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Modeling of Solar Technologies for Desalination

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SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Building Design

OCTOBER 2019

THESSALONIKI – GREECE

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Abstract

This dissertation was written as a part of the MSc in Energy Building Design at the International Hellenic University. This work gives an insight into the current water status globally and desalination technologies capacity used worldwide then further explore different prospects for enterprise solar water desalination technologies to tackle the severe water scarcity issue facing the world. It also gives a comprehensive vision into the latest published works on several solar-based desalination technologies, including solar thermal and membrane technologies, as well as discusses the cost drop of photovoltaic and the use of it for desalination (PV-ED and PV-RO). Moreover, it highlights desalination technologies along with an economic analysis and cost comparison of conventional desalination methods with different solar energy-based techniques. This work modeling a solar-powered desalination technology, specifically RO-PV of an existing plant, will also compare the area of PV panels required to cover the same electrical demand in different regions around the Mediterranean coast at the arid and semi-arid areas in order to produce freshwater using the RO desalination technology.

Firstly, I thank God for having this great chance. I would like to acknowledge my supervisor Professor Georgios Martinopoulos for his support. Special thanks to my beloved parents, my mother Asmaa and my father Jamal, for their support throughout my journey. My sincere thanks to Mr. Rebhy El Sheikh, uncle Ahmed. Finally, I thank everyone who helped and supported me with any assistance throughout the writing of this thesis

Alhindi Shahd

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1. Introduction

The availability of freshwater sources is diminishing hastily as the demand increases rapidly, the continued increase of the population in the globe causes rising demands for natural resources combined with the effects of climate change, especially in arid and coastal regions.

Water and energy management will become more difficult and complicated, with more variations in water and severe weather events, leading to acute flooding and drought due to climate change. 1.2 billion people, about one-fifth of the world's population, live in water-scarce areas [1], and by 2025, approximately two-thirds of the global inhabitants will have no access to clean water [2].

To cope up with this demand, we should develop sustainable and viable water supply, protect freshwater resources, boost efficiency, and lessen our environmental impacts, using desalination as a tool [3].

Notwithstanding the perception of energy and water dependence around the world is a pivotal global link in energy and water issues, the policies that affect each of these sectors are still not well studied at best and unfavorable at worst.

Energy has a major impact associated with water supply, treatment, and distribution. Conversely, energy production requires significant water consumption, leading to an international spotlight on the Water-Energy association, a term used to link these two vital services. This link between energy and water resources is shown in Figure 1 [4].

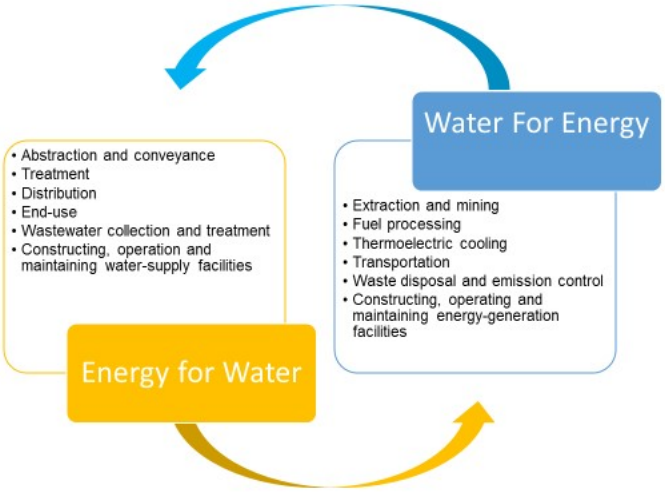


Figure 1 Energy water nexus [4]

As a result of population growth, along with the development of the industrial and agricultural sectors in evolving economies, the available freshwater resources will be depleted, which in turn will cause a rapid deterioration of all of the above [5]. Tackling the situation can occur by finding alternative means of freshwater production. Fortunately, the desalination technology of brackish water and seawater can grapple this issue for humanity to achieve sustainable development goals. Some countries in the Middle East, such as Qatar and Kuwait, are entirely dependent on desalinated water for domestic and commercial supplies [6]. However, conventional desalination plants are energy-intensive, which makes them unsustainable. Fossil fuel desalination has radical effects on the environment [7]; moreover, they have extreme volatility of prices as well as the difficulty of supplying to remote locations.

Desalination produces water by disassociating mineral components from saline water, ensuing drinkable water, which has low levels of total dissolved solids (TDS are dissolved organic and inorganic dissolved salts).

Raw water sources vary around the world. On the one hand, there is a big share of seawater (67%) containing around 3.5% sodium chloride, followed by (19%) brackish water with a concentration of less than 3% sodium chloride, river water (8%). On another hand, there is wastewater with a 6% share as contaminated rejected water after use divided into two categories, Blackwater from toilets otherwise considered as Gray water. However, Freshwater contains less than 1% sodium chloride (NaCl) [8,9]. Under the pressure of the increasing demand on the limited freshwater [5], seawater and brackish water grab the attention of the world for the use of desalination technology as well as the reuse of wastewater.

Although the desalination of seawater has advanced in human history since the use of clay jars and boiling water, it has proven to be one of the most reliable options in water treatment processes, not only meeting the needs of freshwater for drinking but also in all aspects of life including agriculture and industries.

Desalination has the potential to bridge the gap in water scarcity. The difference between freshwater necessities and accessibility will worsen as competing water needs increase along with urbanization as 68% of the world's population in 2050are predicted to live in cities, says UN. Population growth and increased demand for goods and services will lead to an increase in the industrial and agricultural production resulting in an increase in the impact of climate change on the environment. A potential impact on water quality provided may be caused by increased demand for domestic and industrial water [10].

The Food and Agriculture Organization (FAO) has estimated that by 2050, world food production must be increased by 70% to meet the global demand for a population being predicted to reach 9 billion [11]. In parallel with the requirements of other sectors that translate the projections for global primary energy need to increase by one third during the period 2010-2035 [12]. The annual global freshwater market rises and is expected to grow by ~10–12% per decade, giving that the most substantial part is going for agriculture (according to UNESCO, an increase of 38 percent will occur in 2025 compared to 1995 [13]), making energy security and water supply a significant challenge facing contemporary society.

Water, energy, and desalination have a complex correlation, which deepens over time as a growing population and diverse consumption sectors increase the request for water resources [14]. At present, most of the desalination plants are positioned in areas where conventional energy is available at a low cost [15]. At the same time, the international desalination market is growing at a very rapid rate of 55% annually to respond to the exponential increment in demand for potable water, which is mirrored in the enormous investment in desalination technologies globally [16,17].

In Figures 2 and 3, the total worldwide installed capacity by user type is presented. In figure 2, the leading industries using desalination in 2015 are power, refining, oil, and gas. However, the data showed in Figure 3 indicate growth in the mining, food, and beverage, and electronics sectors compared to the historical distribution.

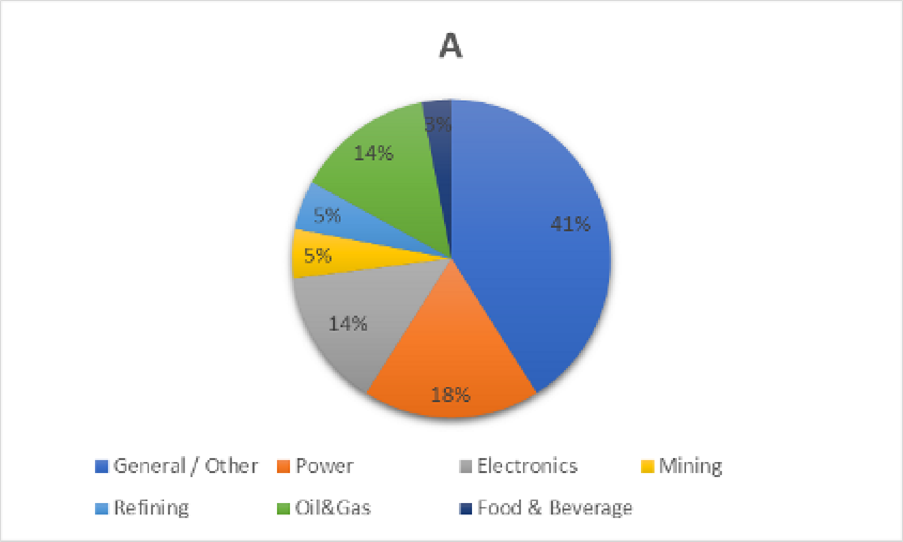


Figure 2 Desalination use in the industrial sector [18]

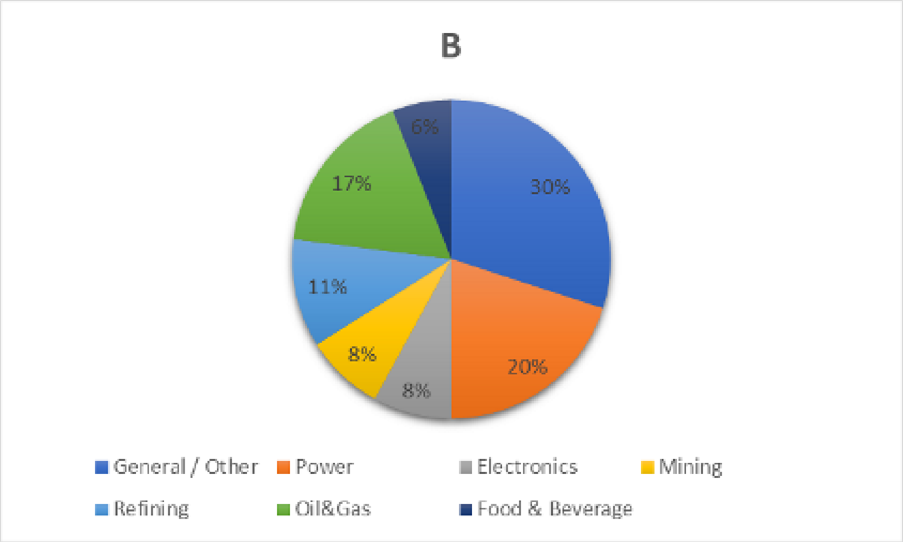


Figure 3 28th Worldwide desalting plant inventory [18]

Even though renewable energy-based desalination may still be relatively expensive, reducing renewable energy costs, technological advances, and increased deployment makes it a cost-effective and sustainable long-term solution that is capable of playing an aggregate role in bridging the water gap. The Middle East and North Africa (MENA) region is one of the most water scarcest regions in the world by 2050; it will fight the water shortages through desalination [18].

Renewable energy sources are continually becoming more widespread and dependable as the costs linked with renewable technology fall yearly, consequently resulting in an extensive use of renewable energy in various parts of the world [19]. Yet, only 1% of total desalinated water in recent years was renewable energy-based [20].

Pike Research had forecasted in 2010 that between 2010 and 2016, the global capacity of desalination plants, including renewable desalination, increased at a compound annual growth rate (CAGR) greater than 9%, per total costs of around the US $88 billion where the MENA region shares 54% of the capacity growth [21].

The electricity grid or fossil fuels may not be the best option for cost-effective energy generation, as in rural and remote areas, onshore, and islands where there is a considerable capacity to rely on for water desalination Due to distances and rough terrain, these areas are not interconnected to the electrical grids. often, the fuels are shipped or flown in from long distances. [20]

The world's water per capita consumption is aggregate twice every two decades and means to beat population growth by twofold [22]. That being the case, water shortage will influence one-third of the population around the world [23,24]. Similarly, it is expected that by 2040, the share of electricity in final consumption moves up towards one-third of the current demand, resulting in a rise in the cost for water use by the energy sector. water scarcity causes an increase in the water price in the energy sector, the energy sector needs electricity, and the price of electricity is increasing. In conclusion, it is a non-ending loop where water and energy prices are correlated [25].

The facts are that renewable energy resources share at the energy mix is which one quarter on 2018 and will rises to two-thirds in 2040 still primarily abandoned and underutilized worldwide compared to their high availability, [25] continuity in fossil fuels as investors perceive them as highly profitable and credible form sources of energy. Nevertheless, widespread desalination technology has led to high energy demand and CO_2 emissions from hydrocarbon energy sources [26].

Investment and funding are key elements to encourage the use of technically viable renewable energy systems, which make the significant potential for the development of integrated desalination technologies as long- and medium-term methods [19,24].

Sustainable desalination systems have yet to be ascertained to meet water needs and if they are technically viable.

By adopting an inland water management strategy, different methods can be used to develop viable alternatives such as desalination, wastewater reuse, and rainwater harvesting systems [27]. The adoption of these methods in desalination techniques has resulted in affordable water supply and increased energy efficiency; it relies on renewable energy sources for water treatment technologies [28,29].

In recent years, the unit cost of energy needed to produce one cubic meter of freshwater has dropped significantly; it leads to remarkable alleviation in the required solar collector areas as well as the number of PV modules in solar-based desalination technologies [30].

Technological innovations will result in abundant freshwater from both seawater and saltwater with minimal penalties on the environment when only relying on renewable and solar energy. Most of the MENA region, the Persian Gulf region, Africa, India, and China allocated on the strategic Sunbelt. Meanwhile, Africa, Asia Pacific, and Middle East countries counted as the most water-deficient areas [19]. Desalination has been influential in enriching the socio-economic in developing countries of these areas. [31]. Likewise, oil-producing nations concluded that they are vulnerable to any future global energy crisis. As a result, they have advanced plans to vary their energy sources. This diversification includes renewable energy sources, primarily solar [32]. Saudi Arabia, for instance, has targeted 23% and 39% of the energy made by photovoltaic and concentrated solar power by 2030 and 2050, in turn [32].

The Gulf Cooperation Council is striving to take advantage of naturally sustainable resource for water production, constructing new desalination plants that mainly rely on solar energy addresses the real threat to resource sustainability [33]. For example, the United Arab Emirates and Saudi Arabia having firm strategies to manage available water basins to prevent rapid degradation and depletion of brackish water levels [19,3

], where 70% of the projected growth of desalination plants between 2007 to 2030 is in SA, the UAE, Kuwait, Algeria, and Libya [35].

Thus, Saudi Arabia prognosticates solar energy to be the best alternative to face the growing demand for water and energy in the long term. In January 2015 Advanced Water Technology (AWT) and Abengoa joint venture was awarded the contract to build the Al Khafji desalination plant in Saudi Arabia, the world’s first large-scale solar-powered desalination plant at a valued cost of US $130 million. It supplies 60,000 m^3 of desalinated seawater per day, ensuring a regular supply of water to the region the whole year round [36].

Giving by the International Desalination Association (IDA), the number of desalination plants worldwide is 19,372 (2017) across all categories versus 18,983 (2016) and a total of 18,436 (2015) [37]. Having a commissioned capacity of 92.5 million m^3/day (2017) serve for the water desires of in excess of 300 million individuals globally who fully/partially rely on desalinated water for their daily water consumption, compared to 88.6 million m3/d in 2016. The accumulative contracted capacity is likely at 99.8 m3/day worldwide (2017) versus 95.6 million cubic meters per day in 2016 [37,38].

The Persian Gulf, Gulf of Oman, and the Red Sea suffer from a critical absence of potable water resources. None the less, 65% of global water desalination capacity installed in the Middle East with high production capacities generally [39]. The world desalination capacities distribution (million m^3/day) in 2009 is shown in Figure 4 [40].

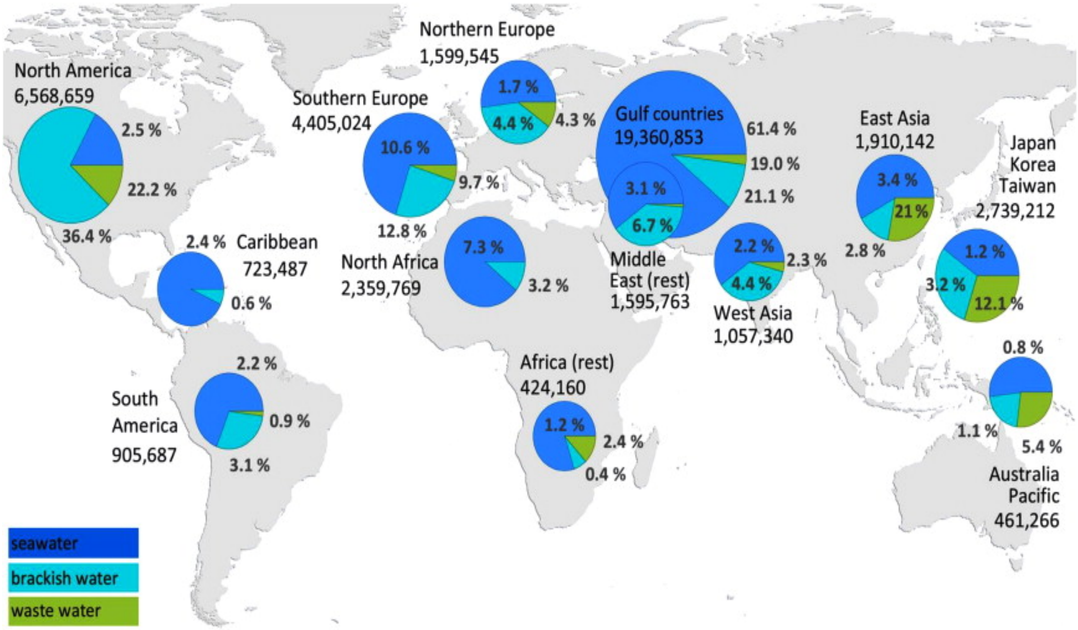


Figure 4 Global distribution of desalination capacitates million m3/day as of 2009 [40]

The MENA area has about 2800 desalination plants making 37.32 million m^3/day of potable water, which is nearly 44% of the global capacity [39,41]. Approximately 54% of the universal growth of desalination plants capacity is expected to occur in the Middle East and North Africa (MENA) region [35], where the 21 million m^3/d of desalinated water produced in 2007 is projected to reach 110 million m^3/d by 2030 [35].

Desalination technology processes are either phase change with evaporating (thermal processes) employing both electricity and heat [42], represented by thermal multi-stage flash (MSF), multi-effect distillation (MED), Thermal or Mechanical Vapor Compression (TVC, MVC) and solar desalination [43], or processes without phase change (membrane technologies), which are only electricity-based [44]. Namely, Reverse Osmosis (RO), Electrodialysis, and Electrodialysis Reversal (ED/EDR) [43]. ED is regularly used for brackish water systems, while RO can be used for both seawater and brackish water [45].

As per the International Desalination Association's statistics, reverse osmosis (RO) covers nearly 65 % of installed capacity, thermal multi-stage flash (MSF) processes mark 21%, multi-effect distillation (MED) delivers 7%, Electrodialysis and Electrodialysis reversal (ED/EDR) make up 3%, nano-filtration provides 2%, and others subsidize 2% as illustrated in Figure 5 [44,46].

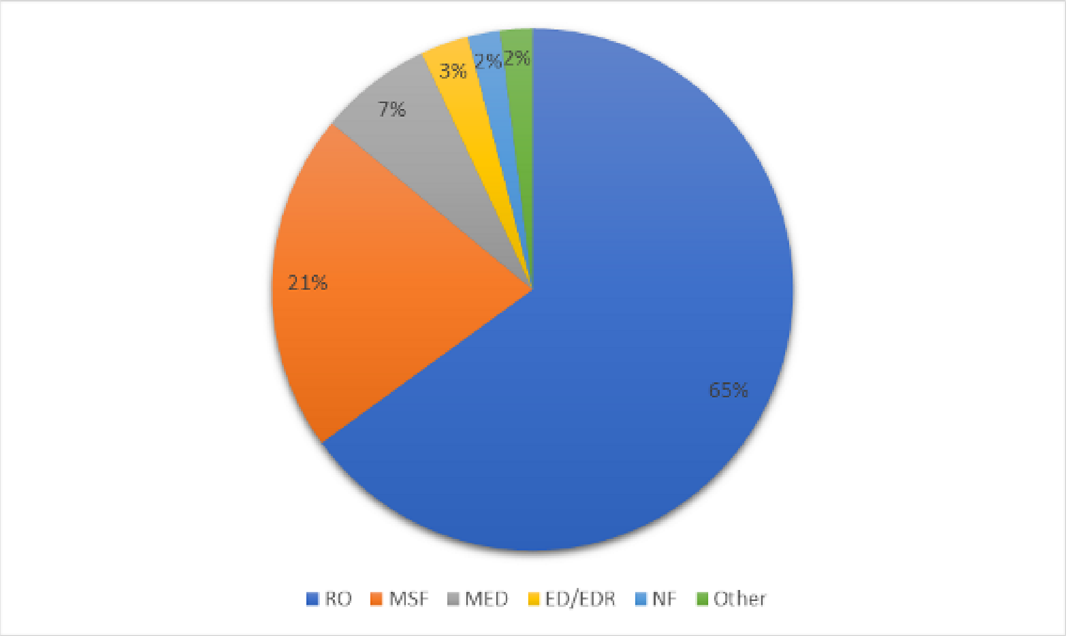


Figure 5 Global installed capacity by technology type[15].

