It has been noteworthy for solar photovoltaic cells and also concentrating solar power plants.

For the generation of electricity, the CSP systems use conventional procedures for driving the generator and turbines. The only difference is the method for the creation of steam. Here, light rays from the sun are concentrated by utilising reflecting mirrors on the receiver for the production of thermal energy, and then this heat energy is used to produce steam [173]. For instance, for the configuration of the CSP system, as shown in Figure 1.36, the light from the sun is fixated on the receptor assembly, and the turbine runs by the thermal energy produced. In the mid-1980s, the installation of the very first operated CSP system was done successfully in the state of California [173], developing CSP as fresh technology with several continuing inventions, in addition to research and development.

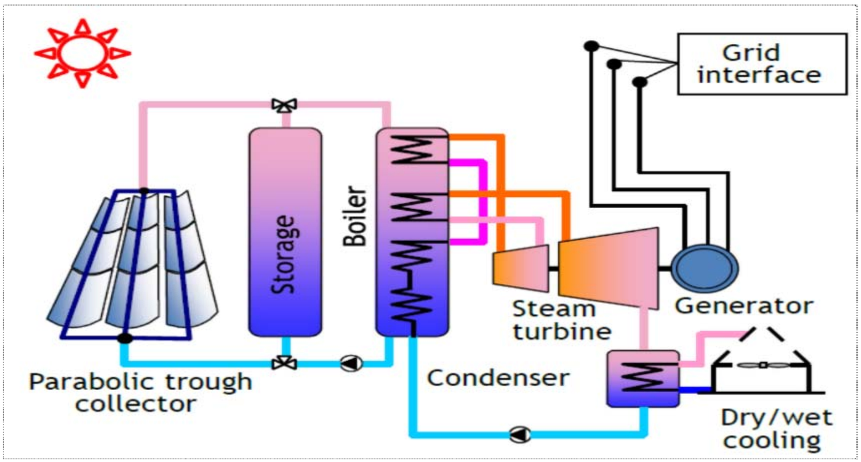


Figure 1.36. Operation cycle of a CSP plant [171,172]

Figure 1.37 [174] puts light on the trend of the price for the entire installation, the factor for volume and LCOE for CSP worldwide. CSP had growing installed volume by the end of 2016 of about five gigawatts and more price ranges compared to other established technologies. Prices are dropping, though, and from 2010 to 2017, the price of electricity for recent custom-built CSP schemes dropped by thirty-three percent to USD 0.22 per kilowatt-hours. The period from 2016 to 2017 faced a revolution for CSP technologies. The public sale consequences for projects to become custom-built from 2020 forward is expected to have meaningfully fewer LCOEs compared to LCOEs in 2017. The parabolic troughs in the line focus type shown in Table 1.11 use particularly cut parabolic glasses for collecting the rays from the sun onto the direct receiver tube for heating the heat-carrying fluids. Linear Fresnel, shown in Table 1.12, works on a similar focus line procedure but utilises plane glasses for absorption.

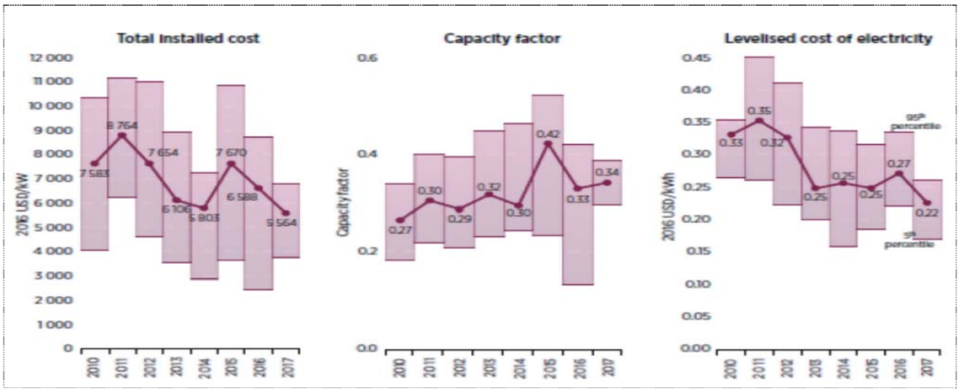
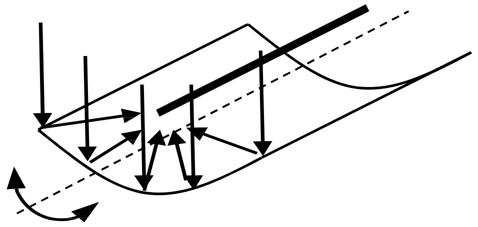


Figure 1.37. Worldwide weighted mean entire installed prices, size factors and LCOE for CSP, 2010-2017.

Few merits of the focus line technology comprise easy techniques of tracking, and its established tilt glasses have very large power of reflection [175]. Theoretic ratios of concentration seem to be less in CSP systems utilising this technology compared to point focus. Heliostats perform the function of concentrating rays from the sun to a receiver on a solar tower (Table 1.13). Heliostats are specially designed mirrors for this purpose. In Stellenbosch University, the parabolic dish technology that concentrates the rays of the sun on the receiver is the reflecting dish (Table 1.14).

Table 1.11: Summary of the parabolic form of CSP

Collector design:



Principles:

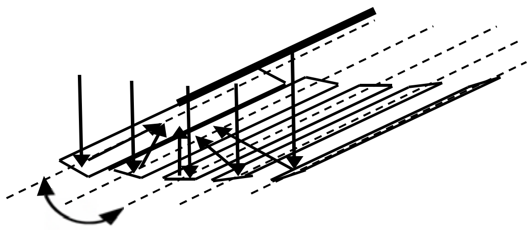
- Tracing: these accumulators track the sun on the solo axis towards the north. In the south, it reflects the sun's rays on the receiver tube located at focus.
- Heat transmission fluid and oil are formerly warmed up in the receptor. This heated fluid is then transported to the energy block for producing superheated mist by the heating system.
- Capacitor features more than fifty percent could be attained, and this system could crossbreed with heat transmitting fluid heater gas fire back up boilers.
- In an Integrated Solar Combined Cycle (ISCC), parabolic trough technology is employed with conventional gas turbine power plants.

Past and status:

- In 1907, the first collector was patented in Stuttgart, though the very first plant was run in Egypt as the fifty-five-kW pumping place in 1911.
- After the oil crisis in late 1979, the first marketable plant was made in the 1980s in California, having unit dimensions extending from fourteen to eighty megawatts and a combined volume of 354 megawatts. These are still working.
- The modern plant is Nevada Solar One, the 64-megawatt plant in the United States.
- In 2009, a feed-in-tariff Spain set up a feed-in-tariff CSP plant.
- It is the most bankable and matured of all CSP technologies, and with respect to credit facilities too, it is supported.

Table 1.12: Summary of linear Fresnel kind of CSP

Collector design:



<u>Principles:</u>

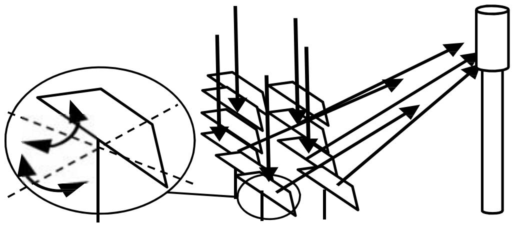
- This has fields which are fixed near the ground, whereas there is a linear receptor at the upper side of the mirrors, with subordinate receptors.
- Flat mirrors are concentrators that are inexpensive, and a tracking component could be linked with mirror facets. The receptor is fixed and needs no tracking.
- In terms of land requirement, it is efficient as the required area is less, and wind load effects are also less because the mirrors are placed close to the ground.

<u>Past and status:</u>

- This is comparatively current technology, but then again, there are some plants and demo projects which showed the feasibility of the idea.
- In 2010, linear Fresnel plants were in progress in Spain. These have a generation volume of thirty megawatts and started processing in 2011. In India, the biggest single-unit plant is a 125-megawatt capacity plant.
- This serves as a substitute to the parabolic trough when there is a necessity of the lesser rate option.

Table 1.13: Summary of central receiver systems type of CSP

Collector design:



Principles:

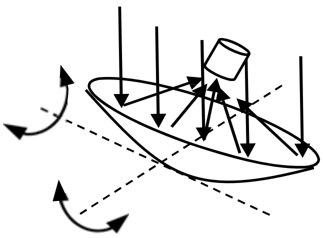
- The solar ground covers heliostats that are employed for focusing emissions from the sun on the topmost receptor tower. These stats could divide the sun into two axes. The point focus arrangement permits more rate of concentrate, resulting in more working temperature and, therefore, stronger competence.
- This technology could work with varied kinds of (HTF), and salt in molten form, water and air under controlled pressure are mostly employed. This is price-effective; nonetheless, it is the purpose of the type of HTF utilised. The volume feature is the other purpose of this and could differ from 25 percent to 74 percent.
- Molten salt employs salt from a solar source that is a mixture of sixty percent NaNO3 and forty percent KNO3. This has a more functioning temperature equal to 56-degrees Celsius and has the actual rewarm vapor cycle. This salt could be employed by way of direct stowage and could make the volume feature more than fifty percent.

Past and status:

- This is a fresh technology, and the first plant started working in 2007. There are many demo missions, and various marketable plants have shown the feasibility of this idea.
- The maturity differs for numerous kinds of technology, and there are plants that can generate range up to 641 megawatts.

Table 1.14: Summary of Parabolic dish type of CSP

Collector design:



Principles:

- A parabolic dish is formed by putting together a number of mirrors. A mirror can be specially designed and specifically cut to form a parabolic dish to be used as a concentrator. Solar rays are concentrated on a receiver placed at the focus, using the parabolic dish. The solar to electric efficiency is high, i.e. more than 30%, and a high temperature is generated in a point focus system.
- Individual parabolic dish units and distributed parabolic dishes are two different versions of the same technology. Individual units use Stirling or Bryton engines, and in distributed dishes, heat is transferred from a parabolic dish array to a power block.
- Water requirement is less, and there are possibilities of plant designs, which are modular. Stirling engines (capacity 3-25kW) are used in most sophisticated parabolic dish systems. The capacity factor is low (between 25-30%).

Past and status:

- Though the technology is almost recent, viable systems have been developed, and a lot of dish generating plants exist. Stirling technology for engines is the base for most of the plants.
- In Peoria (Arizona) in the U.S., a large-scale 1.5 MW (Stirling) parabolic dish technology plant was made for the first time. Condi-Sys (China) bought this in 2012 after getting decommissioned in 2011.

More than 80 percent of the current concentrating solar power plants are parabolic troughs [176], and this enginery is mentioned as the utmost mature of all the concentrating solar power technologies. There are many freshly made big single unit concentrating solar power plants, which are central receiver systems, and this is due to the promising future of heat to electricity transfer competences of the technology and its capability to achieve very high temperatures. Tables from 1.11 to 1.14 express the summary of the four kinds of CSP technology, as revised from [175], [177-179].

1.5.4 Technical Effect Factors of CSP

For example, most of the research studies the technical effect factors of CSP, as studied in South Africa. The major concerning technical factors are specified in [180-182], used as parameters, and attempts to control the difficulties observed in the process of sub-systems were deeply studied. These factors are:

- Balance between plant expenditures and related issues.
- Storage of thermal energy.
- Fluids requirement for transfer of heat.
- Support structures, mirrors, receivers and solar field.
- Large size of plant.

It is necessary to give weight to the experts' opinions about the type of indicator that would have a significant effect on CSP electricity. The cost weight average method was adopted to achieve this goal, and experts were asked for the ranking of indicators, relative to its influence on reducing the CSP electrical energy cost in South Africa. The results revealed that the factor with the minimum influence occupied the lowest rank, and high influence factors received the highest rank.

Five indicators were identified as highly influential on concentrating solar power electricity expenditure reduction, and all of the parameters obtained above 50% of the average rating. See Figure 1.38. It was emphasised that solar mirrors and receivers are the most suitable tools with great efficacy and less expenditure, as the supply of solar energy from the sun has no limit.

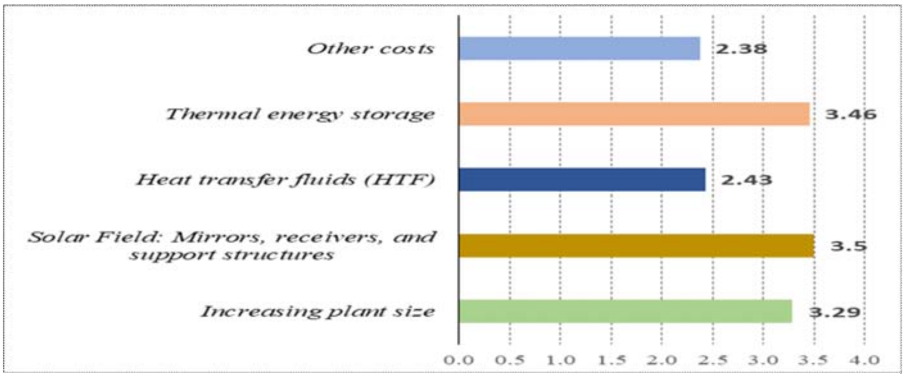


Figure 1.38. Average rating of CSP cost reduction parameters

Solar energy field (including support structure and receivers, along with existing soil and general design of solar energy field). Sustenance infrastructures will mainly focus on safety-related issues of machinery from human activities and natural disorders. Consequently, decreasing the threats related to the construction of local solar energy power plants provide high solar resources. Another vital factor, as indicated by the experts, is to build a low cost but highly efficient storage system for thermal energy. The concentrating solar power (CSP's) ability to hold energy provided a safe way for energy transfer, and its capability to supply electricity whenever and wherever it is needed. A better storage facility will boost the holding ability factor that will ultimately show a reduction in investment prices and build up the truest level of funding agencies.

Plant size was the third indicator. The experts were of the opinion that the large size of a CSP plant, in accordance with the grading, is the size of the plant. Specialists indicated that an increase in the size of the concentrating solar power plant that has provision for the allocation of huge amounts of electrical energy to concentrating solar power plant while bid rounds, ultimately lead to a good learning effect and reduction in cost. Currently, existing CSP plants have unique components and layouts, which are mostly built-in units, so they do not help in learning by doing process [183]. It was considered necessary to roll out CSP technology for the reduction of costs. The overall performance of CSP technology is related to fluids used for the transfer of heat. It is HTF that mainly transfer fluids from the heat receptor to energy-generating arrangements, as well as a facility for heat storage [173,178]. The experts believed that a decrease in the expenditure of HTF is necessary for an overall decrease in the expenses of concentrating solar power electrical energy. Although specialists emphasised some typical aspects, such as the forthcoming RD and D on HTF, should aim for obtaining a reduction in CSP electrical energy cost, as given below.

- More heat-holding capability for stowage of energy by HTF.
- HTF with less viscidness.
- High efficiency in thermal conduction by HTF.

The factors which emerged as creating problems in this research are closely associated and relative to the factors studied by other researchers while struggling for the improvement of efficiencies in HTF in CSP technologies [184-186]. It is imperative from the study that an uplift in the qualities of HTF with the necessary cost-reducing steps will have an immense effect on the cost reduction of electrical energy produced by CSP.

Moreover, some external cost and expenditure on related systems affect the cost of CSP. It's the major issue to have a balance between the cost of the plant and other related issues like grid connection systems, the availability of local experts, the electricity transmission process, and related technical issues, which need to be addressed for the reduction of CSP electricity cost. This segment approves that an attempt to improve the quality of HTF, along with price reduction techniques, will have a great influence in reducing the entire price of electrical power generated by CSP. The experts believed that many uncertainties exist related to these factors. That definitely gives expectations for further improvement. This study also indicates that there is also much room for improvement.

1.5.5 Combining CSP with a Thermal Desalination (Overview): International Example

A uniform configuration is not possible while combining CSP and desalinisation technology. Each site has different design parameters [187]. Water salinity and solar field performance are dependent on the latitude that determines the solar incidence angle, which is the major parameters. Water salinity is a major factor affecting RO unit performance. Other factors affecting the choice of technologies are relative humidity and ambient temperature. In terms of cost and energy consumption (both thermal and electricity), MED is preferred than MSF. MED has a negligible impact on electric production cutback, and it functions with steam at lesser pressure. RO is considered more advantageous compared to MED when considering energy consumption and lower cost [82]. This assumption changes when coupling a CSP power plant and MED. The MED plant makes use of the heat released from electrical power generation, and it helps to replace the condensation unit there by reducing the cost. Here, the primary energy for desalination is obtained from electrical production, and the rest is waste heat to be expelled from the system [187].

RO is considered a better choice compared to thermal desalination, but the opinion changes when a combination of desalination and CSP are considered. A study conducted by the Institute of Technical Thermodynamics in 2007, from the DLR [187] stated that CSP+RO is less advantageous compared to CSP+MED. Their study was located in the North African and Middle East regions. In the seven locations where studies were conducted, CSP+MED showed better performance (between 4 and 11 %) than CSP+RO.

There are similar conclusions from other studies by DLR [188]. The optimum combination is decided according to the location of the plant. The feasibility analysis of a successful combination of the two has not reached a conclusive stage. Still, we are not in a position to find a final answer to the question as to which would be the best option. Any answer chosen at this point would be thoroughly immature in nature.

In recent times, the CSP cost of energy has achieved grid parity in several parts of the world. Solar thermal energy-assisted cogeneration desalination systems using (MED, RO and MSF) have been studied elsewhere, e.g. [189-191]. The coupling of CSP plants with RO units, Low-Temperature Multi-Effect Distillation (LT-MED) and MED-thermal vapor compression (MED-TVC) was studied by Blanco et al. [190] and Palenzuela et al. [189], but sufficient studies were not made to assess the actual impact of a combination of desalination and CSP plants. There were two notable studies at the PSA, where RO systems and MED were tested. In these projects, desalination systems were powered by solar power systems, like the ones used in CSP plants. These projects in the last decade were named Aquasol and Powersol projects. **Appendix-IV** has details regarding these projects. There are many research institutions worldwide, and PSA is one that is into CSP technology development. **Appendix-V** contains details regarding the comparison of different CSP technologies.

1.5.6 Key players

Now many research groups are devoting their time and energy to studying desalination and CSP. One major group is in Spain, functioning associated with CIEMAT. Other notable initiatives from governments include the Cyprus Institute, and there are many private players like Doosan. Now many projects are getting initiated as CSP+D, especially in the Arab nations, where freshwater scarcity is acute, and solar resources are plenty.

Researchers have studied solar thermal desalination with low temperature a for long time, but CSP plant-powered desalination is a relatively new and unresearched topic that has only recently gained momentum. The southern part of Spain and south west USA are the major locations where CSP is found [192].

1.6 Desalination and Photovoltaic Solar Energy (State-of-the-art)

1.6.1 Introduction

The first practical use of solar PV dates back to the 1950s when Daryl Chapin, with a team of engineers in the Bell Labs in the United States of America, invented the first silicon solar power device to convert solar irradiation to electricity for a telephone system in rural areas. The efficiency of the PV cells was only 6% at that time, but nevertheless, it was a great start to the idea of using the sun as a source of energy. The cheap price of oil ($2 per barrel), however, and the beginning of the construction of the first nuclear power plant, which at the time, provided a source of electricity too cheap to meter, hindered research into solar energy during the 1950s. It was in 1954 that the first modern solar cells were made, and they were later used in a U.S. satellite in 1958. In 1974, after the first oil crisis, the need for an alternative source of energy advanced the research, as well as the photovoltaic industry. The continuity of research for solar PV was rescued by space programs. Solar PV represented at the time and till now, the best technology to power satellites. Since the end of the Gulf War, the solar cell market has increased rapidly. The cost of solar electricity has fallen drastically in the past few decades. The main reasons for this are the advancement in technology and mass production of photovoltaics, especially after the first oil crisis in 1974. Climate change is rightly conceived to be the immediate cause behind that and also the necessity to replace fossil fuels with other sustainable alternatives. The price trend of a PV module in the past 40 years is shown in Figure 1.39. The price has decreased to about 300 times cheaper.

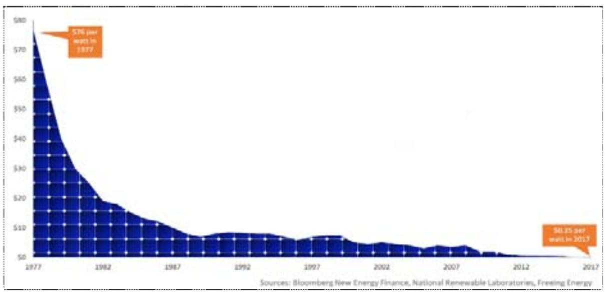


Figure 1.39. Price trend of a PV module since 2010 [196]

When it comes to total installed nominal PV power, Germany was overtaken by China in 2015, Japan in 2016, and the U.S. in 2017. In terms of total installed capacity, China's figures peaked above the European Union's. China's total PV power capacity, annual installations being 53 GW was 135 GW. In 2017, the corresponding global figure was 408 GW, and China's share from this was 33%. The European Union stands next with a total of 108 GW or 26% of the global figures. At the end of 2018, cumulative installations were at 488 GWp. Including off-grid systems, all percentages are in accordance with total global installations [197]. Figure 1.40 reveals the data for total PV installation across the globe in 2018.

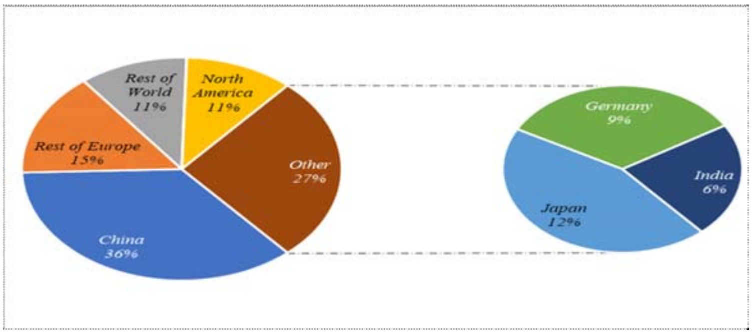


Figure 1.40. Global cumulative PV installation by region status 2018 [198]

1.6.2 Photovoltaic Technology (PV)

A Photovoltaic (PV) system, also recognised as 'Solar cell,' can be described as a semiconductor device designed to produce electricity by converting the electromagnetic radiation from the sun. In the mid-70^{s}, PV cells were used for power in places where it was too expensive to use grid power, and in remote areas, as well as islands.

Today, in some countries, like South Africa, many people are using electricity from PV systems rather than electricity from the main power grid since PV technology is now more efficient and costs less than generating electricity from sunlight [199]. Solar photovoltaics (PV) have attained the status of being the most important solar electric technology in the world. Electricity is generated by the strikes of sunlight on the PV cell, and then the energy supplied by photons from absorbed sunlight results in the release of electrons to create electricity [200]. Figure 1.41 illustrates the major components of solar cell. Photovoltaic technology relies on the use of cells containing semiconductor materials.

These materials, which are referred to as solar cells, are responsible for collecting and transforming solar radiation into electric power. The cell temperature and ambient temperature are important parameters, which influence the cell characteristics and are considered in the modeling of a PV system [201].

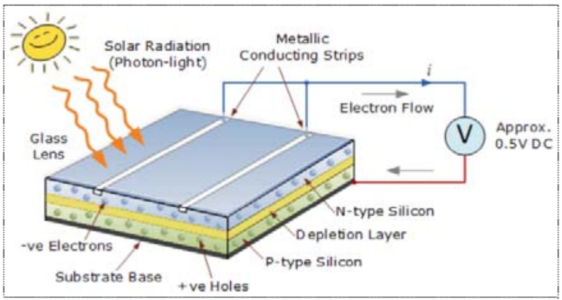


Figure 1.41. Main components for a solar cell photovoltaic

The basic unit of a PV system is the PV cell. They are different sizes, ranging from one centimeter to about 10 centimeters. The maximum output of a single cell is 2 watts and is insufficient for most applications. This, however, necessitates the formation of modules by electrically connecting the cells to increase power output. An array can be formed by further connecting the modules, as depicted in Figure 1.42. An array functionally is the entire generating plant, which can be made of one or many modules. It is according to the required power output that the number of modules in an array is decided.

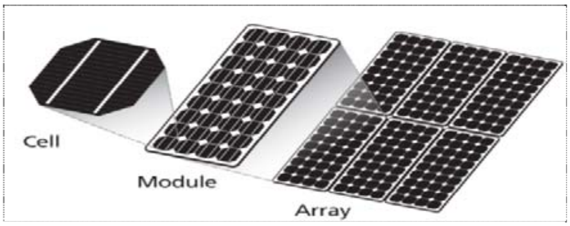


Figure 1.42. PV Cell, Module and Array

Crystalline Silicon (c-Si) and thin-film are the two main types of solar cells. Crystalline silicon cells are made of monocrystalline or multicrystalline silicon, which represents more than 92% of the PV market in 2018. Thin-film PV cells have commercial value, as they are used in several applications like amorphous Silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Dicelenide (CIGS), which occupy a major share of the Photovoltaic market. Figure 1.43 shows the global PV market by type in 2018 [198].

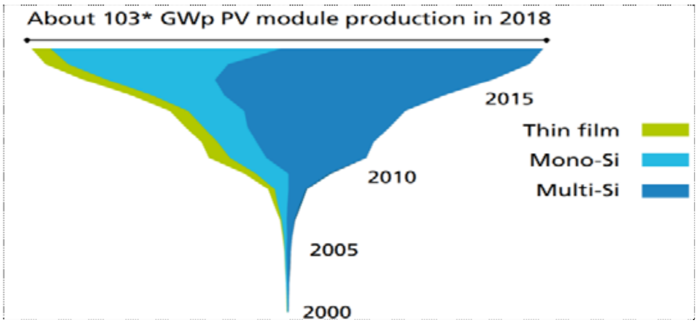


Figure 1.43. Annual PV Production by Technology Worldwide (in GWp)

* 2018 production numbers reported by different analysts vary to some extent.
They estimate that total PV module production is realistically around 103 GWp for 2018.

