SOLAR ENERGY USED FOR SEAWATER DESALINATION IN ARAB COUNTRIES

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ABSTRACT

New water requests are expanding each day on account of industrialization, mechanization and expanded life principles of humanity. Millions of people have no access to a secure source of fresh water Desalination is widely adopted in Arab countries and theMiddle East. One approach to this commoncrisis of water and energy supply is to utilize solar energy sources to produce freshwater by desalination. Major desalination processes consume a large amount of energy derived from oil and natural gas as heat and electricity, while emitting harmful CO_2. Solar desalination has emerged as a promising solar energy-powered technology for producing fresh water. This overview presented in this paper focuses on the economics of solar desalination with an accentuation on the Arab Countries order to estimate the economic benefits of it in comparison with other desalination systems. This study reviews the current solar desalination research activities first, followed by discussions of solar assisted desalination processes and a variety of possible combinations.

Keywords: Solar desalination, Water production cost, Energy cost, Economics

1 INTRODUCTION

Water is an abundant natural resource, as approximately three-quarters of the planet are covered by it. However, 97.5% of this resource is comprised by saline water, leaving only 2.5% of fresh water (Shiklomanov&Rodda, 2003). Moreover, almost two-thirds of this freshwater is inaccessible, since it’s in theice form and snow in the Antarctic, arctic islands and mountainous regions. Accordingly, the accessible freshwater being less than 1% of the global water resource.

Recognizing the importance of water for sustainable development, the United Nations declared 2005-2015 The United Nations declared 2005-2015 the "Water for Life" that the water crisis is ranked third in the 10 risks around the world. According to the report issued by this forum (World Economic Forum, 2014). Indeed, water is crucial for social and economic development. Yet evidence points to the fact that the current use of water is unsustainable (Gleick, 2010). More than the need for the water as a result of population growth, increasing consumption patterns and the development of the industry. The number of the world's population to $9.3*10^9$ by 2050 (United Nations World Water Assessment Programme, 2014). Where the increase in the growth rate in urban areas in the world increases the need for water and food and medicines squadron and other goods which require large quantities of water. And this percentage is expected to increase by 20% by 2050 (United Nations World Water Assessment Programme, 2014). The increase in water demand in the countries experiencing rates of economic and social development. The demand for water for domestic use and in the industry is expected to increase. According to a report from Mckinsey & Company (2009), up to 40% by the year 2030 (Mckinsey& Company Report, 2009). This water scarce future represents a critical challenge to civilization.

The global water demand is continuously increasing due to population growth and economic development. Worldwide water withdrawals surpass 4,000 billion m^3 per year (Rosegrant et al, 2002) and about 25% of the world population encounters freshwater scarcity (UN OCHA, 2010). And as a result of the growing demand for water. Water desalination systems have become the most important source of water for domestic purposes and in agriculture in some areas around the world and especially in the Middle East and North Africa. Where Ida water desalination that there are about 15 thousand desalination plants in the world, with total capacity of 71.7*10^6 m^3/day. About 60% of water used in these units is seawater (IDA in Black & Veatch, 2011). Over the past years, the desalination plants working in countries of the MENA region where approximately 2,800 desalination plants produce 27*10^6 m^3/day distillate water where distillate water from seawater represent 38 % of total capacity (Fichtner, 2011). And the problem of the water desalination dilemma that they need to thermal energy and electrical power, or membrane-based processes using only electricity "Table 1". The dominant desalination processes in use today are based on Reverse Osmosis (RO) and Multi Stage Flash (MSF) which constitute 60.0% and 26.8% of the worldwide capacity, respectively "Fig. 1". The possibility of the implementation of this technology in water desalination depends on certain operating conditions such as electrical energy prices, the type of technical materials used and quality of water in the region.