This work gives an insight into the current water status globally and desalination technologies capacity used worldwide then further explore different prospects for enterprise solar water desalination technologies to tackle the severe water scarcity issue facing the world. It also gives a comprehensive vision into the latest published works on several solar-based desalination technologies, including solar thermal and membrane technologies, as well as discusses the cost drop of photovoltaic and the use of it for desalination (PV-ED and PV-RO). Moreover, it highlights desalination technologies along with an economic analysis and cost comparison of conventional desalination methods with different solar energy-based techniques. This work modeling a solar-powered desalination technology, specifically RO-PV of an existing plant, will also compare the area of PV panels required to cover the same electrical demand in different regions around the Mediterranean coast at the arid and semi-arid areas in order to produce freshwater using the RO desalination technology.

1 Desalination technologies

There are approximately 19,372 desalination plants worldwide giving by the International Desalination Association (IDA) with a worldwide commissioned capacity of 92.5 million m^3/day serves for the water needs of over 300 million people globally rely on desalinated water fully/partially for daily freshwater requirements [37].

At the same time, desalination plants are energy-intensive with a negative environmental impact. There has been major progress over the earlier decade in the development of emerging seawater desalination technologies that can significantly reduce specific energy consumption compared to current conventional processes. Membrane-based solar water desalination has an auspicious future as significant advances in the design of membrane modules, pre-treatment, and energy recovery possibilities have empowered these methods to be cost-competitive compared to thermal processes. Membrane-based desalination has replaced thermal desalination in many parts of the world because of low energy consumption [18]. Table 1 shows a comparison between different desalination technologies used and their energy consumption [44].

Table 1Energy consumption of different desalination technologies [44]

Process	Electrical energy consumption	Thermal energy consumption	Total energy consumption
Seawater reverse osmosis (SWRO)	3–4 kWh/m^3 With energy recovery	-	3–4 kWh/m^3
Multi-stage flash (MSF)	2.5–4 kWh/m3	7.5–12 kWh/m3	10–16 kWh/m3
Multi-effect distillation (MED)	1.5–2 kWh/m3	4–7 kWh/m3	5.5–9 kWh/m3

1.1 Desalination capacity worldwide and future prospects

In the first quarter of 2014, the total global desalination capacity stands at 81 million m^3/day. It was expected to reach over 100 million m^3/day, and by 2015 [17], Respectively 92.5 commissioned capacity in 2017 on a global scale [37]. Membrane processes have a share of 68% of the desalinated water, while 30% produced by thermal processes and other technologies subsidize 2% [18]. There are many sources of desalinated water; it's divided between seawater by 59%, brackish groundwater constitutes 22%, and the rest from saline wastewater and surface water [17]. Considering these figures are constantly changing due to the rapid growth of the desalination market.

Thermal desalination was widespread before the 1990s, just before the popularity of membrane technology, whose reverse osmosis dominates its market. While in the thermal exchange, the competition is between MSF and MED. The increase in desalination capacity attributed to the increase in water demand due to the confinement of direct water sources and the significant technological advances which directly affected the cost of desalination and made it cost-competitive [47].

In some areas, desalination is now able to superiorly compete with traditional water resources and water transmissions for drinking water supplies [48].

1.2 Integration of solar energy and desalination technologies, market potential and process selection

The decide on the most suitable renewable energy desalination technology is subject to several factors; the size of the plant is one of them. Figure 6 shows several desalination kits and renewable energy technologies. The salinity of the feed water and the desired product is another factor, the selection of best techniques or processes involves chemical characterization of raw water resources that must be disinfected or desalinated. Desalination/treatment of contaminated surface water or brackish water is more economical (required less energy) than seawater as it has less salinity. Often, the only available source of water in the seashore is seawater and brackish water presented in interior areas. Remoteness, the existence of access to the electricity grid, technical infrastructure, renewable energy source, and it is availability, potential and exploitation cost are crucial factors to be taken into consideration when selecting the appropriate technology.

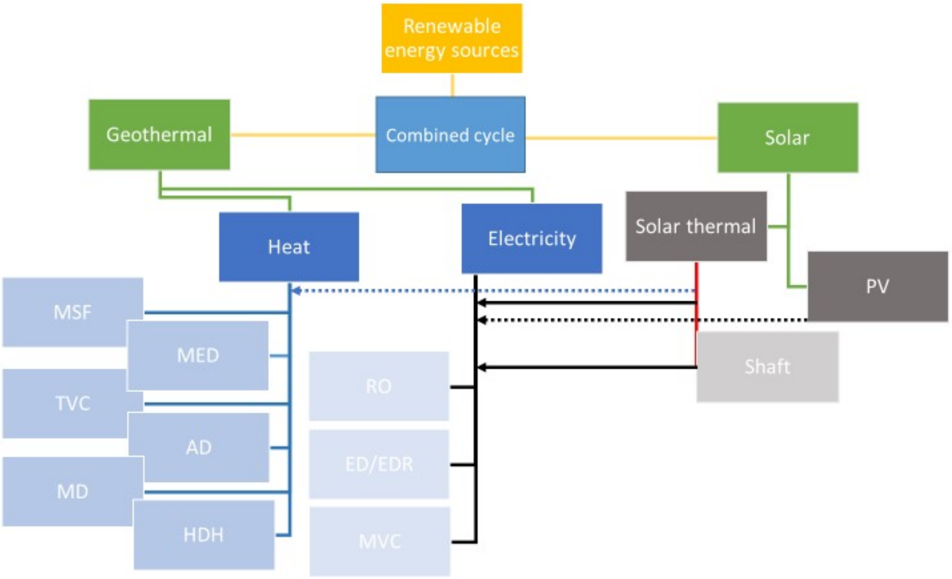


Figure 6 Different combination of desalination renewable integrated systems [49]

Some integrations are more viable for large-scale desalination plants, while others are adequate for small applications. Thermal energy can be directly heated to drive distillation processes or indirectly converted to electricity. Compared to MSF, MED technology has the advantage that it works at lower temperatures. In addition, it is less scalable, cheaper, and more suitable for limited capacity as it is flexible to operate at partial load [50,51].

However, thermal techniques still energy-intensive operations, which account for up to 50% of the operating cost [50,51,52, 53] with limited gain output ratios (GOR). Meaning, large amounts of feed water is required to be heated, and it may affect their integration with RE.

Moreover, the electricity consumption of MSF is almost similar to the total energy required for SWRO, which outperforms MED over MSF (check table 1) [44]. Membrane desalination techniques (RO, ED) or mechanical vapor compression (MVC) use electricity; renewable solar energy should be converted to electricity so it can be used to power the plants.

PV-RO is the most popular among all combinations. Large sizes are plants that are more attractive per small thermal units where heat losses are more significant. More recently, a mixture involving RE-powered membrane desalination and adsorption desalination methods has shown encouraging outcomes. Several MD pilot plants powered with solar energy and geothermal energy have been installed [54,55]. They showed better performance with fewer operational challenges compared to conventional processes. Besides, an experimental solar AD unit produced an 8 m3/day at KAUST in Saudi Arabia not only produced high-quality water with less energy consumption; moreover, it provided adequate cooling for air conditioning at a nominal capacity of 10 R tons (refrigeration tons) [56,57].

In a recent review of solar desalination technologies, Ullah et al. [18], It highlights the environmental impacts of desalination technologies along with economic analysis and cost comparison of conventional desalination methods with various solar-based technologies. The use of solar water desalination is a technically viable option with promising prospects. Still, it is not currently comparable to conventional fossil fuel installations due to the high cost of solar collectors' / PV panels.

Desalination costs are constantly decreasing for solar thermal technologies; however, the authors view that desalination costs may not shrink in the future due to higher costs of energy, raw material, and future operating expenses.

Reverse osmosis technology has consistently outperformed its lower costs for seawater /brackish water consumption and water production costs and has less impact on marine life than distillation-based methods (MED, MSF, and VCD). RO and ED-PV are the most economical membrane-based desalination systems for brackish water.

Chandrashekara et al. [58] performed a review of various solar thermal desalination methods, such as direct and indirect methods. Indirect methods (Humidification and Dehumidification, MD, Solar Pond, MSF, MED, VC) are considered for medium and large desalination systems, while direct processes that use solar stills are adequate for families and small communities. The stills can be efficiently and economically manufactured to meet the daily needs of fresh drinking water and can be improved by simple modification using several locally available materials. Solar stills are sufficient to remove fluoride, coliform, arsenic, mercury, cadmium, bacteria, and viruses.

Reverse osmosis is the preferable method for large-scale desalination. The most common is PV-RO due to the direct use of electric power to desalinate seawater. However, additional power is required, It is known that PV requires only sunlight to generate electricityFeedwaterbut the high solar heat or temperature [59,60] and high relative humidity [61] at seashore adversely affect the performance of the PV.

In the thermal desalination system, due to the high salinity of the water scale forms in the pipes and tubes of the heat exchanger, which reduces the effectiveness of the heat exchanger. MED and MSF are relatively high efficiency with a trade-off in the cost.

The evaporation of water starts at a low temperature even at 40 C in multiple stages up to 39means results in an increase in freshwater production. The solar humidification and dehumidification desalination is yet at the laboratory level and not available in the market. The high relative humidity near the sea increases the performance of the solar humidification and dehumidification plant. Additionally, the high temperature of hot air rises the efficiency and can be achieved with solar evacuated tubes [58].

Ghaffour et al.[49] review paper focuses on integrated systems of solar and geothermal desalination technologies. It also presents an assessment of the benefits and limitations of Innovative and sustainable desalination processes. Moreover, it discusses the promotion of the system and its potential applications.

The authors conclude that geothermal and offshore energy is an attractive option for desalination using mature technologies, especially when low-cost and low-enthalpy sources are available. Also, AD and MD are more suitable for RE, where the use of a combined-cycle of SE and GE desalination process has the ability to provide the most effective method of RE without the energy storage need.

New trends and limitations in the application of renewable energy technologies for desalination are critically revised by Goosen et al. [57]. The paper focuses on environmental impact and sustainable development. It was then considered expanding marketing and argued that in order to help commercial marketing, the government should use incentive tools and policies Such as tax breaks and low-interest loans. There is a need to eliminate aids for fossil fuel energy systems and start taxing its production and use based on regulatory factors and environmental concerns.

The authors conclude in figure 7 that one worrying observation is that renewable energy sources have consistently accounted for only 13% of total energy use over the last 40 years.

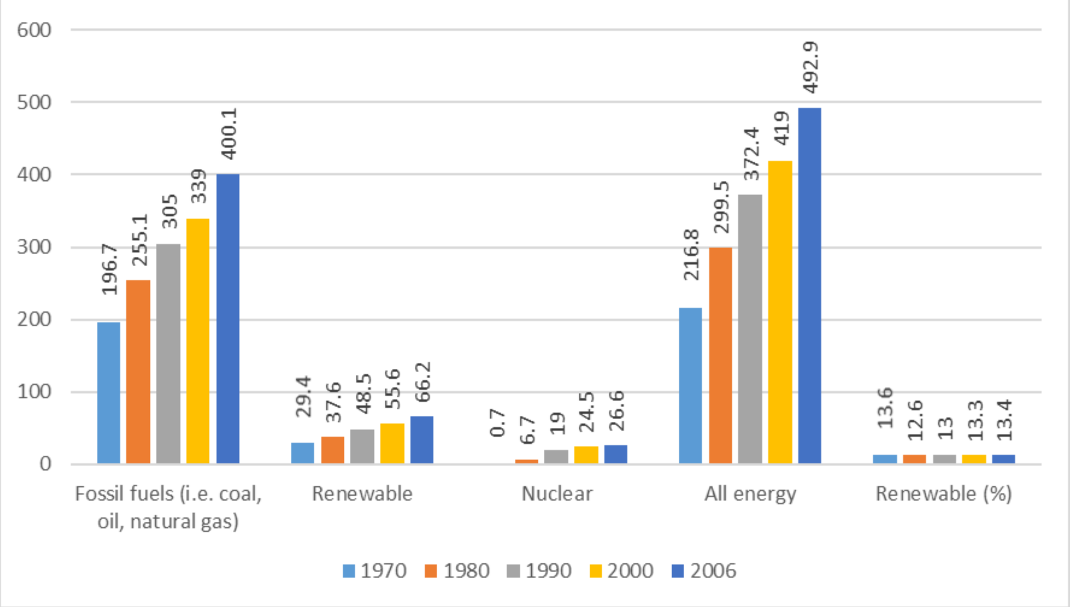


Figure 7 Primary energy use globally between 1970 to 2006 in exajoules (EJ) [57,62]

Hetal et al. [63] concluded that the most suitable desalination combinations were MED/MSF for solar thermal power and RO/ED for PV power (Solar electricity), in addition to RO/VC using wind power. It also reported that 62% of the desalination market share of RE was dominated by RO. Nevertheless, in table 2, PV-RO occupied 32% of RE in 2005, and 19% was wind-RO.

Table 2 Installed capacity share of renewable energy desalination technology [63]

RE- desalination system combination	Installed capacity (%)
PV-RO	32
Wind-RO	19
Others	19
Solar-MED	13
Solar-MSF	6
PV-ED	6
Wind-VC	5

Ghermandi and Messalem [64] speaking about the Market concerns confirmed that CSP and RO desalination is the bright side for large-scale desalination development. They claimed that CSP - RO Systems could compete in the medium term with conventional desalination and thus gain significant market shares and on a small scale in remote areas. A solar desalination experiment has investigated and analyzed 79 systems designs worldwide. The results showed that reverse osmosis solar-powered seawater desalination breaks the necessity of conventional fossil fuels water desalination. It also pointed out that reverse osmosis with photovoltaic power is technically mature and at a low cost of US$ 2-3 per cubic meter, and it is a cost-competitive process in remote areas. Adding that hybrid systems with additional renewable or conventional energy sources achieve as well or excel PV-RO.

1.3 Solar desalination technologies

1.3.1 Solar thermal desalination

Thermal desalination technologies are energy-intensive processes, especially in the presence of high-water salinity levels. In the Middle East and GCC countries, salinity levels range between 35g/L to 45 g/L [65].

Water scarcity and the availability of solar radiation make desalination using solar energy the most appropriate option to alleviate water deficits in these areas [55], Typically solar radiation ranges from 2200 to 2400 kWh / m^2 year [66]. Solar thermal desalination consists of two devices; the solar thermal unit (flat plate, evacuated tube, or solar concentrator) coupled with the distiller of any type which uses the evaporation and condensation principle (MSF, VC, and MED) [55]. The largest desalination plant globally is Ras Al Khair, Saudi Arabia; it's a hybrid plant using MSF, RO, and generating 2,400MW with a capacity of 1,036,000 m3/day. Table 3 shows the top 6th desalination plants around the world [67].

Table 3 The Largest desalination plants in the world [67]

Project	Capacity m^3/day	Process	Details
Ras Al Khair, Saudi Arabia	1,036,000	hybrid	Thermal multistage flash (MSF) and reverse osmosis (RO) with 2,400MW substantial power generation component
Taweelah, UAE	909,200	RO	Once complete, the Taweela power and water complete is expected to raise the emirate's proportion of desalinated produced water by RO from 13 percent today to 30 percent by 2022.
Shuaiba 3, Saudi Arabia	880,000	RO	A second in the list for Saudi Arabia An expansion with a total additional 400,000 m3/day of RO capacity When completed, Shuaiba will eventually overtake Ras Al Khair as the largest operating desalination plant with a full capacity of 1,282,000 m3/day.
Sorek, Israel	624,000	RO	uses 16-inch seawater reverse osmosis membranes in a vertical formation
Rabigh 3 IWP, Saudi Arabia	600,000	RO	A third in the list for Saudi Arabia
Fujairah 2, United Arab Emirates	591,000	hybrid	450,000 m3/day thermal plant MED 136,500 m3/day reverse osmosis facility 2000 MW power plant

The most related solar thermal plants in Saudi Arabia are summarized in Table 4 [68].

Table 4 A view of some solar thermal desalination plants around the world

Project	Location	Year	Capacity(m^3/day)	Process
Yanbu Ph.3	Yanbu, Saudi Arabia	2016	550,070 m^3/d	MSF
Marafiq Yanbu	Yanbu, Saudi Arabia	2013	54,550 m^3/d	MED
Rabigh Power No.2 MSF Unit	Rabigh, Saudi Arabia	2013	9,820 m^3/d	MSF
Yanbu Ph.3	Yanbu, Saudi Arabia	2012	550,000 m^3/d	MSF
Yanbu Ph.2 Expansion	Yanbu, Saudi Arabia	2012	68,190 m^3/d	MED
Qurayyah Add-on CCPP MSF Unit	Qurayyah, Saudi Arabia	2012	6,000 m^3/d	MSF
Yanbu Ph.2 Expansion	Yanbu, Saudi Arabia	2011	68,190 m^3/d	MED
Marafiq Yanbu	Yanbu, Saudi Arabia	2011	54,550 m^3/d	MED
Rabigh Power No.2 MSF Unit	Rabigh, Saudi Arabia	2010	9,820 m^3/d	MSF
Shuaibah Ph.3 IWPP	Jeddah, Saudi Arabia	2009	881,920 m^3/d	MSF
Qurayyah Add-on CCPP MSF Unit	Qurayyah, Saudi Arabia	2009	6,000 m^3/d	MSF
Shuaiba South Rehabilitation	Jeddah, Saudi Arabia	2008	163,660 m^3/d	MSF
Shuaibah Ph.3 IWPP	Jeddah, Saudi Arabia	2006	895,562 m^3/d	MSF
Shuaibah Ph.2	Jeddah, Saudi Arabia	2002	454,600 m^3/d	MSF

2.3.2.1 Solar Powered Multi-Stage Flash Distillation

Solar Powered MSF is a thermal desalination process that uses solar energy as a heat source to heat saltwater under high pressure. The saltwater passes through a series of chambers that the following is at a lower pressure than the previous one. Water passage causes evaporation of saltwater. Later on, evaporated water is collected and re-condensed into refined water. Water that has not evaporated leaves the system with a higher salt concentration as a result of evaporation; the remaining water is appropriately disposed of as waste. Then, the municipal water supply is provided with refined water as potable water [22,69,70]. Illustration of MSF's solar-based operation in Figure 8.