1.6.3 History of Solar Photovoltaic (PV)

It was the French scientist Alexandre Edmond, who observed the conversion of light to electricity utilising electrolytes and metal electrodes [202] 160 years ago. The following table traces the history of PV over the years.

Table 1.15. History of photovoltaic (PV)

Year	Action/News	Ref.
1839	Light-electricity conversion was discovered by Alexandre Edmond Becquerel using metal electrodes and electrolytes.	[203]
1883	American inventor, Charles Fritts, built the first solar cell. He used a thin layer of gold to coat the selenium and form the junctions with a conversion efficiency of 1%.	[204]
1922	Einstein's contribution to explaining the photoelectric effect earned him a Nobel Prize in Physics in 1921.	[205]
1954	Bell laboratory first built and demonstrated silicon PV cells in 1954, which was made from a single p-n junction Si. Since then, SCs have been classified into three different categories. Single/mono crystalline and poly crystalline silicon (c-Si) are considered first-generation solar cells. Amorphous silicon (a-Si), microcrystalline silicon, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) are considered as second-generation solar cells due to the use of thin-film technologies.	[206]

1950s	The first solar cell was invented nearly 50 years ago (in 1954) by Bell laboratories, and inspired by the successful commercialisation of other semiconductor devices, two companies started to produce solar cells. A number of pioneering applications were tried, from toys to stand-alone power supply in remote places, but sales remained extremely small. All space applications would have been impossible if not for solar cells. All the leisure in telecommunication we have now from satellite navigators to TV channels is due to the solar-powered satellites.	[207]
1963	Japan's Sharp Corporation started manufacturing PV modules in 1963 and installed a 42 watt (W) PV module in a lighthouse.	[208]
1966	Astronomical Observatory by NASA makes use of PV array, 1-kilowatt. There is a considerable reduction of 80% in the cost of PVs due to advanced research.	[209]
1970s	Philips, Sharp and Solar Power re-evaluated applications of small commercial modules, especially by the early 1970s. Solar PV begins to appear in many devices due to cost reduction. Railroad crossings, warning lights in navigation, lighthouses, etc. are a few to name. The first modern modules were manufactured in 1976.	[210]
1990	The GaAs/GaSb concentrator solar cell has been described to have a 35% efficient two-chip stack by L. Fraas, J. Gee, K. Emery, et al.	[211]
1990	The producers of solar PV electricity could sell it to utilities at 90% of the retail market price during the 1990s in Germany. Japan and Germany provided funding to subsidize rooftop PV systems in many homes.	[212]
2007	A three-junction cell, metamorphic (GaInP/Ge/GaInAs) shows confirmed efficiency of 40.7% under standard measurements (240 suns _24.0 W/cm^2, AM1.5D, low aerosol optical depth, 25 °C.	[213]
2010	2010 - A solar water heater and extra solar panels were installed at the Presidential residence as per the order from Barack Obama.	[214]
2011	Chinese factories are able to bring the manufacturing cost of silicon PV modules to $1.25 per watt. The number of installations doubled globally. A severe slowdown of solar projects in the U.S. due to the CIGS technology-based Solyndra investment fiasco.	
2013	In 2013, an efficient HCPV of 35.9% was demonstrated by Amonix. Fraas proposed the use of mirrors in space during dawn dusk sun synchronous orbit in order to deflect sunlight to solar farms on earth. Installations passed 100 GW worldwide.	
2015	The manufacturing cost of a CIGS module is calculated to be $0.34 per W.123 for the production of 1000 MWy1. The total production of a CIGS module was above 1.6 GW in 2015.	[215]

2018	Without subsidies, the LCOE (life cycle cost) of PV stations appears less than the life cycle cost of coal-powered plants. The corresponding data is released by International Technology Roadmap for Photovoltaic (ITRPV) in a report. The report also predicted that 40% of global electricity production would be made by PV stations alone and 70% together with wind power by 2050. According to the study made by DNV GL, an international certification center, the total share of RES (Renewable Energy Sources) will reach 80%, making the total elimination of CO_2 emissions possible by 2090.	[216]

1.6.4 Efficiency of Photovoltaic

The performance of solar devices is primarily assessed in terms of efficiency, which is calculated as the ratio of solar output to input energy from the sun. The range and intensity of incident sunlight and temperature of the PV module are crucial factors here.

Thus, the PV efficiency of the module is calculated as the fraction of power changed to electricity and is defined as follows [217]:

since,

$$\mathrm{Pmax} = \mathrm{FF} * \mathrm{Isc} * \mathrm{Voc}$$

then,

$$\mu = (\mathrm{FF}) \frac{\mathrm{Isc} * \mathrm{Voc}}{\mathrm{Pin}}$$

where

- FF = Fill factor
- I_{sc} = Current [A]
- V_{oc} = Cell voltage [V]
- A_{pv} = PV module area [m^2]
- E = Irradiance on the collector surface [W/m^2]
- P_{in} = Input power, which is equal to: $P_{in} = Apv * E$

Low conversion efficiency is considered to be the major drawback of commercially available silicon solar cells. The solar cell industry has witnessed a rapid growth of 30% per year since 2009.

Even though there is considerable growth, solar energy production amounts to less than 1% of the overall produced energy.

The performance and cost of a solar panel are totally dependent on the power conversion efficiency of the PV cells that consist of semiconductor material capturing and transforming the sunlight. In terms of increasing efficiency, the multi-junction (MJ) cell made of expensive gallium arsenide (GaAs) and other different semiconductor materials is considered an emerging and prospective technology. The MJ solar cells are commonly used for solar panels on spacecraft, but they find great use in Concentrator Photovoltaic (CPV), which is a promising new technology, where lenses or mirrors are used to focus light upon the cells. The advantage here is relatively expensive cells like GaAs can be used cost-effectively, but CPVs are still limited to locations with high solar radiation and represent only 0.1% of the PV market [218].

Figure 1.44 indicates the gradual development of laboratory solar cell efficiencies, as well as the efficiency of solar cells of the major types.

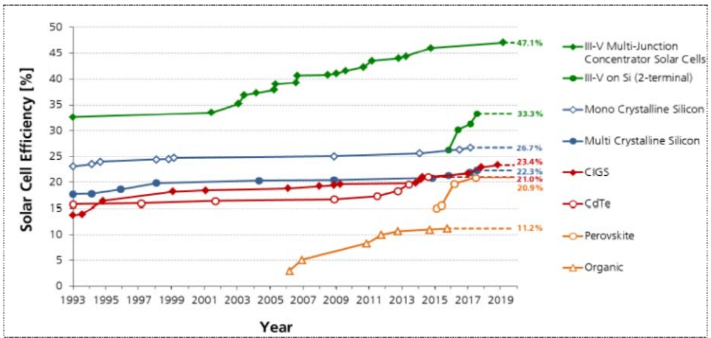


Figure 1.44. Development of laboratory PV cell efficiencies [219]

1.6.5 Cost analysis as examples for RO Desalination Plants in different countries

As mentioned earlier, there are a number of factors that determine the capital and operating costs of a desalination unit. These factors are highly dependent on the geographic region, making the same plants run at a reduced cost in one country compared to another, as shown in the projects mentioned in Table 1.16.

As shown, the per-unit water purification cost is lower in the Arabian Gulf compared to the USA and Australia, reaching less than 0.6 $\$/m^3$ per day. Although in all countries for comparison purposes, the same technique, such as SWRO (Sea Water Reverse Osmosis), is used for the purpose of comparison. However, moderate regulations regarding brine disposal are one main reason for this reduced cost, which is the effect of a decrease in waste disposal cost. Moreover, in the Arabian Gulf, the water quality used is 500 ppm, whereas, in USA and Australia, it is 200 ppm. This, in turn, also decreases the production cost. These two are the main factors contributing to the lower production cost in the Arabian Gulf compared to Australia and the USA.

Table 1.16. SWRO Desalination plants running in different countries across the globe to produce desalinated water

Country	**Australia** [220]	**Arabian Gulf** [221]	**USA** [222]
Expected shelf life (in years)	20	20	20
Unit location (city)	Tugin	Fujairah	Carlsbad
Plant name	Gold Coast Desalination Plant	Fujairah F1 Extension SWRO	Carlsbad Desalination Project
Construction year	2009	2013	2014
Water recovery	45%	45 to 50%	45 to 50%
Unit production capacity (in m^3/day)	13.3×10^4	13.6×10^4	18.9×10^4
Purified water impurities (in ppm)	200	500	200
Salinity of feed water (in ppm)	38×10^3	45×10^3	36×10^3
Device used for energy recovery (company name)	DWEER's energy recovery device	Energy recovery, Inc.	Energy recovery, Inc.
Intake	Open intake	Open intake	Open intake
Type of desalination	Double pass seawater reverse osmosis desalination (SWRO)	Double pass seawater reverse osmosis desalination (SWRO)	Double pass seawater reverse osmosis desalination (SWRO)

Technique being used for water post-treatment	Purification through lime, carbon dioxide, and chlorine along with fluoridation	Purification through lime, carbon dioxide, and chlorine along with fluoridation	Purification through lime, carbon dioxide, and chlorine along with fluoridation
Technique being used for water post-treatment	Filtration with dual medium	Dissolved gas flotation (DSF) along with filtration	Filtration with dual medium
Government environmental limitations	Strict	Moderate	Very Strict
Energy consumption (in kWh/ m^3)	3.4	3.7 to 4	-
Disposal of brine	Disposal 300 meters down the sea through diffusers	Disposal directly into sea	Disposal directly into sea
Total investment cost (in $)	94.3×10^7	20×10^7	$69.2× 10^7
Operating cost ($ per year)	32×10^6	26.9×10^6 (estimated)	53.1×10^6
Simple annualised CAPEX, US$/year	$47,150,000	N/A	N/A
Per unit water purification cost (in $/$m^3$/day)	1.63	< 0.6	1.86

*1 Total unit cost to owner that included payments, finance fees on pipeline, misc. construction improvements, misc. O/M costs, admin costs.
*2 Estimated

1.6.6 Coupling Solar (PV) Energy and Reverse Osmosis (RO) Desalination

Many combinations are possible by coupling desalination methods and solar power, as discussed previously. A combination of PV modules and RO membranes is the most commonly used option in solar powered RO desalination units, as shown in Figure 1.45.

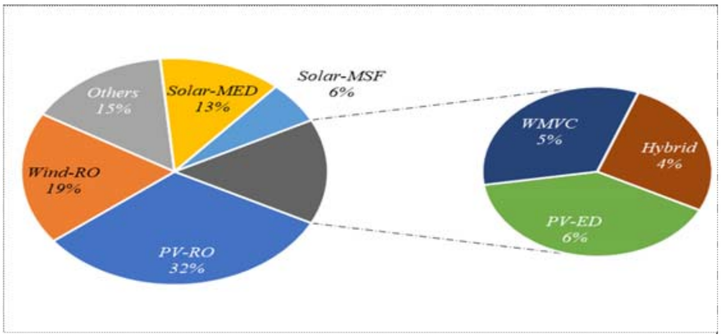


Figure 1.45. Energy usage pattern of desalination plants [223]

Figure 1.46 shows a simple configuration. As per the diagram, photovoltaic panels are used to power a high-pressure pump and a feed pump, and the source water is pressurised. Water then passes through an RO membrane array, making it fit for human consumption. This process leaves behind brine, which has a high concentration of salt as only a small portion is desalinated. The membranes are configured as cross-flow separators due to energy considerations. Devices like turbines or pressure exchangers are used to harness the energy trapped inside the brine. PV-RO systems have remained a topic of much research, and precise and efficient modeling of the same was performed using different parameters [224-231]. The suitability of the system for different geographic locations like Eritrea [228,229], Jordan [224,225], Greece [226,227], etc. were also analysed. Performed studies involved experiments with different configurations [228,229] and components, including devices with energy recovery functions [230].

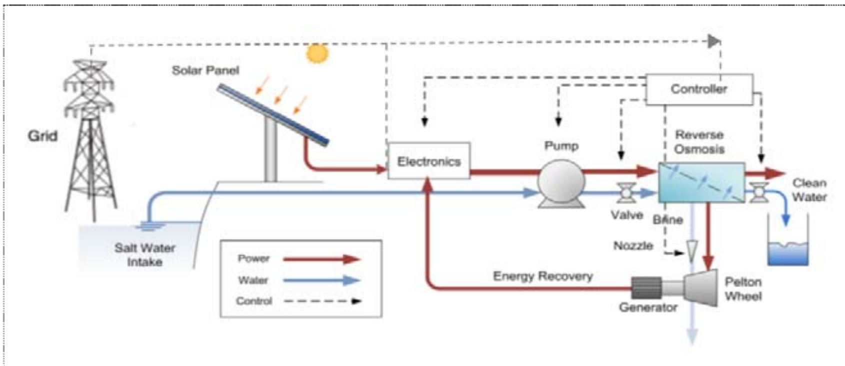


Figure 1.46. Simple sketch photovoltaic powered reverse osmosis [245]

The field testing of many systems has been performed. [225,228,229], [232-244]. The considered systems had a water production capacity of 100L – 10 m^3 per day. For seawater and brackish water, different kinds of systems were used. Of the two, it was brackish water PV-RO systems, which have been made and tested in various regions [232-235,243,244]. Due to reduced pressure requirements, most of these systems do not contain an energy recovery device. Examples are the systems made and tested in Portugal [235] Brazil [234] Southwestern United States [233] and Jordan [243]. Some of the small brackish water PV-RO systems use energy recovery devices like Solar Flow. Such systems were used in the Australian Outback. [232].

Reverse osmosis, as a process, is energy-intensive in nature. Unlike large scale desalination plants, small plants show more energy sensitivity due to the absence of economies of scale [246].

Increasing the efficiency of a PV-RO system through optimisation can have considerable implications, making it a clean and sustainable source for many parts of the world. Figure 1.47 depicts the energy usage pattern at various stages in the seawater RO process. It is evident that in a seawater desalination plant, about 84% of the total energy is consumed by the high-pressure pumps. They are installed for pressurizing the feed water.

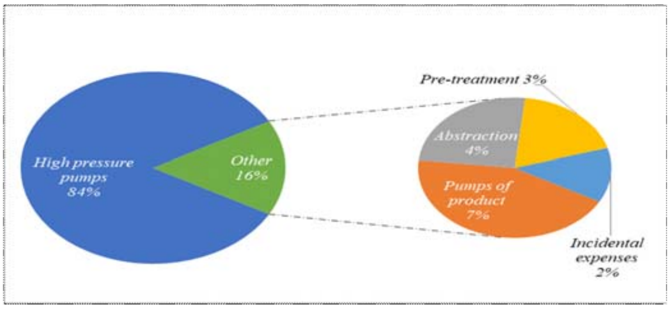


Figure 1.47. Energy consumption pattern in seawater reverse osmosis desalination [247]

Nowadays, there are PV-RO systems, which are functional [227-229], [236-242], [248]. Previously developed systems were majorly a combination of a battery bank and PV array. Considering the inefficiency of the previous systems, researchers focused on increasing system efficiency and were relatively successful. It was the Canary Islands Technological Institute, which developed a battery-based unit [236,237]. Spectra Water makers [242], have also brought in battery-based systems. Researchers have also developed hybrid wind/solar RO units [239-241]. Also, extensive research in this field has enabled the invention of increasingly cost-effective PV-RO units for seawater, without batteries [227-229], [248].

To ensure consistent and efficient water production in bigger RE (Renewable Energy)-powered RO plants, grid connections are used. The Al Khafji plant in Saudi Arabia is a notable example, and the capacity of the plant is 60000 m^3 per day [249]. The relative advantage of such plants over the conventional fossil-fuel powered plants is that they are more economical, considering the availability of RES and high feed-in tariff [250]. It is seen that the RO plants, which are grid connected, are too taxing on national grids, and they affect the stability of the grid. Nearly 12% of electrical power generation in the GCC (Gulf Cooperation Council) is utilised for desalination [251,252].

These plants drastically affect the grid stability and quality of power by causing flicker, harmonics and voltage rise [250,253]. Completely renewable reverse osmosis plants are an ideal option to maintain grid stability. This also enables a high fraction of renewable energy.

1.6.7 Summary

This section presented the most important literature concerning the rise in popularity of solar photovoltaic (PV) cells around the world, as well as the key elements for the coupling of PV energy with Reverse Osmosis (RO) desalination. The main points of this chapter are:

- The relatively low conversion efficiency of PV cells is considered to be the major shortcoming of the technology, although research efforts over the last decade permitted efficiency increase and cost reduction.
- The two main factors that influence the Seawater RO cost are the regulations with regard to brine disposal and the regulations concerning the required water quality. Stricter regulations result in higher SWRO costs.
- Various technologies of coupled PV-RO have been studied for water desalination; the most common ones use batteries and grid connections to ensure system efficiency and cost-effectiveness.

1.7 Objectives

The overarching aim of this thesis is the reduction of the cost of desalination water in arid and semi-arid countries characterised by the scarcity of water resources and abundance of sunlight, which highly depend on seawater desalination technologies, such as Saudi Arabia. The consideration of environmental issues and the solar power potential of such countries leads to the use of solar systems as a basis to achieve this aim. More specifically, the main objectives of this dissertation are:

- Recommendation of the optimal technology type (PT, CRT and LFR) for a standalone Concentrated Solar Power (CSP) assisted MED-TVC desalination system based on efficiency in terms of desalination cost, storage capacity, cost of water and steam production cost.
- Understanding the influence of climatic conditions on the operational performance, reliability and optical and thermal efficiencies of the solar collecting system.
- Development of recommendations for the optimum operating and economic conditions for a hybrid system that combines fossil fuel energy and solar energy in an alternating operation mode.
- Development of an analytical strategy for decision-makers to select the most adequate desalination technology (between MED, MSF, or RO) as a function of site conditions, as well as economic and socio-cultural features
- Development of a system based on photovoltaic cells (PV) with reverse osmosis (RO) for seawater desalination without storage batteries, considering both technical and financial aspects.
- Development of an optimised simulation model for RO, partly powered with PV solar cells.

1.8 Research Methodology

In order to achieve the aforementioned objectives, experimental, analytical and surveying tools are employed, which are explained hereafter:

- Employing techno-economic evaluation tools to identify the optimal technology (PT, CRT and LFR) for CSP assisted MED-TVC in terms of water cost and fuel savings.
- Performing extensive experimental studies on a CSP pilot plant using the improved Fresnel solar collector developed by the Hitachi Company, Japan. The measurements covered a period of one year with the aim to assess the effect of climatic conditions on the operational performance, reliability and optical and thermal efficiencies of the solar collecting system.

- Employing an analytical hierarchy process for deciding on the most efficient desalination technology (MED, MSF, or RO) in a reliable and, most importantly, site-specific manner, including environmental, economic and socio-cultural features.
- Conducting surveys to trace the experts' opinion with regard to the main factors influencing the decision on the desalination technique to be selected.
- Processing real-time data for identifying the effect of climatic conditions on the performance of solar cells integrated into the MED thermal desalination technique. The data were collected during a period of one year in Ras Al-Khair, Saudi Arabia.

The developed methodology is described in further detail in the following chapter.

1.9 Research Contributions

The main personal contributions of the author to the research community through the present thesis were the following:

- Proposing a novel approach for seawater desalination using solar energy to provide a long-term solution to the water scarcity problem.
- Analysing the technical and financial aspects of different desalination methods when combined with solar energy technologies.
- Developing general modelling approaches that can be easily adapted to climate conditions different from the ones in Saudi Arabia.

The author contributions are evidenced by the following four international peer-reviewed papers that are published out of the present doctoral study:

- Paper I – "Techno-economic evaluation of concentrated solar thermal (heat only) assisted satellite med-TVC" by M. A. Saroosh, Osman Hamed, H. Chung, **Khalid Al-Shail** et al., published in the International Desalination Association World Congress on Desalination and Water Reuse, San Diego, CA, USA, 2015.
- Paper II – "Concentrating solar power for seawater thermal desalination" by Osman Hamed, Hiroshi Kosaka, Khalid Bamardouf, **Khalid Al-Shail** and Ahmed Al-Ghamdi. Published in the Desalination, 396, pp.70-78, 2016.

- Paper III – "Use of an analytical hierarchy process for the selection of adequate desalination technologies for Spain and the Gulf Cooperation Council" by **Khalid Al-Shail**, Javier Ordóñez and Mohamed Khayet. Published in the Desalination and Water Treatment, 146, pp. 98-106, 2019.
- Paper IV – "Optimum design of PV-RO system solar-powered seawater desalination without storage in Saudi Arabia (Case study)" by **Khalid Al-Shail**, Javier Ordóñez and Mohamed Khayet. Published in the 9th International Conference on Clean and Green Energy-ICCGE held in Barcelona, Spain, 2020.
- Presentation in the committee of the Sustainable Development Forum (2016), **Khalid Al-Shail,** "Prospects of Utilisation of Renewable Energy Source for Sustainable Development Desalination Processes in K.S.A." at the Civil Engineering School of the University of Granada during 29-30th of September-2016, Spain.

1.10 Outline of the thesis

The thesis is organised into four chapters. Figure 1.48 shows the flow-chart of the thesis.

In Chapter one, the problem statement and the research issues are addressed. Moreover, the state-of-the-art with regard to water desalination techniques, factors affecting water desalination cost, and site conditions is also presented. A solution to the mentioned research problem is proposed on the basis of solar energy. The following sections present the state-of-the-art of desalination techniques when combined with solar energy, both in the form of concentrated solar power and photovoltaic energy. Afterwards, the objectives of the present research are outlined. The research methodology followed in this study is also introduced, together with the guided data collection, analysis and development of theory.

Chapter two presents the materials and methods that are employed throughout the study. This includes first the description of the analytical hierarchy process (AHP) to determine the most suitable desalination technique in the Gulf Cooperation Council (GCC) states and Spain. The following section presents the employed methods for the two case studies that investigate the combination of desalination with thermal energy: concentrated solar thermal assisted satellite MED-TVC and Fresnel solar collection system thermal desalination plant. Finally, the methodology adopted for the case study of the optimum design of PV-RO system solar-powered seawater desalination without storage in Saudi Arabia is described.

Chapter three presents the results and the associated discussion for the case studies mentioned in the previous paragraph.

Finally, Chapter four draws together conclusions and recommendations with some suggested future research directions.

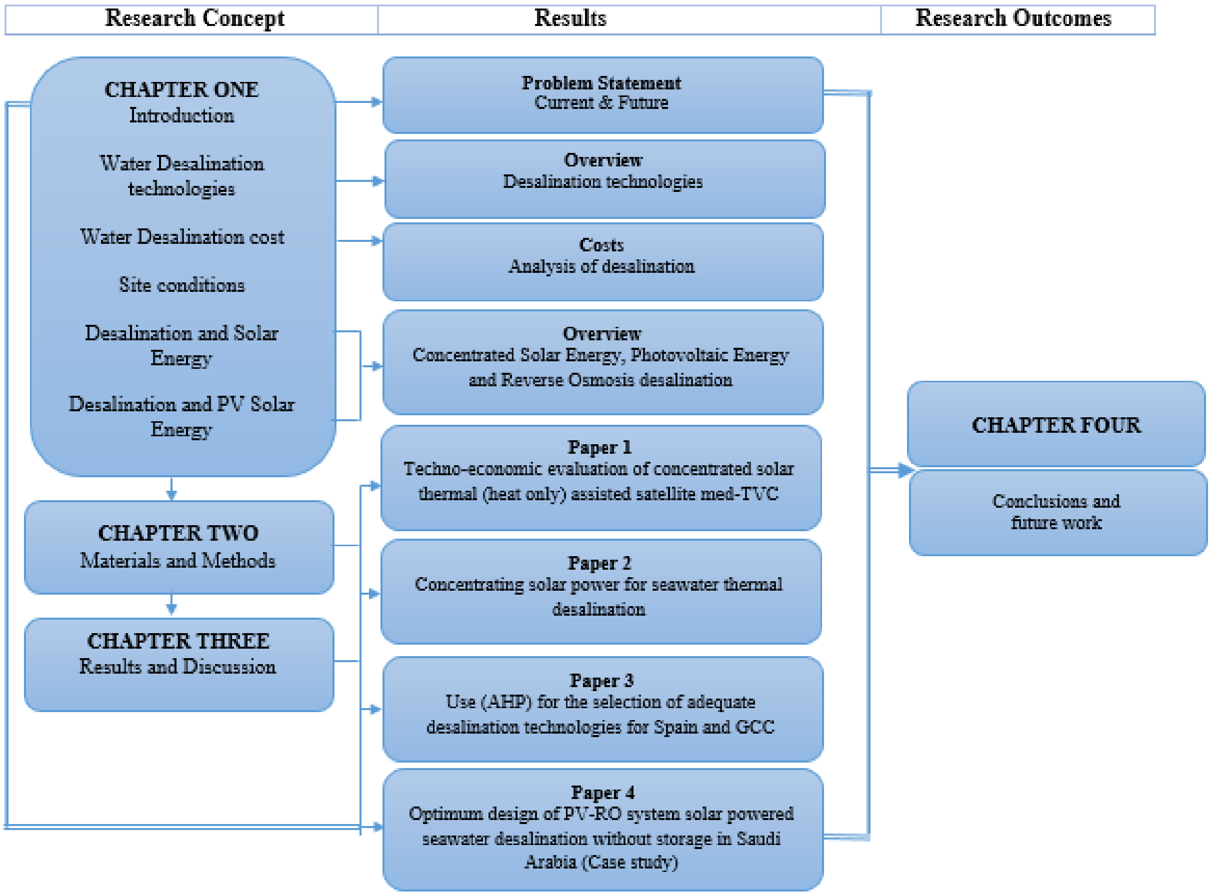


Figure 1.48. Flow chart illustrating the research concept, results and research outcomes

Chapter 2 – Materials and Methods

2.1 Use of AHP for the Selection of Adequate Desalination Technologies for Spain and GCC countries

2.1.1 Introduction

Desalination is being used in various countries with limited freshwater resources, such as Spain and the Gulf Cooperation Council (GCC) countries, including UAE, KSA, Kuwait, Bahrain, Oman, and Qatar. Around 45% of the total World's desalination capacity is owned by these countries [98]. Moreover, UAE, Saudi Arabia, Kuwait and Qatar are among the top ten global desalination users [99]. The GCC countries started seawater desalination in the nineteenth century, whereas in Spain, the units were first built in the 1960s. The two primary technologies used there for desalination are [100]:

- Thermal Distillation (MSF and MED)
- Membrane-based processes (RO and ED)

Both of them have been discussed in Chapter 2. All these techniques have their own pros and cons. Therefore, the country, site location, environmental conditions, and availability of fuel are some of the primary factors that must be taken into account when selecting the appropriate technology. It is reported that the choice of technology must be made with the following perspectives in mind [101]:

- Minimize the energy cost
- Reduce the waste (brine) and
- Control the environmental footprint.