Table 1. Major Desalination Technologies

Thermal Technologies	Membrane Technologies
Multi Stage Flash, MSF Multi Effect Distillation, MED Vapor Compression, VC	Reverse Osmosis, RO Electro dialysis, ED

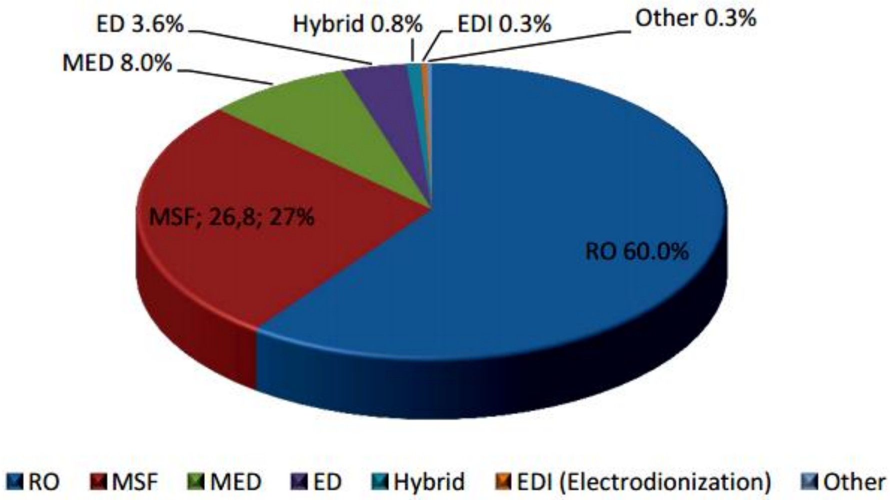

Figure 1. Desalination Technology Market (IDA in Koschikowski, 2011)

2 ENERGY REQUIREMENTS

Water desalination consumes large amounts of energy and this causes an increase in the cost of one liter of water. The power required depends on different factors such as the technology used and factory design and quality and the feed water temperature. The cost of produced water depends on the energy requirement of desalination processes.

Energy requirements for desalination have declined drastically throughout the most recent 40 years, due to improvement in the technology and are expected to keep decreasing. Several factors that can minimize the energy required in desalination: system design, pumping efficiency, energy recovery, advanced membrane materials and innovative technologies.

Thermal desalination requires both thermal and electricity energy, with the exception of MVC. In thermal desalination processes, the low temperature heat represents the main percentage of the energy input while the electricity is needed for the pumps. In MSF theprocess operates at a top brine temperature (TBT) between 90-110ºC. The total electrical equivalent energy required by MSF varies between 19.58-27.25 kWhe/m^3. In the case of MED, thebrine temperatures range between 64-70ºC.

The total electrical power consumption varies between 14.45- 21.35 kWhe/m^3, considering a power-plant efficiency of 30%. The electrical power consumption in MVCvaries between 7-12 kWhe/m^3, while in TVC is about 16.26 kWhe/m^3 (Al-Karaghouli&Kazmerski, 2013).

In the case of membrane desalination processes, the energy consumption depends mainly on the salinity of the feed water and the recovery rate. The average power consumption of RO ranges between 3.7 to 8 kWh/m^3 for seawater. For SWRO unit with energy recovery the power consumption varies between 4 to 6 kWh/m^3 at 24.000 m^3/day capacity. For BWRO unit's the power consumption ranges between 1.5 and 2.5 kWh/m^3(Al-Karaghouli&Kazmerski, 2013). In the case of ED, the electrical consumption varies between 0.7-2.5 kWh/m^3 for low salinity feed water and 2.64-5.5 kWh/m^3 for salinity between 2500-5000 ppm (Al-Karaghouli&Kazmerski, 2013). The energy consumption of main commercial desalination technologies are shown in "Table 2".

Table 2. Energy Consumption indesalination technologies (Al-Karaghouli&Kazmerski, 2013) and (Ghaffour et al., 2013)

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

3 RENEWABLE ENERGY-POWERED DESALINATION

Renewable energy sources such as solar photovoltaic and thermal, wind or geothermal energy can be utilizedthe desalination plant, as using locally available renewable resources is likely to be cost-effective.