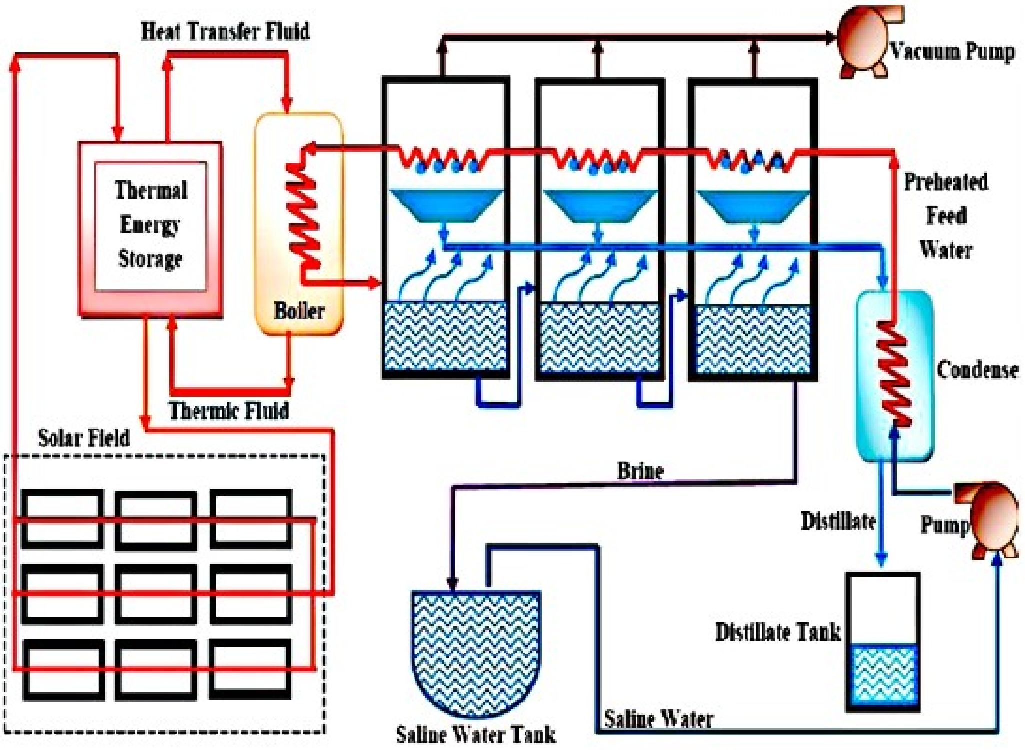


Figure 8 Solar powered MSF distillation [71].

MSF is a frequent thermal technology used in the Middle East [72]. The world's largest desalination plants Ras Al Khair in Saudi Arabia is the best evidence, hybrid desalination plant utilizing the highest MSF unit capacity in the world. Ras Al Khair MSF unit is capable of producing 91,000 m^3/d of desalinated water a volume enough for the consumption of 300,000 people [73].

The gain output ratio (GOR) is the ratio of the amount of thermal energy required in the desalination process (in other words, the distilled water mass-produced from 1 kg of steam), MSF unit is usually manufactured as GORs in the range of 6.5-8 with a recovery ratio (RR) of 6% [70,74].

The capital cost of a standalone solar-powered MSF plant consists of solar units (including the collectors, storage, PV arrays, powered generator) and the desalination unit (steam generator, Chambers). The operating costs share less than one-fifth of the total cost (i.e., chemical cost, maintenance cost, and personnel cost) [75].

The charge of one cubic meter of desalinated water produces from solar-MSF plants is around US$1.4 [76,77]. A financial evaluation on solar-MSF- with fossil fuel backup and a fossil fuel-driven MSF plant implemented by García-Rodríguez and Gómez-

Camacho [78] presented there are two main parameters influencing water cost. The first is the performance ratio (PR). The second is the solar fraction, which illustrates the energy requirements of the plant supplied by the collector field [79].

2.3.2.2 Multi-Effect Distillation

MED recognized as one of the thermal desalination categories, which works under the principle of heating saltwater in the presence of pressure, which in turn causes water to flow through a series of stages. Using solar energy or fossil fuel combustion, the heat needed to evaporate is provided in the first chamber. Later, the vapors produced in the previous chamber are used to heat the feed water in the posterior chamber consecutively so that the steam is of lower pressure than the last chamber. Part of the feed water evaporates, leaving a brine with a slightly higher concentration than the original water. To separate the condensed water vapor (distilled water) during the phases, the basic procedure uses the condensation heat to deliver heat for the next set of saltwater and produce more water vapor as the phases progress [22,58].

The solar-powered Multi-Effect distillation is illustrated in Figure 9.

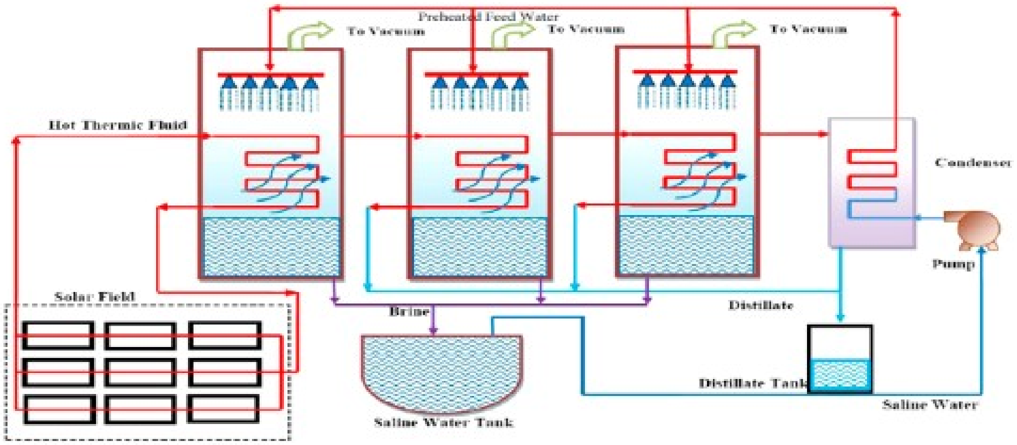


Figure 9 Solar powered MED distillation [80].

The MED technology is superior to MSF in terms of thermodynamics as the first axis, while the additional is the reduction of energy consumption (the energy consumption of MED is lower) [81]; increasing the heat transfer area in MED is an improvement in thermal desalination technology [82]. It allows the addition of a larger number of stages (10-16), as with salt temperature that can reach maximum of as low as 70 ° C, increasing the heat transfer area reduced the temperature slightly in a range of 1.5-2.5 ° C at each stage causing a rise in performance efficiency. All of the above plays a vital role in the apparent reduction of cost and high-profit rate, taking into account the lower prices in processing and operation. More detailed, in MED the quality of the feed water does not play a role as in reverse osmosis [83,84].

Methods for supplying seawater evaporators vary, including mixed feed, parallel, forward, and backward systems [85,86].

2.3.2.3 Vapor Compression Distillation

Vapor Compression distillation is a process where the main driving force is the vapor compression, which produces heat for vaporizing the seawater. [18]

It has the concept of a heat pump process, it pumps heat from a low-temperature sink to a higher temperature sink, as what happens in the refrigerant where the heat is pumped from the air inside to the ambient [87].

In this technique, solar energy is used to generate steam from seawater, so a thermal or mechanical compressor is used to compress steam. This system is characterized by the usage of steam as a sufficient medium to heat its liquid and concentrated solutions, from which the steam was primarily made, as the increase in vapor pressure causes an increase in condensation temperature. Incoming seawater plays a vivid role, acting as the coolant of compressed vapor, which leads to the condensation of distilled water and at the same time, as a source that is heated to produce more steam [88,89] as shown in Figure 10.

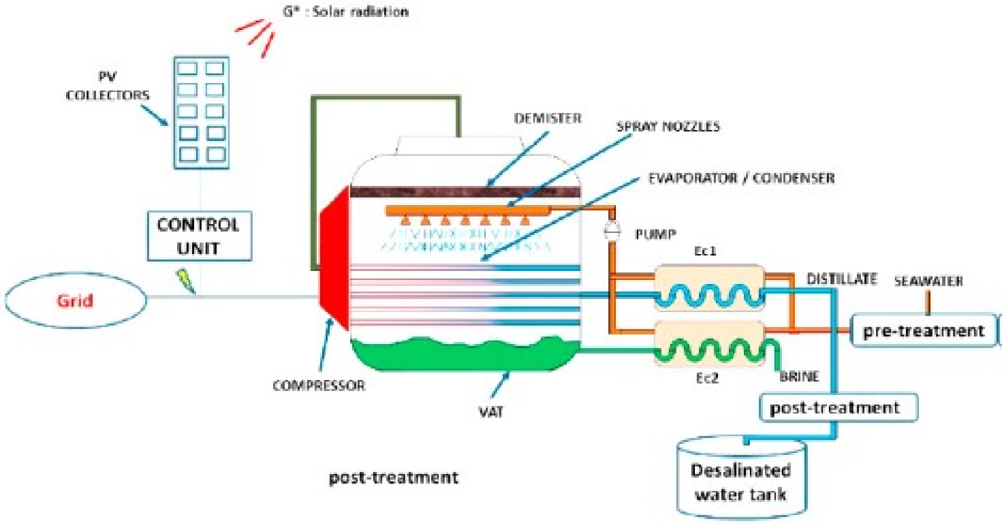


Figure 10 Solar VCD system [90].

VCD is commonly used in small independent applications or large-scale applications merged with multi-effect distillation. The key difference in VCD technology is that vapor pressure is applied to change the boiling point of water [91].

This technology outperforms its MSF and MED counterparts with the smaller equipment used and the lower operating expenses. However, it is declining due to higher energy consumption, and its initial cost, as well as the cost of maintaining compressors and heat exchangers, are also higher compared with the other systems [18].

1.3.2 Membrane Processes

Solar Powered Reverse Osmosis

In this technology, the brine is pushed under the influence of high pressure through a semi-permeable membrane, during this process, the saltwater remains at the source side, and semi-pure water is passed on the downstream side. The efficiency of the desalination is influenced by the membrane cleanliness. Therefore, water is treated before, and after passing, before the desalination phase, saltwater passes some initial filters to separate the particles. After desalination, often, the pH is accustomed to normal, and the microbes are eliminated [22,92].

Solar-powered RO has several combination choices to be integrated with; as shown in figure 11, the system can be connected to solar ponds, collectors and panels

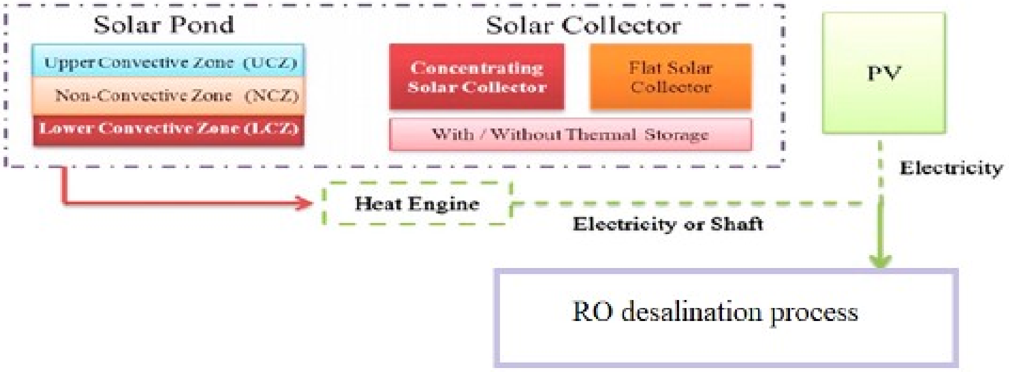


Figure 11 Solar driven RO system [93].

In a recent review of solar-thermal desalination technologies, Ullah et al. [18] noted the use of solar energy for desalination is a technically viable option and has promising prospects, yet it is not similar to conventional fossil fuel installations due to the high cost of solar collector/PV panels. However, desalination costs are declining incessantly for solar thermal technologies, mainly in RO technology, due to the great evolution in plant capacity and better process design, better and efficient membranes and materials, etc. Nevertheless, the author is of the view. For seawater consumption and water production cost in the RO system is less than distillation-based techniques (MSF, MED, and VCD) due to RO's high efficiency in the recovery tools, technical enhancement in membrane manufacture, reliable scaling controlling and greater effectiveness in pumps adding that RO minimizes marine life impacts. For brackish water, RO-PV and ED-PV are the most economical membrane-based desalination systems.

RO plant contains five main gears, that is a supply system, pretreatment filters, pumps, RO membrane, and a post-treatment system [94,95]. Recently, the largest desalination plant has been designed and operated in Saudi Arabia (Ras Al Khair) as a hybrid (thermal multistage flash (MSF) and reverse osmosis (RO) with 2,400MW substantial power generation component), it has a production capacity of 1,036,000 m3/day. It is following in order with Taweelah (UAE) and Shuaiba 3 (Saudi Arabia) being 909.200 and 880.000 m3/day, respectively. When Shuaiba 3 is completed, it will overtake Ras Al Khair as the largest operating desalination plant with a total capacity of 1,282,000 m3/day [67].

PV-RO system is on-demand in demonstration plants due to the ease of standardization and scaling of PV and RO components [96,97], while solar-thermal RO lag behind in the marketing phase [7].

Research executed to study the application of solar thermal energy for desalination by interconnecting an Organic Rankine Cycle with seawater reverse osmosis (ORC-RO) [98]. It revealed the benefit of seawater acting as a heat sink for the ORC condenser while it is preheated instantaneously to raise the RO membrane permeability, which results in low power consumption [99].

The amount of energy needed and the price of desalination to produce water using RO are highly dependent on the efficiency of the desalination unit, membrane design, and feed water salinity-TDS [100]. The effectiveness of a PV- RO unit subject to the ability of all components of the system [21].

In RO desalination plant, modifications applied on (temperature, pressure, or the concentration of the feed water) marks in the system outcome, RO membranes are affected by the recovery rate and the pressure limit. Noting that as the pressure increases, the membrane rejection increases. Feeding water flowing through the membrane affected both water flux and salt rejection rates. [101] Thus, it is vital to understand the rejection features of each membrane nature and guarantee that it encounters the desired quality.

However, above a fixed pressure limit, no increase happens in the rejection through the membrane, and some salt passage occurs during the flow of water. The maximum recovery rate that the RO system achieves depends on the chemistry of the feed water. More detailed, the concentration of the dissolved salts in the feed water and its predisposition to precipitate on the superficies of the membrane as a mineral scale [101].

RO is distinguished from MSF and MED because the problems of physical erosion are much lower, but common disadvantages are the membrane scaling due to precipitation of salts. In RO, the polymeric materials are preferable over the alloys [102].

1.3.2.1 Membrane Distillation

Membrane distillation combines both of membrane desalination and thermal distillation techniques. Due to the temperature difference of the membrane, the water vapor proceeds through the hydrophobic membrane, accordingly separated from the feed water state, molecular water (as in a high-pressure steam state) passes through into the hot compartment. The difference in temperature works as momentum in the form of a vapor pressure gradient, which distinguishes the membrane distillation that the driving force is not a pure thermal force, where distillation takes place at a considerably lower temperature from conventional thermal distillation.

MD can be classified into four different arrangements, as shown in Figures 12 and 13 [7, 103].

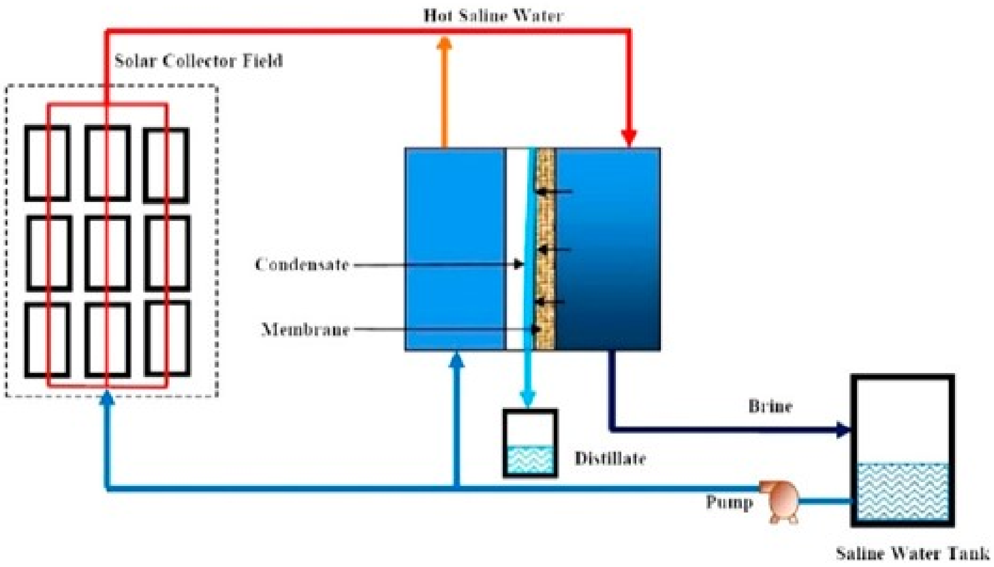
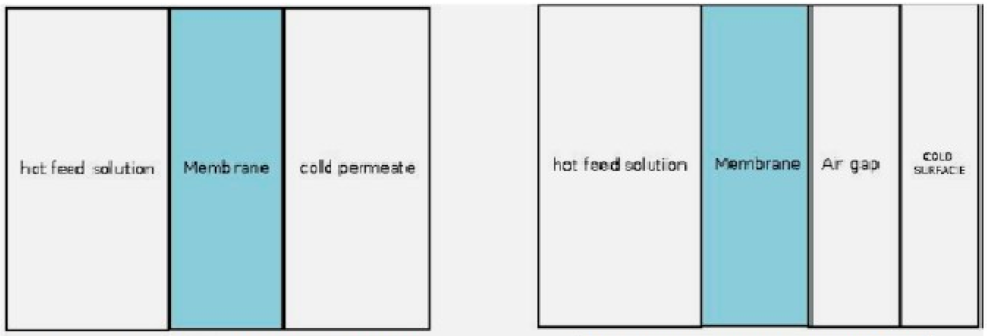
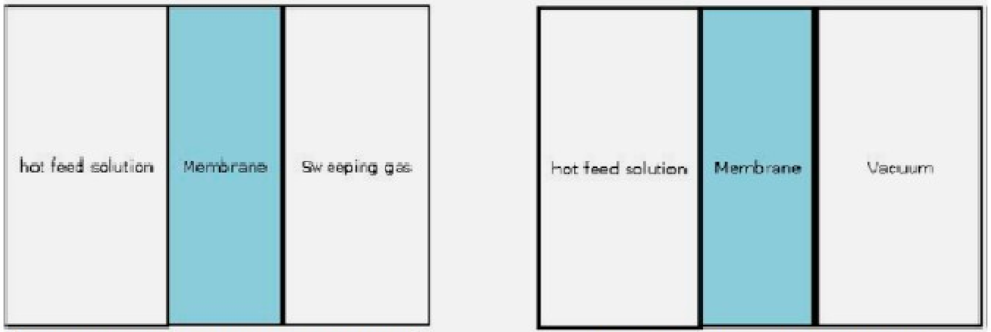


Figure 12 Solar powered MD [7].



Direct contact membrane distillation (DCMD)

Air gap membrane distillation (AGMD)



Sweeping gas membrane distillation (SGMD)

Vacuum membrane distillation (VMD)

Figure 13 Schematic illustration of MD formations [104]

Various investigations were conducted to determine: A. the freshwater production rates and the active requirements of the various gears of the system, the dual system DCMD / SGSP was found to outperform a similar network consisting of air-gap, dealing with nearly six times the water flow compared to its counterpart (SGSP). It was noticed that a high water flux could be achieved if controlled to reduce heat loss, where a noteworthy 30% heat loss observed at different parts, and 70% of the heat extracted used to power the desalination processes [105,106].

The observation presented that productivity, as well as system efficiency, can be accomplished by improving operating conditions [105,107]. “including system temperature, water flow rate, salt absorption rate, cooling temperature, and the diameter of the system layer” [18].

At low temperatures such as industrial waste heat, solar energy, and geothermal energy, membrane distillation is often the best and most economically competitive solution. [108] The system can be improved by integrating heat recovery units into the MD to result in an expansion of the use of this technology to reach rural areas [18]. Guan et al. [109] In their study, they have focused on the heat recovery mechanism to improve system-level heat utilization (using Aspen Plus), and derived an implicit expression of the GOR to prove the relationship between heat use and process parameters. As a result, they pointed out the importance of exploiting the limited thermal energy resources for high water production, as in the case of low-grade waste heat, a high percentage of GOR is required. Moreover, higher GOR was achieved using thicker and less conductive membranes to reaching high resistance to heat transfer.

There are various views in the MD system regarding energy consumption and technology cost. Some researchers argue that MD compared to MED and MSF is inappropriate for energy consumption due to lower thermal efficiency in the membrane and added resistance to mass passage [110], while others consider that MD energy consumption is roughly the same in MSF with less pumping power [111].