The literature reveals that integrated methods must be adopted to find the optimal solution [102]. The analytical hierarchy process (AHP) is one such sophisticated method capable of making appropriate technology selection as per the defined criteria. Furthermore, it is capable of using quantitative along with qualitative criteria for decision-making. This process has already been applied in the energy sector in Malaysia, Thailand, and Bangladesh [103-105]. The scheme is also applied to select the most economical desalination technique in GCC countries [106].

To apply this scheme in the selection of desalination techniques, MSF, RO, and MED technologies were used for comparison. The shortcomings of the previous research were also considered [106]. These techniques were selected as more than 90% of the whole desalinated water production is attributed to them [107], whereas ED only produces 3% of the total desalinated water. It was concluded that RO is the most appropriate desalination method for Spain. However, another researcher re-analysed this case study and suggested revising some inconsistent matrices along with a few calculations, which may result in different conclusions [108].

2.1.2. The Analytic Hierarchy Process (AHP) method

The alternative hierarchy process (AHP) is an efficient decision-aiding tool [131,132]. Saaty, the inventor of this method, described it as “a general theory of measurement” [133]. It compares and then prioritizes all alternatives to make a final decision [134]. This method is applied in various fields, including desalination [135-140]. Hajeeh and Al-Othman employed it to find the most suitable desalination technology in the GCC countries, while Mohsen and Al-Jayyousi used it in the region of Jordan [141][106][44][9]. Figure 2.1 shows the steps of the analytic hierarchy process [142].

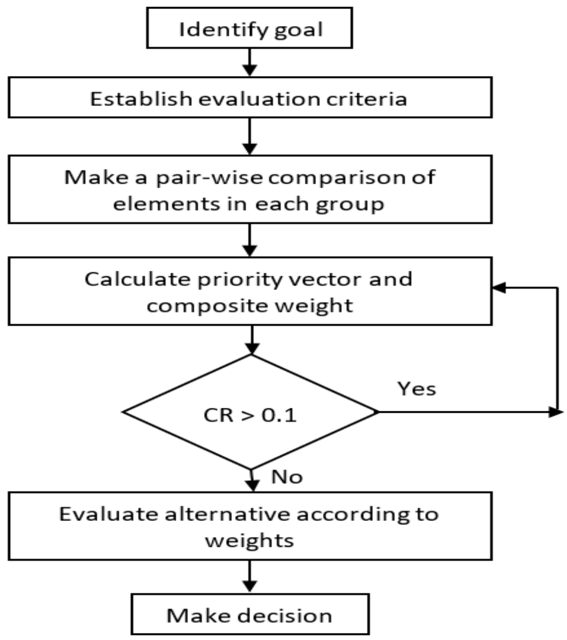


Figure 2.1 The step by step approach of the AHP method

Step 1: The problem is broken into a hierarchy of the following components:

- Goals: the objective to be achieved.
- Criteria: the elements based on which the alternatives are evaluated.
- Alternatives: the possible set of actions, from which a good choice need to be chosen.

The extent to which the goal is achieved by fulfilling the different criteria; each of these components is identified with respect to the problem at hand. Sometimes, an additional 'sub-criteria' component is used below 'criteria,' particularly in complex problems [143], which, however, does not pertain to the present case. Figure 2.2 shows the main elements of the AHP process.

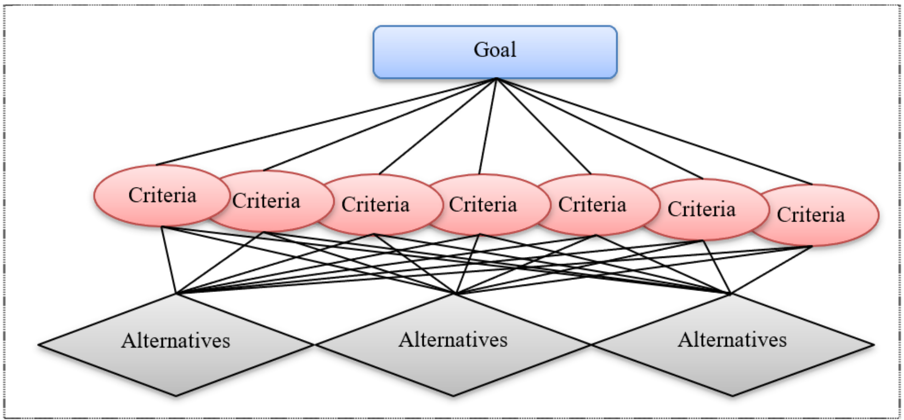


Figure 2.2. The main elements of the AHP process

Step 2: Data is collected from experts or stakeholders from the qualitative pairwise comparison based on the hierarchy described in **Step 1**. Experts are asked to score each criteria into one of the following categories:

- Equal
- Marginally strong
- Strong
- Very strong
- Extremely strong

Step 3: "Pairwise comparison matrices" are created from the various criteria and alternatives. Matrices are developed based on $n(n$-1) judgements, where n stands for the number of elements in each level. For every pairwise comparison, reciprocals are assigned to the conjugate pair.

Thus, if criterion i is judged to be twice as important as criterion k, then criterion k is considered to be half as important as i. More formally, the matrix A is formed based on the following rules [141]:

$$a_{ik} = \begin{cases} 1/a_{ki} & \text{where } a_{ki} \neq 0 \\ 1 & \text{if } i = k \end{cases}, \quad \text{for all } i, k = 1, 2, \ldots., n \qquad (1)$$

The diagonal elements of matrix A are unity, with the connotation that any criterion is exactly as important as itself. In particular, the $n \times n$ pairwise comparison matrix can be described as [141]:

$$A = \begin{pmatrix} 1 & a_{12} & \vdots & a_{1n} \\ 1/a_{12} & 1 & \vdots & a_{2n} \\ \cdots & \cdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{pmatrix} \qquad (2)$$

Step 4: The overall priority or weight of the i^{th} element (w_i) can be found from the normalised principal eigenvector W by solving the following standard linear algebra equation [141]:

$$AW = \lambda_{\max} W \qquad (3)$$

where $\lambda_{\max}$ is the largest eigenvalue of A, and W is normalised in the sense that the sum of all its components is equal to 1. The n components of W give the weights of the n different criteria considered.

Step 5: The pairwise comparisons are said to be consistent if transitivity is preserved across all elements of A [141]:

$$a_{ik} = a_{ij} a_{jk} \qquad \text{for all } i, j, k \qquad (4)$$

However, it is possible to accommodate a certain amount of inconsistency in the ratings. The threshold is given by the constraint that the consistency ratio (CR) should be less than or equal to 0.1 [141]. The consistency ratio is defined as:

$$CR = \frac{CI}{RI} \qquad (5)$$

where the consistency index (CI) is computed as [141]:

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (6)$$

And the random index (RI) is the average value of CI for the random matrices using the Saaty scale [109] given in Table 2.1.

Step 6: The final step of the AHP method consists of aggregating the local preferences $LP_k(a_i)$ of each alternative a_i based on the weights w_k of the k^{th} criteria C_k. This gives the composite weights $CW(a_i)$ of each alternative a_i as [141]:

$$CW(a_i) = \sum_k w_k LP_k(a_i) \qquad (7)$$

where w_k is the k^{th} component of the eigenvector W obtained in equation (3).

Table 2.1. Random consistency indices for the different important levels.

Definition	**Importance scale (*n*)**	**Random index (*RI*)**
Equal importance	1	0.00
Intermediate values	2	0.00
Moderate importance	3	0.58
Intermediate values	4	0.90
Strong importance	5	1.12
Intermediate values	6	1.24
Very strong importance	7	1.32
Intermediate values	8	1.41
Extreme importance	9	1.45

2.1.3. Expert Panel Description

2.1.3.1 Selection of expert panel

Wind and Saaty (1980) noted that the expert panel size is not critical in AHP analysis if the participants of the survey are specialised in the field. Some AHP literature notes that the size of the expert panel does not matter if the representation of the sample is secure. For example, the AHP method is commonly used for group decision-making.

Dyer and Forman [144] point out the benefits of using AHP for group decision-making through decomposition, comparative judgment, and synthesis of priorities. A small expert panel size allows a diverse and invigorating discussion and also limits the overwhelming effects of having too many respondents trying to interact [145]. The overwhelming participation of participants can cause interaction and conflict [146]. However, the knowledge and experience of the participants can be used to formulate multiple judgments. In addition, Duke and Aull-Hyde [147] state that an expert panel person of one is enough to implement the AHP methodology because the AHP is not a statistically based methodology. A purposive sampling strategy can be used in the AHP model [148].

The purposive sampling is common in AHP studies because judgments are elicited from targeted respondents who are familiar with the subject under study [149]. For example, Oncu et al. [150] described their sampling methodology as “purposive” while collecting a make or buy decision study for defense system procurements in Turkey. Ugboma and Song et al. [151,152] have used the purposive sampling strategy without identifying their sample size. This indicates that purposive sampling can be used without any specific sample size.

2.1.3.2 Formation of an expert panel

Expert opinions are required to be quantified in this research because of the challenge of limited data availability in desalination technologies and the integration between qualitative and quantitative in complex decision-making problems. Information and questionnaires were sent to each expert. Most of these experts have long-standing experience of over twenty to forty years. A total of 15 experts were chosen from Spain, including professors, CEOs, senior researchers, and project managers working in different national or international organisations. All of them have made a significant contribution to the field of water purification in various publications and projects. The panel for GCC countries contained 12 experts, including professors and researchers at various levels in different universities or consultants, coordinators, and directors of various organisations or programs at the national and international levels. Many of them have experience in thermal or multiple-effect distillation, reverse electrodialysis, membrane distillation technologies for desalination and global climate change studies. These experts have authored numerous journal articles, seminars or conference presentations to their credit.

The experts were asked to utilise the weights as a generalised guideline. In this study, seven criteria were involved in the analysis. The assumption was that different technologies could be evaluated by questioning the experts of that field. These experts represented both the private and public entities. Two groups were selected by using purposive sampling. This selection was based on the experience and knowledge of each individual. The below-mentioned qualifications had to be met by each expert:

- Role in decision-making for GCC and Spain.
- Representation of government, private stakeholders, or industry in a balanced proportion.
- Experience of more than 20 years in water desalination.
- Expertise in acquiring or implementing proposed desalination techniques at a strategic level in the long run.
- Researchers and academic staff from research centers, universities, or companies in GCC countries and Spain.

2.1.3.3 Data Collection and Procedures

All selected experts were contacted, and sufficient information was provided to them via email and/or telephone prior to the case study (A list of participants is provided in **Appendix-II**). A questionnaire (**see Appendix -III**) was developed for opinion collection that was subsequently used in AHP decision-making. Filling the questionnaire required approximately 20 to 30 minutes. The participants were asked to return the questionnaire either by fax or email. Personal data collected using the questionnaire included name, organisation/company, and the number of years of professional experience in order to confirm that participants had in-depth knowledge in the relevant area. To comply with the EU General Data Protection Regulation (GDPR), the names of the experts contacted to fill the form have been kept as anonymous.

2.1.3.4 Criteria description

In Chapter 1 of this dissertation, many factors affecting the desalination cost, are discussed in detail. Moreover, Zhou and Tol [153] also reviewed the primary criteria on which the desalination cost depends. For the sake of choosing the most influencing parameters, the recommendations by Hajeeh and Al-Othman were followed, and below-mentioned parameters were selected [106]:

- Purified water quality (C1): Each technique has its own constrain of water purity that can be achieved. Hence, it is a primary factor used for determining the appropriate choice.
- Water recovery (C2): This is another important factor that influences the choice of technology. Recovery is defined as the ratio of water purified to the water fed.
- Rate of energy consumption (C3): This factor has a substantial effect on the desalination technique selection.
- Efficiency of equipment and type of energy utilisation (C4): The efficiency of each piece of equipment contributes to the overall efficiency and subsequently affects the cost of the whole unit.
- Available technology (C5): In order to have a commercially successful plant, the role of this factor is significant. The availability of expertise in selected technologies is vital to run the plant at a lower cost.
- Plant capacity (C6): Plant capacity directly determines the per unit production cost. The higher the capacity, the lower the associated cost will be.
- Total cost (C7): Total purification cost, including land price, fixed capital, and maintenance cost is also an influential factor.

All these factors play a vital role in determining the cost of water purification. The three selected techniques are compared on the basis of these above-mentioned parameters.

2.1.3.5 Expert evaluation of criteria

For comparison, three well-established desalination techniques of Spain and the GCC countries were selected, as mentioned below:

- Multi-Stage Flash (a_1)
- Multi-Effect Distillation (a_2); and

- Reverse Osmosis RO (a_3)

Figure 2.3 shows the three elements of the AHP process chosen here.

The experts replied to the questionnaire based on the gradation scale for the quantitative comparisons of alternatives, also graded as random index (*RI*) and shown in Table 2.1. Based on the opinion received from experts about the relative importance of the different criteria, two pairwise comparison matrices were constructed for Spain and the GCC countries. The matrices are presented in Tables 2.2 and 2.3.

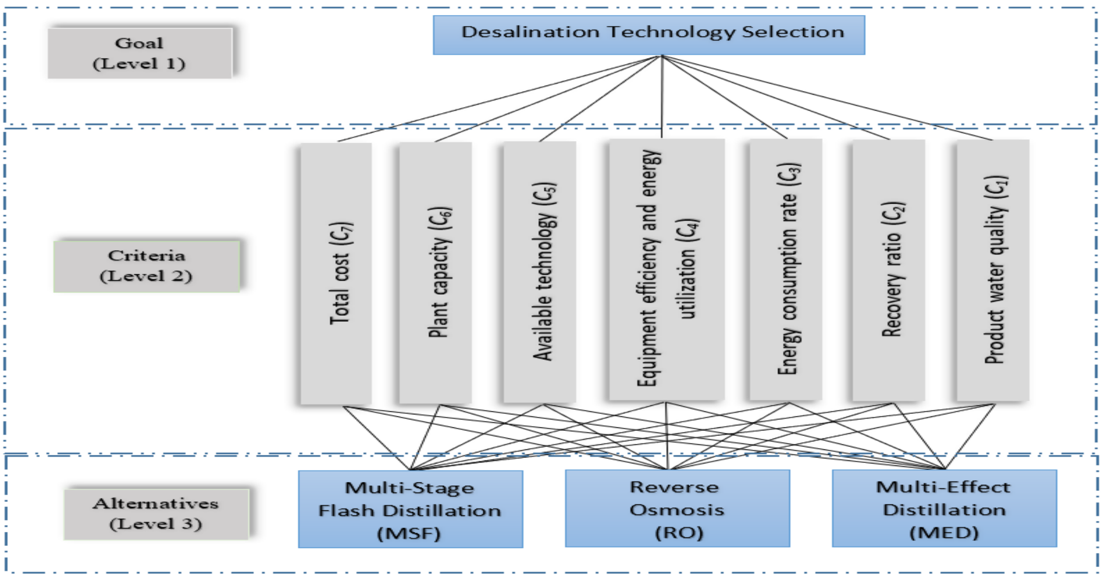


Figure 2.3. Hierarchical representation with three alternatives and seven criteria.

These entries, in turn, represent the preferences of the different criteria in relation to each other. For example, in the case of Spain, the product water quality (criterion C1) was assessed vis-à-vis other criteria by experts, and their relative fractional importance values are presented in Table 2.2. Compared with water recovery (C2), product water quality (C1) was five times less preferred. In contrast, compared with the range of energy consumption (C3), C1 was six times less preferred. Similarly, the data in Table 2.3 for the GCC countries indicates that product water quality (C1) was two times more preferred than water recovery (C2) and equally preferred as the range of energy consumption (C3).

Table 2.2. Fractional importance of the compared criteria for Spain.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6	C_7	w_k×100
C_1	1	1/5	1/6	1/3	1/2	1	1/9	3.2%
C_2	5	1	1	4	7	6	1/4	18.7%
C_3	6	1	1	5	6	5	1/4	19.0%
C_4	3	1/4	1/5	1	5	6	1/6	10.3%
C_5	2	1/7	1/6	1/5	1	1/2	1/9	3.4%
C_6	1	1/6	1/5	1/6	2	1	1/6	4.0%
C_7	9	4	4	6	9	6	1	41.4%

Table 2.3. Fractional importance of the compared criteria for the GCC countries.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6	C_7	w_k×100
C_1	1	2	1	1/2	1/3	3	1/3	9.5%
C_2	½	1	1/7	1/2	1/3	1	1/9	4.0%
C_3	1	7	1	1/3	2	5	1/4	15.0%
C_4	2	2	3	1	2	2	1/5	15.0%
C_5	3	3	1/2	1/2	1	2	1/6	11.0%
C_6	1/3	1	1/5	1/2	1/2	1	1/5	5.0%
C_7	3	9	4	5	6	5	1	40.6%

Briefly, the ratings of the intersection of each row with each column provide the degree of preference in comparison with each other. If the number in the rating is larger than 1, the criterion in that row is preferred over the criterion in the column by the given specific amount. Alternatively, if the number is less than 1, the criterion in the column is preferred over the criterion in the row by its reciprocal value. According to Ali and Danesh [154], the best way to evaluate the intensity of preference between the two elements is by using a nine-point scale, as shown in Table 2.1. Then, the suitable RI value may be selected from Table 4.4, which translates the grades to the scale of 0 to 1, which makes further calculations easier. The RI values listed in Table 2.1 are used for both consistent and non-consistent matrices. When CR is less than 0.1, the consistency of the ratings is considered to be adequate [141]. Otherwise, the pairwise comparison matrix is considered invalid (Figure 2.1), which may be successively modified to fulfill the said criteria. The estimation of alternative local priorities can be carried out by utilising a similar process for every criterion.

2.2 Desalination and Thermal Solar Energy

2.2.1. Case studies

2.2.1.1 Concentrated solar thermal assisted satellite MED-TVC: methodology

Introduction

According to the United Nations World Water Development report in 2014, 25% of Saudi Arabia's domestic fossil fuel production is used in water desalinating plants. Studies show that by 2030, this percentage may rise to as high as 50% [193]. Due to the need to save fossil fuel resources in KSA and the increased demands of fresh water, it is concluded that it is time to shift to alternative energy resources for supplying water desalination plants with thermal energy for better economic solutions.

Design and Research Conducted (Modelling approach)

Two locations within Saudi Arabia, Yanbu on the Red Sea coast and Jubail on the Arabian Gulf coast, as shown in Figure 2.4 with different annual Direct Normal Irradiation (DNI). Jubail, 1938 kWh/m^2 and Yanbu 2237 kWh/m^2, as shown in Figure 2.5, were used as case study areas for the techno-economic evaluation of the CSP assisted (MED-TVC) plant according to satellite-derived data.

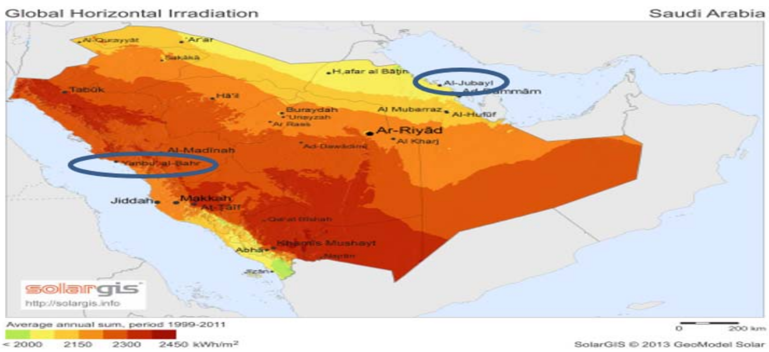


Figure 2.4. KSA DNI map showing locations and DNI values at Yanbu and Jubail

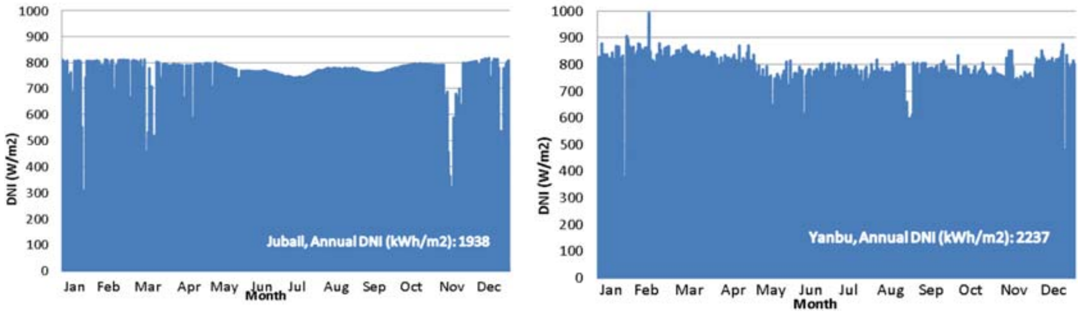


Figure 2.5. Direct Normal Irradiation (DNI) at Yanbu and Jubail.

Modelling of the solar field was performed using the System Advisor Model (SAM), developed by the National Renewable Energy Laboratory (NREL), followed by careful matching with the thermal power requirement for the MED-TVC to estimate the solar field area. The following three solar thermal power technologies were investigated within SAM: (a) Parabolic Trough (PT), (b) Central Receiver Tower (CRT) and (C) Linear Fresnel Reflector (LFR), as shown in Figure 2.6, for supplying the MED-TVC plant with the steam needed.

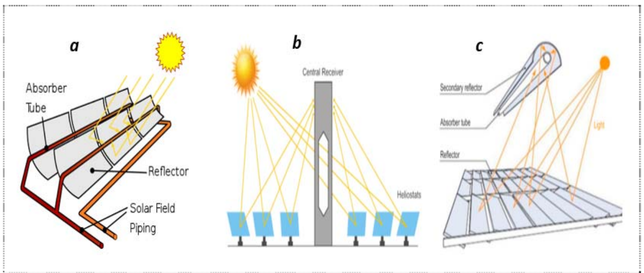


Figure 2.6. Parabolic Through (a), Central Receiver Tower (b), and linear Fresnel reflector (c)

The SAM output in terms of solar field area and annual solar field thermal energy was then used as input into a Microsoft Excel program developed by the authors to estimate the levelised cost of water (LCOW). For the calculation parameters, such as the required capacity (m^3/d), the performance ratio (PR), temperatures and pressures of inlet steam and exit water it has is assumed in **Appendix-VI**. For the calculations within Microsoft Excel, the specific costs of various components associated with the solar field are directly integrated. Costs related to capital expenditure (CAPEX), operational and maintenance expenditure (OPEX) are calculated. This plant is assisted with thermal storage (TES) and fossil fuel backup options (FF) with 88% boiler efficiency in order to supply the plant with heat during solar thermal energy cutouts so that this plant produces water continuously.

The following seven scenarios were examined for each site location:

1) 8 hr/24 hr on LFR with 0 hr/24 hr on thermal energy storage (TES), and16 hr/24 hr on fossil fuel boiler steam.
2) 8 hr/24 hr on PT with 0 hr/24 hr on TES, and 16 hr/24 hr on fossil fuel boiler steam.
3) 8 hr/24 hr on PT with 8hr/24 hr on TES, and 8 hr/24 hr on fossil fuel boiler steam.
4) 8 hr/24 hr on PT with 14 hr/24 hr on TES, and 0 hr/24 hr on fossil fuel boiler steam.
5) 8 hr/24 hr on CRT with 0 hr/24 hr on TES, and 16 hr/24 hr on fossil fuel boiler steam.
6) 8 hr/24 hr on CRT with 8 hr/24 hr on TES, and 8 hr/24 hr on fossil fuel boiler steam.
7) 8 hr/24 hr on CRT with 14 hr/24 hr on TES, and 0 hr/24 hr on fossil fuel boiler steam.

2.2.1.2 Fresnel Solar collecting system thermal desalination plant

Objective

The main objective of this case study consisted in evaluating the effect of climatic conditions on the performance of Fresnel Solar collecting systems. To achieve this objective, an extensive series of pilot plant measurements were conducted for one year in Saudi Arabia in cooperation with the Hitachi Zosen Corporation (Hitz) of Japan by integrating an improved Fresnel CSP collector with the thermal desalination plant.