As desalination worldwide capacity currently surpasses 71.7*10^6 m^3/day, this solution leads to a high incidence of falls in the emissions from petroleum products. As for the cost of renewable energy is expected to decrease as a result of the rapid development, so as to be more attractive and especially in remote areas. (IRENA, 2012).

The renewable-powered desalination represents capacity less than 1% of the world's desalination capacity (Shatat et al., 2013). The dominant renewable energy source for water desalination is solar photovoltaic (PV), used in 43% of the existingrenewable energy desalination plants, followed by solar thermal and wind energy. Renewable energy sources currently utilized for desalination are shown in "Fig. 2".

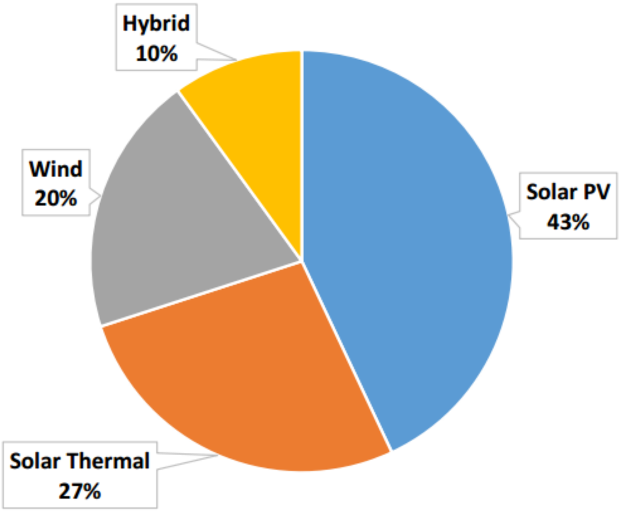

Figure 2. Renewable energy sources currently utilized for Desalination (Quteishat& Abu-Arabi, 2012)

The combination renewable energy source/desalination technology will depend on a variety of factors such as: location, salinity of feed-water, available renewable energy sources, plant capacity or availability of grid electricity. The possible combinations can observe in "Table 3".

Table 3. Possible combinations or renewable energy and desalination technologies

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

3.1 Solar powered desalination

Solar thermal energy can be converted to electrical energy or thermal energy. The solar photovoltaic used to produce the electrical energy and utilized in RO and ED. Thermal energy can be collected directly to the water, as solar stills, or by using solar thermal collection systems, to be utilized in thermal desalination processes such as MSF, TVC and MVD.

3.1.1 Solar stills

Solar stills are mainly suited for small production systems where the water demand is less than 200 m^3/day. Due to the low production rate, and the requirement of a large area for solar collection, solar stills are not considered a viable option for large-scale production, the comparative installation costs tend be higher than other desalination systems (Shatat et al. 2013). "However, solar stills become economically viable for small-scale production for many remote and rural regions, especially for small water requirements" (Al-Karaghouli&Kazmerski, 2013). Various researchers have attempted to increase the efficiency of solar stills by modifying the design. For example, solar stills can be coupled with solar collectors in order to increase productivity (Shatat et al. 2013). "Since solar stills have a production of 3 to 5 l/day m^2, a 120-200 m^2 land area would be needed to supply a family that consumes 0.6 m^3/day" (Goswami&Stefanakos, 2013). The solar stills are shown in "Fig. 3".