However, membrane distillation has the advantage of conventional separation methods, which is easily upgraded to a broader range due to its compact design and modularity, it is also a suitable solution in gentle water treatment under reasonable temperature conditions. However, the defects of wetting the membrane lead to lower water quality. Also, MD has less water flow compared to other desalination techniques [104,112].

1.3.2.2 Electro-Dialysis and Electro-Dialysis Reversal

ED is an electrochemical separation process that employs the electrical potential of an ion-selective membrane and operates under ambient pressure, leaving freshwater behind during the flow of feed water. The feed water ionized under the effect of electricity, then the solution ions separated into negative and positive. Negative charge salt ions transit the anion-porous membrane in the way to a positive electrode. Similarly, the positive salt ions pass through the cation porous membrane reaching a negative electrode. By this phase, the dissolved solids removed from the feed seawater. In the PV-ED system, the electrodes are linked to an external PV source in a container of saline, and the salts are removed through selective ion membranes placed between two electrodes, as shown in figure 14 [18].

In the ED process, the most critical energy requirement is the direct current, which separates the ionic substances in the membrane. The use of energy in this process is directly proportional to the removed salts giving that the saline water has a salinity of no more than 6 g / l and not less than 0.4 g / l of dissolved solids. Moreover, ED is capable of producing less brine and recover more freshwater. In EDR, cation and anion reverse to regularly alternate current flow, which makes it an identical method. The feed water circulated within the system, and per hour the polarity rotated four times, creating a scrubbing mechanism reducing the membrane scaling and a higher recovery rate reaching 94% [113].

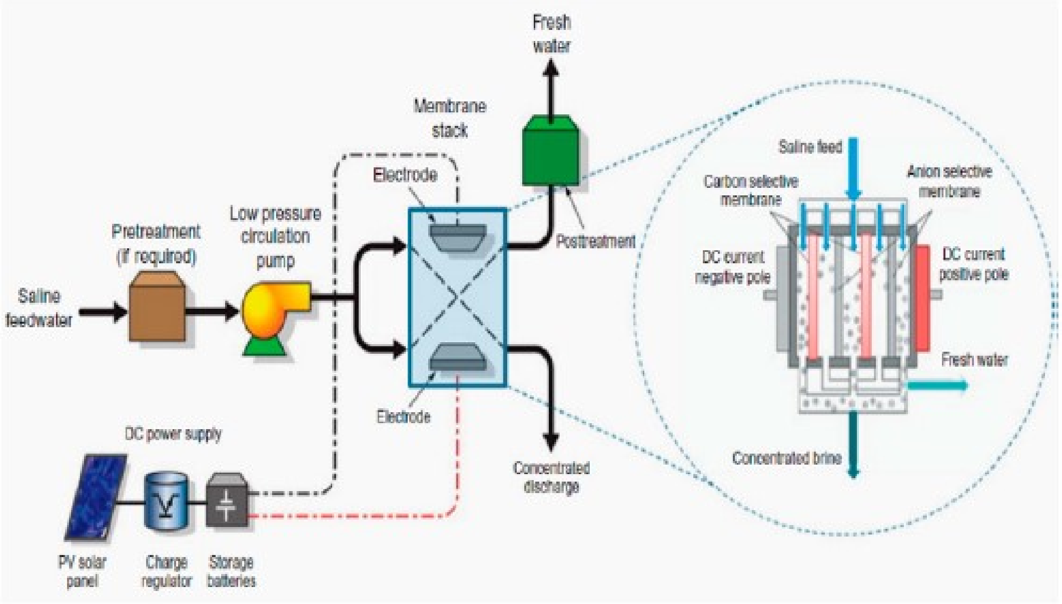


Figure 14 Schematic illustration PV/ED system [114].

1.4 Photovoltaic desalination

1.4.1 PV-RO Review

Several papers have been presented to review and study the possibility of adopting solar energy as an energy source for water desalination. This is illustrated by the following works: Status of solar thermal-driven reverse osmosis desalination [115]. Seawater desalination using renewable energy sources [116]. Ali et al. [94] reviewed the indirect solar desalination, and it is market potential as a viable solution. Li et al. [102] made a review of the solar-assisted seawater desalination. Charcosset et al. [117] present the design and implementation of membrane processes coupled with RE, including RO, MD, and ED for brackish water and seawater. It also reviewed the key fallouts of mathematical models and economic feasibility using these techniques.

Many models of PV-RO have been implemented and evaluated in various regions under the stress of freshwater scarcity. Ahmad and Schmid [118] calculated the feasibility of brackish water desalination in the Egyptian deserts and rural regions using PV systems. In the same context, Gocht et al. [119] described the Jordanian trial on brackish water, utilizing a directly coupled RO-PV system while the Spanish experience of employing a small PV-RO plant at the Gran Canaria Island was described by Herold et al. [120].

Richards and Schäfer [121] highlighted the design consideration of a solar-powered desalination system for remote communities in Australia.

Feasibility studies have been performed in Sicily, one was for the PV-RO system in Agrigento [122], and another was in Ginostra for a hybrid system (PV-diesel powered seawater reverse osmosis) [123]. Calise et al. [124] simulated and assists an innovated solar tri-generation system.

PV–RO desalination system was assessed by Bouguecha et al. [125], Kalogirou, [126] and Tzen et al. [127]. Al Suleimani and Nair [128] presented a comprehensive cost analysis of solar-powered reverse osmosis in a remote area (Heelat Ar Rakah) of the Sultanate of Oman.

Thomson et al. [129-131] developed a fascinating study based on simulation and implementation. The seawater PV-RO system designed for Eritrea without batteries with excellent energy efficiency over a wide operating range.

Hasnain and Alajlan [132] made a cost analysis on a coupled PV–RO brackish water desalination plant with solar stills in Riyadh, Saudi Arabia.

An attractive small PV–RO system introduced by Joyce et al. [133] designed for water purification, the system could be used in rural sites as well as during disasters.

Finally, Khaydarov and Khaydarov in Uzbekistan proposed a new solar-powered natural osmosis driven system (does not require external pumping) [134].

1.4.2 PV- ED Review

Several studies, system evaluation, cost analysis, and pilot plants of the PV-ED system have been implemented.

Lundstorm [135] was a pioneer in introducing the first small-scale solar-powered electrodialysis for water desalination utilizing PV. The Laboratory for Water Research, University of Miami, USA did experimental research on PV–ED [136], as well as a similar work, was performed by the University of Bahrain [137]. Ishimaru [138] studied the feasibility of a brackish water PV-ED in remote areas of Japan. Gomkale [139] stated that PV–ED is the most advantageous mean for desalting brackish water in providing drinking water for remote Indian villages. Almadani [140] experimented with a configuration of PV-ED and the effect of flow rate and temperature on the product quality. Ortiz et al. [141] presented a mathematical model of an ED-PV system. Depends on the geographical location, the model enables the design of electrodialyzer size and the number and configuration of the PV modules.

Some of the old PV-ED systems allocated around the world are Thar desert, India [142], Fukue City, Nagasaki, Japan [143], and Ohsima Island, Nagasaki, Japan [144].

A study considering the sustainability of a PV-ED system in terms of energy and the environmental impact has been done by Fernadez Gonzalez et al. [145] It concluded that the ecological impact was less and that PV-ED might be more cost-effective than the conventional system.

The usage of Photovoltaics cells integrated into ED technology is more attractive than other systems for remote areas, where brackish water and sunshine are available throughout the year, with no access to low-cost fuel and has a shortage or no electrical power. [7,89].

1.5 RO- Organic Rankine Cycle (ORC-RO)

Reverse osmosis technology relies on a high-pressure pump to feed the membrane to feed water where energy consumption is mainly associated with it, the energy consumption in reverse osmosis technology is five to six times less than in thermal technologies, this demand can be achieved by the conversion of solar energy to mechanical energy [146].

Solar / low-temperature Rankin cycles have the potential to produce power or electricity, and there are several ways to implement it. The low-temperature Rankine cycle system has been developed to generate electricity with an efficiency of 4.3% using n-Pentane as a working fluid by Nguyen et al. [147]. It has also been used in the application of tri-generation [148]. The performance of the ORC in the southern regions of Iran has been analyzed by Aghamohammadi et al. [149].

Schuster et al. [150] evaluated an RO-ORC prototype plant using evacuated tube collectors with the direct flow using a scroll expander as an expansion machine in the model. The system described shown in figure 15.

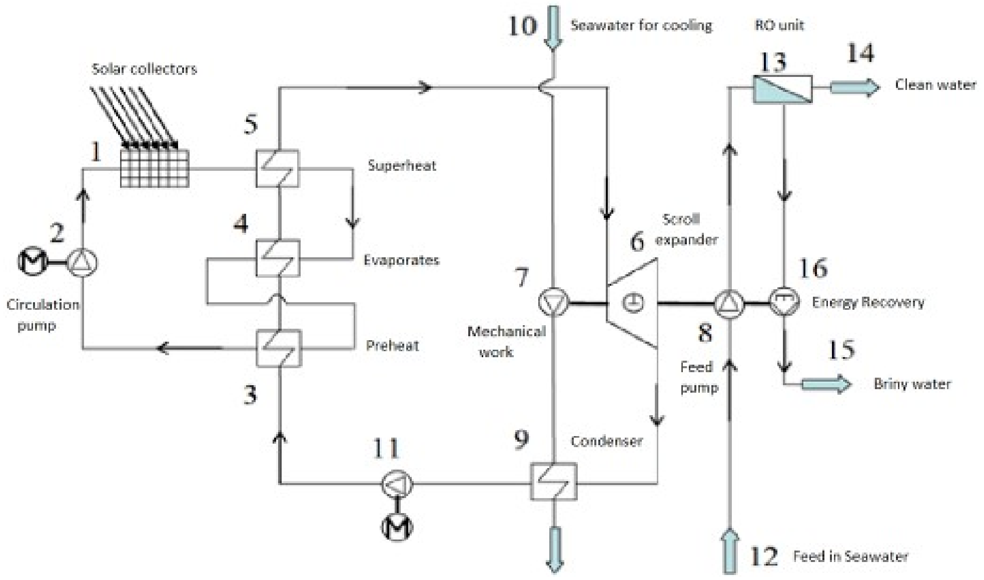


Figure 15 Schematic design of the RO-ORC system [150].

A dynamic simulation was done using IPSEpro linked to an external algorithm since it proved a steady-state solution. The external tool takes into account the changing of solar irradiation, temperature as well as load behavior. IPSEpro uses libraries for the analysis of power plants, element design, proving test calculations, and on-line optimization [151]. When the predefined model was not sufficient, they modified it with the Model Development Kit (MDK).

For R245fa, desuperheater improves efficiency on a large scale, while in the case of R134a, it leads to an extra cost, as it has positive effects on cycle efficiency only in the presence of high superheating with the availability of the expensive large heat exchangers. An overview of the working fluids is given in table 5.

Table 5 Refrigerants characteristics

Refrigerant	T_c [°C]	p_c [bar]	$T_{s,\ 1\ bar}$ [°C]	$p_{s,\ 20\ °C}$ [bar]
R134a	101.1	40.6	-27.1	5.7
R245fa	154.1	36.4	14.9	1.2

Manolakos et al. [152] compared the cost of water production for a PV-RO system with an ORC-RO system. The results showed that with a constant thermal source the lowest cost reached 1.83 €/m^3, but it is challenging to implement, followed by the value of water production of 4.47 €/m^3 for PV-RO system and a significant difference in the high cost of ORC-RO system attributed to the installation costs of solar collectors' field to be 10.34 €/m^3.

In 2010 another design was proposed to use waste heat as a steady thermal source; it is two-stage ORC-RO desalination using TRNSYS V16.0 software for the design [98].

1.6 Water production costs of Solar energy desalination plants

Desalination is a costly process due to its high energy required to complete the process. For example, in RO plants, it takes 3 to 10 kWh of energy to produce cubic meters of freshwater from seawater [152]. Conversely, conventional drinking water treatment plants typically consume less than 1 kW / m3 [153,154]. The cost of producing 1,000 gallons of typical freshwater drops to US$ 2, compared to desalination plants that cost between $ 2.50 and $ 5 for the same amount of freshwater [153,155].

Increased demand for water in recent years and technological advances have led to significant growth of desalination capacity due to the confinement of traditional sources.

As a result, there was a substantial reduction in the cost of desalination, which made it able to compete with other water sources [156,157,158].

When deciding on the choice of desalination technology, total investment, type of project contract, government incentives, local subsidies, and water costs play a role in decision making [159], the cost of water produced is influenced by factors such as the technology used and the concentration of TDS in feed water whether it is seawater or brackish water [160], capacity, type of plant, labor, location, and type of energy used and it is cost [161,162].

In Table 6, the cost of desalination decreases as the capacity of the plant increases, and the concentration of salts decreases (Table 7) [163].

Table 6 Desalinated water production cost connected to the capacity [164]

Capacity (m^3/day)	Cost (Euro/m^3)	
	Seawater	Brackish water
3,800	0.97	0.50
7,600	0.70	0.27
19,000	0.54	0.21
38,000	0.50	0.17
57,000	0.49	0.15

In the same vein, phase-change (thermal) desalination processes require large amounts of energy for the evaporation of saltwater. When conventional energy sources are used to operate it, generally, it has large production capacities that are expensive compared to membrane plants. In the case of brackish water, membranes are cost-effective [19,165]. The evaluation of large-scale plants cost is illustrated in Figure 16. RO and thermal desalination are presented.

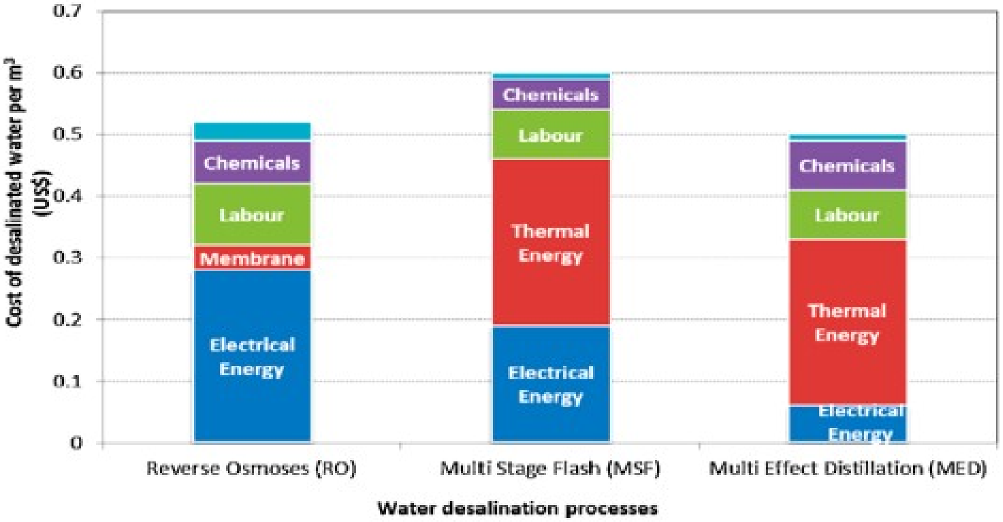


Figure 16 RO and thermal desalination cost [18].

Membrane-based water desalination requires electricity as the primary input energy, unlike its thermal-based counterparts (electricity and heat), which makes its energy consumption less, and these can be reduced by integrating energy recovery systems Figure17. Moreover, its lightweight has a compact design and high productivity, which made it superior to the thermal-based desalination process [166].

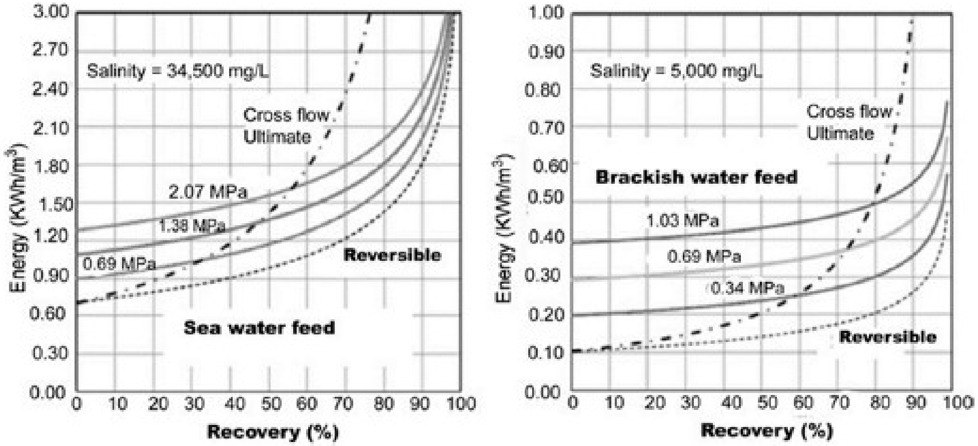


Figure 17 Energy VS Recovery of RO desalination (Seawater & brackish water feed) [19]

More recently, reverse osmosis has been widely used as a result of technological improvements leading to lower costs. From Table 8, it is clear that, like any other desalination process, costs in small plants increase and vice versa. On the other hand, as previously mentioned, fossil fuels are often the driving power for the operation of thermal desalination plants resulting in higher unit costs, as shown in the table for each of the thermal technologies MSF, MED, and VCD [167.168].

Table 7 RO desalination cost compared to the feeding water and the plant capacity [167]

Feedwater	Plant Desalination (m^3/day)	Desalination Cost/m^3 (US$)
Seawater RO	Less than 100	1.5-18.75
	250-1000	1.25-3.93
	15,000-60,000	0.48-1.62
	100,000-320,000	0.45-0.66
Brackish water RO	Less than 20	5.63-12.9
	20-1200	0.78-1.33
	40,000-46,000	0.26-0.54
MSF	Less than 100	2.20-8.80
	12,000-55,000	0.84-1.31
	Greater than 91,000	0.46-0.89
MED	23,000-528,000	0.46-1.54
VCD	1000-1200	1.77-2.34

Solar collectors' / PV panels' cost is still high, but its integration with desalination units reduces the energy cost of desalination [167,169,170]. Due to the low profitability of solar-powered installations, the unit price of solar desalinated water is very high compared to those powered by fossil fuels. However, it is an ideal solution to reduce carbon dioxide emissions and thus reduce the contribution to global warming [171]. Table 8 shows the cost of water production for possible combinations of solar desalination plants.

Table 8 water production cost for possible combinations of solar desalination plants [49]

Solar process	Typical capacity (m^3/day)	Energy demand (kWh/m^3)	Water cost (US$/$m^3$)
Solar still	<0.1	Solar passive	1.3-6.5
Solar (MEH)	1-100	Thermal:100 Electrical: 1.5	2.6-6.5
Solar (MSF)	1	Thermal: 81-144	1-5
Solar tower MSF	1	Total: 53.7	-
Solar/CSP MED	>5000	Thermal: 60-70 Electrical:1.5-2 Total:50-94	2.3-2.8
Solar tower MED	1	Total: 42.4	-
Solar tower VC	1	Electrical: 55.5	-
PV-RO	<100	Electrical: Brackish water (BW):0.5-1.5, Seawater (SW):4-5 BW-SW: 1.2-19 Electrical: 41-45	BW:6.5-9.1 SW:11.7-15.6 3-27
PV-EDR	<100	Electrical: BW: 3-4 BW: 0.6-1	10.4-11.7 3-16
Solar MD	0.15-10	Thermal: 150-200 / 100-600 /436 / 180-2200	10.4-19.5 13-18
Solar AD	8	Electrical:1.38 Total:39.8	0.7 electrical cost only

Brackish water solar reverse osmosis technology is expected to outperform its peers and be the least expensive, even on fossil fuels. Rapid technological improvements in membranes and energy recovery leading to lower costs as well as lead to the expectation of a gradual decrease in the cost of desalination of about 4% to 5% annually [172,173].

Ebensperger et al. [174] have noticed that the cost of RO plants has been reduced up to 1/3 in between 2003/2005 to 1995/1997 (Figure 18).