Methodology and test setup

The following Figure 2.7 presents the components of the setup used for the CSP demonstration plant, namely the solar concentrating system (in this case, the solar Fresnel reflector), the receiver tube, the steam generator, the condenser, and the high and low-temperature heat transferred fluid oil accumulator tanks. The solar reflector consisted of 6 parallel rows. Each row consists of 92 curved mirrors located in the North-South direction, with the total covered area being equal to 662.4 m^2. A linear absorber pipe formed from 24 SCHOTT PTR®70 receivers is located at the focus of the mirrors to receive direct solar radiation up to 400 °C. When solar radiation acts on the Fresnel collectors, it gets transferred to the oil-based heat transfer fluid (HTF) and flows into the receiver tube. The heated HTF is accumulated in the high-temperature tank and is then sent to the steam generator as a heat source. Low-temperature HTF discharged from the steam generator returns to the low-temperature tank and is sent to the receiver tube again by thermal HTF circulation pumps.

The generated steam then passes either to a condenser, thus simulating an MSF brine heater, or directly to an existing MSF pilot plant to provide part of the required steam.

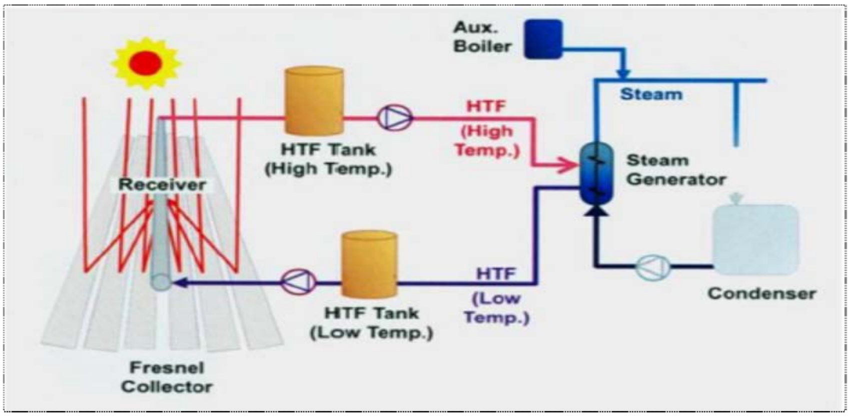


Figure 2.7. Components of the experimental setup for the Concentrated Solar Power (CSP) system [195]

With regard to the performed measurements, the temperature of the oil that passes through the receiver, the volumetric flow rate, as well as the key features of the produced steam (quantity, pressure, and temperature), were measured. Direct Normal Irradiance (DNI) is measured using a pyrheliometer, which follows the sun's movement. With regard to temperature measurement, platinum thin film RTD class B sensors with a tolerance of ±0.3 °C were used. The oil flow rate was measured using a flow meter with a measured error of ±0.05%, while steam flow rate and pressure were measured by a flow meter with dual sensors, allowing to keep track of pressure and pressure differential. All data are measured every 10 secs and are then used as input to calculate the thermal energy that is absorbed and lost by the receiver and the amount of solar incidence received by the collector. The daily parameters are averaged on the basis of each set of measurements.

2.3 Desalination and PV Solar Energy

2.3.1. Introduction

Water shortage has emerged as a crucial problem in many parts of the globe. Two major key players are there to intensify this problem: the first is the climatic change in the world, and the second is excessive use of fresh water. It is estimated that the global temperature will rise from 1.4 to 5.8 Celsius until 2100 [254]. The water cycle is closely associated to these variations and, consequently, the quality of water is being affected significantly. The Middle East region, in general, and the Gulf Cooperation Council (GCC) countries (including Saudi Arabia) in specific, are badly exposed to an intense shortage of water, mainly by significant growth in population, fast expansion in industry, and ever-increasing droughts [255]. Saudi Arabia, ranked 13^{th} in the world, is enjoying the status of the biggest state in the Arabian Peninsula. The mean naturally occurring water resources per person is 6000 m^3 across the globe, while the estimated figure for Saudi Arabia is 84.8 m^3 per person [254]. On the other hand, the total intake of water per person is 250 L in Saudi Arabia, which is the third-highest in the world, and it is estimated to rise by 30% by 2035 [256]. It is predicted that if the country continues to withdraw the freshwater resources at its present degree, aquifer reserves can satisfy current needs for only three more decades at best [256]. Under the prevailing situation, water desalination is the best strategic choice for resolving the water shortage issues.

2.3.2. Optimum Design of PV-RO System Solar Powered Seawater Desalination without storage (Case study in Saudi Arabia)

Vision 2030 is a program declared by Saudi Arabia in April 2016. The motive behind this vision is to switch over Saudi Arabian financial resources from exports of oil and related goods, which are to be diminished in future to any other sustainable alternatives. To start with, a plan was launched for the production of renewable energy resources figured at 9.5 GW by 2030. On one side, this plan is forecasted to boost the country's economy, along with the reduction of fossil fuel consumption, plus having a good impact on the ecological system [266,267]. The earth's surface receives great amounts of solar energy and has no match among other sources of energy available. Whether solar energy is harnessed by concentrating solar power (CSP) or using photovoltaic (PV) panels, there is plenty of potential for solar energy in Saudi Arabia.

Figure 2.8 represents the Direct Normal Irradiation (DNI) and global horizontal irradiation (GHI) in Saudi Arabia [268], while Figure 2.9 shows those two indicators, in addition to a third indicator, which is the diffuse horizontal irradiation (DHI) [269].

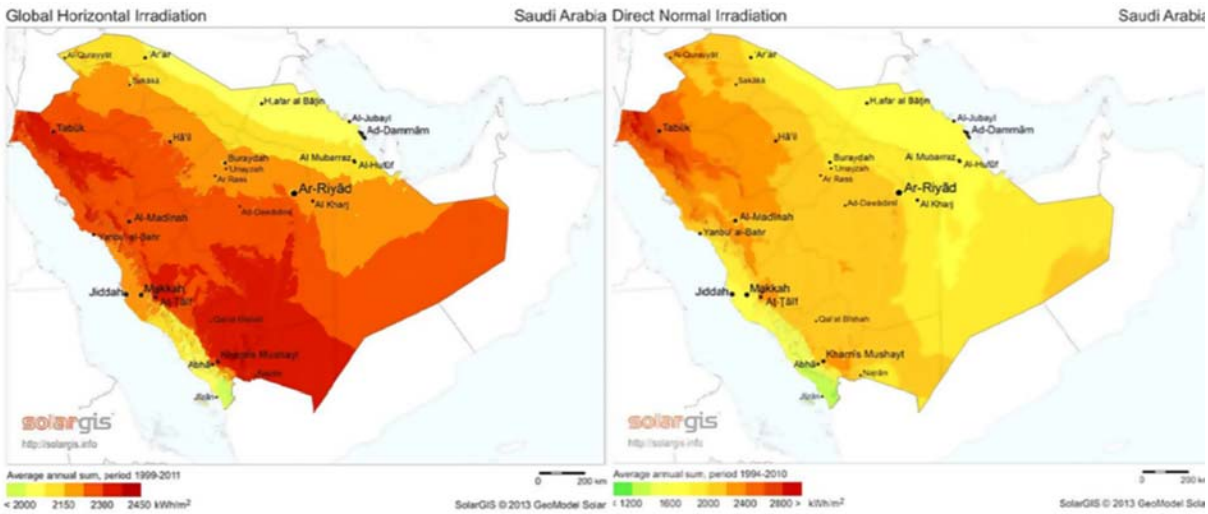


Figure 2.8. Global Direct Normal Irradiation and horizontal irradiation GHI in KSA from 1999 to 2011

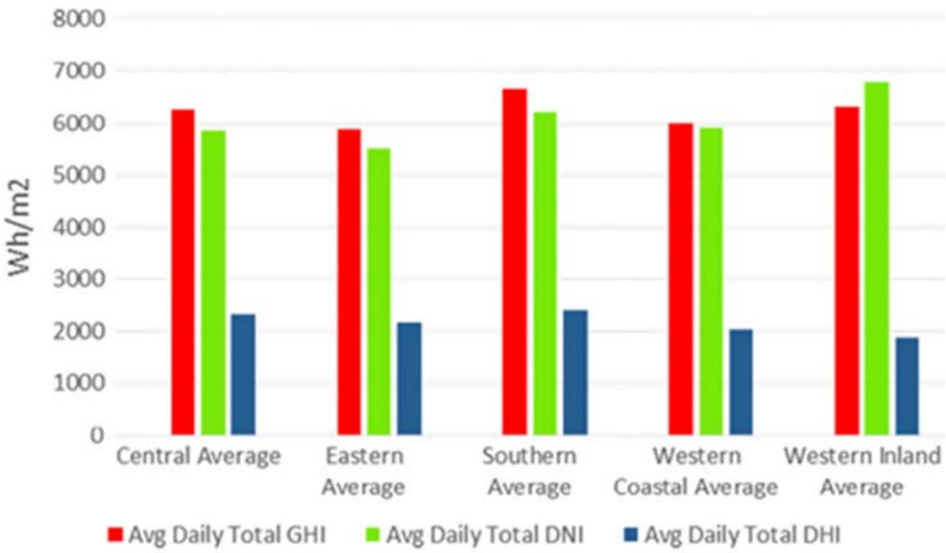


Figure 2.9. A review from Oct 13 to Sep 2014 for solar irradiance by region in Saudi Arabia

The main objective of this study is to explore the feasibility of integrating reverse osmosis desalination with PV panels without using batteries for the purification of water in Saudi Arabia.

For the identification of potential, an economic study was carried out with the objective of finding the per unit (kWh) cost for solar energy. In addition, the optimum energy ratio, which could be extracted through a PV plant in a day span, is also investigated. For the purpose of this case study, the reverse osmosis plant was selected to be in Saudi Arabia on the coast of the Arabian Gulf. The figures showing energy utilisation are based on actual one-year data from the selected reverse osmosis plant. Solar radiation data from Saudi Arabia's renewable resources monitoring and mapping program was acquired, and it was used to calculate the energy generated by the PV panels and the cost per kWh, as well as the percentage of electrical energy consumption that can be generated by PV [270]. At the end, for the purpose of the analysis of the feasibility of integration between reverse osmosis desalination and solar energy, the energy requirement for a purification plant, which could be provided by PV panels, was investigated.

2.3.3. Methodology

To achieve the stated objective, the study was carried out in accordance with the guidelines provided in Modi and Stodola, 2009 [271]. To conduct the research, data of hourly energy consumption in an existing desalination plant situated in Ras Al Khair, Saudi Arabia, were acquired. The location of the plant is 27° 32' 12.12" North and 49° 8' 20.4" East, and it is located 90 kilometers north of the city of Al Jubail.

The energy consumption data of this plant were examined thoroughly as a case study in order to forecast the amount of solar radiation needed based on the PV system efficiency [272,273]. As mentioned earlier, direct and solar radiation data were obtained from Saudi Arabia's renewable resources monitoring and mapping program. To assess the feasibility of using PV panels to operate a reverse osmosis desalination plant, a solar PV plant was designed. To bridge the gap between the energy consumed by the reverse osmosis plant and the energy generated by the PV plant, we used the same plants that utilise fossil fuel as an energy source. To attain the electrical energy produced by the PV plant, we calculated the amount of solar plant generated energy on an hourly basis. Direct fraction of solar radiation (H_b) which approaches the surface of earth without scattering or absorption by the atmosphere, is called direct beam solar radiation, while the scattered radiation, which is assumed to hit the surface of earth from all directions, is termed as diffused radiation (H_d). The amount of H_d varies, depending upon the forecast conditions. Diffuse radiation varies from 10% of entire radiation on a clear day to approximately 100% on a cloudy day. Reflected radiation

(Hr) from the surroundings and the earth's surface also need to be taken into consideration [271]. Total global radiation (H) comprising diffuse, direct, and reflected radiation, is given by:

$$H = Hr + H_d + H_b \quad (1)$$

The total amount of energy hitting the panel was determined by the incidence angle of sunlight, for every point in time for each arrangement. [273].

$$I_{panel} = I_{beam} \cdot \cos\theta + I_{ddiffuse} \cdot F_{ps} \quad (2)$$

where,

- I_{panel} = Total radiation on the panel
- I_{beam} = Direct radiation on the panel
- θ is equal to 90 degrees when the sun's ray is parallel to the panel, and 0 degree when perpendicular to the panel.
- $I_{ddiffuse}$ = Diffuse radiation on the panel
- The terms F_{ps} and F_{pg} are considered as view parameters: These are the geometric terms used for the description of part of the ground or sky that is directly exposed to the panel.

Solar radiation at Ras Al-Khair that affects the panels of the photovoltaic solar plant can be used to determine the amount of solar plant generation in terms of energy. A wide range of powers of the dissipated photovoltaic solar plants is defined that allow obtaining a curve that describes plant power and the price of produced electrical energy. Likewise, different values of the performance ratio of the plant have been assumed. The performance ratio (PR) allows evaluating the quality of a photovoltaic installation calculated as the relationship between the real energy generated by the plant and the theoretical energy that can be generated. This ratio is independent of the orientation of a photovoltaic installation and the solar irradiation that affects it and allows to compare the operation of different facilities. The photovoltaic solar plant for each one of the peak powers was defined and examined, and the cost of the kWh generated by each one of the plants was calculated. For the calculation of the price of electrical energy, calculating the reimbursement for borrowed money on the basis of fixed payments and a fixed interest ratio were assumed, considering that the start of the period is the point when imbursement becomes due.

$$Q = \frac{Pv}{1+(1-(1/(1+r)^{n})} \quad (3)$$

where,

- Q per annum payment of borrowed money on the basis of fixed payments and fixed interest ratio.
- Pv Current evaluation. That is the total price of PV solar power plants.
- r loan interest rate
- n twenty-five years

To obtain cost per kWh of electricity from the PV solar plant, it is necessary to divide Q (per annum payment of borrowed money on the basis of fixed payments and fixed interest ratio) by the usable energy.

$$P = \frac{Q}{\text{Usable energy (kWh)}} \quad (4)$$

where, P = price of kWh.

Chapter 3 – Results and Discussion

3.1 Use of AHP for the Selection of Adequate Desalination Technologies for Spain and GCC countries: results and discussion

This research considered three main desalination technologies, namely, RO, MED and MSF, which were investigated based on the experts' opinions. These technologies were deployed to structure the required decision hierarchy.

The pairwise comparisons were evaluated with the hierarchy elements, as depicted in Figure 2.3, from the upper to the lower levels. This evaluation was followed by a calculation of both the ratings and weights of the criteria for each type of technology, as described in the subsection 2.1.2, with the steps shown in Tables 2.2, 2.3 and 3.1.

Table 3.1. Pairwise comparison of the different technologies with respect to the various criteria for Spain and the GCC countries.

	Spain				GCC countries			
	MSF	MED	RO	$w_k \times 100$	MSF	MED	RO	$w_k \times 100$
	Product water Quality (C_1)							
MSF (a_1)	1	1	7	46.7%	1	9	9	82.0%
MED (a_2)	1	1	7	46.7%	1/9	1	1	9.0%
RO (a_3)	1/7	1/7	1	6.6%	1/9	1	1	9.0%
	Recovery Ratio as a function of the feed (C_2)							
MSF (a_1)	1	1/2	1/9	7.4%	1	9	1/7	26.5%
MED (a_2)	2	1	1/9	11.7%	1/9	1	1/6	6.8%
RO (a_3)	9	9	1	80.8%	7	6	1	66.7%
	Energy Consumption rate per unit water product (C_3)							
MSF (a_1)	1	1/2	1/9	7.4%	1	1/9	1/9	5.2%

MED (a_2)	2	1	1/9	11.7%	9	1	1/7	23.7%
RO (a_3)	9	9	1	80.8%	9	7	1	71.0%
	Equipment efficiency and type of Energy utilisation (C_4)							
MSF (a_1)	1	1	1/9	9.1%	1	9	1	47.4%
MED (a_2)	1	1	1/9	9.1%	1/9	1	1/9	5.2%
RO (a_3)	9	9	1	81.8%	1	9	1	47.4%
	Available Technology (C_5)							
MSF (a_1)	1	9	1	47.3%	1	7	1	45.0%
MED (a_2)	1/9	1	1/9	5.3%	1/7	1	1/9	6.0%
RO (a_3)	1	9	1	47.4%	1	9	1	49.0%
	Plant Capacity (C_6)							
MSF (a_1)	1	9	1	47.3%	1	9	1	47.3%
MED (a_2)	1/9	1	1/9	5.3%	1/9	1	1/9	5.3%
RO (a_3)	1	9	1	47.4%	1	9	1	47.4%
	Total Cost (C_7)							
MSF (a_1)	1	1/9	1/7	6.0%	1	9	2	58.0%
MED (a_2)	9	1	1	49.0%	1/9	1	1/9	5.0%
RO (a_3)	7	1	1	45.0%	1/2	9	1	37.0%

The final results of the distributed questionnaires are summarised in Table 3.2.

Table 3.2. Composite weights (*CW*) of the different desalination technologies in Spain and the GCC countries.

Criterion	Spain				GCC countries			
	w_k	MSF	MED	RO	w_k	MSF	MED	RO
C_1	0.032	0.467	0.467	0.067	0.095	0.818	0.091	0.091
C_2	0.187	0.074	0.118	0.808	0.041	0.265	0.068	0.667
C_3	0.190	0.074	0.118	0.808	0.150	0.052	0.237	0.711
C_4	0.103	0.091	0.091	0.818	0.150	0.474	0.053	0.474
C_5	0.034	0.474	0.053	0.474	0.11	0.451	0.059	0.49
C_6	0.041	0.474	0.053	0.474	0.048	0.474	0.053	0.474
C_7	0.414	0.059	0.49	0.451	0.406	0.579	0.052	0.368
$CW\times100$	–	11.0%	32%	57%	–	47%	21%	32%

The most dominant criterion in the selection of desalination technology is the total cost (C_7). The percentage weights (*k*) of this criterion are found to be 41.4% for Spain, and 40.6% for the GCC countries (Figure 3.1). This is rather logical because such technologies generally involve very high costs. The second most dominant criterion is the rate of energy consumption per unit of water product (C_3), with percentage weights of 19% for Spain and 15% for the GCC countries.

The next most dominant criterion is the equipment efficiency and energy utilisation (C_4), with percentage weights of 10.3% for Spain and 15% for the GCC countries. This criterion is then followed by the water recovery (C_2), with percentage weights of 18.7% for Spain and 4% for the GCC countries.

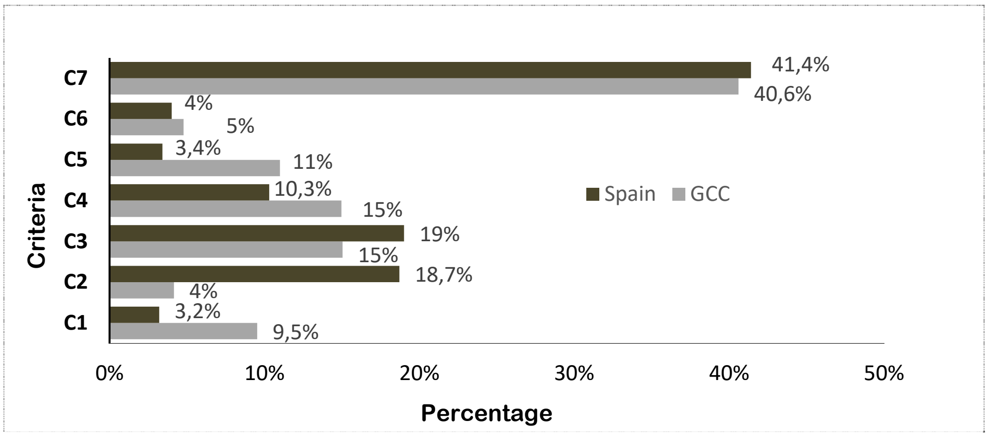


Figure 3.1. Pairwise comparisons of different criteria and their percentage weights (w_k) in the GCC countries and Spain.

The fifth most important criterion is the available technology (C_5), representing percentage weight values of 3.4% for Spain and 11% for the GCC countries. The product water quality (C_1) is the next greatest criterion, with percentage weights of 3.2% for Spain and 9.5% for the GCC countries. The last criterion is the plant capacity (C_6), which has percentage weights of 5% and 4% for the GCC countries and Spain, respectively. Table 3.1 lists the constructed matrices related to the pairwise comparisons of various technologies using the abovementioned criteria and their different assigned weights. Moreover, Table 3.3 summarizes the rankings of multiple technologies for each criterion with the specified composite weights. Based on the gathered data, criteria and different alternatives, the composite weights of various desalination technologies in both the GCC countries and Spain were calculated. The results of the processed data are presented in Tables 3.2 and 3.3 in the form of height and ranks.

Table 3.3. Ranking of the different desalination technologies according to the various criteria in Spain and the GCC countries.

Criterion	Spain			GCC countries		
	MSF	MED	RO	MSF	MED	RO
C_1	1	1	2	1	2	2
C_2	3	2	1	2	1	3
C_3	3	2	1	3	2	1
C_4	2	2	1	1	2	1
C_5	1	2	1	2	1	3
C_6	1	2	1	1	2	1
C_7	3	1	2	1	3	2

Figure 3.2 shows that the most suitable technology for Spain is RO (57%), followed by MED (32%) and MSF (11%). In contrast, for the GCC countries, the most preferred technology is MSF (47%), followed by RO (32%) and MED (21%). In Spain, the main advantages of the RO technology are the satisfactory fulfilment of the requirements for high quality of the produced water, intermediate capital cost and operational flexibility [138]. RO has a meaningful impact on reducing the high water demands of domestic and industrial users. On the other hand, the MSF technology has certain advantages for the GCC countries. These advantages include the simplicity of MSF facilities, the high technological reliability and excellent water capacity of single MSF units [53].

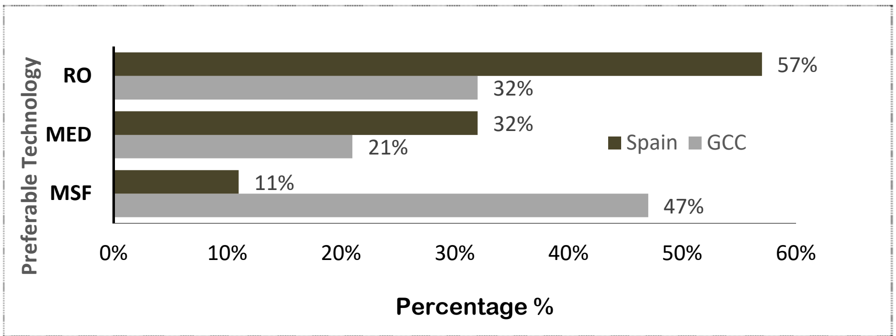


Figure 3.2. Ranking of different desalination technologies based on the composite weights of the criteria for the GCC countries and Spain.

However, MSF requires larger energy consumption than MED and RO technologies, which is readily available at a reasonable cost in the Gulf countries.

In addition, an MSF plant can comfortably work with higher salinity levels of input water, which is another possible reason for the experts' opinion being tilted toward choosing this technology for the GCC countries. With this finding, which summarily differs from the findings of Hajeeh and Al-Othman [106], it is expected that MSF will be viewed as a prospective alternative to RO in the Gulf countries and elsewhere where fuel is cheap.

3.2 Desalination and Solar Thermal Energy: results

3.2.1. Concentrated solar thermal assisted satellite MED-TVC

The normalised LCOW for water production using fossil fuel, along with PT, LFR or CRT and allocating a different amount of hours for TES per day, is shown for Yanbu and Jubail in Figure 3.3a and Figure 3.3b, respectively, as a function of the fossil fuel price (in USD/bbl). The breakeven fossil fuel price for the different CSP technologies and both site locations was calculated through normalisation with respect to the LCOW obtained when only fossil fuel at 100 USD/bbl is used for MED-TVC desalination.

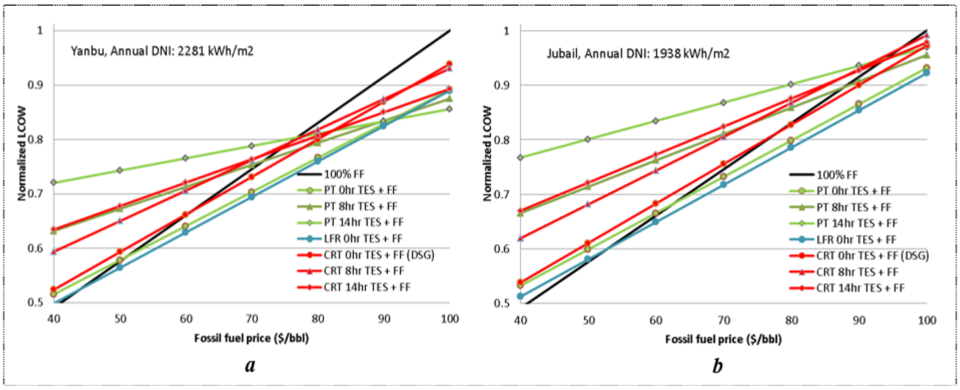


Figure 3.3. Normalised LCOW variation as a function of Fossil Fuel (FF) price for (a) Yanbu, Red Sea coast and (b) Jubail, Arabian Gulf coast [194].

According to the studies conducted, a huge amount of bbl is needed when producing fresh water using FF only, for example, 80481 bbls are needed to produce one million Imperial Gallons of fresh water per day (MIGD).

The breakeven normalised (LCOW) between fossil fuel and various CSP technologies with different storage cases is given for Yanbu and Jubail in **Appendix-VII**. Figure 3.4 shows an example of a CSP (heat only) model-assisted satellite (MED-TVC) plant, the CSP technology used in this example is the PT Technology. PT supplies the MED-TVC with the heat required through heat exchanging for the liquid used.