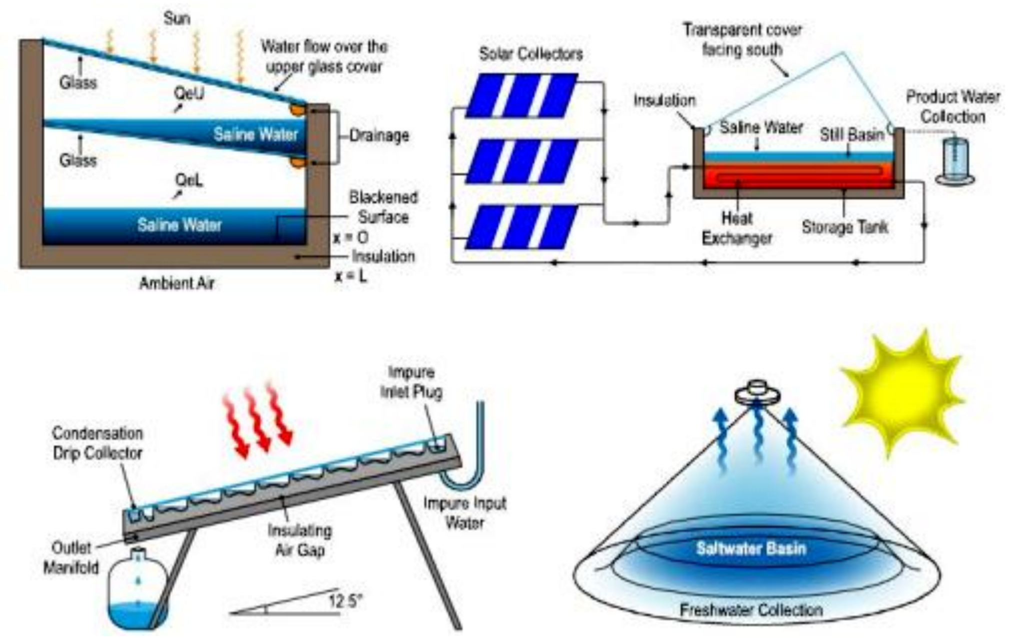

Figure 3. Diverse types of Solar Stills (Al-Karaghouli&Kazmerski, 2013).

3.1.2 Solar ponds

Solar ponds used tocollect and stored the thermal energy. The solar pond composes of three layers: the upper layer (upper convection zone), the middle layer (non-convection zone or salinity gradient zone) and the lower layer (storage zone or lower convection zone). The temperature at the bottom of the pond can reach to90ºC. The largest storage capacity of solar ponds can be useful for the continuous operation of the MED, the TVC and the MSF desalination plants. Research has shown that for MED system the optimal thicknesses of the three layers of the solar pond are 0.3 m, 1.1 m and 4 m, for the upper, medium and lower layers, respectively as shown in "Fig. 4" (Goswami&Stefanakos, 2013).

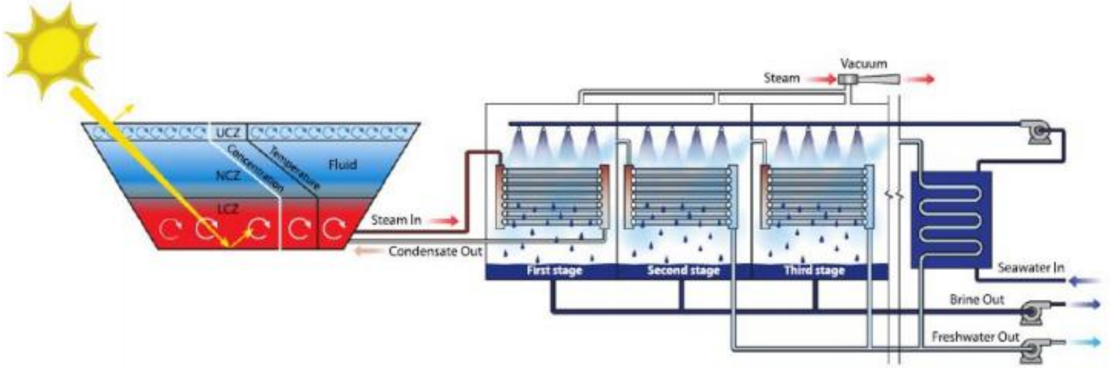

Figure 4. Solar Pond with MED desalination (Goswami&Stefanakos, 2013)