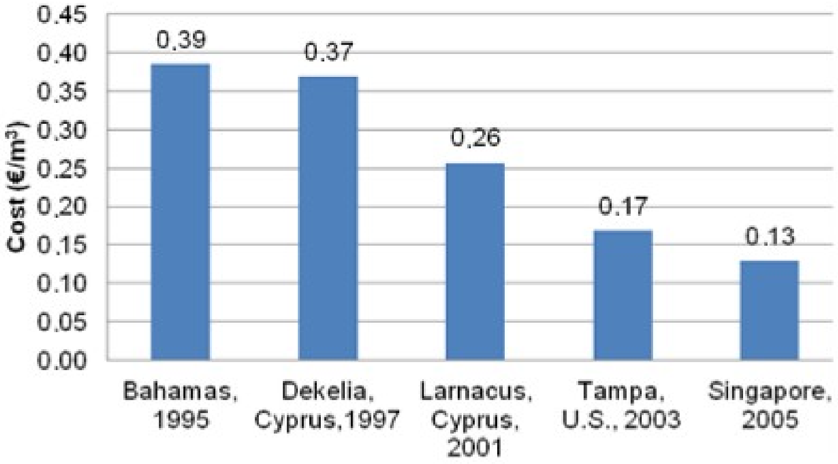


Figure 18 RO water production cost drop from 1995 to 2005 [174]

Thus, the solar-based membrane-based desalination system in abundant solar energy areas makes desalination more reasonable and sustainable with minor influence on the environment [166]. However, it should be noted that the cost of renewable energy desalination still estimated to be higher [175]. An illustration of the cost per feeding water and energy source used is shown in table 9.

Table 9 Water production cost the cost per feeding water and energy source [169]

Feedwater Source	Energy Source	Cost (US$/m^3)
Seawater	Conventional energy	0.38-2.97
	Photovoltaics panels energy	3.45-9.9
	Wind power	1.1-5.5
Brackish water	Conventional energy	0.23-1.17
	Photovoltaics panels energy	4.95-11.35
	Geothermal energy	2.2

2 Case study and contribution

2.1 Problem statement

The availability of freshwater sources is diminishing hastily as the demand increases rapidly, the continues increase of the population in the globe causes a rising demand for natural resources combined with the effects of climate change, especially in arid and coastal regions.

Water and energy are vital possessions for living beings on this planet. The water and energy resources have helped to achieve lushness and development in several parts of the developed world, while many regions suffer from stark freshwater and energy scarcities [176].

1.2 billion individuals around the world experience having access to unsafe, polluted drinking water, services delivery itself through unreliable sanitary systems. [5]. Drinking water of adequate excellence has become a rare consumption product. Unluckily, in addition to being in scarcity, freshwater resources are not just as distributed geographically worldwide [177]. Tackling the situation can occur by finding alternative means of freshwater production. Fortunately, desalination technology has the capability to grapple this issue. However, it is very energy-intensive, and it has radical effects on the environment [7]. Raw water sources vary around the world. One of them is the seawater (67%) contains around 3.5% sodium chloride [8,9].

Although the desalination of seawater has advanced in human history, it has proven to be one of the most reliable options in water treatment processes, not only meeting the needs of freshwater for human livelihood but also in industries.

Africa, Asia Pacific, and Middle East countries counted as the most water-deficient areas [19]. Desalination has been influential in enriching the socio-economic in developing countries of these areas. [31] Likewise, it is realized that they are vulnerable to any future global energy crisis. As a result, they have introduced advanced plans to vary their energy sources. This diversification includes renewable energy (RE), sources primarily solar [32]. As a result of population growth, along with the development of the industrial and agricultural sectors in evolving economies, the available freshwater resources will be depleted, which in turn will cause a rapid deterioration of all of the above. Desalination of brackish water and seawater has the potency to meet the increasing freshwater needs of humanity. That being the case, water dearth will influence one-third of the population around the world while the rest will suffer serious water lack [104]. Similarly, it is expected that by 2040 the share of electricity in final consumption moves up towards one-third of the current demand, resulting in a rise of the cost for water use by the energy sector [25]. By 2050, world food production must be increased by 70% to meet the global demand for a population being predicted to reach 9 billion [11], in parallel with the demands of other sectors that translate the projections for global primary energy desire to excess by one third during the period 2010-2035 [12]. The annual global freshwater market rises and expected to grow by ~10–12% per decade, giving that the largest part for agriculture (according to UNESCO, an increase of 38 percent from 1995 to 2025 [13]), making energy security and water supply a major challenge facing contemporary society.

Desalination addresses water by disassociating mineral components from saline water, ensuing drinkable water, which has low levels of organic and inorganic dissolved salts called total dissolved solids (TDS). The number of desalination plants worldwide is 19,372 (2017) across all categories [37]. These have a commissioned load of 92.5 million m3/day serve for the water needs of over 300 million persons worldwide who fully/partially rely on desalinated water for their daily water consumption [37,38].

The facts are that renewable energy resources are still largely abandoned and underutilized worldwide compared to their high availability, continuity in fossil fuels as investors perceive them as highly profitable and credible form sources of energy. Nevertheless, widespread desalination technology has led to high energy demand and CO2 emissions from hydrocarbon energy sources [26].

Technological innovations will result in abundant freshwater from both seawater and saltwater with minimal penalties on the environment when only relying on renewable and solar energy. Most of the MENA region, the Persian Gulf region, Africa, India, and China allocated on the strategic Sunbelt. The real threat to resource sustainability can be addressed by taking advantage of the naturally sustainable resource for water production, constructing new desalination plants that mainly rely on solar energy [33].

2.2 Methodology

The previous chapters gave a comprehensive vision into the current desalination status globally and desalination technologies then further explore the varies ways for enterprise solar water desalination methods to grab the stark water lack issue facing the world. In order to achieve the purpose of this study, methodological steps should be followed

- A desalination plant features will be adopted as a model.

Desalination technology processes are either phase change with evaporating (thermal processes) [42], represented by thermal multi-stage flash (MSF), multi-effect distillation (MED), Thermal, or Mechanical Vapor Compression (TVC, MVC) and solar desalination [43]. Alternatively, processes without phase change (membrane technologies), which are only electricity-based [44]. Namely, Reverse Osmosis (RO), Electrodialysis, and Electrodialysis Reversal (ED/EDR) [43].

ED is commonly used for brackish water installations, while RO can be used for both, brackish and seawater [45], RO covers nearly 65 % of installed capacity in the world [15]. At the same time, desalination plants are energy-intensive with a negative environmental impact. There has been a critical enhancement over the past decade in the development of emerging seawater desalination technologies that can significantly reduce specific energy consumption compared to current conventional processes.

Membrane desalination techniques (RO, ED) or mechanical vapor compression (MVC) use electricity. Renewable solar energy should be converted to electricity, so it can be used to power the plants [44]. Membrane-based solar water desalination has an auspicious future as significant advances in the design of membrane modules, pretreatment, and energy recovery possibilities have empowered these methods to be cost-competitive compared to thermal processes. Membrane-based desalination has replaced thermal desalination in many parts of the world because of low energy consumption [18].

Membrane-based water desalination requires electricity as the primary input energy, unlike its thermal-based counterparts (electricity and heat), which makes its energy consumption less, and these can be reduced by integrating energy recovery systems. Moreover, its lightweight has a compact design and high productivity, which made it superior to the thermal-based desalination process [166].

The main source of desalinated water is seawater, with a share of 59% [17]. The lower energy consumption of all desalination technologies is the Seawater reverse osmosis (SWRO), the use is limited to the electrical energy only in a range of 3–4 kWh/m^3 with energy recovery [44].

Reverse osmosis technology has consistently outperformed its lower costs for seawater /brackish water consumption and water production costs and has less impact on marine life than distillation-based methods (MED, MSF, and VCD). RO and ED-PV are the most economical membrane-based desalination systems for brackish water [18].

The most suitable desalination combinations were MED/MSF for solar thermal power and RO/ED for PV power (Solar electricity), It also reported that RO dominated 62% of the desalination market share of RE. Nevertheless, PV-RO occupied 32% of RE in 2005 [63].

The most common is PV-RO due to the direct use of electric power to desalinate seawater. However, additional power is required, It is known that PV requires only sunlight to generate electricity, but the high solar heat or temperature [59,60] and high relative humidity [61] at seashore adversely affect the performance of the PV.

The use of solar water desalination is a technically viable option with promising prospects. Still, it is not currently comparable to conventional fossil fuel installations due to the high cost of solar collectors'/PV panels [18].

- Parametric analysis in arid and semi-arid areas around the Mediterranean coast

Reverse osmosis with photovoltaic power is technically mature and at a low cost of US$ 2-3 per cubic meter, and it is a cost-competitive process in remote areas. [64] It is visible when the top six largest desalination plants around the world are using RO technology mainly or a hybrid plant using RO [67]

The cost of water produced is influenced by factors such as the technology used and the concentration of TDS in feed water whether it is seawater or brackish water [160], capacity, type of plant, labor, location, and type of energy used and it is a cost [161,162]. The cost of desalination decreases as the capacity of the plant increases, and the concentration of salts decreases [163].

The average Mediterranean Sea Salinity is 36,000 (ppm of TDS) [179], .and the coastal cities were chosen for the study are Nador-Marroco, Algiers-Algeria, Tunis-Tunisia, Tripoli-Libya, Alexandria-Egypt, Jaffa- Palestine, Beirut-Lebanon, Latakia-

Syria, Izmir-Turkey, Larnaca-Cyprus, Athens-Greece, Rome-Italy, Cagliari- Sardinia, Marseilles-France, Barcelona-Spain.

In RO desalination plant, modifications applied on (temperature, pressure, or the concentration of the feed water) marks in the system outcome, RO membranes are affected by the recovery rate and the pressure limit. Noting that as the pressure increases, the membrane rejection increases. Feeding water flowing through the membrane affected both water flux and salt rejection rates [101].

However, above a fixed pressure limit, no increase happens in the rejection through the membrane, and some salt passage occurs during the flow of water. The maximum recovery rate that the RO system achieves depends on the chemistry of the feed water, i.e., the TDS in the feed water and its tendency to deposition on the surface of the membrane as a mineral scale [101].

- Annual water production and electricity consumption

The amount of energy needed and the price of desalination to produce water using RO are highly dependent on the efficiency of the desalination unit, membrane design, feedwater salinity (TDS), rate of recovery, and the pressure [19,100,163]. The effectiveness of a PV- RO unit subject to the efficiency of all components of the system [21].

Thus, the average salinity of the Mediterranean water is going to be considered as the salinity of feeding water in all stations of the study areas. In other words, electricity consumption is assumed to be the same in all stations.

- The use of Solar technology, PV as the energy-producing system

Solar collectors'/ PV panels cost is still high, but its integration with desalination units reduces the energy cost of desalination. [167,169,170]. Due to the low profitability of solar-powered installations, the unit price of solar desalinated water is very high compared to those powered by fossil fuels. However, it is an ideal solution to reduce carbon dioxide emissions and thus reduce the contribution to global warming [171].

The high cost of production is the main obstacle in the competition of PV technology over conventional energy resources. According to the GTM Research report, the majority of production costs are expected to fall as a result of advanced technological innovations that reduce waste, increase efficiency, and reduce manual labor and increase automation. All of the previous has caused production costs to descent from 50 cents per watt to 36 cents per watt in the fourth quarter of 2012 by the end of 2017 [180].

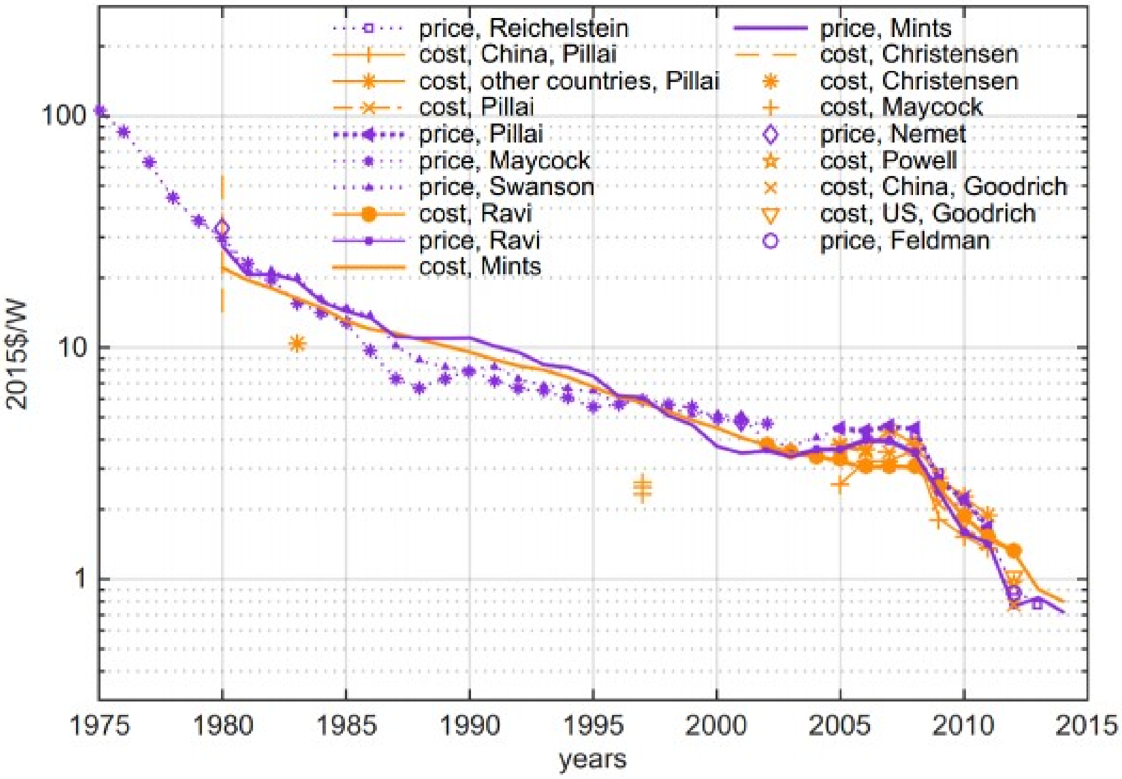


Figure 19 Module costs and prices decline over the past three decades [181]

Over the past 40 years, since the PV unit penetrated the market, the unit price has fallen rapidly. Thus, in the near future, PV technology can be expected to compete with traditional resources, figure 19. Kavlak et al. [181] developed a conceptual framework and a quantitative method for estimating the causes of cost changes in technology and applying them to PV modules. The group of the researchers created a cost model to estimate the reasons for the difference. They concluded in their paper that the main factors contributing to the reduction of PV energy costs are changing over time.

One of the variables is the low-level mechanisms. During the period 1980-2012, the efficiency rise was the leading cause of cost reduction which contributed 23%, "non-silicon materials by 21%, silicon prices 16%, silicon use 14%, and chip area 11%, Plant size is 11%, yield 7%" which is fairly evenly distributed and which explains the relative stability of the decline over the past years, all of which together contribute to lower cost per watt.

Other is the high-level mechanisms, together contributed an estimated 60% of the cost reduction during the period 1980-2012:

Private research and development or funded by the government have historically had the most significant impact contributing 59%, scale economies 22%, and finally learning by doing devoted 7%. However, more recently, after 2001, scale economies have come close to the importance of R&D and are likely to be a means of further cost reductions. The other shares contributed by another five mechanisms.

Rapid technological improvements in membranes and energy recovery leading to lower costs as well as lead to the expectation of a gradual decrease in the cost of desalination of about 4% to 5% annually [172,173]. It has been noted that the cost of RO plants has reduced up to 1/3 in between 2003/2005 to 1995/1997 [174].

- SAM as a simulation tool to model the PV system and find if it is viable.

The System Advisor Model (SAM) developed by NREL (the U.S. Department of Energy’s National Renewable Energy Laboratory) and provided as an open-source tool. SAM is a techno-economic tool that calculates the performance and financial metrics of RE projects. SAM produces results in the shape of graphs and tables in the purpose of the user can evaluate his results financially, technology comparing for decision making.The tool simulates the performance of PV, CSP, solar hot water , wind, geothermal, and biomass systems, and it is able to make a basic comparison with conventional or other types of systems.

A weather data file is required to run the simulation, and it describes the RE source and weather conditions in the study area. The program offers the user several libraries of performance data and coefficients that describe the characteristics of commercially available system components such as PV modules and inverters ..etc. At the same time, the user is able to change the data to a custom one. The financial models vary for projects such as Residential building, Commercial facility, Third-party ownership, Power generation, and Single owner that either buy and sell electricity. SAM's financial models calculate financial metrics for various types of power projects based on a project's cash flows over an analysis period specified by the user. The metric reports can be Levelized cost of energy, Electricity cost with and without RE, Electricity savings, After-tax net present value, and Payback Period. [NREL]

In conclusion, an RO desalination plant is going to be used as a case study for the energy consumption then a PV system is going to be used to cover the energy demand of the processes.

To calculate the demand of photovoltaic cells in meters square to cover the energy needed to produce one cubic meter of water is going to be implemented using the SAM tool.

In order to work on modeling a solar-powered desalination technology, firstly, a case study of an existing plant in the Mediterranean region is needed. Then the energy consumption of the case study will be used as input to measure and size the solar energy technology.

2.3 Water scarcity – Gaza as a case study:

The blockage of the Gaza strip the last years has caused repetitive humanitarian crises, leaving the strip in a constant shortage of humanitarian needs and a loss of the necessities of life (water, food, energy).

This case study focuses on the energy-water nexus and the role of clean water to create a sustainable living environment for the citizens of Gaza that could boost the economic growth in Gaza, where the quality of services, triple sustainability in social, economic, and environmental issues can be achieved.

Gaza Struggles to meet even basic needs, A UN report in 2012 had warned that Gaza would be unlivable by 2020, the consumption of water per capita in Gaza is a way less than the recommended by the World Health Organization leaving aside that a very high percentage of water reached to consumers is unfit for human consumption.

2.3.1 General understanding of Gaza

Gaza today is with close to two million people confined to a strip of land comprising (45 km in length, 5-12 km in width) in an area around some 365 km² [182], Gaza projected population in 2030 is to reach 3.1 million people [182]. Gaza's population density is the third-largest in the world, with over 5,200 inhabitants/km^2[183].

2.3.2 Electricity

The power blackouts per day in the Gaza Strip are between 18 to 20 hours. In effect, there has been a decline in electricity supply hours 6-4 hours per day.

It is estimated that only 26-46% of Gaza's energy demand is currently met [185]; Gaza Strip's total electricity supply capacity approximately is 208 MW (power plant and imports) while its electricity demand is estimated to be around 452 MW which expected to increase to about 600 MW by 2020 [186].

The recent severe electricity crisis began in June 2017, when Israel agreed to the PA's request to reduce electricity to Gaza since they cannot pay the bill anymore – the PA pays the electricity bill for the Israelis as they are the suppliers while the people of Gaza live in poverty.

2.3.3 Water

30% of Gaza residents are deprived of their right to water as a result of the constant electricity outage, the average of water consumption per capita in the Gaza Strip is 60 liters, while the minimum recommended by the World Health Organization is a daily 100 liters per capita[184]. 96% of Gaza groundwater contamination with untreated wastewater and seawater is unfit for human consumption [187].

Due to the limited access to safe drinking water, 40% of the inhabitants receive only 4 to 6 hours of water supply in 3 to 5 days, and 90% of the population in Gaza rely on purchasing water from private trucking [188]. The cost of water derived by the private sector is exceptionally high, at 30 NIS (about $7) per cubic meter, while the cost of water supplied through the municipal supply network range between One to Two NIS per cubic meter posing a heavy financial burden [189].

Why there is a lack of safe water?

Only four percent of the groundwater consider as drinkable water as a result of pollution and seawater intrusion, while the remaining percentage requires purification and desalination to become drinkable.

Consequently, over ~90% of the total water exploited in the Gaza Strip is no longer adequate for human consumption — that is not matching the World Health Organization (WHO) due to chloride concentration exceeding 250 ml/l [190].