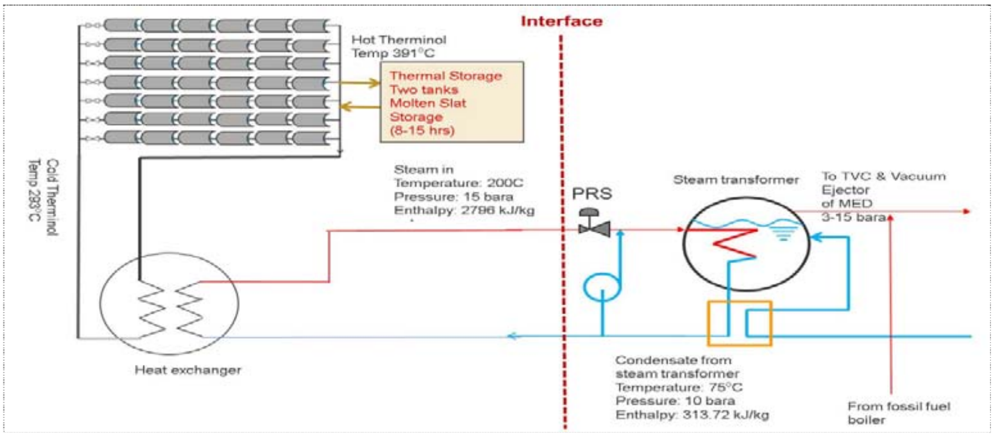


Figure 3.4. PT based CSP and MED standalone configuration with TES

In conclusion, using CSP (heat only) with different power technologies (PT, LFR and CRT) in small water distillation plants in cooperation with an FF backup is an optimal economic solution. If the main criterion is the amount of fossil fuel saved in (bbl/yr), the PT technology is shown to be the most competitive, especially when the allocated time for Thermal Energy Storage is higher. On the other hand, if one considers the payback period as the main criterion, the LFR is shown to be the most competitive option and will be paid back within five years of investment with a 20% rate of return. These remarks are valid for both Yanbu and Jubail.

3.2.2. Fresnel Solar collecting system thermal desalination plant

The performed solar measurements showed that the collector efficiency mainly depends on climate condition parameters like Direct Normal Irradiance (DNI), ambient temperature, receiver temperature, as well as heat losses. It was found that the best performance of the Fresnel solar system happens when the outlet temperature of the oil leaving the receiver is at a relatively low value, the lowest temperature studied is 225 ºC. At that temperature value (225 ºC), the overall system efficiency ranges from 30% to 63%, the collector thermal efficiency ranges from 60% to 80%, and the optical efficiency ranges from 60% to 80%.

As an indication of the Fresnel collecting system's performance, the equivalent (or levelised) cost of water (LCOW) is calculated for a desalination plant run by fossil fuel in \$/bbl. The measurements show that when the annual DNI level increases from 1132 kWh/m^2 to 1937 kWh/m^2, the LCOW reduces from \$92/bbl to \$52/bbl, which means that the LCOW is approximately inversely proportional to the annual DNI of the site where the plant is located, as shown in Figure 3.5. The measurements have also shown that a combination of a Fresnel Solar collecting system with a MED thermal desalination plant becomes more effective if no thermal energy storage (TES) is applied.

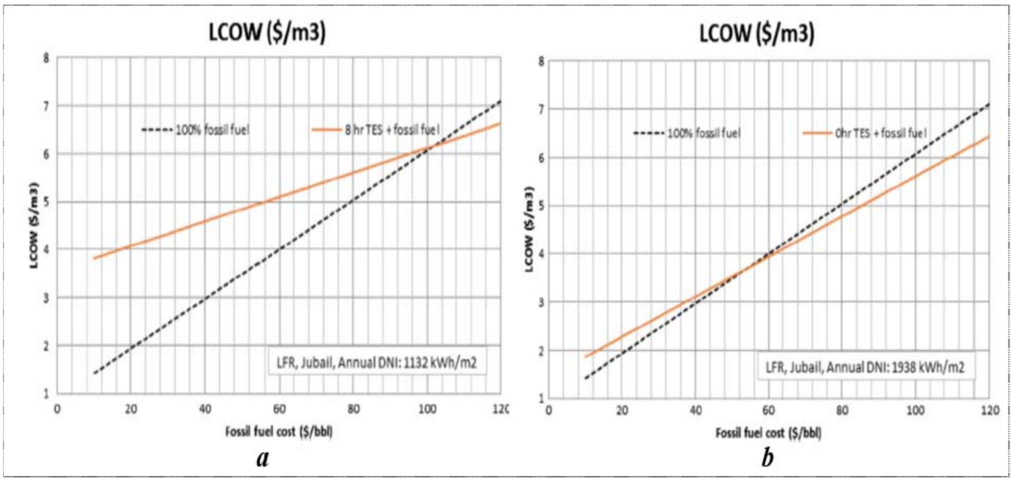


Figure 3.5. Normalized LCOW variation as a function of Fossil Fuel cost for (a) DNI = 1132 kWh/m^2 and (b) DNI = 1938 kWh/m^2 [195]

3.2.3. Summary of Case Studies results

The first case study shows that for a concentrated solar thermal assisted MED-TVC:

- If the main objective is to maximize the amount of fossil fuel that is saved, then the Parabolic Trough technology proves to be the most competitive one, particularly when the Thermal Energy Storage duration is higher.

- If the payback period of the investment is considered as the main objective, then the Linear Fresnel Reflector (LFR) gives the most viable option.

In the second case study, the LFR performance is assessed as a function of the climatic conditions through a pilot test. It is shown that:

- The measurements show that the Levelised Cost of Water (LCOW) is approximately inversely proportional to the annual DNI of the site where the plant is located.
- It is shown that when a Fresnel Solar collecting system is combined with a MED thermal desalination plant, its effectiveness increases with a lower duration of thermal energy storage.

3.3 Optimum Design of PV-RO System Solar Powered Seawater Desalination without storage: Case study results

The prime objective of this research work is to optimize energy from the sun, which can be used in accordance with the energy utilisation curve of plants. From the data relating to direct radiation and diffuse radiation, sun energy produced by a plant is obtained hourly. Figure 3.6 shows the solar energy generated by the plant (installation) as an average time for different months. The generated solar energy is higher in summer and is lower in winter, logically. During winter, days are shorter compared to the summers, and the forecast gets cloudy, which results in less solar power generated.

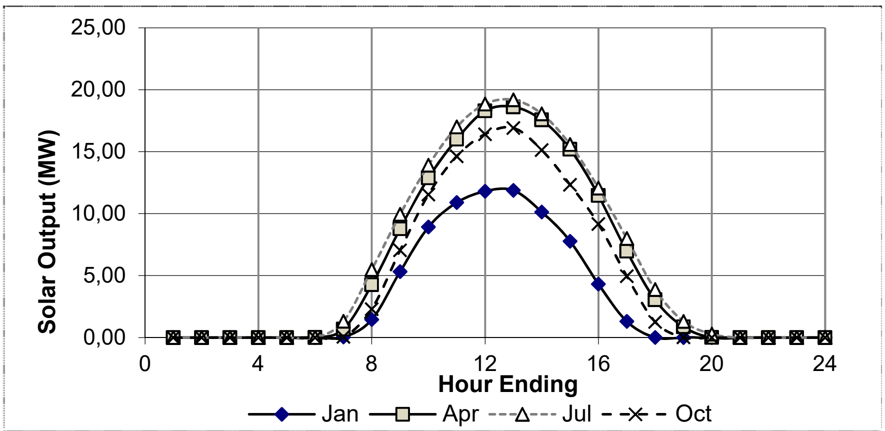


Figure 3.6. Mean solar array outcome for four months in KSA

Hourly real annual consumption data from the Ras Al-Khair plant, as well as the solar data from King Abdullah City for renewable energy and atomic energy, have been obtained. Figure 3.7 illustrates the electricity consumption curve required for the operation of the Ras Al-Khair desalination plant (in March), which is supported by the electrical grid that uses fossil fuels and energy that can be shared by solar energy.

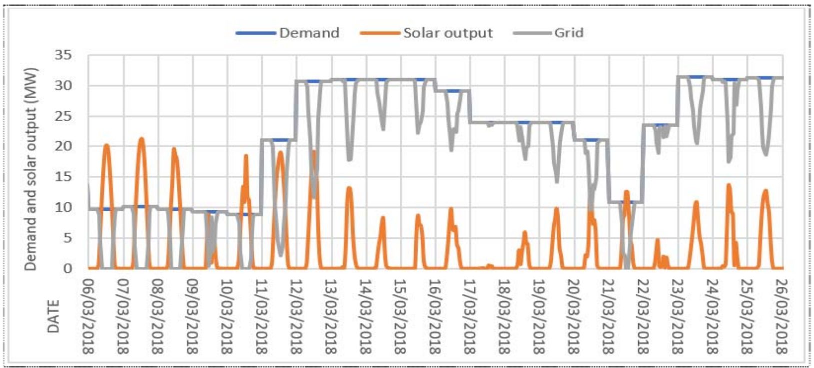


Figure 3.7. Demand and Solar Contributions for Azimuthal Tracking Panel

It is noteworthy, as shown in the graph, that during the month of April, there were certain periods of time when the actual consumption of the plant decreased. These periods are related to technical stops necessary to carry out the maintenance. Figure 3.8 shows the average electricity consumption required for a day during January, and the solar generated by cells to provide the energy needed to operate the plant during daylight hours. We notice the presence of wasted energy higher than the required energy in the afternoon.

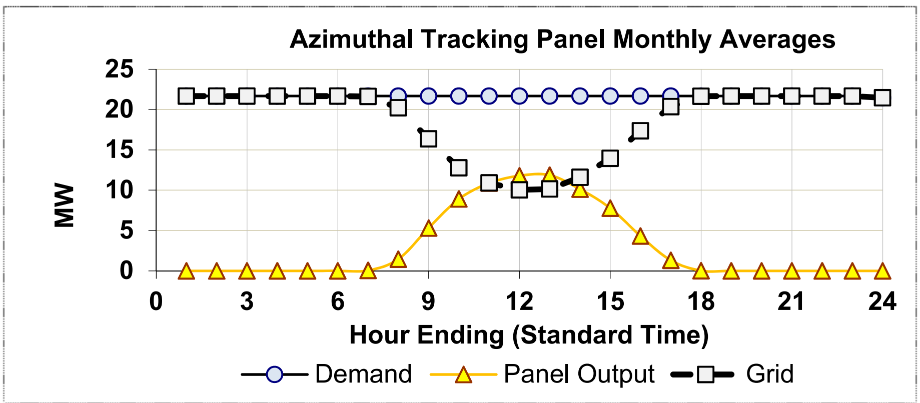


Figure 3.8. Demand, PV electricity consumption and grid consumption

These hypotheses will be carried out and summarised in the following section when we estimate the cost of generating one kW per hour from the solar plant. So, we can establish the restrictive criterion that during the entire period of operation of the plant, the total energy generated by the solar plant is utilised for its consumption in the desalination plant. This alternative is conditioned by the low consumption that occurs during technical halts.

Another hypothesis would be to allow the energy generated by the solar plant to exceed consumption in certain periods, as described above.

In order to do so, we will set a maximum percentage of generated energy that will not be used by the installation and could be discharged to the national grid electricity at a sale price equal to zero. With the actual consumption data of the plant and the energy produced from the solar photovoltaic plant, the amount of energy that can be consumed in the desalination plant (Usable energy) is obtained. The energy generated that would not be used (not usable energy) is due to the fact that in certain periods, the energy generated by the solar plant is higher than the energy consumed by the desalination plant. It is assumed as a hypothesis that this energy is either sent to the network at a price equal to zero euros, or the solar plant is disconnected during those periods in case it could not be connected to the network, in order to analyse the feasibility of the use of desalination plants without storage.

3.3.1. Financial study

The financial study of the solar plant, which can be employed to estimate the price for electrical energy produced from the photovoltaic solar power plant and assessment for the feasibility of solar plants, is carried out. In order to do so, first, the plant capacity is defined. The calculations have been made for the following cases: 1, 2, 3, 4, 5 MWp, and 10, 20, 40, 60, 80, and100 MWp.

For each of the cases, the following parameters of the plant are considered:

- Efficiency of panels: 12%.
- Performance Ratio (PR): 100%, 90% and 80%.
- Plant cost: 0.835 €/kWp.
- Life cycle of the PV plants: 25 years.

Also, it is considered that the interest rate for the loan (r) is 4%, and the costs of operation and maintenance reach 0.1 €/watt. The price of the electricity generated by each of the facilities studied is calculated as indicated by equation 4 (§2.3.3).

3.3.2. Total investment

Figure 3.9 shows all the data which was obtained to evaluate the feasibility of the solar plant is summarised. The optimal design of the capacity of the solar plant was found to be about 20 megawatts; therefore, the wasted energy will be about 20%.

In this case, the production cost for the solar plant is 0.025 euros per kWh, which is less than the current tariff price of the kilowatt of electricity in Saudi Arabia, estimated at 0.043 euros.

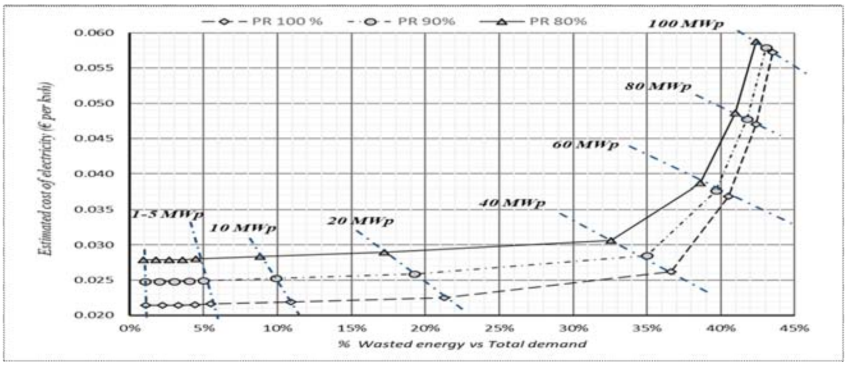


Figure 3.9. The estimated cost of electricity over the percentage of wasted energy

In the following graph (Figure 3.10), it can be seen that the amount of solar energy generated in the photovoltaic solar plant is exponentially related to the size of plant: by increasing the size of the plant, the amount of solar energy generated in the photovoltaic solar plant increases and cannot be used to cover the energy consumption of Ras Al-Khair and such, as shown in Figure 3.8. The gray area is the ideal area of design capacity. In the case of design for capacity greater than 60 megawatts, the price of kilowatts per hour will exceed the tariff of electricity consumption in Saudi Arabia.

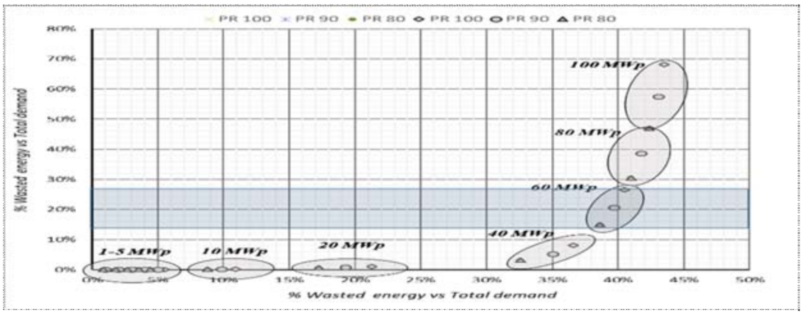


Figure 3.10. Wasted energy generated in relation to the size of the plant

If the percentage of non-usable energy is less than 2% is considered as a criterion, the size of the plant would be 20 MWp.

In this case, it can cover around 20% of the total energy consumption at a price of around 0.025 €/kWh. The price of electrical energy in KSA is 0.043 €/kWh. The cost of electricity generated by the plant exceeds 0.043 €/kWh when the plant is greater than 60 MWp.

Chapter 4 – Conclusions and Future Work

The main research work of this dissertation consists of the following parts: (a) Concentrated Solar Power (CSP) using Multiple Effect Distillation (MED), and (b) Photovoltaic (PV) cells combined with Reverse Osmosis (RO). Section 8.1 presents a summary of the performed case studies and highlights the key contributions of this thesis, while Section 8.2 outlines several related research questions that were outside the scope of this thesis and should be addressed in future studies.

4.1. Contributions and Conclusions

4.1.1. Analytic Hierarchy Process for the Selection of Adequate Desalination Technologies in Spain and GCC countries

This dissertation proposes the selection of an adequate desalination technology to be made on the basis of an Analytical Hierarchy Process (AHP) to include site-specific conditions.

A panel of experts for Spain and the Gulf Cooperation Council (GCC) was formed, and a set of criteria was created. The data was collected through questionnaires, and analytical tools were used to treat them. The main conclusions of this study are:

- The multi-stage flash technology is the most appropriate desalination technology for the GCC countries, mainly because of the relatively low cost of fossil fuel and high seawater salinity.
- Reverse osmosis is the most suitable desalination technology for Spain since its associated with lower operating costs and results in high -quality water.
- The total cost of freshwater production is shown to be the dominant criterion when selecting the most appropriate technology, followed by the energy consumption of desalination plants.

4.1.2. Concentrated Solar Power-assisted Multiple Effect Distillation

The techno-economic evaluation of the three most commonly available CSP technologies (Parabolic Trough, Central Receiver Tower, and Linear Fresnel Reflector) was performed for two locations in Saudi Arabia (Jubail and Yanbu). The breakeven fossil fuel price for the different CSP technologies and both site locations was calculated through normalisation with respect to the LCOW obtained when only fossil fuel at 100 USD/bbl is used for MED-TVC desalination. The conclusions of this study are as follows:

- The Parabolic Trough technology is the most competitive if the amount of fossil fuel that is saved is the determinant criterion.
- Fuel saving increases if the allocated time for Thermal Energy Storage is higher.
- The Linear Fresnel Reflector technology is the optimal solution if one considers only the payback period of the investment as the governing criterion.

The second case study investigated the effect of climatic conditions on the performance of the Linear Fresnel Reflector (LFR) through a series of measurements during a period of one year. The following conclusions can be drawn from this pilot test:

- The Levelised Cost of Water (LCOW) is approximately inversely proportional to the annual Direct Normal Irradiation (DNI) of the site where the plant is located.
- It is shown that when a Fresnel Solar collecting system is combined with a MED thermal desalination plant, its effectiveness increases with a lower duration of thermal energy storage.

4.1.3. Photovoltaic (PV) cells combined with Reverse Osmosis (RO)

The main objective of this case study was to investigate the possibility of using photovoltaic panels instead of batteries within a desalination system using reverse osmosis in Saudi Arabia. To achieve this objective, the hourly energy consumption data of an existing RO desalination plant that is located in Ras Al-Khair, Saudi Arabia, were gathered and analysed. The electrical energy produced by the PV cells was calculated on the basis of hourly direct solar radiation data, which were obtained from Saudi Arabia's renewable resources monitoring and mapping program. The economic study revealed that the optimal capacity of the RO plant using PV cells is approximately 20 megawatts. This solar plant unit corresponds to a production cost for the solar plant of only 0.025 euros per kWh and an amount of wasted energy of approximately 20%.

4.2. Future Research

The present section discusses the issues that should be addressed by future research as a continuation of the present thesis. The proposed further steps are described in the following with regard to CSP and PV technology separately as well as the Analytic Hierarchy Process for selecting the most appropriate desalination technology for a given area.

4.2.1. Analytic Hierarchy Process for the Selection of Adequate Desalination Technologies

An efficient method to decide on the most appropriate water desalination technologies for the GCC countries and Spain based on the AHP method is presented. These countries experience a lack of freshwater projects, due to the high cost and energy demands of desalination plants. Therefore, the GCC countries and Spain need more detailed investigations of the scenario in order to determine the most appropriate desalination technologies. According to the opinions of experts in both the GCC countries and Spain, the dominant criterion to select the most appropriate technology emerged to be the total cost of freshwater production, followed by the energy consumption of desalination plants. The results of this study revealed that the most suitable technology in the GCC countries is multi-stage flash (MSF), while reverse osmosis (RO) is the most suitable desalination technology for Spain. The choice of MSF in the Gulf is possibly prompted by the high feed water salinity, cheap availability of fossil fuel, as well as important financial, industrial and ecological conditions. The factors affecting the choice of RO as the recommended desalination technology in Spain could possibly be the lower operating cost, carbon footprint and demand for high-quality water. It is envisaged that the present recommendations will help industries in these regions to consider the appropriate technologies for a better business and prospective future. However, there is still room for improvement in both technologies to further flourish this industry. Novel, out-of-the-box strategies must be explored, such as the integration of cheaper renewable energy resources with these conventional technologies to reduce the production cost further.

4.2.2. Concentrated Solar Power-assisted Multiple Effect Distillation

The present thesis provided an extremely valuable method for the techno-economical evaluation of Concentrated Solar Power (CSP) technologies. Such method can be used to analyse CSP technologies under different climatic conditions than the ones of Saudi Arabia, in particular in terms of Direct Normal Radiation and can be extended to cover the influence of other parameters for which assumptions were made for the purpose of this thesis (e.g. fossil fuel boiler efficiency). Although a significant number of current applications include thermal power plants together with CSP desalination plants, which is often termed to as co-generation mode, additional research focusing on the response of desalination plants without generation of electricity power is needed.

This research will contribute to a deeper understanding of standalone desalination plants' response and is expected to act as a benchmark for further studies aiming at the optimisation of the function of CSP desalination plants.

From the conducted literature review, it was identified that there are a number of desalination and CSP plants across the world. Many thermal power plants make use of the very same power cycles used in CSP plants and there are desalination plants that function in co-generation with thermal power plants. What seems to be essential is further research on linking CSP and the thermal desalination process for fresh water generation without electricity power, as there is insufficient data to understand how water-desalination plants behave (Non-co-generation mode). To the knowledge of the authors, no studies have been performed on using the thermal energy from the CSP plants (no power production) for standalone desalination.

4.2.3. Photovoltaic (PV) cells combined with Reverse Osmosis (RO)

The present thesis investigated the efficiency of combining PV cells with RO desalination plants without energy storage. The investigation was conducted through a case study of an existing RO desalination plant in Ras Al-Khair, Saudi Arabia. A very valuable further step would consist of applying the same methodology to other existing RO plants in Saudi Arabia and/or in countries of the GCC, North Africa or Spain, with different input in terms of solar radiation (direct, diffused, and reflected). This will create a very useful basis for recommendations for the optimal plant capacity as a function of solar radiation. Such information will be particularly appreciable by decision-makers (stakeholders and government entities) and for long-term desalination plans. Moreover, further technological and research efforts should be directed towards ways of reducing storage costs in order to allow a regularised desalination process over the course of a day without depending on fossil fuels for bridging the deficit between day and night operations.

With regard to the performed financial study, several parameters, such as panel efficiency, plant cost and service life, had to be fixed. Further parametric studies will be needed to assess the influence of these factors in the cost performance of RO plants coupled with PV cells. Moreover, what is crucial for decision makers and government entities is the development of tools for assessing the influence of factors related to capital investment and state initiatives on the final cost of water. Such information is expected to be of great assistance for tracing future environmentally-friendly, and in this case, solar panel-friendly policies from state organisations, such as capital interest rate reductions, tax exemptions, and land cost reductions. Several assumptions were performed in the context of the present thesis with regard to the life cycle of RO plants running using solar power from PV cells. Further studies should also focus on the long-term advantages of this method over currently used methods based on fossil fuels. This can be performed through a full life cycle analysis of this RO plant, using PV cells and fossil fuels, including investment cost, operation cost, maintenance cost and frequency, upgrade cost and frequency, among others.

PV is a futuristic technology, and small scale PV-RO plants will be a viable option for supplying remote villages or small hotels. However, batteries that store the energy during the day in PV systems are practically challenging, especially in hot tropical climates. One of the contributions to the objectives of this thesis is the optimal design of the use of photovoltaic cells with reverse osmosis desalination (PV-RO) without storage. When functioning without batteries, the output from a PV array may vary, depending upon the intensity of the sunlight and irradiance, necessitating the connected RO system to operate at variable available power. For large scale applications, energy storage systems have remained impractical. The installation of such systems requires a huge area, expensive capital, and many types of equipment like charge controllers [246]. Factors like price, short lifetime and regular replacements affect the economic feasibility of batteries, thereby increasing the cost of water production [207,224,246].

The study by [239,247] compares the cost of water production in an SWRO system when it functions with battery storage and without battery storage. The increase shown in one study is from 7.8 to 8.3 €/m^3 [239], and another one is 10 to 13 \$/m^3 242. Thus, energy storage is viable in small units and not preferred in large installations [231,248,249]. Thus, recent research aims at coupling RO plant and RES without making use of backup options [223,225,230]. However, further research should be conducted on PV-RO as a desalination process without batteries or storage, as there is insufficient number of studies based on real data to understand how reverse osmosis plants are designed with photovoltaics during the sunshine period during the day only, for all four seasons and to know the conditions of climate for the whole year.

References

[1] Verdaguer, M., Molinos-Senante, M., Clara, N., Santana, M., Gernjak, W., and Poch, M. (2018). Optimal fresh water blending: A methodological approach to improve the resilience of water supply systems. *Science of the total environment*, *624*, 1308-1315.

[2] DESA, U. (2016). International Decade for Action 'Water for Life'2005-2015. [Online] Available from: www.un.org/waterforlifedecade/scarcity.shtml.

[3] Miller, S., Shemer, H., and Semiat, R. (2015). Energy and environmental issues in desalination. Desalination, 366, 2-8.

[4] Falkenmark, M. (1989). The massive water scarcity now threatening Africa: why isn't it being addressed?. Ambio, 112-118.

[5] M. Vivian and B. Shender, "Water Stress Map | Aftermath," 2016. [Online]. Available: https://aftermathblog.wordpress.com/2006/01/19/water-stress-map/.