3.1.3 Indirect Solar thermal

Desalination can be coupled with indirect solar thermal technologies such as concentrated solar power (CSP) power plants.The CSP coupled with desalination plant, the CSP units generate the thermal and electrical energy to drive MED and MSF units. The electrical energy produces from CSP unit can be supplied to MED as shown in "Fig. 5". The CSP plant can also be used in conjunction with an RO plant by producing the need electricity. Internal studies from Bechtel Power Corp. concluded that CSP-RO coupling is more efficient and requires less energy than CSP-MED coupling **(Al-Karaghouli&Kazmerski, 2013)**.

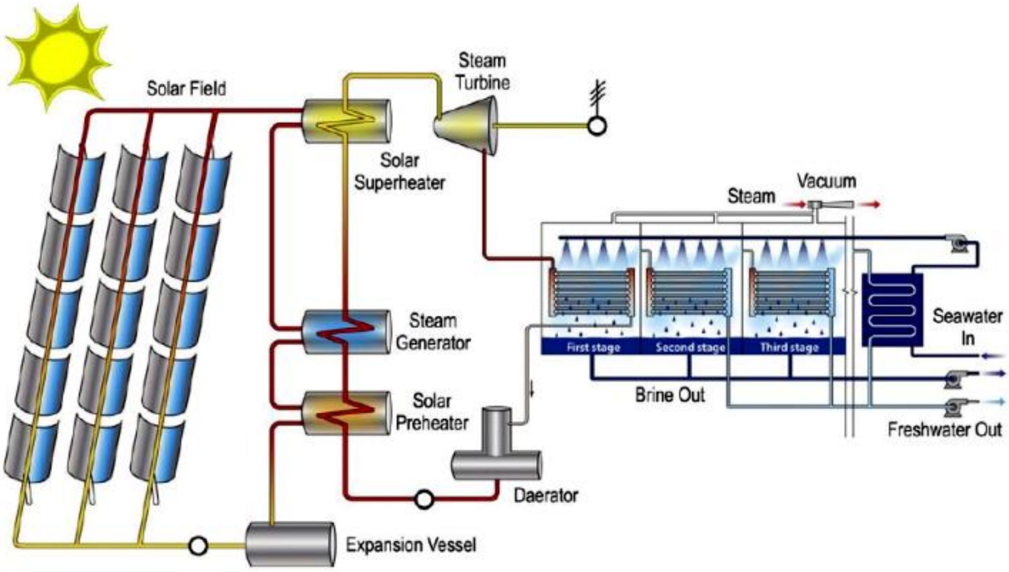

Figure 5. Schematic of CSP connected with MED (Al-Karaghouli&Kazmerski, 2013)

3.1.4 Solar photovoltaic

Solar PV systems can be connected directly to RO or ED desalination processes as both require electrical energy for the pumping system as shown in "Fig. 6". The system can include a set of batteries for energy storage, in order to stabilize the energy input of the RO unit, and a charge controller that regulates the charge of the batteries, avoiding deep discharges and overcharge (Richards & Schafer, 2010).

The productivity of PV coupled with membrane desalination reached to 5 m^3/day for brackish water and 10 m^3/day for seawater.