The Gaza aquifer appears to have already passed the point of no return and needs to be regenerated before it can be sustainably used again. This leaves the population of the Gaza Strip without a reliable and affordable water source [183].

Are we able to tackle the problem?

In 2017 UNICEF, funded by the European Union, has established the largest desalination plant in Gaza with the cost of €10 million plant, improving access to drinking water for 75,000 people and producing 6,000 m^3 of potable water daily in the southern Gaza Strip, namely 35,000 residents in Khan Younis and 40,000 residents in Rafah. [201].

2.3.4 A Solar-Powered Water Solution for Gaza

Gaza has, however, a high potential for the development of solar resources [192]. This makes solar power an attractive option. The innovative photovoltaic electro dialysis desalination system is thus a potential game-changer for safe water production in the Gaza Strip since it reduces energy use by up to 60 percent [193]; operates only through solar power; transforms around 90 percent of the water it extracts from the aquifer into fresh drinking water [193], and lowers production costs.

2.4 Short Term Low Volume (STLV) desalination plant as a case study [183].

Water scarcity is a vital issue globally. Due to the increasing demands of freshwater in high salinity, polluted, and remote areas, the development of non-conventional water resources is essential. A case study for a 20000 m3/day RO desalination plant in Gaza, Palestine, is reviewed and analyzed. According to the plant location and site characteristics, several considerations have been evaluated in the design of the RO desalination plant. The overall objective of the STLV project is to mitigate the health and socio-economic impact on the Gaza Strip population due to the lack of sufficient drinking water and the contamination of the available water as well as the contribution to the protection of the groundwater resources, increase access to 90 liters per capita per day (l/c/d) of safe water for drinking and domestic purposes and to reduce pressure on the aquifer. Based on this salinity and using the Energy Consumption Calculator for Seawater RO software (by Ghiu, S and Filteau), Samples of seawater taken from the middle area of the Gaza strip which is close to the site, indicate TDS values of 36,000 mg/l in winter up to 38,000 mg/l in summer. A rough estimation of the energy consumption per desalinated m3 is estimated at 4.03 kWh/m3.

The Short Term Low Volume (STLV) seawater desalination plant to serve southern parts of the Gaza Strip governorates as a reference for the future detailed design of Phase 2A with a capacity of 6,000 m3 /d and 2B with a role of 8,000 m3 /d. The first phase was completed, and A PV system was installed to run one line of the three lines of the first phase (2,000 m3/d). Currently, it is being expanded to reach 20,000 m3/d capacity of potable water for a total of 250,000 residents.

2.4.1 Operating Parameters

Design Operating Conditions According to the plant location and site characteristics, several considerations have been evaluated to design a 20000 m3 /day RO desalination plant. The design basis and operating conditions are mentioned in Table 10.

Table 10 Design basis and Operating Conditions of the RO desalination system Operating Pressure

water temperature	Reverse osmosis is a pressure process at ambient temperature; the gross volume of the brine discharges is at the same temperature as feeder seawater. Occasionally, the temperature of a small quantity of water may rise to 33 °C due to the membrane's maintenance.
Raw water TDS	TDS values of 36,000 mg/l in winter up to 38,000 mg/l in summer
The recovery rate	45%
Energy recovery device	minimum efficiency of 94%.
Feedwater pH	6.5 to 9.5
Post treatment:	
CaCo3	60 ppm
Free of chlorine	0.5 mg/l
Chemical Dosing Ratio:	
a. Sodium bisulfate	5-10 g/m3
b. Anti-scalant	0.5 g/m3
d. Sodium Hypo chlorite	0.5 to 1 g/m3
e. Caustic Soda	0.5 to 1 g/m3

The Desalination Plant consists of:

Pre-treatment Unit, Sand filters, Intermediate tank, Sodium bisulfate dosing system, Anti-scalant, Booster pumps, Cartridge filter, Seawater Reverse Osmosis units, Energy Recover Device (ERD), Water Supply Pumping Station, Reject (brine drainage system), Chemicals storage rooms, Post-treatment and treated water tank.

2.4.2 Seawater Reverse Osmosis units

In the first phase, three trains of seawater RO vessels were constructed for the purpose of desalination. The recovery rate of this system is 45%, which means that 55% of the treated water will be rejected in the form of brine.

Table 11 Summary of STLV desalinated water lines

		desalinated water produced	The number of beneficiaries (individuals)	Capacity (m^3/year)	Annual electricity needed (kWh)	Plant requirements in terms of electricity installed capacity (MW)	
Phase 1		(3 x 2,000 m^3/d)	75,000	2,190,000	8,825,700	1.5	
Phase 2	2 A	(3 x 2,000 m^3/d)	75,000	2,190,000	8,825,700	2.54	~ 1
	2 B	(4 x 2,000 m^3/d)	10,000	2,920,000	11,767,600		~ 1.5

The type of selected membrane is a hydranautics membrane (SWC4B max). The dimension of each element is 8" x 40", surface: 40 m^2, number of elements: 427, element per pressure vessel and average flux rate: 14.6 $l/hr/m^2$. The main RO desalination building designed to contain all components, including both 2A and 2B Phases.

2.4.3 Operating Requirement

Table 12 Chemicals Needed (ml/m3) according to CMWU

Pretreatment	
Shock chlorination NaOCl 1 h per week	40
pH adjusts acid HCl	15
Coagulant Ferric chloride or sulfate	10
RO	
SBM (sodium bisulfite based mixture)	35
Anti-scalant	0.7
pH adjust soda	unnecessary
Post-treatment	
Ca(OH)2 (lime) injection for 10% only	50
pH adjust soda	13
Disinfection NaOCl	10
Citric acid (cleaning)	0.12 ton/year

2.4.4 Pretreatment

Chlorine with a maximum dose of 10 g/m^3, coagulant, and acid will be added inline in between the beach and the sand filter.

“The chlorine system will be used to disinfect the water for the purpose of preventing biofouling that may occur due to the attack of microorganisms to the RO membrane. Coagulant will be added to the feedwater to remove colloidal matter by forming flocs and to increase the efficiency of filtration. The acid will also be injected into the feed water to adjust the pH to less than 8 to prevent the formation of calcium carbonate and the RO membrane scaling.” [183].

Disinfection of raw water:

"Raw water pumped up from wells is disinfected by sodium hypochlorite (NaClO) injection, and the sterilized water is stored in a raw water storage tank. Chlorine disinfection is used as it deactivates most pathogenic microorganisms quickly. Chlorination is regularly used where biological-fouling anticipation is needed." [183].

2.4.5 Energy management

The electricity is the power supply of the STLV. The STLV Phase 1 used the Reverse Osmosis (RO) technology for seawater desalination and powered by 3 diesel generators (680 kVA power rate each) as well as 1.5 MW from the grid, solar PV made of 7 kWp capacity roof-top panels on the administration building and other additional 120 kWp rooftop capacity above the first STLV buildings. However, according to the design of Phase 1, a 240kW capacity rooftop plant can be installed on the STLV roof facilities.

The second phase of the STLV (under construction) will produce a total of 14,000 m^3 a day for both sub-phases 2A (6,000 m^3) and 2B (8,000 m^3).

Phases 2A and 2B with 3 and 4 desalination RO lines, respectively is to rely on the GEDCo grid, the future solar plant as well as on a number of diesel engines (gensets) (600 kVA each) (3 for Phase 2A and 4 for the Phase 2B) In other words, it will be necessary to install three gensets of 600 kVA each for each line to produce 2,000 m^3 autonomy during night and day and especially in case of total failure of the GEDCo grid.

Finally, it was recommended to install an additional genset (1,000 kVA) common to both Phases 2A and 2B to be operated as a spinning capacity to compensate for the production reduction during periods of regular maintenance and failures of other gen-sets, maintain the water production volume and water pressure on RO process filters to an acceptable level mainly during night time also in case of failure of electricity supply from the Gaza local grid loop. This will avoid their deterioration; it is recalled that the filters are the most expensive and sensitive parts of the entire desalination.

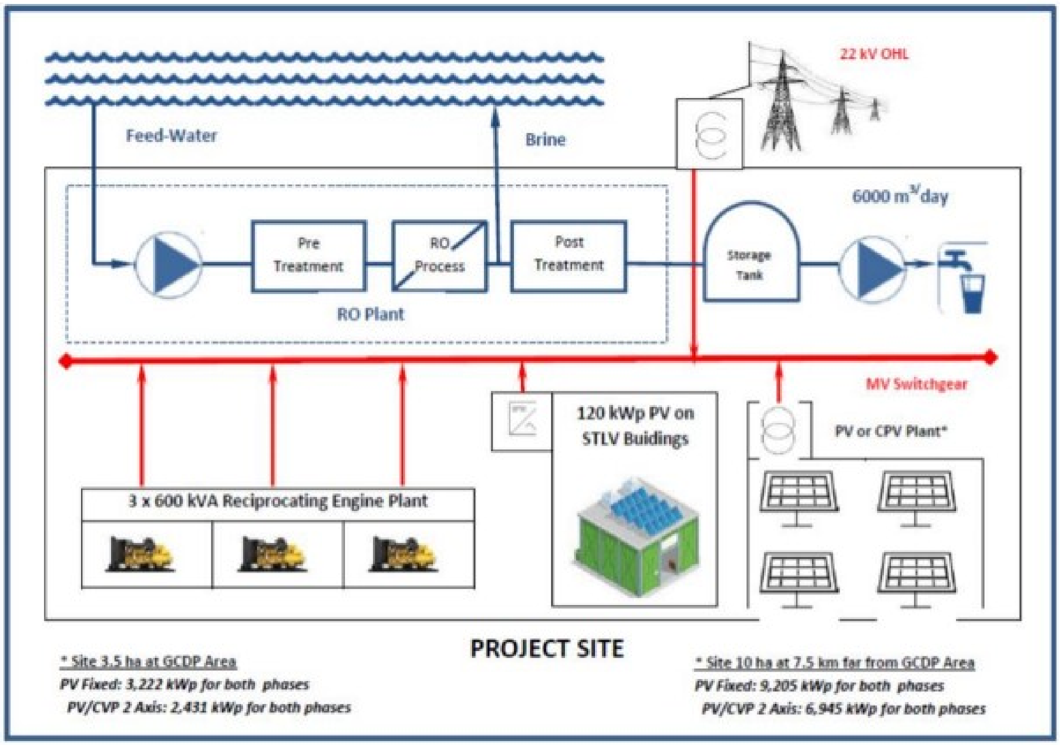


Figure 20 STLV General Diagram for Phase 2A [183].

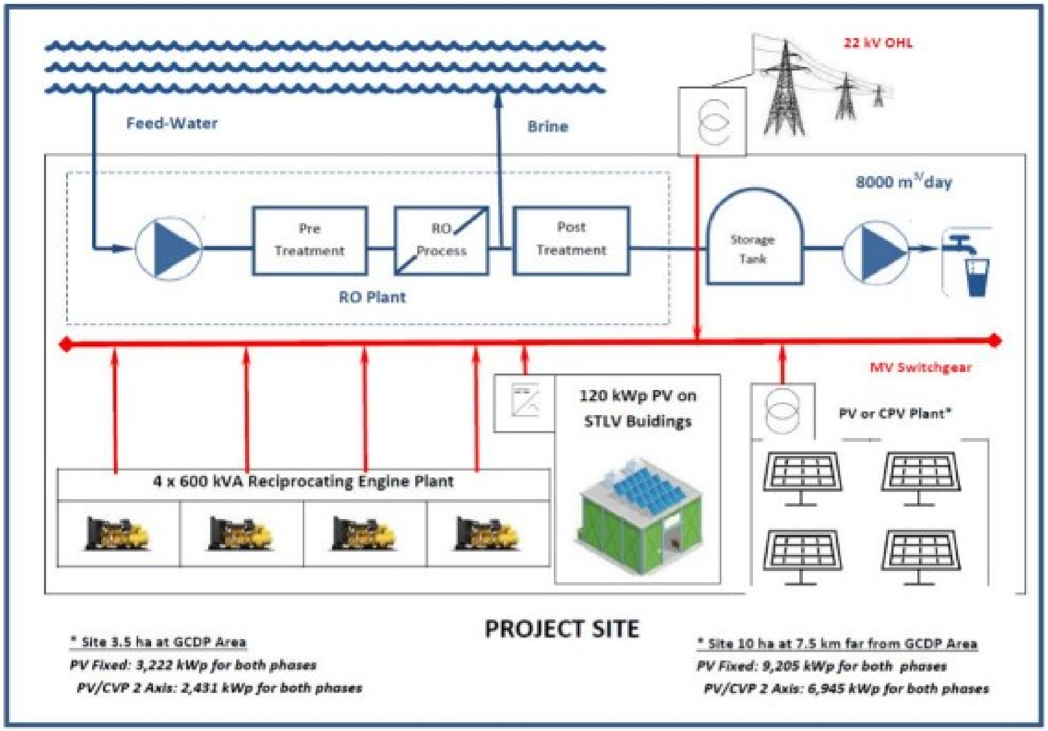


Figure 21 STLV General Diagram for Phase 2B [183].

Energy and efficiency:

As a result of introducing the Variable Frequency Drives (VFD) for the pumping system, it facilitated enhancing the plant efficiency by over 5% of the set target; it reduces the energy requirement from 4.03 kWh/m^3 to 3.8kWh/m^3 of desalinated water [186].

3 Sizing the PV system

A desalination plant features will be adopted as a model to be generalized to more than one geographic location in the Mediterranean basin region, a study to calculate the demand of photovoltaic cells meters square to cover the energy needed to produce one cubic meter of water is going to be implemented.

In order to work on modeling a solar-powered desalination technology, Using the case study of the STLV plant in Gaza, Palestine, the energy consumption of the case study will be used as input to measure and size the solar energy technology. The project was scaled down to cover the production of one line (2000 m^3 daily) in terms of energy.

Production of 2000 m3 daily (One line):

2000 m^3/day * 3.8kWh/m3 = 7600 kWh / day

7600 kWh * 365 = 2774000 kWh annually

3.1 Water salinity and stations for the study

Absolute salinity is acquainted as the intensity of dissolved salts in seawater, expressed in grams per kilogram, the Practical Salinity Unit (PSU)parts per thousand is also used the same for the Practical Salinity Scale (PSS) to come from seawater's electrical conductivity, temperature, and pressure. Salinity variates throughout the year. ice freezing and melting, precipitation, evaporation, and runoff are the causes behind the variations. The changes in seawater density cause ocean circulation tens to hundreds of meters in depth below the surface. The depth, temperature, salinity affect the seawater density [194]. Flowing is measures of Sea/Oceans salinity in the globe.

Table 13 Sea/Ocean salinity (ppm of TDS) [195].

Sea/ Ocean	Salinity (ppm of TDS)
Baltic Sea	28,000
∗ North Sea	34,000
Pacific Ocean	33,600
South Atlantic Ocean	35,000
Mediterranean Sea	36,000
Red Sea	44,000
Persian Gulf	43,000-50,000
Dead Sea	50,000-80,000
Worldwide Average	34,800

It is considered that the energy consumption will remain the same for all regions (as it is assumed that all study areas around the Mediterranean have the average salinity).

The average Mediterranean Sea Salinity is 36,000 (ppm of TDS) [195], the coastal cities were chosen for the study are Nador-Morocco, Algiers-Algeria, Tunis-Tunisia, Tripoli-Libya, Alexandria-Egypt, Jaffa- Palestine, Beirut-Lebanon, Latakia-Syria, Izmir-Turkey, Larnaca-Cyprus, Athens-Greece, Rome-Italy, Cagliari- Sardinia, Marseilles-France, Barcelona-Spain. In the following graph, the stations are illustrated.

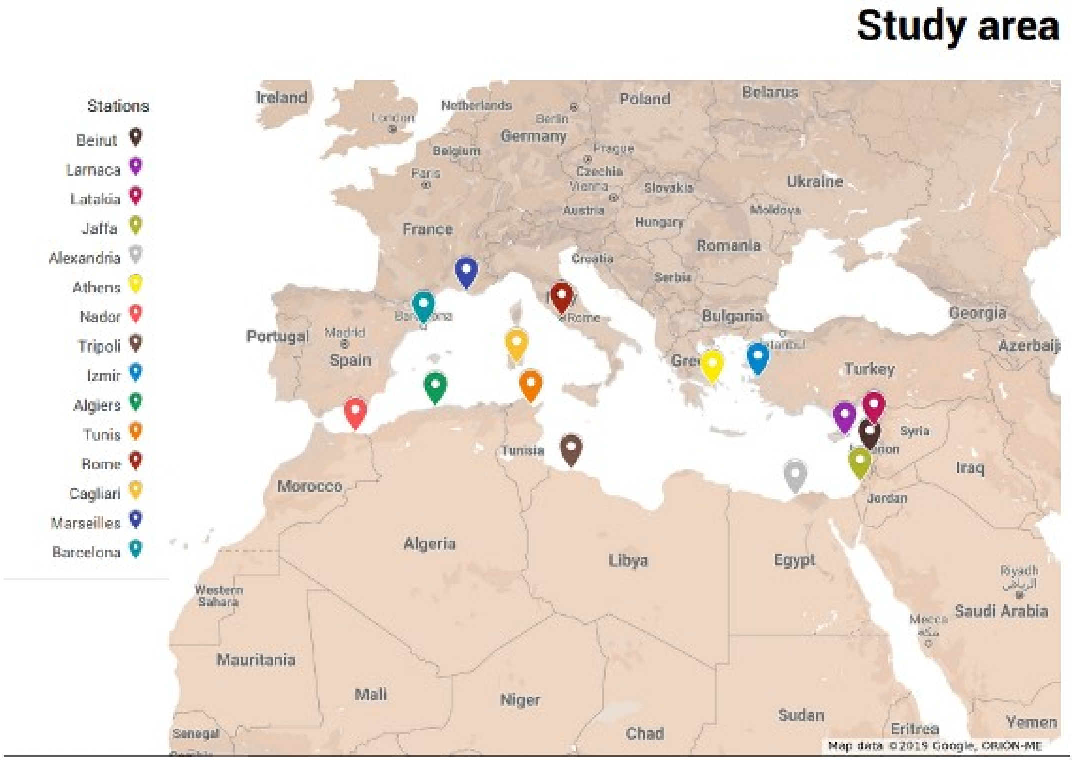


Figure 22 Stations for the PV system study

Table 14 Location (latitude, longitude) of the stations for the PV system study

Location		Latitude	longitude
Turkey	Izmir	38° 25' 7.86" N	27° 7' 43.392" E
Greece	Athens	37° 59' 1.7160" N	23° 43' 39.1404" E
Morocco	Nador	35°10'5.27" N	-2°56'0.67" W
Libya	Tripoli	32° 53' 7.2708" N	13° 10' 48.5796" E
Tunisia	Tunis	33° 47' 35.38" N	9° 33' 38.76" E
Algeria	Algiers	36° 44' 14.0352" N	3° 5' 11.2992" E
Spain	Barcelona	41° 23' 24.7380" N	2° 9' 14.4252" E
France	Marseilles	43°17'49" N	5°22'51.9" E
Italy	Rome	41° 54' 10.0152" N	12° 29' 46.9176" E
Sardinia	Cagliari	39°13'25.83" N	9°7'17.98" E
Syria	Latakia	35° 31.287' N	35° 47.544' E
Lebanon	Beirut	33° 53' 19.0680" N	35° 29' 43.7280" E
Palestine	Jaffa	32° 03' 9.68" N	34° 45' 6.55" E
Egypt	Alexandria	31° 12' 20.7108" N	29° 55' 28.2936" E
Cyprus	Larnaca	34° 55' 23.1456" N	33° 38' 2.5620" E

3.2 Photovoltaics

Photovoltaic is a term that describes the change of light into electricity. A typical PV system employs solar panels, each comprising a number of solar cells, which generate electrical power. PV installations may be ground-mounted, rooftop-mounted, or wall-mounted. In this work, it is presumed that the system is mounted in the height of one to a two-story building.

Solar PV has preferences as an energy source: once installed, its operation generates no pollution and no greenhouse gas emissions. It offers humble scalability in regards to power needs, and silicon has large availability in the Earth’s crust.