[6] Molden, D. (2008). Water security for food security: findings of the Comprehensive Assessment for Sub-Saharan Africa. [This report draws directly from the book Water for food, water for life: a Comprehensive Assessment of Water Management in Agriculture] (No. 614-2016-40823).

[7] Bakker, K. (2012). Water security: research challenges and opportunities. Science, 337(6097), 914-915.

[8] Cosgrove, W. J., and Rijsberman, F. R. (2014). World water vision: making water everybody's business. Routledge.

[9] Hamdy, A., Ragab, R., and Scarascia-Mugnozza, E. (2003). Coping with water scarcity: water saving and increasing water productivity. Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage, 52(1), 3-20.

[10] Gleick, P. H. (1993). Water reserves on the earth. In Water in Crisis: A Guide to the World's Freshwater Resources (p. 13). Oxford University Press.

[11] Ritchie, H and Roser, M. (2019) "Water Use and Stress". Published online at OurWorldInData.org. [Online]. Available: 'https://ourworldindata.org/water-use-stress

[12] Hassan, N. (2016). Ground Water Depletion Due To Water Mining–A Threat. Journal of Environmental Science, Computer Science and Engineering and Technology.

[13] U. N. DESA, "United Nations Department of Economic and Social Affairs/Population Division (2009): World Population Prospects: The 2008 Revision," Internet: http://esa. un. org/unpp (gelesen am 16, 2010.

[14] National Intelligence Council (US). (2000). *Global Trends 2015: A Dialogue About the Future with Nongovernment Experts*. The Council.

[15] Wada, Y., Flörke, M., Hanasaki, N., Eisner, S., Fischer, G., Tramberend, S., ... and Wiberg, D. (2016). Modeling global water use for the 21st century: Water Futures and Solutions (WFaS) initiative and its approaches. Geoscientific Model Development, 9, 175-222.

[16] Margat, J., Frenken, K., and Faurès, J. M. (2005). Key water resources statistics in aquastat. IWG-Env, International Work Session on Water Statistics, Vienna, 20-22.

[17] Hull, J. (2009) “Water Desalination: The Answer to the World’s Thirst?” [Online]. Available: https://www.fastcompany.com/1139300/water-desalination-answer-worlds-thirst

[18] James, K., Campbell, S. L., and Godlobe, C. E. (2002). Watergy: Taking advantage of untapped energy and water efficiency opportunities in municipal water systems. In Watergy: taking advantage of untapped energy and water efficiency opportunities in municipal water systems. Alliance to Save Energy. ⟨http://pdf.usaid.gov/pdf_docs/Pnact993.pdf⟩ [Accessed 14 November 2019].

[19] Veza, J. M. (2001). Desalination in the Canary Islands: an update. Desalination, 133(3), 259-270.

[20] Goh, P. S., Matsuura, T., Ismail, A. F., and Ng, B. C. (2017). The Water–Energy Nexus: Solutions towards Energy-Efficient Desalination. Energy Technology, 5(8), 1136-1155.

[21] Pinto, F. S., and Marques, R. C. (2017). Desalination projects economic feasibility: A standardisation of cost determinants. Renewable and Sustainable Energy Reviews, 78, 904-915.

[22] Papapetrou, M., Cipollina, A., La Commare, U., Micale, G., Zaragoza, G., and Kosmadakis, G. (2017). Assessment of methodologies and data used to calculate desalination costs. Desalination, 419, 8-19.

[23] Ioannis, D., Theodoros, L., and Nikitas, N. (2013). Application of FMEA to an offshore desalination plant under variable environmental conditions. International Journal of Performability Engineering, 9(1), 105-116.

[24] Gude, V. G. (2015). Energy storage for desalination processes powered by renewable energy and waste heat sources. *Applied Energy*, *137*, 877-898.

[25] Hamdy, A., Ragab, R., and Scarascia-Mugnozza, E. (2003). Coping with water scarcity: water saving and increasing water productivity. *Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage*, *52*(1), 3-20.

[26] Ghaffour, N., Missimer, T. M., and Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination*, *309*, 197-207.

[27] ID Association. (2014). Desalination by the Numbers| IDA. *Int. Desalin. Assoc. 101*, *543*.

[28] Ghaffour, N. (2009). The challenge of capacity-building strategies and perspectives for desalination for sustainable water use in MENA. *Desalination and Water Treatment*, *5*(1-3), 48-53.

[29] Service, R. F. (2006). Desalination freshens up. Science (New York, NY), 313(5790), 1088.

[30] Shannon, M. A., Bohn, P. W., Elimelech, M., Georgiadis, J. G., Marinas, B. J., and Mayes, A. M. (2010). Science and technology for water purification in the coming decades. In *Nanoscience and technology: a collection of reviews from nature Journals* (pp. 337-346).

[31] Schiermeier, Q. (2008). Purification with a pinch of salt: climate change, growing populations and political concerns are prompting governments and investors from California to China to take a fresh look at desalination. Quirin Schiermeier wades in. *Nature*, *452*(7185), 260-262.

[32] I. D. A. (IDA), Worldwide Desalinating Plant Inventory, Oxford, UK, 2006.

[33] Adroit Market Research, "Global Water Desalination Market Analysis, Industry Report, 2018-2025," [Online]. Available: https://www.adroitmarketresearch.com/industry-reports/water-desalination-market.

[34] "Water Desalination Market by technology, by source of water - Growth, Future Prospects andamp; Competitive Analysis, 2018 – 2026," 2018. [Online]. Available: https://www.credenceresearch.com/report/water-desalination-market.

[35] I. D. Association, Global Desalination Market Growth Continues, 2017.

[36] Kalogirou, S. A. (2005). Seawater desalination using renewable energy sources. Progress in energy and combustion science, 31(3), 242-281.

[37] Voutchkov, N.(2012) Desalination engineering: planning and design, McGraw Hill Professional.

[38] Islam, M. S., Sultana, A., Saadat, A. H. M., Shammi, M., and Uddin, M. K. (2018). Desalination technologies for developing countries: A review. Journal of Scientific Research, 10(1), 77-97.

[39] Mandani, F., Ettouney, H., and El-Dessouky, H. (2000). LiBr H2O absorption heat pump for single-effect evaporation desalination process. *Desalination*, *128*(2), 161-176.

[40] Strathmann, H. (2010). Electrodialysis, a mature technology with a multitude of new applications. *Desalination*, *264*(3), 268-288.

[41] Pankratz, T., Virgili, F., and Hasler, P. (2014). IDA desalination yearbook 2014–2015. *Topsfield, MA: IDA*.

[42] *Awerbuch, L. (2014) "Hybrid Desalination: The Best of Both Worlds? - WaterWorld,". [Online]. Available: https://www.waterworld.com/articles/wwi/print/volume-9/issue-5/technology-case-studies/hybrid-desalination-the-best-of-both-worlds.html.*

[43] Hamed, O. A., Hassan, A. M., Al-Shail, K., and Farooque, M. A. (2009). Performance analysis of a trihybrid NF/RO/MSF desalination plant. *Desalination and Water Treatment*, *1*(1-3), 215-222.

[44] Li, C., Goswami, Y., and Stefanakos, E. (2013). Solar assisted sea water desalination: A review. *Renewable and Sustainable Energy Reviews*, *19*, 136-163.

[45] Younos, T. (2005). The economics of desalination. Journal of Contemporary Water Research and Education, 132(1), 39-45.

[46] Watson, I. C., Morin, O. J., and Henthorne, L. (2003). Desalting handbook for planners. Desalination research and development program report, 72.

[47] Khayet, M. (2013). Solar desalination by membrane distillation: Dispersion in energy consumption analysis and water production costs (a review). Desalination, 308, 89-101.

[48] Kim, Y. M., Lee, Y. S., Lee, Y. G., Kim, S. J., Yang, D. R., Kim, I. S., and Kim, J. H. (2009). Development of a package model for process simulation and cost estimation of seawater reverse osmosis desalination plant. Desalination, 247(1-3), 326-335.

[49] Huehmer, R., Gomez, J., Curl, J., and Moore, K. (2011). Cost modeling of desalination systems, International Desalination Association (IDA) Congress. Perth, IDAW/PER11-302.

[50] Frioui, S., and Oumeddour, R. (2008). Investment and production costs of desalination plants by semi-empirical method. Desalination, 223(1-3), 457-463.

[51] Fryer, J. (2010). An investigation of the marginal cost of seawater desalination in California. *Sponsored by Residents for Responsible Desalination*, 1-24.

[52] Hilton, R. W., and Platt, D. E. (2013). *Managerial accounting: creating value in a dynamic business environment*. McGraw-Hill Education.

[53] Ettouney, H. M., El-Dessouky, H. T., Faibish, R. S., and Gowin, P. J. (2002). Evaluating the economics of desalination. *Chemical Engineering Progress*, *98*(12), 32-39.

[54] Ghaffour, N., Missimer, T. M., and Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination*, *309*, 197-207.

[55] Hisham, T. (2002). El-Dessouky, Hisham M. Ettouney, Fundamental of Salt Water Desalination, Kuwait University.

[56] Al-Hengari, S., ElMoudir, W., and El-Bousiffi, M. A. (2015). Economic assessment of thermal desalination processes. Desalination and Water Treatment, 55(9), 2423-2436.

[57] Bakish, Robert A. "Practice of desalination." (1973). Noyes Data Corporation, Park Ridge, NJ,1973, ISBN: 0-8155-0478-0.

[58] Wade, N. M. (2001). Distillation plant development and cost update. Desalination, 136(1-3), 3-12.

[59] Karagiannis, I. C., and Soldatos, P. G. (2008). Water desalination cost literature: review and assessment. Desalination, 223(1-3), 448-456.

[60] Al-Karaghouli, A., and Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. Renewable and Sustainable Energy Reviews, 24, 343-356.

[61] Zhou, Y., and Tol, R. S. (2005). Evaluating the costs of desalination and water transport. *Water resources research*, *41*(3).

[62] Buros, O. K. (2000). *The ABCs of desalting* (p. 30). Topsfield, MA: International Desalination Association*. Retrieved from http://www.miliarium.es/Desalinizador/The ABCs of Desalting.pdf*

[63] Farooque, A. M., Jamaluddin, A. T. M., Al-Reweli, A. R., Jalaluddin, P. A. M., Al-Marwani, S. M., Al-Mobayed, A. A., and Qasim, A. H. (2008). Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices. *Desalination*, *219*(1-3), 137-159.

[64] Gentle, J. E. (2009). Computational Statistics. (J. Chambbers, D. Hand, and W. Hardle, Eds.) (2009th ed., pp. 453–467). Fairfax: Springer New York.

[65] Al-Sofi, M. A., Hassan, A. M., Hamed, O. A., Dalvi, A. G. I., Kither, M. N., Mustafa, G. M., and Bamardouf, K. (2000). Optimisation of hybridized seawater desalination process. *Desalination*, *131*(1-3), 147-156.

[66] Micale, G., Cipollina, A., and Rizzuti, L. (2009). Seawater desalination for freshwater production. In *Seawater desalination* (pp. 1-15). Springer, Berlin, Heidelberg.

[67] Baig, M. B., and Al Kutbi, A. A. (1998). Design features of a 20 migd SWRO desalination plant, Al Jubail, Saudi Arabia. *Desalination*, *118*(1-3), 5-12.

[68] Prihasto, N., Liu, Q. F., and Kim, S. H. (2009). Pre-treatment strategies for seawater desalination by reverse osmosis system. *Desalination*, *249*(1), 308-316.

[69] Wolf, P. H., Siverns, S., and Monti, S. (2005). UF membranes for RO desalination pretreatment. *Desalination*, *182*(1-3), 293-300.

[70] Avlonitis, S. A. (2002). Operational water cost and productivity improvements for small-size RO desalination plants. Desalination, 142(3), 295-304.

[71] Pankratz, T. (2013). IDA desalination Year book “2012-2013”, Water Desalination Report. (R. Owen, Ed.). Oxford, UK: Media Analytics Ltd, The Jam Factory.

[72] Huehmer, R., Gomez, J., Curl, J., and Moore, K. (2011). Cost modeling of desalination systems, International Desalination Association (IDA) Congress. Perth, IDAW/PER11-302.

[73] Ettouney, H., El-dessouky, H., Faibish, R. S., and Gowin, P. J. (2002). Evaluating the Economics of Desalination. CEP Magazine, (December), 32–39. Retrieved from http://library.certh.gr/libfiles/PDF/SPIN-172-EVALUATING-by-ETTOUNEY-in-CEP-V-98-ISS-12-PP-32-39-Y-2002.pdf.

[74] Wittholz, M. K., O'Neill, B. K., Colby, C. B., and Lewis, D. (2008). Estimating the cost of desalination plants using a cost database. *Desalination*, *229*(1-3), 10-20.

[75] Al-Sahali, M., and Ettouney, H. (2007). Developments in thermal desalination processes: Design, energy, and costing aspects. Desalination, 214(1-3), 227-240.

[76] Ettouney, H., and Wilf, M. (2009). Commercial Desalination Technologies, An Overview of the Current Status of Applications of Commercial Seawater Desalination Processes. In G. Micale, L. Rizzuti, and A. Cipollina (Eds.), Seawater Desalination (pp. 77–107). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-01150-4.

[77] Lomax, I. (2009). The pace of change in seawater desalination by reverse osmosis. In Water Management in 2020 and Beyond (pp. 251-258). Springer, Berlin, Heidelberg. http://link.springer.com/chapter/10.1007/978-3-540-89346-2_13.

[78] Helal, A. M., Al-Malek, S. A., and Al-Katheeri, E. S. (2008). Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates. *Desalination*, *221*(1-3), 1-16.

[79] Khawaji, A. D., Kutubkhanah, I. K., and Wie, J. M. (2008). Advances in seawater desalination technologies. *Desalination*, *221*(1-3), 47-69.

[80] Kavvadias, K. C., and Khamis, I. (2010). The IAEA DEEP desalination economic model: a critical review. *Desalination*, *257*(1-3), 150-157.

[81] Al-Karaghouli, A., and Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, *24*, 343-356.

[82] Sommariva, C. (2010). *Desalination and advanced water treatment: Economics and financing* (Vol. 40). Hopkinton, MA: Balaban Desalination Publications. Retrieved from http://www.amazon.com/Desalination-Advance-Treatment-Economics- Financing/dp/0866890696.

[83] Micale, G., Cipollina, A., and Rizzuti, L. (2009). Seawater Desalination for Freshwater Production. In A. Cipollina, G. Micale, and L. Rizzuti (Eds.), seawater desalination conventional and renewable energy processes (1st ed., pp. 1–15). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-01150-4.

[84] Pilat, B. (2001). Practice of water desalination by electrodialysis. *Desalination*, *139*(1-3), 385-392.

[85] Buros, O. (2000). The ABCs of desalting (Second Edi.). Topsfield, Massachusetts, USA: International Desalination Association. Retrieved from http://www.miliarium.es/Desalinizador/The ABCs of Desalting.pdf.

[86] Spiegler, K. S., El-Sayed, Y. M., and Primer, A. D. (1994). Balaban Desalination Publications. Santa Maria Imbaro.

[87] Spiegler, K. S., and El-Sayed, Y. M. (2001). The energetics of desalination processes. *Desalination*, *134*(1-3), 109-128.

[88] Kalogirou, S. A. (2001). Effect of fuel cost on the price of desalination water: a case for renewables. *Desalination*, *138*(1-3), 137-144.

[89] Blank, J. E., Tusel, G. F., and Nisanc, S. (2007). The real cost of desalted water and how to reduce it further. *Desalination*, *205*(1-3), 298-311.

[90] Water Reuse Association Desalination Committee. (2012). Seawater desalination costs. White paper. *Alexandria, VA: Water Reuse Association. Retrieved from https://watereuse. org/wp-content/uploads/2015/10/WateReuse_Desal_Cost_White_Paper. pdf. Access March*, *20*, 2018.

[91] Alameddine, I., and El-Fadel, M. (2007). Brine discharge from desalination plants: a modeling approach to an optimized outfall design. *Desalination*, *214*(1-3), 241-260.

[92] Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., and Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. *Water research*, *43*(9), 2317-2348.

[93] Prihasto, N., Liu, Q. F., and Kim, S. H. (2009). Pre-treatment strategies for seawater desalination by reverse osmosis system. *Desalination*, *249*(1), 308-316.

[94] Pontié, M., Rapenne, S., Thekkedath, A., Duchesne, J., Jacquemet, V., Leparc, J., and Suty, H. (2005). Tools for membrane autopsies and antifouling strategies in seawater feeds: a review. *Desalination*, *181*(1-3), 75-90.

[95] Al-Sofi, M. A., Hassan, A. M., Hamed, O. A., Dalvi, A. G. I., Kither, M. N., Mustafa, G. M., and Bamardouf, K. (2000). Optimisation of hybridized seawater desalination process. *Desalination*, *131*(1-3), 147-156.

[96] *SWCC. (2013b). Saline Water Conversion Corporation (SWCC), Annual report No. 39 (2012). Riyadh, Saudi Arabia.*

[97] Advisian Worley Group (2019) URL http://https://www.advisian.com/en-gb/global-perspectives/the-cost-of-desalination# Accessed: 3 January 2020.

[98] Dawoud, M. A. (2012). Environmental impacts of seawater desalination: Arabian Gulf case study. *International Journal of Environment and Sustainability*, *1*(3).

[99] Ed James, International Water Summit 2015: GCC forecast to raise desalination capacity by 40% by 2020, [online], available at http://www.albawaba.com/business/internaional-water-summit-2017-gcc-countries-are-global-leaders-desalinaion-926452.

[100] Mezher, T., Fath, H., Abbas, Z., and Khaled, A. (2011). Techno-economic assessment and environmental impacts of desalination technologies. *Desalination*, *266*(1-3), 263-273.

[101] Gude, G. (2018). *Emerging Technologies for Sustainable Desalination Handbook*. Butterworth-Heinemann.

[102] Tuzkaya, G., and Gülsün, B. (2008). Evaluating centralized return centers in a reverse logistics network: An integrated fuzzy multi-criteria decision approach. *International Journal of Environmental Science and Technology*, *5*(3), 339-352.

[103] Ahmad, S., and Tahar, R. M. (2014). Selection of renewable energy sources for sustainable development of electricity generation system using analytic hierarchy process: A case of Malaysia. *Renewable energy*, *63*, 458-466.

[104] Limmeechokchai, B., and Chawana, S. (2007). Sustainable energy development strategies in the rural Thailand: The case of the improved cooking stove and the small biogas digester. *Renewable and Sustainable Energy Reviews*, *11*(5), 818-837.

[105] Ahammed, F., and Azeem, A. (2013). Selection of the most appropriate package of Solar Home System using Analytic Hierarchy Process model in rural areas of Bangladesh. *Renewable Energy*, *55*, 6-11.

[106] Hajeeh, M. A. (2006). Fuzzy approach for water desalination plants selection. Water and Geoscience, 53-62.

[107] ESCWA, Role of Desalination in Addressing Water Scarcity, E/ESCWA/SDPD/2009/4, United Nations Publication Sales No. E.09.II.L.7, (2009).

[108] Başaran, M. A., Dilek, E. F., and Atay, M. T. (2010). Comment to paper entitled “Application of the analytical hierarchy process in the selection of desalination plants” in 174 (2005) 97–108. *Desalination*, *261*(1-2), 1-2.

[109] Saurí, D., and del Moral, L. (2001). Recent developments in Spanish water policy. Alternatives and conflicts at the end of the hydraulic age. *Geoforum*, *32*(3), 351-362.

[110] March, H., Saurí, D., and Rico-Amorós, A. M. (2014). The end of scarcity? Water desalination as the new cornucopia for Mediterranean Spain. *Journal of Hydrology*, *519*, 2642-2651.

[111] Barciela, Fernando (2013) Tapping the oceans of the world. https://elpais.com/elpais/2013/01/07/inenglish/1357573268_753450.html Accessed: 3 March, 2019.

[112] Zarzo, D. and Rubio, M. (2004) Panorama actual de la desalación y de la reutilización para usos agrícolas [Actual desalination panorama and re-utilisation by agriculture], Riegos y drenajes XXI, (136), 22-27.

[113] Corral, Miguel Torres. "Desalination of seawater: cutting-edge technologies." Chemistry and industry: QeI 506 (2000): 41-45.

[114] Figures, O. U. R., Words, S., The, F., Activity, R., Map, O. U. R. R., Conservation, W., … Report, A. O. U. R. (2017). Our figures.

[115] García-Rubio, M. A., and Guardiola, J. (2012). Desalination in Spain: A growing alternative for water supply. *International journal of water resources development*, *28*(1), 171-186.

[116] Manero, A. (2008). Comparative water management practices in California and Spain. Minor thesis, Universitat Politècnica de Catalunya, BarcelonaTech. https://upcommons.upc.edu/handle/2099.1/6053 Accessed: 3 April, 2019.

[117] González-Gómez, F., García-Rubio, M. A., and Guardiola, J. (2012). Introduction: Water policy and management in Spain. *International Journal of Water Resources Development*, *28*(1), 3-11.

[118] García-Rubio, M. A., and Guardiola, J. (2012). Desalination in Spain: A growing alternative for water supply. *International journal of water resources development*, *28*(1), 171-186.

[119] Energy, U. R. (2012). Water Desalination Using Renewable Energy.

[120] Al-Zubari, W. K. (1998). Towards the establishment of a total water cycle management and re-use program in the GCC countries. *Desalination*, *120*(1-2), 3-14.

[121] Roudi-Fahimi, F., Creel, L., and De Souza, R. M. (2002). Finding the balance: Population and water scarcity in the Middle East and North Africa. *Population Reference Bureau Policy Brief*, 1-8.

[122] Abdalla, O., Kacimov, A., Chen, M., Al-Maktoumi, A., Al-Hosni, T., and Clark, I. (Eds.). (2017). *Water resources in arid areas: the way forward*. Springer.

[123] Purnama, A., Al-Barwani, H. H., and Smith, R. (2005). Calculating the environmental cost of seawater desalination in the Arabian marginal seas. *Desalination*, *185*(1-3), 79-86.

[124] DesalData (2019) URL http://desaldata.com Accessed: 3 March 2019.

[125] Shahzad, M. W., Thu, K., Li, A., Ismail, A. B., and Ng, K. C. (2015). Adsorption Cycle and Its Hybrid with Multi-Effect Desalination. *Desalination Updates*, 185.

[126] *Shomar, B., 2013. water resources, water quality and human health in regions of extreme stress: middle East. J. Earth Sci. Clim. Change 4, 153–164.*

[127] Aleisa, E., and Al-Zubari, W. (2017). Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity. *Environmental monitoring and assessment*, *189*(11), 553.

[128] The Food and Agriculture Organisation of the United Nations (2010) Water use, by sector and by source. United Nations. http://www.fao.org/nr/water/aquastat/main/index.stm. http://www.fao.org/nr/water/aquastat/countries_regions. Accessed 2018.

[129] Khan, M. Z., Nizami, A. S., Rehan, M., Ouda, O. K. M., Sultana, S., Ismail, I. M., and Shahzad, K. (2017). Microbial electrolysis cells for hydrogen production and urban wastewater treatment: A case study of Saudi Arabia. *Applied energy*, *185*, 410-420.

[130] FAO (2009a) FAO Water Report 34. http://www.fao.org/nr/water/aquastat/countries_regions. Accessed 2019.

[131] Saaty, T.L. (1988). The Analytic Hierarchy Process, McGraw Hill. *New York, 324.*

[132] Saaty, T. L. (1994). Highlights and critical points in the theory and application of the analytic hierarchy process. *European journal of operational research*, *74*(3), 426-447.

[133] Saaty, R. W. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical modelling*, *9*(3-5), 161-176.

[134] Saaty, T. L. (1980). The analytic hierarchy process McGraw-Hill. *New York*, *324*.

[135] Chan, F. T., and Kumar, N. (2007). Global supplier development considering risk factors using fuzzy extended AHP-based approach. *Omega*, *35*(4), 417-431.

[136] Dağdeviren, M., and Yüksel, İ. (2008). Developing a fuzzy analytic hierarchy process (AHP) model for behavior-based safety management. *Information sciences*, *178*(6), 1717-1733.

[137] Kulak, O., and Kahraman, C. (2005). Fuzzy multi-attribute selection among transportation companies using axiomatic design and analytic hierarchy process. *Information Sciences*, *170*(2-4), 191-210.

[138] Dağdeviren, M., Yavuz, S., and Kılınç, N. (2009). Weapon selection using the AHP and TOPSIS methods under fuzzy environment. *Expert Systems with Applications*, *36*(4), 8143-8151.

[139] Amiri, M. P. (2010). Project selection for oil-fields development by using the AHP and fuzzy TOPSIS methods. *Expert systems with applications*, *37*(9), 6218-6224.

[140] Kilincci, O., and Onal, S. A. (2011). Fuzzy AHP approach for supplier selection in a washing machine company. *Expert systems with Applications*, *38*(8), 9656-9664.

[141] Mohsen, M. S., and Al-Jayyousi, O. R. (1999). Brackish water desalination: an alternative for water supply enhancement in Jordan. *Desalination*, *124*(1-3), 163-174.

[142] Berrittella, M., Certa, A., Enea, M., and Zito, P. (2007). An analytic hierarchy process for the evaluation of transport policies to reduce climate change impacts. Available at: https://iris.unipa.it/bitstream/10447/18356/1/10447-18356.pdf (Accessed on: October 15, 2019).

[143] Mu, E., and Pereyra-Rojas, M. (2017). Understanding the analytic hierarchy process. In *Practical decision making* (pp. 7-22). Springer, Cham.

[144] Dyer, R. F., and Forman, E. H. (1992). Group decision support with the analytic hierarchy process. *Decision support systems*, *8*(2), 99-124.