PV systems have the disadvantage that the power output is dependent on direct sunlight, so some power is lost if a tracking system is not used since the cell will not be directly facing the sun at all times. Dust, clouds, and any other obstacles in the atmosphere also diminish the power output. Another issue to deal with is the intensity of the energy production in the hours corresponding to main insolation, which does not frequently correspond to the peaks in demand in human activity cycles. Unless recent societal patterns of consumption and electrical networks mutually adjust to this scenario as the demand response action in the smart cities. still, electricity needs to be stored in other forms for later use

3.3 Main system components

3.3.1 Module

The module used in this study is Mono-c-Si technology. Namely, SunPower SPR-X22-360 consists of 96 cells with a total module area of 1.63 m². The Module capacity 359.96 DC Watts with a 22.0701% nominal efficiency.

The energy efficiency of this technology is more stable for around 12-15 years after installation, where others deteriorate earlier, as well as, the long experience in the Mediterranean countries of installing this technology [183].

The following figures 23 and 24 show the module model used and its characteristics at reference conditions, reference condition (Total Irradiance = 1000 W/m^2, Cell temp = 25 C)

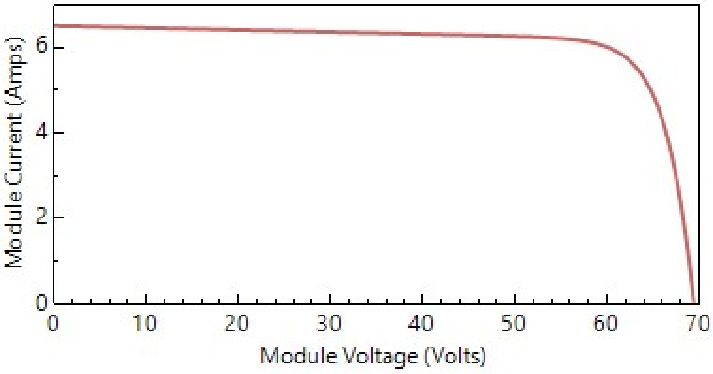
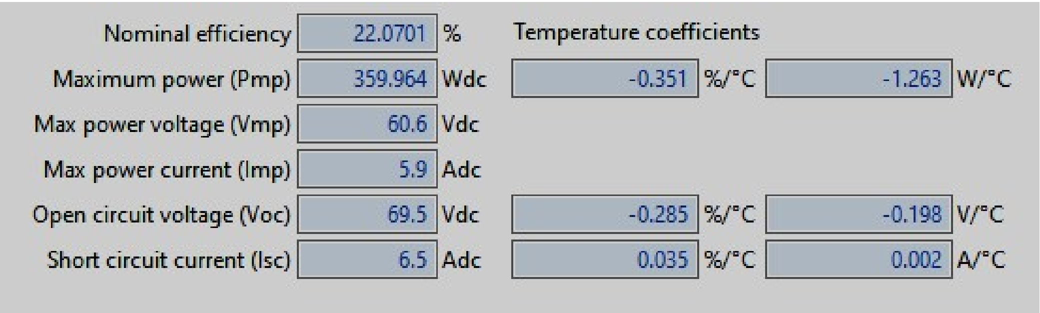


Figure 23 The module at current vs. voltage at reference conditions



Nominal efficiency	22.0701	%	Temperature coefficients			
Maximum power (Pmp)	359.964	Wdc	-0.351	%/°C	-1.263	W/°C
Max power voltage (Vmp)	60.6	Vdc				
Max power current (Imp)	5.9	Adc				
Open circuit voltage (Voc)	69.5	Vdc	-0.285	%/°C	-0.198	V/°C
Short circuit current (Isc)	6.5	Adc	0.035	%/°C	0.002	A/°C

Figure 24 Characteristics of the module at reference conditions

3.3.2 Inverter

The inverter used in this study is a 15 AC kW capacity. Namely, SunPower: SPR-15000m-3, the Input voltage 300 - 800 VDC DC V with a 97.66% CEC weighted efficiency.

The following figures 25 and 26 show the inverter used and its characteristics that fit the required energy needed to be produced.

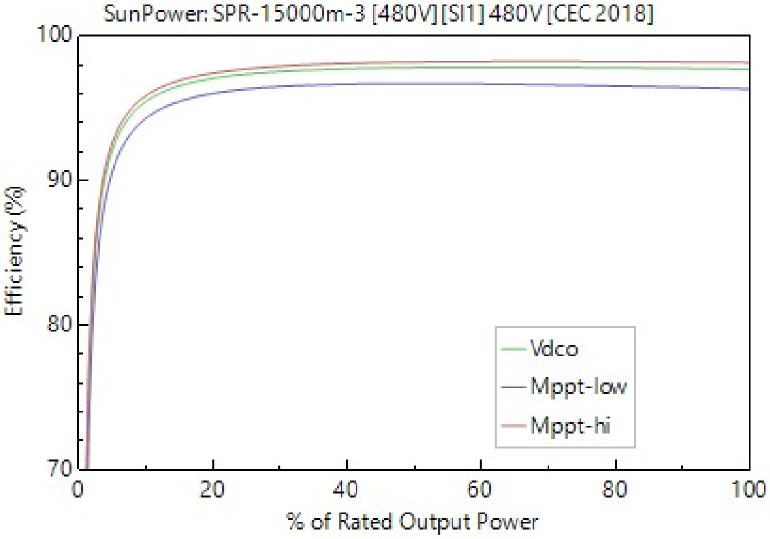
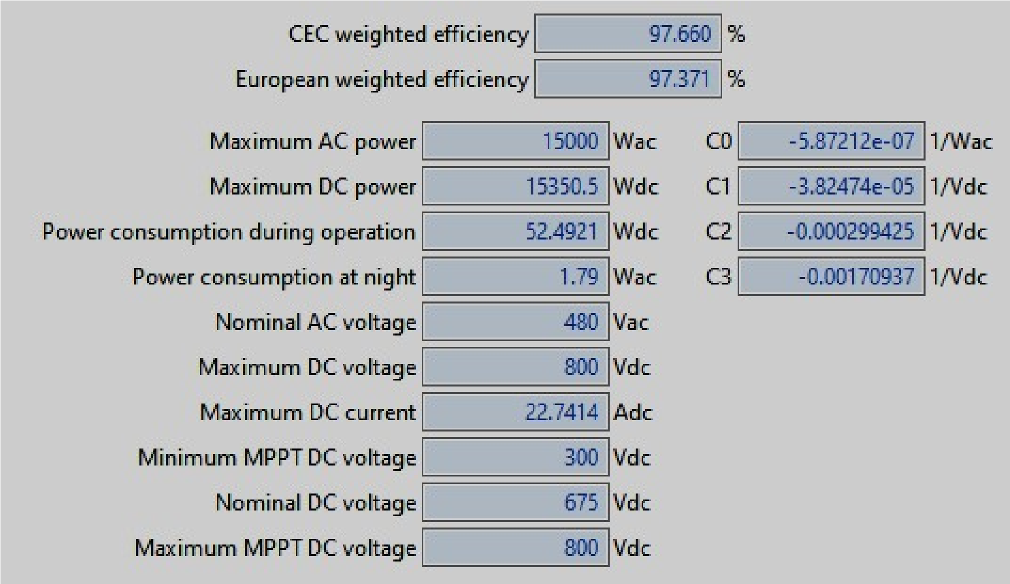


Figure 25 Efficiency curve



CEC weighted efficiency	97.660	%			
European weighted efficiency	97.371	%			
Maximum AC power	15000	Wac	C0	-5.87212e-07	1/Wac
Maximum DC power	15350.5	Wdc	C1	-3.82474e-05	1/Vdc
Power consumption during operation	52.4921	Wdc	C2	-0.000299425	1/Vdc
Power consumption at night	1.79	Wac	C3	-0.00170937	1/Vdc
Nominal AC voltage	480	Vac			
Maximum DC voltage	800	Vdc			
Maximum DC current	22.7414	Adc			
Minimum MPPT DC voltage	300	Vdc			
Nominal DC voltage	675	Vdc			
Maximum MPPT DC voltage	800	Vdc			

Figure 26 Characteristics of the inverter

3.4 Simulation using SAM

In order to design the PV system required, SAM (System Advisory Model) was used as a tool for simulation. A weather data of the stations (Typical-year hourly data) must be available to run the simulation. Weather data were collected from a repository of free climate data for building performance simulation in the SAM-ready EPW format (One building) [196].

3.4.1 Optimal tilt angle

SAM was used to figure the optimal design of the PV system in each station. Many tilt angels were adopted in order to find the highest annual production. Table 15 shows different tilt angels for the study locations. The tilt angle changes relative to the latitude of the city. the lowest tilt angle observed is 28 in Tripoli-Libya at the south of the Mediterranean while the highest is 37 in Barcelona-Spain at the Northern coast of the Mediterranean.

Table 15 The optimal tilt angle

Location	The optimal tilt angle
Latakia	34
Beirut	33
Jaffa	30
Gaza	29
Alexandria	30
Larnaca	34
Izmir	35
Athens	30
Nador	32
Tripoli	28
Tunis	30
Algiers	31
Barcelona	37
Marseilles	36
Rome	33
Cagliari	29

3.4.2 Systems design

In all stations, the system orientation was a fixed structure with no tracking, all facing south(180 deg. Azimuth) with different tilt angles depending on the optimal tilt angle for each station, as explained previously. The system number of modules per string varied between 10 modules per string or 11 modules per string (related to the inverter capacity), then connected stings in parallel to cover the energy needed and 0.3 ratios for the ground coverage.

The arrangement was made depending on the best use of the PV modules to cover as much as close to the annual energy demand with less number of inverters and modules, assuming that its an annual net metering system which is the more consumer initial cost-friendly since it covers the whole year demand using the grid as storage. In all stations, the same module and inverter were used. The total number of modules and inverters, as well as the arrangement, tilt angle, varies. The less number of modules to produce the aimed amount of electricity to run the desalination plant is in Alexandria-Egypt of 4092 panels 11*372 modules in strings and strings in parallel respectively. 6413 modules are the maximum number of modules arrangments at the station of Cagliari-Sardinia, Table 16 shows the best arrangement simulation results generated from SAM for all study areas.

Table 16 Simulation results of different scenarios – all stations

Location	#Modules of per string	# of strings in parallel	Total # Modules	# In-verters	Tilt angle	AC/DC ratio	Goal (kWh)	system production (kWh)	Extra Production (kWh)
Barcelona	11	467	5137	112	37	1.1	2774000	2774220	220
Jaffa	11	459	5049	109	30	1.11	2774000	2779918	5918
Algiers	11	459	5049	110	31	1.1	2774000	2776866	2866
Nador	11	410	4510	98	32	1.1	2774000	2779073	5073
Latakia	11	393	4323	94	34	1.1	2774000	2779425	5425
Larnaca	10	414	4140	90	34	1.1	2774000	2774811	811
Athens	11	467	5137	112	30	1.1	2774000	2776546	2546
Beirut	10	419	4190	91	33	1.1	2774000	2775811	1811
Tripoli	11	429	4719	103	28	1.1	2774000	2779842	5842
Alexandria	11	372	4092	89	30	1.1	2774000	2778957	4957
Rome	11	517	5687	124	33	1.1	2774000	2778231	4231
Izmir	11	456	5016	109	35	1.1	2774000	2777185	3185
Tunis	11	458	5038	110	30	1.1	2774000	2774742	742
Cagliari	11	583	6413	140	29	1.1	2774000	2778174	4174
Marseilles	11	468	5148	112	36	1.1	2774000	2776254	2254

The Capacity Factor of the photovoltaics system ranged between 13.7% in Cagliari recording the minimum energy yield at the first year and 21.5% in Alexandria with the highest energy yield, Alexandria also shows that 3.34 m^2 of photovoltaics is enough to produce one cubic meter of freshwater using the RO-PV technology.The performance ratio of all stations is 0.80 or 0.81, while Marseilles and Barcelona are 0.82 and 0.83 respectively, more details are illustrated in table 17.

Table 17 A summary of simulation results of the best scenario for all stations

Location	Total module area (m^2)	Capacity factor (year 1)	Energy yield (year 1) kWh/kW	Performance ratio (year 1)	Extra production (kWh)	The area in m^2 needed to produce 1 m^3 of freshwater
Alexandria	6,674.1	21.5%	1,887	0.81	4957	3.33705
Larnaca	6,752.3	21.3%	1,862	0.81	811	3.37615
Beirut	6,833.9	21.0%	1,840	0.81	1811	3.41695
Latakia	7,050.8	20.4%	1,786	0.81	5425	3.5254
Jaffa	8,234.9	17.5%	1,530	0.80	5918	4.11745
Barcelona	8378.4	17.1%	1,500	0.83	220	4.1892
Algiers	8078.4	17.4%	1,528	0.81	2866	4.0392
Nador	7335.8	19.5%	1,712	0.81	5073	3.6679
Athens	8378.4	17.1%	1,502	0.80	2546	4.11745
Tripoli	7696.7	18.7%	1,6360	0.80	5842	3.84835
Rome	9275.8	15.5%	1,357	0.81	4231	4.6379
Izmir	8181.1	17.6%	1,538	0.81	3185	4.09055
Tunis	8217.6	17.5%	1,530	0.81	742	4.1088
Cagliari	10459.6	13.7%	1,203	0.81	4174	5.2298
Marseilles	8396.4	17.1%	1,498	0.82	2254	4.1982

The total number of modules used to produce a specific amount of electricity depends on the location of the power plant, the meteorological data, terrain, pollution as it affects the solar radiation intensity at the study area.

The result shows that the latitude, the total numbers of panels and the number of inverters has a proportional correlation, figure 27, 28. Cagliari shows a slight difference in the simulation result compared to the other stations (figure 29), in latitude Rome and Barcelona are located at 41 North while Cagliari is on 39 North, the result shows that Cagliari needs more modules to produce the target amount of electricity to run the desalination plant. These results spot the light on the effect of atmospheric conditions on the work of solar cells and solar intensity at a specific location, for example, the relative humidity, dust, clouds, etc.

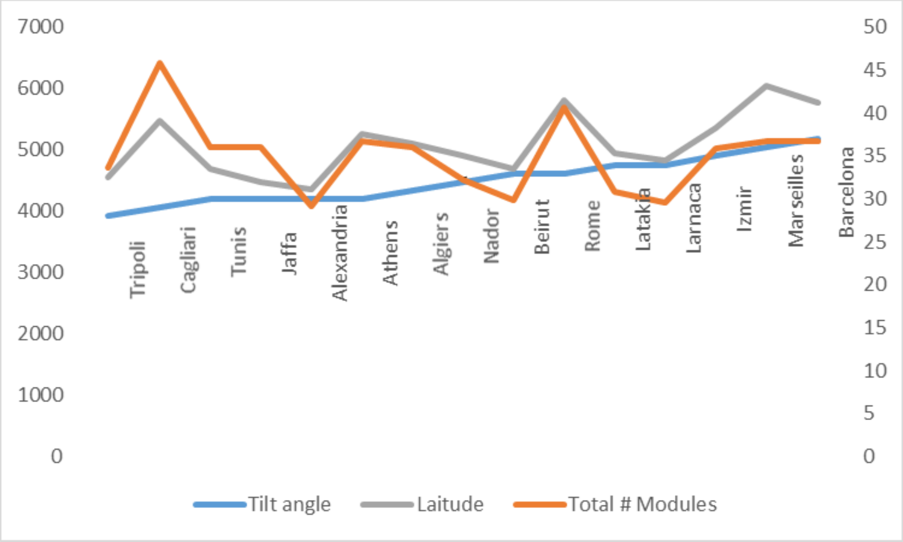


Figure 27 Tilt angle, latitude and the number of modules correlation

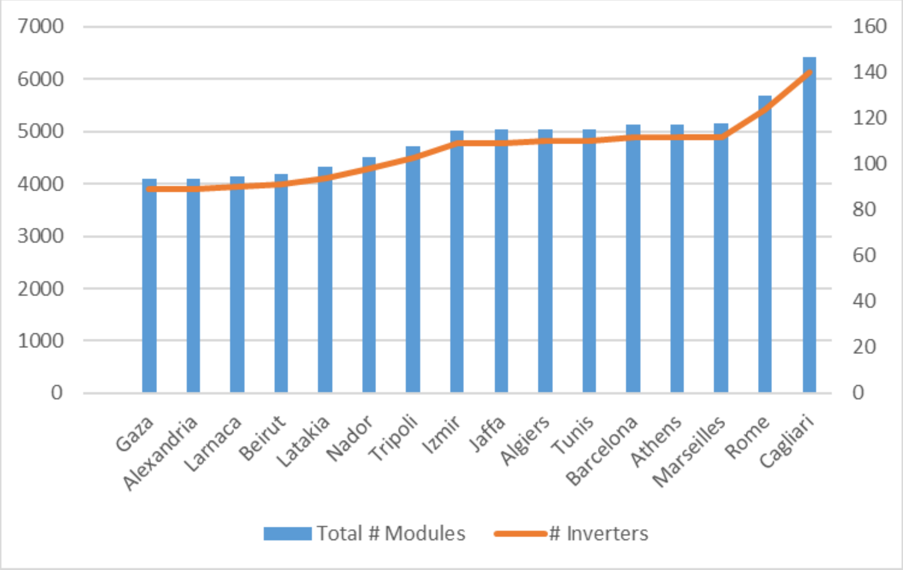


Figure 28 PV modules and the inverters

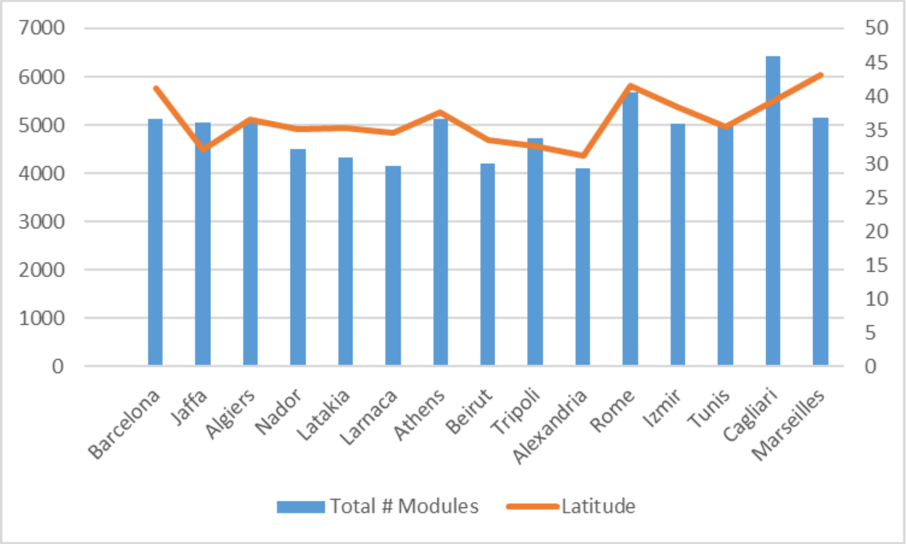


Figure 29 The latitude and the numbers of modules

The highest capacity factor of the photovoltaics system was 21.5% in Alexandria with the highest energy yield of 1,887 kWh/kW at the first year, Alexandria also shows that 3.34 m^2 of photovoltaics is enough to produce one cubic meter of freshwater using the RO-PV technology. In order to have more understanding of Alexandria station one more scenario with 1 MW installed capacity was implemented. The 1MW system is compared with a 1.5 MW installed capacity that used to cover the 2774000 kWh annually.

The annual energy production of the 1MW PV is 1,889,972 kWh around 68% of the 1.5 MW system. The maximum monthly production was observed on April (177,994 kWh) and the minimum was on December (125,854 kWh) while the monthly need is 231166.67 kWh, figure 30 compares the energy production of the 1MW system with the 1.5MW system and the monthly energy need to run the desalination plant.