[145] Firestone, J. M. (2006). Risk intelligence metrics: An adaptive metrics center industry report. Executive Information Systems.

[146] Forman, E. H., and Selly, M. A. (2001). *Decision by objectives: how to convince others that you are right*. World Scientific. Retrieved from http://www.mdm.gwu.edu/forman/DBO.pdf. (Accessed on: December 15, 2019).

[147] Duke, J. M., and Aull-Hyde, R. (2002). Identifying public preferences for land preservation using the analytic hierarchy process. *Ecological Economics*, *42*(1-2), 131-145.

[148] Bernard, H. R. (2002). Research Methods in Anthropology 3rd edition. Edited by: Walnut Creek.

[149] Baylor, M. S. (2010). *A model for maximizing port stakeholder valuation of modal infrastructure alternatives: An analysis using the Analytic Hierarchy Process*. University of Delaware.

[150] Öncü, A. A., Oner, M. A., and Başoğlu, N. (2003). 'Make or Buy'Analysis for Local Manufacture or Import Decisions in Defense System Procurements Using AHP: The Case of Turkey. In *Proceedings of PICMET* (Vol. 2).

[151] Ugboma, C., Ugboma, O., and Ogwude, I. C. (2006). An analytic hierarchy process (AHP) approach to port selection decisions–empirical evidence from Nigerian ports. *Maritime Economics and Logistics*, *8*(3), 251-266.

[152] Song, D. W., and Yeo, K. T. (2004). A competitive analysis of Chinese container ports using the analytic hierarchy process. *Maritime Economics and Logistics*, *6*(1), 34-52.

[153] Zhou, Y., and Tol, R. S. (2005). Evaluating the costs of desalination and water transport. *Water resources research*, *41*(3).

[154] Ghassemi, S. A., and Danesh, S. (2013). A hybrid fuzzy multi-criteria decision-making approach for desalination process selection. *Desalination*, *313*, 44-50.

[155] Podobnik, B. (2006). *Global energy shifts*. The Energy and Resources Institute (TERI).

[156] Nozik, A. J. (2005). Exciton multiplication and relaxation dynamics in quantum dots: applications to ultrahigh-efficiency solar photon conversion. *Inorganic chemistry*, *44*(20), 6893-6899.

[157] Koschikowski, J. (2011). Water desalination: when and where will it make sense. *Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany*.

[158] SOLAR ENERGY URL http://www.inforse.org/europe/dieret/Solar/solar.html, Accessed: 19 March 2019.

[159] Shemer, H., and Semiat, R. (2017). Sustainable RO desalination–Energy demand and environmental impact. *Desalination*, *424*, 10-16.

[160] Chu, Y., and Meisen, P. (2011). Review and comparison of different solar energy technologies. *Global Energy Network Institute (GENI), San Diego, CA*.

[161] El-Sebaii, A. A., and El-Bialy, E. (2015). Advanced designs of solar desalination systems: A review. *Renewable and Sustainable Energy Reviews*, *49*, 1198-1212.

[162] Ali, M. T., Fath, H. E., and Armstrong, P. R. (2011). A comprehensive techno-economical review of indirect solar desalination. *Renewable and Sustainable Energy Reviews*, *15*(8), 4187-4199.

[163] Omara, Z. M., Kabeel, A. E., and Abdullah, A. S. (2017). A review of solar still performance with reflectors. *Renewable and Sustainable Energy Reviews*, *68*, 638-649.

[164] Varun, A. K. (2010). Solar stills: a review. *Renewable and Sustainable Energy Reviews*, *14*(1), 446-453.

[165] Raluy, R. G., Serra, L., and Uche, J. (2005). Life cycle assessment of desalination technologies integrated with renewable energies. *Desalination*, *183*(1-3), 81-93.

[166] Qiblawey, H. M., and Banat, F. (2008). Solar thermal desalination technologies. *Desalination*, *220*(1-3), 633-644.

[167] https://www.intechopen.com/books/desalination-and-water-treatment/solar-desalination.

[168] Hermosillo, J. J., Arancibia-Bulnes, C. A., and Estrada, C. A. (2012). Water desalination by air humidification: Mathematical model and experimental study. *Solar Energy*, *86*(4), 1070-1076.

[169] Dhahri, A., and Omri, A. (2013). A review of solar chimney power generation technology. *International Journal of Engineering and Advanced Technology*, *2*(3), 1-17.

[170] Viebahn, P., Lechon, Y., and Trieb, F. (2011). The potential role of concentrated solar power (CSP) in Africa and Europe—A dynamic assessment of technology development, cost development and life cycle inventories until 2050. *Energy Policy*, *39*(8), 4420-4430.

[171] Bettter World. 2017. Time for more Concentrated Solar Power Plants? Solar Power. [Online]. Available: https://www.betterworldsolutions.eu/time-for-more-concentrated-solar-power-plants/ [2018, May 16].

[172] Gauché, P., von Backström, T. W., and Brent, A. C. (2012, May). A value proposition of CSP for South Africa. In *Southern African Solar Energy Conference (SASEC)* (pp. 1-12).

[173] Kalogirou, S. A. (2013). *Solar energy engineering: processes and systems*. Academic Press.

[174] IRENA (2019), Renewable Power Generation Costs in 2018, International Renewable Energy Agency, Abu Dhabi. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

[175] Gauché, P. (2016). *Spatial-temporal model to evaluate the system potential of concentrating solar power towers in South Africa* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

[176] Xu, X., Vignarooban, K., Xu, B., Hsu, K., and Kannan, A. M. (2016). Prospects and problems of concentrating solar power technologies for power generation in the desert regions. *Renewable and Sustainable Energy Reviews*, *53*, 1106-1131.

[177] Craig, O. O., Brent, A. C., and Dinter, F. (2017). Concentrated solar power (CSP) innovation analysis in South Africa. *South African Journal of Industrial Engineering*, *28*(2), 14-27.

[178] Duffie, J. A., and Beckman, W. A. (2013). *Solar engineering of thermal processes*. John Wiley and Sons.

[179] Fichtner. 2010. Assessment of Technology Options for Development of Concentrating Solar Power in South Africa, in Final report prepared for for World Bank and ESAP. [Online]. Available: https://www-cif.climateinvestmentfunds.org/sites/default/files/Presentation - WB (Eskom) Project - 2010_12_07 .pdf [2016, November 25].

[180] Kulichenko, N., and Wirth, J. (2012). *Concentrating solar power in developing countries: Regulatory and financial incentives for scaling up*. The World Bank.

[181] *WWF. 2015. Concentrated Solar Power: A strategic industrial development opportunity for South Africa. Gland, Switzerland. [Online]. Available: http://awsassets.wwf.org.za/downloads/concentrated_solar_power_report_final.pdf [2019, February 12].*

[182] *REN21. 2016. Renewables 2016 Global Status Report, Global Status Report. Edited by K. Seyboth, F. Sverrisson, F. Appavou, A. Brown, B. Epp, A. Leidreiter, C. Lins, E. Musolino, H. E. Murdock, K. Petrichenko, T. C. Farrell, T. T. Krader, A. Tsakiris, J. L. Sawin, J. Skeen, and B. Sovacool. Renewable Energy Policy Network for 21st Century.*

[183] *Schmalensee, R. (2015). The future of solar energy: A personal assessment. Energy economics, 52, S142-S148.*

[184] Cordaro, J. G., Rubin, N. C., and Bradshaw, R. W. (2011). Multicomponent molten salt mixtures based on nitrate/nitrite anions. *Journal of Solar Energy Engineering*, *133*(1), 011014.

[185] Vignarooban, K., Xu, X., Arvay, A., Hsu, K., and Kannan, A. M. (2015). Heat transfer fluids for concentrating solar power systems–a review. *Applied Energy*, *146*, 383-396.

[186] Pacio, J., and Wetzel, T. (2013). Assessment of liquid metal technology status and research paths for their use as efficient heat transfer fluids in solar central receiver systems. *Solar Energy*, *93*, 11-22.

[187] *German Aerospace Center (DLR), "Aqua-CSP Study Report, Concentrating Solar Power for Seawater Desalination, Final Report," German Aerospace Center (DLR), Stuttgart, 2007.*

[188] Wilde, R. (2005). Case study of a concentrating solar power plant for the cogeneration of water and electricity. *Undergraduate thesis at Deutsches Zentrum für Luft-und Raumfahrt, Stuttgart and Rheinisch-Westfälische Technische Hochschule Aachen, Germany*.

[189] Palenzuela, P., Zaragoza, G., Alarcón, D., and Blanco, J. (2011). Simulation and evaluation of the coupling of desalination units to parabolic-trough solar power plants in the Mediterranean region. *Desalination*, *281*, 379-387.

[190] Blanco, J., Palenzuela, P., Alarcón, D., Zaragoza, G., Guillén, E., and Ibarra, M. (2011). Assessment of suitable configurations for combined Solar Power and Desalination plants. In *2nd European Conference on Polygeneration*.

[191] Ali, M. T., Fath, H. E., and Armstrong, P. R. (2011). A comprehensive techno-economical review of indirect solar desalination. *Renewable and Sustainable Energy Reviews*, *15*(8), 4187-4199.

[192] International Energy Agency (IEA), “Technology Roadmap, Solar Thermal Electricity, 2014 Edition,” International Energy Agency (IEA), Paris, 2014.

[193] Water, U. N. (2014). The United Nations world water development report 2014: water and energy. United Nations, Paris.

[194] Saroosh, M. A., Ahmed, S., Hamed, O. A., Al-Shail, K. A., Ihm, S., Chung, H., ... and Abu-Derman, F. A. (2015). Technoeconomic evaluation of concentrated solar thermal (heat only) assisted satellite MED-TVC. In *IDA World Congress*.

[195] Hamed, O. A., Kosaka, H., Bamardouf, K. H., Al-Shail, K., and Al-Ghamdi, A. S. (2016). Concentrating solar power for seawater thermal desalination. *Desalination*, *396*, 70-78.

[196] The freeing Energy Project MARCH 10, 2019 BY BILL NUSSEY

Accessed: 19 December 2019. https://www.freeingenergy.com/why-does-the-cost-of-renewable-energy-continue-to-get-cheaper-and-cheaper/

[197] Burger, B. (2017). Fraunhofer institute for solar energy systems ISE.

[198] Zhang, X., and Bauer, C. 9 Solar photovoltaics (PV).

[199] Hasan, M. A., and Sumathy, K. (2010). Photovoltaic thermal module concepts and their performance analysis: a review. *Renewable and sustainable energy reviews*, *14*(7), 1845-1859.

[200] Jack, J. J. B., Noble, D., and Tsien, R. W. (1975). Electric current flow in excitable cells.

[201] Skoplaki, E., and Palyvos, J. A. (2009). On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Solar energy*, *83*(5), 614-624.

[202] Williams, R. (1960). Becquerel photovoltaic effect in binary compounds. *The journal of Chemical physics*, *32*(5), 1505-1514.

[203] Esayas, H. (2018). *Design and Performance Analysis of Small-Scale Milk Chiller by Using PV System* (Doctoral dissertation, AAU).

[204] Cheng, T. C., Cheng, C. H., Huang, Z. Z., and Liao, G. C. (2011). Development of an energy-saving module via combination of solar cells and thermoelectric coolers for green building applications. *Energy*, *36*(1), 133-140.

[205] Niaz, M., Klassen, S., McMillan, B., and Metz, D. (2010). Reconstruction of the history of the photoelectric effect and its implications for general physics textbooks. *Science Education*, *94*(5), 903-931.

[206] Hasan, M. D. (2017). Cathode Interface Engineering for High Performance Planar Perovskite Solar Cells.

[207] Jacobsson, S., Sandén, B., and Bångens, L. (2004). Transforming the energy system—the evolution of the German technological system for solar cells. *Technology analysis and strategic management*, *16*(1), 3-30.

[208] Gangopadhyay, U., Jana, S., and Das, S. (2013). State of art of solar photovoltaic technology. In *Conference Papers in Science* (Vol. 2013). Hindawi.

[209] Matroni, D. R. (2011). Photovoltaic System Acceptability in the Future.

[210] Green, M. A. (2005). Silicon photovoltaic modules: a brief history of the first 50 years. *Progress in Photovoltaics: Research and applications*, *13*(5), 447-455.

[211] Fraas, L. M., Avery, J. E., Sundaram, V. S., Dinh, V. T., Davenport, T. M., Yerkes, J. W., ... and Emery, K. A. (1990, May). Over 35% efficient GaAs/GaSb stacked concentrator cell assemblies for terrestrial applications. In *IEEE Conference on Photovoltaic Specialists* (pp. 190-195). IEEE.

[212] van den Heuvel, S. T., and Van den Bergh, J. C. (2009). Multilevel assessment of diversity, innovation and selection in the solar photovoltaic industry. *Structural Change and Economic Dynamics*, *20*(1), 50-60.

[213] King, R. R., Law, D. C., Edmondson, K. M., Fetzer, C. M., Kinsey, G. S., Yoon, H., ... and Karam, N. H. (2007). 40% efficient metamorphic GaInP⁄GaInAs⁄Ge multijunction solar cells. *Applied physics letters*, *90*(18), 183516.

[214] Frass, L. (2014) "Low cost solar electric power".1st edn. New York: Springer

[215] Ramanujam, J., and Singh, U. P. (2017). Copper indium gallium selenide based solar cells–a review. *Energy and Environmental Science*, *10*(6), 1306-1319.

[216] Pilipenko, A. (2019, March). The Main Problem of Photovoltaic Energy and Possible Ways to Solve It: Historical and Technical Approach. In *2019 International Conference on Engineering Technologies and Computer Science (EnT)* (pp. 112-116). IEEE.

[217] Assembe, C. O. (2016). *Integrated Solar Photovoltaic and Thermal System for enhanced energy efficiency* (Doctoral dissertation, Cape Peninsula University of Technology).

[218] Philipps, S. P., Bett, A. W., Horowitz, K., and Kurtz, S. (2015). *Current status of concentrator photovoltaic (CPV) technology* (No. NREL/TP-5J00-65130). National Renewable Energy Lab.(NREL), Golden, CO (United States).

[219] Green, M. A., Emery, K., Hishikawa, Y., Warta, W., and Dunlop, E. D. (2015). Solar cell efficiency tables (*Version 45). Progress in photovoltaics: research and applications, 23(1), 1-9. Graph: Fraunhofer ISE 2019*

[220] Crisp, Gary. "Desalination in Australia" presentation, May 2010.

[221] Global Water Intelligence. Volume 12, Issue 12, December 2011.

[222] San Diego County Water Authority. "Overview of Key Terms for a Water Purchase Agreement between the San Diego County Water Authority and Poseidon Resources" presentation, September 2012.

[223] Elfaqih, Albashir KH. and Said O. Belhaj. "Economic analysis of SWRO desalination plant design using three different power systems." *2019 10th International Renewable Energy Congress (IREC)* (2019): 1-6.

[224] Mohsen, M. S., and Jaber, J. O. (2001). A photovoltaic-powered system for water desalination. *Desalination*, *138*(1-3), 129-136.

[225] Hrayshat, E. S. (2008). Brackish water desalination by a stand-alone reverse osmosis desalination unit powered by photovoltaic solar energy. *Renewable Energy*, *33*(8), 1784-1790.

[226] Mohamed, E. S., and Papadakis, G. (2004). Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. *Desalination*, *164*(1), 87-97.

[227] Mohamed, E. S., Papadakis, G., Mathioulakis, E., and Belessiotis, V. (2008). A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems—a technical and economical experimental comparative study. *Desalination*, *221*(1-3), 17-22.

[228] Thomson, M. (2003). *Reverse-osmosis desalination of seawater powered by photovoltaics without batteries* (Doctoral dissertation, © A. Murray Thomson).

[229] Thomson, M., and Infield, D. (2003). A photovoltaic-powered seawater reverse-osmosis system without batteries. *Desalination*, *153*(1-3), 1-8.

[230] Went, J., Kroemke, F., Schmoch, H., and Vetter, M. (2010). The energy demand for desalination with solar powered reverse osmosis units. *Desalination and Water Treatment*, *21*(1-3), 138-147.

[231] Schies, A., Went, J., Heidtmann, C., Eisele, M., Kroemke, F., Schmoch, H., and Vetter, M. (2010). Operating control strategies and dimensioning of photovoltaic powered reverse osmosis desalination plants without batteries. *Desalination and Water Treatment*, *21*(1-3), 131-137.

[232] Dallas, S., Sumiyoshi, N., Kirk, J., Mathew, K., and Wilmot, N. (2009). Efficiency analysis of the Solarflow–An innovative solar-powered desalination unit for treating brackish water. *Renewable Energy*, *34*(2), 397-400.

[233] S. F. Cheah, "Photovoltaic Reverse Osmosis Desalination System," ITN Energy Systems, Inc., Littleton, CO2004.

[234] Riffel, D. B., and Carvalho, P. C. (2009). Small-scale photovoltaic-powered reverse osmosis plant without batteries: Design and simulation. *Desalination*, *247*(1-3), 378-389.

[235] Joyce, A., Loureiro, D., Rodrigues, C., and Castro, S. (2001). Small reverse osmosis units using PV systems for water purification in rural places. *Desalination*, *137*(1-3), 39-44.

[236] Herold, D., Horstmann, V., Neskakis, A., Plettner-Marliani, J., Piernavieja, G., and Calero, R. (1998). Small scale photovoltaic desalination for rural water supply-demonstration plant in Gran Canaria. *Renewable Energy*, *14*(1-4), 293-298.

[237] Herold, D., and Neskakis, A. (2001). A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria. *Desalination*, *137*(1-3), 285-292.

[238] Al Suleimani, Z., and Nair, V. R. (2000). Desalination by solar-powered reverse osmosis in a remote area of the Sultanate of Oman. *Applied Energy*, *65*(1-4), 367-380.

[239] Tzen, E., Theofilloyianakos, D., and Kologios, Z. (2008). Autonomous reverse osmosis units driven by RE sources experiences and lessons learned. *Desalination*, *221*(1-3), 29-36.

[240] Tzen, E., Perrakis, K., and Baltas, P. (1998). Design of a stand alone PV-desalination system for rural areas. *Desalination*, *119*(1-3), 327-333.

[241] Tzen, E., Theofilloyianakos, D., Sigalas, M., and Karamanis, K. (2004). Design and development of a hybrid autonomous system for seawater desalination. *Desalination*, *166*, 267-274.

[242] Watermakers, S. (2009). SSW 3500 Datasheet.

[243] Abdallah, S., Abu-Hilal, M., and Mohsen, M. S. (2005). Performance of a photovoltaic powered reverse osmosis system under local climatic conditions. *Desalination*, *183*(1-3), 95-104.

[244] Richards, B. S., and Schäfer, A. I. (2003). Photovoltaic-powered desalination system for remote Australian communities. *Renewable Energy*, *28*(13), 2013-2022.

[245] Bhujle, A. S. (2013). *Autonomous control and membrane maintenance optimisation of photovoltaic reverse osmosis systems* (Doctoral dissertation, Massachusetts Institute of Technology).

[246] Bilton, A. M., Wiesman, R., Arif, A. F. M., Zubair, S. M., and Dubowsky, S. (2011). On the feasibility of community-scale photovoltaic-powered reverse osmosis desalination systems for remote locations. *Renewable Energy*, *36*(12), 3246-3256.

[247] Wilf, M. (2004, December). Fundamentals of RO-NF technology. In *International conference on desalination costing, Limassol*.

[248] M. Thomson and D. Infield, "Laboratory demonstration of a photovoltaic-powered seawater reverse-osmosis system without batteries," Desalination, vol. 183, pp. 105-111, 2005.

[249] Ahmed, F. E., Hashaikeh, R., and Hilal, N. (2019). Solar powered desalination–Technology, energy and future outlook. *Desalination*, *453*, 54-76.

[250] Siddiqi, A., and Anadon, L. D. (2011). The water–energy nexus in Middle East and North Africa. *Energy policy*, *39*(8), 4529-4540.

[251] Marzooq, M., Alsabbagh, M., and Al-Zubari, W. (2018). Energy Consumption in the Municipal Water Supply Sector in the Kingdom of Bahrain. *Computational Water, Energy, and Environmental Engineering*, *7*(03), 95.

[252] Alsayegh, O., Alhajraf, S., and Albusairi, H. (2010). Grid-connected renewable energy source systems: challenges and proposed management schemes. *Energy Conversion and Management*, *51*(8), 1690-1693.

[253] Shafiullah, G. M., Oo, A. M., Ali, A. S., and Wolfs, P. (2013). Potential challenges of integrating large-scale wind energy into the power grid–A review. *Renewable and sustainable energy reviews*, *20*, 306-321.

[254] DeNicola, E., Aburizaiza, O. S., Siddique, A., Khwaja, H., and Carpenter, D. O. (2015). Climate change and water scarcity: the case of Saudi Arabia. *Annals of global health*, *81*(3), 342-353.

[255] Mokheimer, E. M., Sahin, A. Z., Al-Sharafi, A., and Ali, A. I. (2013). Modeling and optimisation of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia. *Energy Conversion and Management*, *75*, 86-97.

[256] Drewes, J. E., Patricio Roa Garduño, C., and Amy, G. L. (2012). Water reuse in the Kingdom of Saudi Arabia–status, prospects and research needs. *Water Science and Technology: Water Supply*, *12*(6), 926-936.

[257] Caldera, U., Bogdanov, D., Afanasyeva, S., and Breyer, C. (2018). Role of seawater desalination in the management of an integrated water and 100% renewable energy based power sector in Saudi Arabia. *Water*, *10*(1), 3.

[258] Market, G. W. (2017). Meeting the world's water and wastewater needs until 2020. *Global Water Intelligence*, *18*(5).

[259] https://www.businesswire.com/news/home/20180125006048/en/Saudi-Water-Desalination-Capacity-Sets-Global-Record

[260] Saline Water Conversion Corporation http://www.swcc.gov.sa/Arabic/Pages/Home.aspx (accessed Dec. 30, 2019).

[261] Gude, V. G. (2016). Desalination and sustainability–an appraisal and current perspective. *Water research*, *89*, 87-106.

[262] Fthenakis, V., Atia, A. A., Morin, O., Bkayrat, R., and Sinha, P. (2016). New prospects for PV powered water desalination plants: case studies in Saudi Arabia. *Progress in Photovoltaics: Research and Applications*, *24*(4), 543-550.

[263] Rambo, K. A., Warsinger, D. M., Shanbhogue, S. J., and Ghoniem, A. F. (2017). Water-energy nexus in Saudi Arabia. *Energy Procedia*, *105*, 3837-3843.

[264] Taher, N., and Hajjar, B. (2013). *Energy and environment in Saudi Arabia: Concerns and opportunities*. Springer Science and Business Media.

[265] Trieb, F., and Elnokraschy, H. (2007). Concentrating solar power for seawater desalination. *IWCT*, *12*, 2-13.

[266] Saudia Arabia Vision 2030 http://vision 2030.gov.sa (accessed Dec 30, 2019).

[267] Jurgenson, S., Bayyari, F. M., and Parker, J. (2016). A comprehensive renewable energy program for Saudi Vision 2030.

[268] Solar GIS solargis.com (accessed Dec 30, 2019).

[269] Zell, E., Gasim, S., Wilcox, S., Katamoura, S., Stoffel, T., Shibli, H., ... and Al Subie, M. (2015). Assessment of solar radiation resources in Saudi Arabia. *Solar Energy*, *119*, 422-438.

[270] Atlas, R. R. (2015). King Abdullah City for Atomic and Renewable Energy (KA CARE), Saudi Arabia. *Online: http://rratlas. energy. gov. sa*.

[271] Stodola, N., and Modi, V. (2009). Penetration of solar power without storage. *Energy Policy*, *37*(11), 4730-4736.

[272] King D L, Boyson W E and Kratochvil J A 2002 Analysis of factors influencing the annual energy production of photovoltaic systems Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002. pp 1356–61

[273] Duffle, J. A., and Beckman, W. A. (1991). Solar engineering of thermal processes. seconded.

Appendices

Appendix-I

Table I.1 Water Resources National Plan (PHN) water desalination projects in Spain latest by June 2009

Autonomous region	Province	Desalination plants	Capacity (m^3/day)	Situation
Cataluña	Girona	La Tordera plant enlargement	40,000	Project approved
	Barcelona	Barcelona	240,000	Under construction
Baleares	Baleares	4 plants	68,000	Under construction
Valencia Community	Alicante	Alicante, I plant enlargement	24,000	Operating since 2004
		Antonio León Martínez Campos	96,000	Operating since 2004
		San Pedro del Pinatar II	200,000	Operating since 2004
		Alicante II	96,000	Operating since 2004
		Torrevieja	320,000	Under construction
		Mojón plant enlargement	16,000	Project approved
		Denia	36,000	Project approved
		Marina Baja, Campello	72,000	Under construction
		Vega Baja	160,000	Public consulting
	Castellón	Oropesa	72,000	Under construction
		Moncófar	60,000	Project approved
	Valencia	Sagunto	32,000	Under construction
Murcia	Murcia	Valdelentisco	200,000	Operating since 2004
		Aguilas-Guadalentin	280,000	Under construction
Andalucía	Almería	Carboneras I	168,000	Operating since 2004
		Nijar	80,000	Under construction
		Bajo Almanzora	80,000	Under construction
		Campo de Dalías	120,000	Under construction
		Adra	20,000	Public consulting
	Málaga	Marbella	80,000	Operating since 2004
		El Atabal	240,000	Operating since 2004
		Costa del Sol Occidental	80,000	Project approved
Canary Islands	Canarias	Canarias I	36,000	Under construction
		Canarias II	40,000	Project approved
Ceuta	Ceuta	Ceuta I	30,000	Operating since 2004

Appendix-II

The following is the list of experts from Spain and GCC who participated in the research study:

From Spain:

1. Khayet. Mohamed.
Company / Organisation: University Complutense of Madrid
Key Qualifications: Professor and senior researcher in the field of membrane science, nanotechnology and desalination. He coordinated various national and international research projects. More than 20 years' experience in the field.

2. Hicham El Bakouri
Company / Organisation: RandD Center, Abengoa Water.
Key Qualifications: Researcher; Seawater reverse osmosis brine management; Evaluation of emerging desalination processes; Participation in R&D projects.

3. Gracia de Lourdes
Company / Organisation: Professors in University of Seville.
Key Qualifications: Efficient design on Water Desalination Facilities; Design and implementation of impact evaluations.

4. Julián Blanco Gálvez
Company / Organisation: CIEMAT- PSA (Almeria, Spain)
Key Qualifications: Senior Researcher of the Spanish Ministry of Education and Science. Head of Environmental Applications of Solar Energy. Large experience in the management and coordination of large international research projects and consortiums in the field of solar energy and desalination applications.

5. Diego-César Alarcón Padilla
Company / Organisation: CIEMAT- PSA (Almeria, Spain)
Key Qualifications: Ph.D. Coupling of a double-effect absorption heat pump to a desalination system: application to solar distillation- Senior Researcher in the Environmental Applications of Solar Energy Unit.

6. Jorge Pérez Pérez
Company / Organisation Professors in University of Granada.
Key Qualifications Ph.D. Civil Engineering, Researcher in water treatment "Membrane" Technologies, as well working in water treatment with big and leading companies in the water sector, such as CADAGUA and ACCIONA Aguas.

7. Miguel Angel Gómez Nieto
Company / Organisation Professors in the University of Granada.

Key Qualifications: Head of service public domain management hydraulic in the Andalusian water agency and head of the provincial coastal service in Almería belonging to the ministry of agriculture and fisheries, food and environment of the state.

8. Jose Manuel Poyatos
Company / Organisation: Associate Professor in University of Granada.
Key Qualifications: PhD Chemical Engineer, researcher in water and wastewater treatment for 15 years with more than 60 papers with impact factor publishing in this field.

9. Juan Antonio de la Fuente
Company / Organisation: Canary Islands Institute of Technology (ITC).
Key Qualifications: Projects Engineer at the Water Department; Participation in more than 20 international and national research projects related to desalination.

10. Rocío Rodríguez-Aguilera
Company / Organisation: RandD Center, Abengoa Water.
Key Qualifications: PhD Process and Chemical Engineering; Participation in 13 International Projects as Principal Investigator in the Desalination Process; Management of research groups

11. Domingo Zarzo
Company / Organisation: Chemical Engineering Dept. University of Alicante,
Key Qualifications: Researcher. R&D projects about water treatment, desalination, marine pollution, founding member of the Renewable Energy Desalination Working Group of the European Desalination Society

12. Eva Mur Ortega
Company / Organisation: IDOM
Key Qualifications. Water Projects Manager; Water Treatment and Purification; membrane technologies for water; Environmental Anal. Chemistry.

13. Guillermo Zaragoza del Aguila
Company / Organisation: CIEMAT-Plataforma Solar de Almería/ Fundación Cajamar
Key Qualifications: Senior researcher on solar desalination; Scientific responsible of the environmental research department; Coordinator of the Renewable Energy Desalination‖ Working Group of the European Innovation Partnership on Water.

14. Baltasar Peñate
Company / Organisation: ITC /Head of Desalination Section
Key Qualifications: Wastewater treatment technologies; Emerging Technologies to Address Water Treatment Problems in Developing Countries; Evaluation of national and international energy policies related to desalination; Researcher and Projects Manager of the Department (Regional and International projects on desalination.

15. Pilar Fernández Ibáñez
Company / Organisation: Head of the group of Solar Treatment of Water of Platform Solar de Almería.
Key Qualifications: Doctor in Sciences Applied Physics (Water); Researcher for water treatment with solar energy; EU and National R&D project; Water disinfection with solar radiation; Senior researcher; Peer-reviewed publications in Science Citation Index Journals.

From GCC:

1. Hammed. Osman.
Company / Organisation: Saline Water Desalination Research Institute (SWDRI), Saline Water Conversion Corporation.
Key Qualifications: Head Thermal Department, research in thermal desalination, Chemical Engineering, and Mechanical Engineering. He is currently engaged in the development of thermal desalination technologies and allied power generation systems.

2. Hany Al-Ansary.
Company / Organisation: King Saud University.
Key Qualifications: Coordinator of multiple-effect distillation technology transfer program with the Saline Water Conversion Corporation and Doosan Heavy Industries.

3. Akili D. Khawaji
Company / Organisation. Royal Commission for Jubail and Yanbu
Key Qualifications: Director for Marafiq Company Program; Design and calculation of desalination systems.

4. Hassan A. Arafat
Company / Organisation: Khalifa University, KU · Center for Membrane and Advanced Water Technology.
Key Qualifications: Professor in the Dept. of Chem. and Env. Eng. at Masdar Institute; He has authored one book, 90 book chapters and journal papers, one patent, and 100+ conference papers.

5. Shadi W Hasan
Company / Organisation: Khalifa University of Science and Technology - Masdar City Campus
Key Qualifications: Assistant Professor; Technical analysis, calculation, modeling, simulation; Supervisor of Ph.D. theses related to water treatment.

6. Mohamed F. Hamoda
Company / Organisation: United Arab Emirates University, Water and Environmental Engineering.
Key Qualifications: Assistant Professor; Reverse electrodialysis desalination system designed with photovoltaics.

7. Aliewi, Amjad S
Company / Organisation: Kuwait Institute for Scientific Research, Water Research Center.

Key Qualifications: Researcher in Water Resources Engineering and Civil Engineering; Operation and maintenance of desalination projects with renewable energy.

8. Mohammed Darwish.
Company / Organisation: Kuwait Foundation for the Advancement of Science.
Key Qualifications: Consultant at Kuwait Foundation for the Advancement of Sciences; Desalination and Water Treatment Reverse osmosis.

9. Yousef Al-Wazzan
Company / Organisation: Water Resources Division, Water Desalination Department, Kuwait Institute for Scientific Research.
Key Qualifications: Researcher; Thermal desalination systems Reverse osmosis, Membrane distillation.

10. Yassine Charabi
Company / Organisation: Department of Geography, College of Arts, Sultan Qaboos University
Key Qualifications: Associate Professor; Director, Center for Environmental Studies and Research of Desalination.

11. Salem Ali Al-Jabri
Company / Organisation: Department of Soils, Water, and Agricultural Engineering.
Key Qualifications: Assistant Professor; Peer-reviewed publications in Science; working on desalination projects dedicated to the evaluation of different desalination systems.

12. B.S. CHOUDRI
Company / Organisation: Center for Environmental Studies and Research (CESAR).
Key Qualification: Senior Research Scientist; experience in Research, Consultancy and Project Management in varied Sustainability Initiatives, including Water, Global Climate Change and Community engagement.

Appendix-III

QUESTIONNAIRE

Use of an analytical hierarchy process for the selection of adequate desalination technologies for Spain and the Gulf Cooperation Council

Dear participant,

In the following sheets, I would like to elicit your opinion as an expert on desalination research, as knowledge and economics.

Background:

This research is an attempt to identify the most suitable technology for the specific conditions used by soliciting expert opinions. Based on the main relevant factors, the Analytical Hierarchy Process was utilised to select the most appropriate technology for seawater desalination in Spain and GCC. The selection process in this study was limited to seven factors and water distillation process aforementioned. The water distillation process is taken into consideration in this research as it is important to select the most appropriate technology relevant to the region for the water desalination process.

The analytic hierarchy process included three-levels. The first level is goals: the objective to be achieved; the second level is Criteria: the elements based on which the alternatives are evaluated; and, finally, the third level presents the alternatives: the possible set of actions, a good choice from which will depend. You can see this in Figure 1.

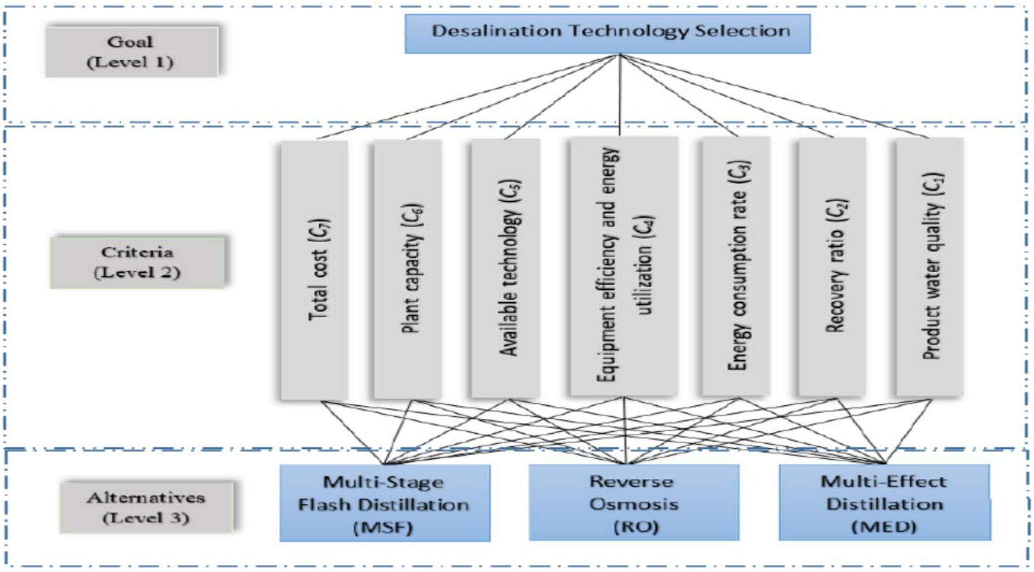


Figure 1. Three-level hierarchal representation of the problem with seven criteria and three alternatives

In more detail, the following sheets, we would like to elicit your opinion as an expert in order to select amongst the alternatives. The pairwise comparison scale by Saaty, reported in **Table-1**, can be used to express the importance of one element over another.

Acronyms and Abbreviations for Criteria and Alternatives:

Symbol	Criteria
C_1	Product water quality
C_2	Water Recovery
C_3	Energy consumption rate
C_4	Equipment efficiency and type of energy utilization
C_5	Available technology
C_6	Plant capacity
C_7	Total cost
Symbol	**Alternatives**
a_1	Multi-stage flash MSF
a_2	Multi-effect distillation MED
a_3	Reverse Osmosis RO

Note: we use the number 9 to represent any criteria or technology that is absolutely more important than another.

If you think that the product water quality is more important than recovery ratio, then put a mark between number 1 and 9 on the left side, while if you think the recovery ratio is more than the product water quality, then mark the right side.

Table 1. Scale of Comparison (Saaty):

Extreme Importance	Very strong Importance	Strong Importance	Moderate Importance	Equal Importance	Moderate Importance	Strong Importance	Very Strong Importance	Extreme Importance
9	7	5	3	1	3	5	7	9

First compare the criteria with each other:

1. Product water quality (Choose Number) (-) — Recovery ratio as a function of the feed (-) (Choose Number)

9	7	5	3	1	3	5	7	9

2. Product water quality (Choose Number) (-) — Energy consumption per unit product water (Choose Number) (-)

9	7	5	3	1	3	5	7	9

3. Product water quality (Choose Number) (-) — Equipment efficiency and energy utilization (Choose Number) (-)

9	7	5	3	1	3	5	7	9

4. Product water quality (Choose Number) (-) — Available technology (Choose Number) (-)

9	7	5	3	1	3	5	7	9

5. Product water quality (Choose Number) (-) — Plant capacity (Choose Number) (-)

9	7	5	3	1	3	5	7	9

6. Product water quality (Choose Number) (-) — Total cost (Choose Number) (-)

9	7	5	3	1	3	5	7	9

7. Recovery Ratio (Choose Number) (-) — Energy consumption per unit product water (Choose Number) (-)

9	7	5	3	1	3	5	7	9

8. Recovery Ratio (Choose Number) (-) — Equipment efficiency and energy utilization (Choose Number) (-)

9	7	5	3	1	3	5	7	9

9. Recovery Ratio (Choose Number) (-) — Available technology (Choose Number) (-)

9	7	5	3	1	3	5	7	9

10. Recovery Ratio (Choose Number) (-) — Plant capacity (Choose Number) (-)

9	7	5	3	1	3	5	7	9

11. Recovery Ratio (Choose Number (-)) — Total cost (Choose Number (-))

9	7	5	3	1	3	5	7	9

12. E . C. per unit product (Choose Number (-)) — Equipment efficiency and energy utilization (Choose Number (-))

9	7	5	3	1	3	5	7	9

13. E . C. per unit product (Choose Number (-)) — Available technology (Choose Number (-))

9	7	5	3	1	3	5	7	9

14. E . C. per unit product (Choose Number (-)) — Plant capacity (Choose Number (-))

9	7	5	3	1	3	5	7	9

15. E . C. per unit product (Choose Number (-)) — Total cost (Choose Number (-))

9	7	5	3	1	3	5	7	9

16. Available technology (Choose Number (-)) — Plant capacity (Choose Number (-))

9	7	5	3	1	3	5	7	9

17. Available technology (Choose Number (-)) — Total cost (Choose Number (-))

9	7	5	3	1	3	5	7	9

18. Plant capacity (Choose Number (-)) — Total cost (Choose Number (-))

9	7	5	3	1	3	5	7	9

Second compare the technology together with respect to each criteria:

Pair-wise comparison of the different technologies with respect to equipment efficiency and energy utilization (EE).

1. MSF (Choose Number (-)) — MED (Choose Number (-))

9	7	5	3	1	3	5	7	9

2. MSF (Choose Number (-)) — RO (Choose Number (-))

9	7	5	3	1	3	5	7	9

3. MED (Choose Number (-)) — RO (Choose Number (-))

9	7	5	3	1	3	5	7	9

Pair-wise comparison of the different technologies with respect to energy consumption rate (EC).

4. **MSF** Choose Number (-) **MED** Choose Number (-)

9	7	5	3	1	3	5	7	9

5. **MSF** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

6. **MED** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

Pair-wise comparison of the different technologies with respect to required product quality (PQ).

7. **MSF** Choose Number (-) **MED** Choose Number (-)

9	7	5	3	1	3	5	7	9

8. **MSF** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

9. **MED** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

Pair-wise comparison of the different technologies with respect to the available technology (AT).

10. **MSF** Choose Number (-) **MED** Choose Number (-)

9	7	5	3	1	3	5	7	9

11. **MSF** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

12. **MED** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

Pair-wise comparison of the different technologies with respect to plant capacity (PC).

13. **MSF** Choose Number (-) **MED** Choose Number (-)

9	7	5	3	1	3	5	7	9

14. **MSF** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

15. **MED** Choose Number (-) **RO** Choose Number (-)

9	7	5	3	1	3	5	7	9

Pair-wise comparison of the different technologies with respect to recovery ratio (RR).

16. **MSF** Choose Number (-) **MED** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

17. **MSF** Choose Number (-) **RO** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

18. **MED** Choose Number (-) **RO** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

Pair-wise comparison of the different technologies with respect to total cost (TC).

19. **MSF** Choose Number (-) **MED** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

20. **MSF** Choose Number (-) **RO** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

21. **MED** Choose Number (-) **RO** Choose Number (-)

9	**7**	**5**	**3**	**1**	**3**	**5**	**7**	**9**

Please give us any additional comment (optional):

____

____

____

____

Name: ____
Organization/Company: ____

This survey can be returned by email to kalshail13@gmail.com
It can be sent by fax to (+34) 722120003
Or by mail to Calle Pacifico,38 Bluqe,2 Portal,3 29004 Malaga – Spain.

Khalid AL-Shail
PhD Student
With many thanks for your effort and time.

Appendix IV

Comparison of CSP technologies

The CSP technologies used in this study are compared in Table-1.

Table-1. Comparison of parabolic trough (PT), linear Fresnel (LFR) and central receiver tower (CRT) technologies:

Solar Field Type	Parabolic Trough	Linear Fresnel	Central Receiver Tower
State of the Art	Commercial	Commercial	Commercial
Typical Unit Size (MW)	5 - 200	1 - 200	10 - 100
Construction Requirements	Demanding	Simple	Demanding
Operating Temperature (^{o}C)	390	270 - 550	550 - 1000
Heat Transfer Fluid	Synthetic oil, water/steam	Water/steam	Air, molten salt, water/steam
Thermodynamic Power Cycle	Rankine	Rankine	Brayton, Rankine
Power Unit	Steam turbine	Steam turbine	Gas turbine, steam turbine
Experience	High	Moderate	Moderate
Reliability	High	Moderate	Moderate
Thermal Storage Media	Molten salt, concrete, PCM (phase change material)	Molten salt, concrete, PCM (phase change material)	Molten salt, ceramics, PCM (phase change material)
Combination with Desalination	Simple	Simple	Simple
Integration to the Environment	Difficult	Simple	Moderate
Operation requirements	Demanding	Simple	Demanding
Land Requirement	High	Low	High

Appendix-V

Table-1. First Project (AQUASOL)

<table>
<tr>
<td>(AQUASOL)

Project in
Spain</td>
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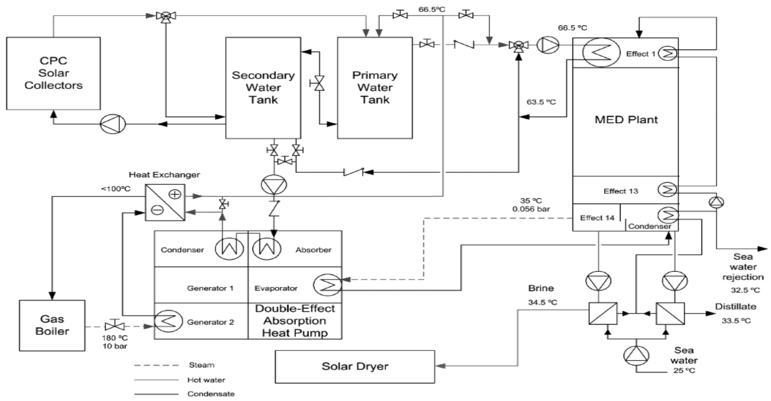

Configuration of AQUASOL seawater desalination system
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<td>The Aquasol project started in 2002 with a duration of four years. Its main objective was to develop MED desalination technology that could be powered by solar energy [59]. The development of an improved Double Effect Absorption Heat Pump (DEAHP), and the reduction to zero of brine discharge were also in the to-do-list. A 500 m^2 Compound Parabolic Concentrator (CPC) solar collector field, two water storage tanks, and a MED, together with a DEAHP using H_2O-LiBr, were erected and operated, and sub-systems have been modelled to estimate system behaviour and develop control techniques for maintaining optimal operating conditions [60]. The results showed that plant specific consumption was in the order of 60 to 70 kWh per m^3 in the solar only mode, and 35 to 40 kWh per m^3 when using the DEAHP (fossil fuel mode only). During the testing, it was concluded that very reduced thermal losses were happening during operation or at night from the thermal storage system, allowing a simple and flexible operation of the MED plant, both when powered by the solar field or with gas and the DEAHP.</td>
</tr>
</table>

Table-2. Second Project (Powersol)

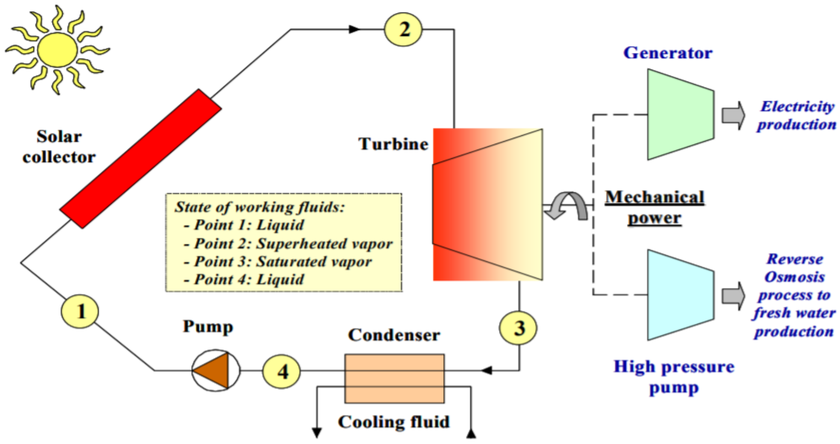
(POWERSOL) **Project in** **Spain**	 General concept of POWERSOL technology
	The Powersol project started in 2007 and was assigned to last roughly three years. Its objective was to develop a shaft power generation technology for rural communities based on solar heat thermodynamic cycle, using low to medium temperatures able to power a RO unit. In this project, mechanical energy could be used to directly produce electricity or power a RO unit. A full technical and economic evaluation of these technologies was made, the solar heated thermodynamic cycle was modeled, and three solar collectors prototypes to operate at 80ºC, 100-150ºC, and 200-250ºC, were developed and constructed (using static flat plate collectors, static CPC and a sun-tracking parabolic trough collector).

Table-3. Third Project (AQAB Hotel and RESORT AYLA OASIS)

(AQAB Hotel and RESORT AYLA OASIS) **Project in Jordan**	The DLR study of 2007 on the usage of CSP to power desalination technologies analysed the feasibility of a specific case-study: the Aqaba Hotel and Resort AYLA OASIS project. This study was made by a Jordanian/German consortium to assess the economic and technical feasibility of an integrated usage of 10 MW of power to produce, 10 000 m^3 per day of desalted water, using RO and 40 MW of cooling for the Ayla Oasis Hotel Resort in Aqaba, Jordan. This project assumed the installation of a linear Fresnel concentrating collector field, with a flat Fresnel structure and the usage of a gas boiler to provide steam to a steam turbine. This project aimed to prevent the hotel from buying energy and water from the public grid, to operate compression chillers installed on its rooftop. Additional electricity capacity would need to be installed, equivalent to a natural gas consumption of 85 MW, to produce electricity and fresh water. The project consisted of the usage of absorption chillers for base-load operation during the holiday season, and compression chillers to be used during the peak and intermittent demand [6]. The cold water produced by both types of chillers would flow in a cold-water district grid, connecting the power plant and the different hotel users. According to the DLR study, the usage of such a system would require less than 35% of fuel input, resulting in better efficiency of combined generation and the solar fuel saver. The project consists of an installed capacity of 56 MW using natural gas and 14 MW solar, producing a total of 67 MW. From the 67 MW produced, 15 MW corresponded to electric power, 5 MW were used in compression chillers, and 10 MW used as electricity in the local grid. The remaining 52 MW produced in the form of steam at 100 ºC were used for powering an absorption chiller (24 MW input), and an RO desalination plant (28 MW input). The absorption chillers would convert the 24 MW input in 18 MW thermal, and the compression chillers would convert the 5 MW input to 22 MW thermal. The project is currently under construction.

Appendix-VI

Table-1. Calculation of the energy requirements of a MED-TVC based on a PR of 9

MED	
Capacity (MIGD)	1
Capacity (m^3/day)	4546
PR	9
Pressure of steam to ST (bar)	15
Temperature of steam to ST (^{0}C)	200
Enthalpy of steam to ST (kJ/kg)	2796.02
Condensed water pressure in ST (bar)	10
Condensed water temperature in ST (^{0}C)	75
Enthalpy of condensed water in ST (kJ/kg)	313.72
Gained Output Ratio (GOR)	9.6
Thermal power required (MWt)	13.6
Thermal energy required per day (MWh)*	108.84
Thermal energy required per sun hour (MWh)	13.6

* Assuming there are only 8 hours of sunlight

Appendix-VII

Table-1. Break even fossil fuel price obtained with different CSP technologies for Yanbu

Yanbu: annual DNI 2281 kWh/m^2	**8hr LFR**	**8hr PT**			**8hr CRT**		
	0hr TES	**0hr TES**	**8hr TES**	**14hr TES**	**0hr TES**	**8hr TES**	**14hr TES**
Capacity factor	0.23	0.26	0.52	0.73	0.19	0.34	0.49
Break even fossil fuel price ($/bbl)	44	51	71.5	77	61	76	74
Normalised break even LCOW	0.53	0.60	0.78	0.80	0.68	0.78	0.75
Fossil fuel saved (bbl/yr)	18650	21038	42067	59030	14918	27282	39604
Yearly cash flow based on fuel savings @ 100 $/bbl (million $)*	1.8650	2.1038	4.2067	5.9030	1.4918	2.7282	3.9604
IRR (%)*	21.18	17.13	11.66	10.74	6.71	12.11	12.28
Payback period (years)#	4.71	5.79	8.26	8.87	12.78	7.99	7.89

Table-2. Break even fossil fuel price obtained with different CSP technologies for Jubail

Jubail: annual DNI 1938 kWh/m^2	**8hr LFR**	**8hr PT**			**8hr CRT**		
	0hr TES	**0hr TES**	**8hr TES**	**14hr TES**	**0hr TES**	**8hr TES**	**14hr TES**
Capacity factor	0.19	0.2152	0.4302	0.6035	0.15	0.27	0.39
Break even fossil fuel price ($/bbl)	52.5	62.5	87.5	94	78	96	93.5
Normalised break even LCOW	0.6	0.675	0.9	0.95	0.825	0.975	0.95
Fossil fuel saved (bbl/yr)	15664	17317	34624	48568	11780	21624	31715
Yearly cash flow based on fuel savings @ 100 $/bbl* (million $)	1.5664	1.7317	3.4624	4.8568	1.1780	2.1624	3.1715
IRR (%)*	17.7	13.9	9.3	8.5	4.6	9.2	9.5
Payback period (years)#	5.60	7.03	10.04	10.78	16.19	10.08	9.86

*Assuming that the discount rate (5%) negates fuel price escalation (5%)