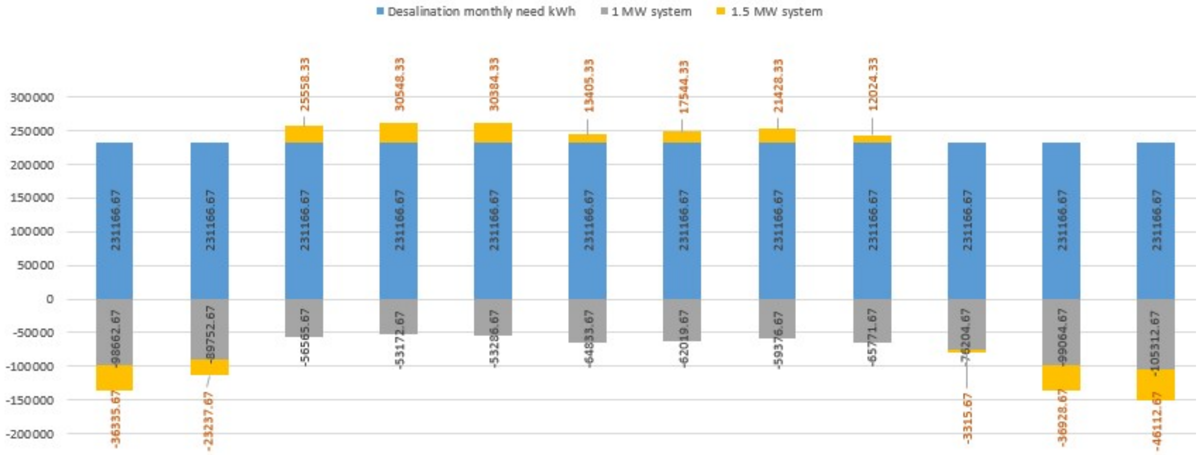


Figure 30 Alexandria monthly energy production and need

Figure 31 shows that on April the 1.5 MW system has the capacity of producing 2264.3 cubic meters of desalinated water as maximum and it accedes the goal of 2000 m^3 in 7 months of the year, the total extra production on these months is 1305.5 m^3while the total need of the other months is 1262.6 m^3, the annual sum up is an extra capacity to produce 42.9 m^3 of freshwater. However, the 1MW system is disabled to cover the monthly need for electricity to run the desalination line of its full capacity. The annual water shortage using the 1MW system is 7648.369 m^3 causing a 31.87% shortage of the designed annual capacity of the desalination line which is about 4 months' coverage.

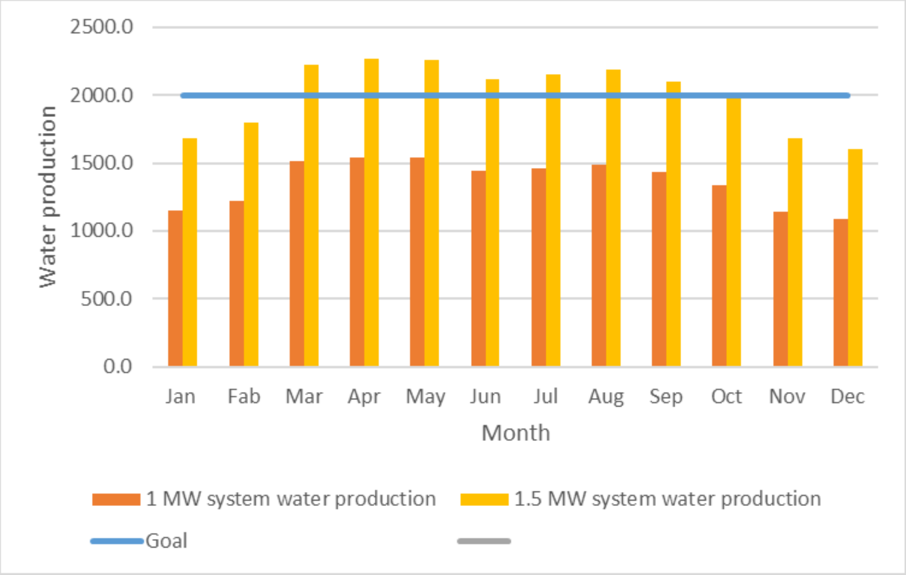


Figure 31 Alexandria monthly water production and need

The average monthly insufficiency of covering the energy need to produce 2000 m^3 of freshwater using the 1MW system is about 30%. Figure 32 also shows that the 1.5 MW system has the ability to have a 2.2% extra annual energy to cover the desalination line need.

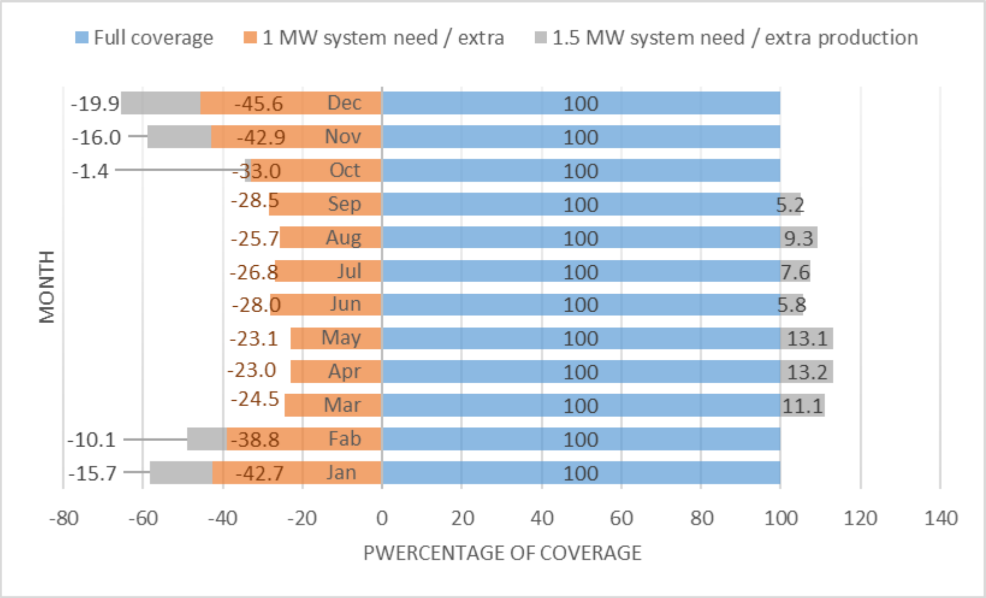


Figure 32Alexandria 1MW and 1.5MW systems percentage of coverage

The 1MW system was inadequate to cover the energy need so other scenarios were implemented for Alexandria station. In the previous comparison as mentioned earlier, the system used was fixed-mounted with no tracker or any moving axis. New simulations of a fixed axis, 1 moving axis, 2 moving axes and azimuth axis were done for both of the 1MW and 1.5 MW systems.

The results in Table 18 show the annual production of different scenarios. The change from a fixed system to an azimuth, 1-axis and 2-axis tracking system adds around 20%, 23% and 29% efficiency to the system respectively.still, adding a tracking system to the 1MW system does not cover the annual energy need, for example, the 1MW system with 2-axis tracking system has an insufficiency of around 12% while around 32% insufficiency for the fixed axis system as shown in figure 33.

Table 18 Annual production of different tracking configurations for Alexandria

System	Annual production (kWh)
1MW-Fixed	1889976
1.5MW-Fixed axis	2778963
1MW-Azimuth axis	2262126
1.5MW-Azimuth axis	3326104
1MW-2axis	2436165
1.5MW-2axis	3581904
1MW-1axis	2331954
1.5MW-1axis	3428766

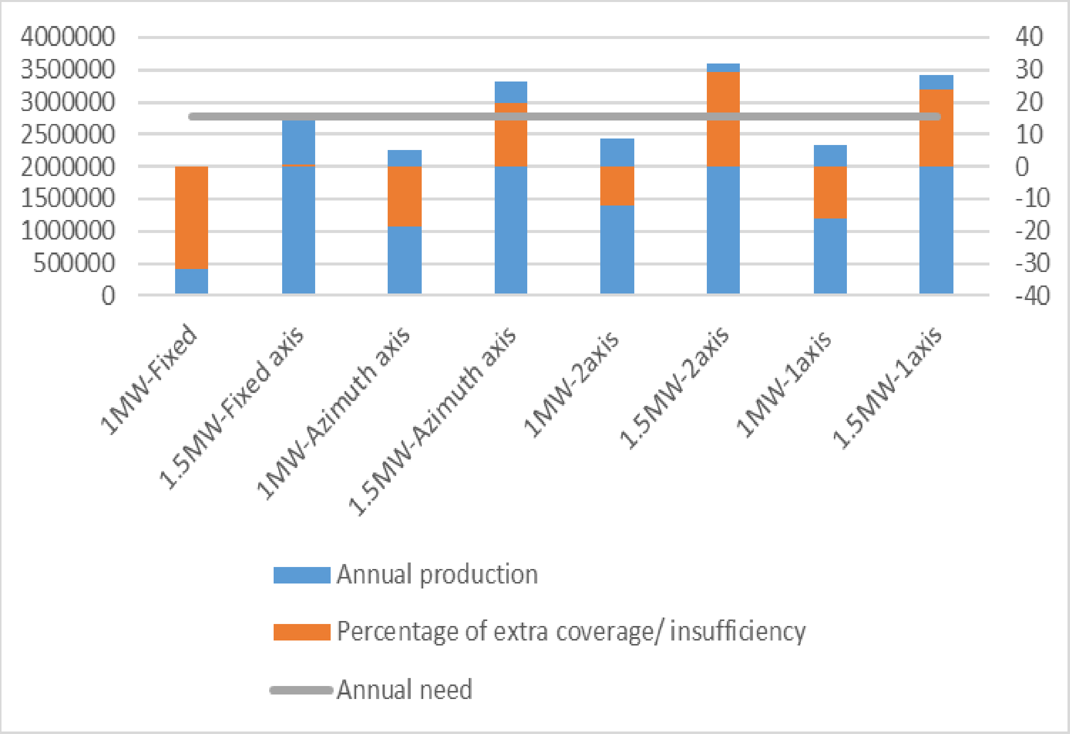


Figure 33 tracking systems annual production and the percentage of extra coverage/insufficiency

The change of the tracker from 1-axis to a 2-axis tracker has no major effect on energy production (adds around 1% increase of the energy production) for both September and March months. However, March has around 10% more energy production in both tracking systems than it is in September for the 1.5MW system and 4% for the 1MW system.

The Azimuth axis system outperforms the 1-axis system in May, June and July while the 1-axis system has better performance in the other months of the year. Finally, in figure 34, the 2-axis tracker has the highest energy production throughout the year compared to the other tracking systems for both the 1MW system and the 1.5MW system.

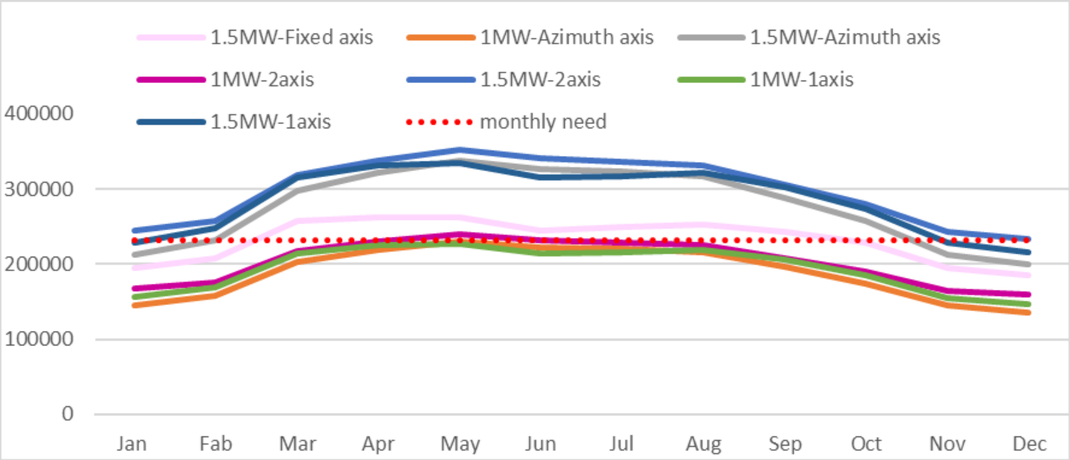


Figure 34 Tracking systems monthly production

4 Conclusion

The aim of this work was modeling a solar-powered desalination technology, specifically RO-PV of an existing plant, as well as, comparing the area of PV panels required to cover the same electrical demand in different regions around the Mediterranean coast in order to produce a daily 2000 m3 of freshwater using the RO desalination technology. The most important observations of this study are concluded below.

- Pros of using reverse osmosis are:

- processes without phase change.
- RO can be used for both, brackish and seawater.
- RO covers nearly 65 % of installed capacity in the world.
- RO use electricity. Renewable solar energy should be converted to electricity, so it can be used to power the plants.
- RO solar water desalination has an advances in the design of membrane modules, pre-treatment, and energy recovery possibilities. Moreover, its lightweight has a compact design and high productivity.
- cost-competitive compared to thermal processes.
- The lower energy consumption of all desalination technologies is the Seawater reverse osmosis (SWRO), the use is limited to the electrical energy only in a range of 3–4 kWh/m^3 with energy recovery.
- RO has less impact on marine life.
- RO and ED-PV are the most economical membrane-based desalination systems for brackish water.
- RO dominated 62% of the desalination market share of RE. Nevertheless, PV-RO occupied 32% of RE in 2005.
- The most common technology is PV-RO due to the direct use of electric power to desalinate seawater.

- Reverse osmosis with photovoltaic power is technically mature and at a low cost of US$ 2-3 per cubic meter.

- The total number of modules and inverters, as well as the arrangement, tilt angle required to produce a specific amount of electricity varies. It depends on the location of the power plant, the meteorological data, terrain, pollution as it affects the solar radiation intensity in the study area.
- The result shows that the latitude, the total numbers of panels and the number of inverters has a proportional correlation, these results spot the light on the effect of atmospheric conditions on the work of solar cells and the solar intensity at a specific location, for example, the relative humidity, dust, clouds, etc.
- The less number of modules to produce the aimed amount of electricity to run the desalination plant is in Alexandria-Egypt of 4092 panels 11*372 modules in strings and strings in parallel respectively. 6413 modules are the maximum number of modules arrangments at the station of Cagliari-Sardinia.
- The Capacity Factor of the photovoltaics system ranged between 13.7% in Cagliari recording the minimum energy yield at the first year and 21.5% in Alexandria with the highest energy yield. The low percentage is attributable to the nature of the solar radiation, which is available only on day time making no energy production during the night.
- Alexandria shows that 3.34 m^2 of fixed photovoltaics is enough to produce one cubic meter of freshwater using the RO-PV technology, while 5.23 m^2 is required in Cagliari-Sardinia.
- In Alexandria, the annual energy production of the 1MW PV is around 68% of the 1.5 MW system.
- On April the 1.5MW system has the capacity of producing 2264.3 cubic meters of desalinated water as maximum and it accedes the goal of 2000 m^3 in 7 months of the year, the total extra production on these months is 1305.5 m^3while the total need of the other months is 1262.6 m^3, the annual sum up is an extra capacity to produce 42.9 m^3 of freshwater. Assuming that it is an annual net metering system connected to the grid which is the more consumer initial cost-friendly since it covers the whole year demand using the grid as storage.

- The 1MW system is disabled to cover the monthly need for electricity to run the desalination line of its full capacity. The annual water shortage using the 1MW system is 7648.369 m^3 causing a 31.87% shortage of the designed annual capacity of the desalination line which is about 4 months’ coverage.
- The average monthly insufficiency of covering the energy need to produce 2000 m^3 of freshwater using the 1MW system is about 30%. The 1.5 MW system has the ability to have a 2.2% extra annual energy to cover the desalination line need.
- The change from a fixed system to an azimuth, 1-axis and 2-axis tracking system adds around 20%, 23% and 29% efficiency to the system, respectively.
- Adding a tracking system to the 1MW system (fixed axis, 1 moving axis, 2 moving axes and azimuth axis) was inadequate to cover the annual energy need. For example, the 1MW system with a 2-axis tracking system has an insufficiency of around 12% while around 32% insufficiency for the fixed axis system.
- The change of the tracker from 1-axis to a 2-axis tracker has no major effect on energy production (adds around 1% increase of the energy production) for both September and March months. However, March has around 10% more energy production in both tracking systems than it is in September for the 1.5MW system and 4% for the 1MW system.
- The Azimuth axis system outperforms the 1-axis system in May, June and July while the 1-axis system has better performance in the other months of the year.
- The 2-axis tracker has the highest energy production throughout the year compared to the other tracking systems for both the 1MW system and the 1.5MW system.
- For future studies, it is recommended to run more scenarios for all of the other stations in order to have more understanding of the PV performance in the Mediterranean region. The output data can be used to run a regression model; the regression analysis can describe the relationship between the different variables. The regression equation can also be used for predictions.
- Finally, in order to find the optimal PV arrangement for any study area, an economic study should be implemented. There are many factors to take into consid-

eration when implementing the economic study of different scenarios, such as the polices at each country, tax, energy price and availability, Feed in Tariff, funding, etc.

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Appendix

LIST OF ACRONYMS AND ABBREVIATIONS:

AD adsorption desalination

CAES compressed air underground heat storage

CPV concentrating photovoltaic

CRS central receiver systems

CSP concentrated solar power

CST concentrated solar thermo-electric

ED electrodialysis

EDR Electro-Dialysis reversal

FAO Food and Agriculture Organization of the United Nations

GCC Gulf Cooperation Council

GE geothermal energy

GOR gain output ratio

HDH humidification–dehumidification

HFC heliostat field collector

HTF heat transfer fluid

KACST King Abdulaziz City for Science and Technology

KAUST King Abdullah University of Science and Technology

MD membrane distillation

MED multi-effect distillation

MENA Middle East and North Africa MSF multi-stage flash

MVC mechanical vapor compression

MWt Megawatt thermal

O&M Operation and maintenance

Tc critical temperature

Ts normal boiling temperature

p_c critical pressure

p_s normal vapor pressure

PTC parabolic trough collector

PV photovoltaic

RE renewable energy

RO reverse osmosis

SE solar energy

SPT solar power tower

SWRO seawater reverse osmosis

TDS total dissolved solids

UHCPV ultra-high concentrator photovoltaic

AC/DC Alternating/Direct Current

$ USD

°C Degrees Centigrade

°F Degree Fahrenheit

µm Micrometer

Cl Chloride

CPV Concentrator Photovoltaic

CSP Concentrated Solar Power

DNI Direct Normal Irradiance

EC European Commission

ED Electro Dialysis

ERD Energy recovery device

EU European Union

FIT Feed-in Tariff

Ft foot

g gram

GCDP Gaza Central Desalination Plant

GEDCo Gaza Electricity Distribution Company

GOM General Operational Manual

GOR Gained-Output-Ratio

Gpm Gallon per minute

GR Grade

GRP Glass Reinforced Plastic

GWh Giga Watt-hour

H hour

HCPV High Concentrated Photovoltaic

HP High pressure

kg Kilogram

kJ Kilo Joule

KVA Kilo volt-ampere

kWp kilowatt peak

m^2 squared meters

m^3 Cubic Meter

m^3/d Cubic Meter per day

MCM Million Cubic Meters

MD Membrane Distillation

MED Multiple Effects Distillation

MEH Multi-Effect Humidification

mg/l Milligram per liter

MGD Million Gallons per Day.

MJ Mega Joule

MSF Multistage Flash Desalination

MVC Mechanical Vapour compression

MW Megawatt

NO3 Nitrates

PEA Palestinian Energy Authority

PENRA Palestinian Energy and Natural Resources Authority

PPM Part Per Million

PR Progress Ratio

psi pound per square inch

PSI Palestinian Solar Initiative

PV Photovoltaic

PVDF Polyvinylidene Difluoride

PWA Palestinian Water Authority

RE Renewable Energy

RES Renewable energy sources

RO Reverse Osmosis

SS Stainless Steel

STLV Short Term Low Volume

SWRO Seawater Reverse Osmosis

TAF Technical Assistance Facility

TDH Total Dynamic Head

TDS Total Dissolved Solids

UNICEF United Nations Children's Fund

WHO World Health Organization