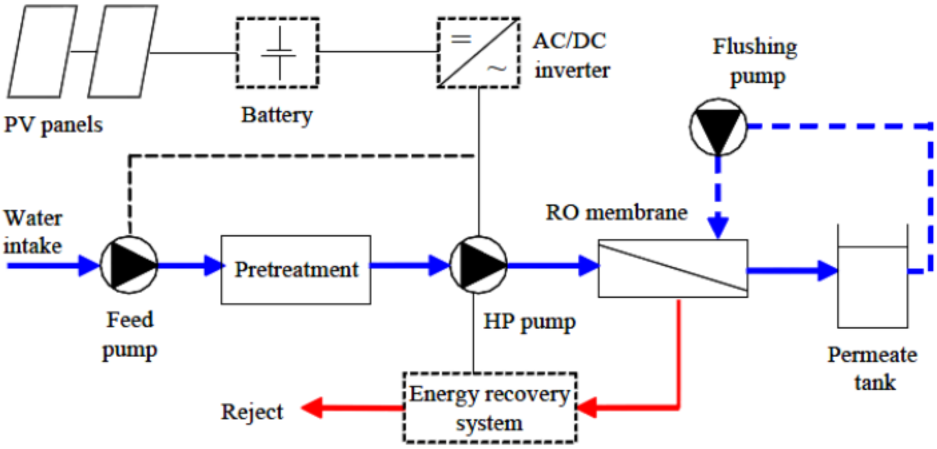

Figure 6. Schematic of PV-RO system (Ghermandi&Messalem, 2009)

3.2 Wind powered desalination

The mechanical power and electrical power generated by the wind turbine are used to drive the desalination system (Ma & Lu, 2011).

3.3 Geothermal - powered desalination

Geothermal energy can be used for heat and electricity generation, making it an option to couple with the desalination system. Geothermal energy produced the water at low temperature (less than 100 ºC), medium temperature (between 100 to 150ºC) and high temperature (greater than 150ºC).
The first desalination units operates with geothermal energy constructed in USA in 1972, followed by units in France, Tunisia and Greece. The advantage of geothermal energy integrated with desalination system, the therma starage is not needed (Eltawil et al. 2009).

3.4 Hybrid - powered desalination

Hybrid renewable energy sources are the concept of combining more than one renewable energy resource. A hybrid Wind-PV-RO plant was presented, reaching a promising value for water production cost of 5.21 €/m^3 (Ma & Lu, 2011). Another study with the same configuration, in Eritrea, East Africa determined that a system with 35 m3/day production had a specific energy consumption of about 2.33 kWh/m^3(Gilau& Small, 2008).

4 DESALINATION MARKETS

Currently as clear from Figure 7, most of the desalinated water comes from seawater sources, 63%, followed by brackish water with 19% and only 5% comes from wastewater sources.

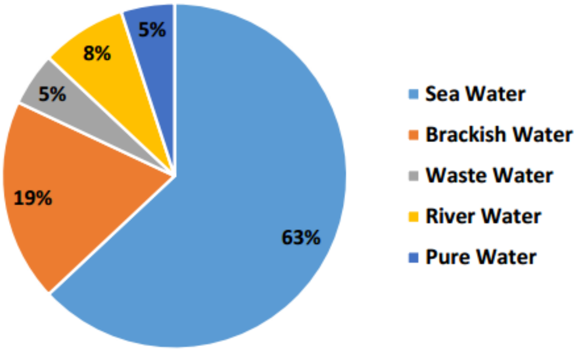

Figure 7. Sources of Feed Water for Desalination processes (Lattemann et al. 2010)

Sea water desalination using renewable energy more than high rates in most countries of the world, such as Saudi Arabia, Australia, Jordan, Egypt, Morocco, United Arab Emirates, Turkey, Cyprus or Spain. The growth increases in dry areas with high solar energy and especially in growth increases in dry areas with high solar energy and especially in Middle East and North Africa (MENA).

4.1 Middle east and north Africa (MENA) region

The hydrological analysis confirms that the per capita share of water in the Middle East are among the lowest in the world, reports indicate that the situation will deteriorate. According to the United Nations Food and Agriculture and that the total quantities of available water per capita less than 2000 cubic meters and is likely to become less than 1,000 cubic meters per capita in drought years and this causes in the presence of severe restrictions on the socio-economic development and environmental protection. Considering this and examining"Fig.8", it can be concluded that by 2020-2030 water availability in the MENA region will be a severe constraint to socio-economicdevelopment and environmental protection in all the countries that are comprised in the MENA region.

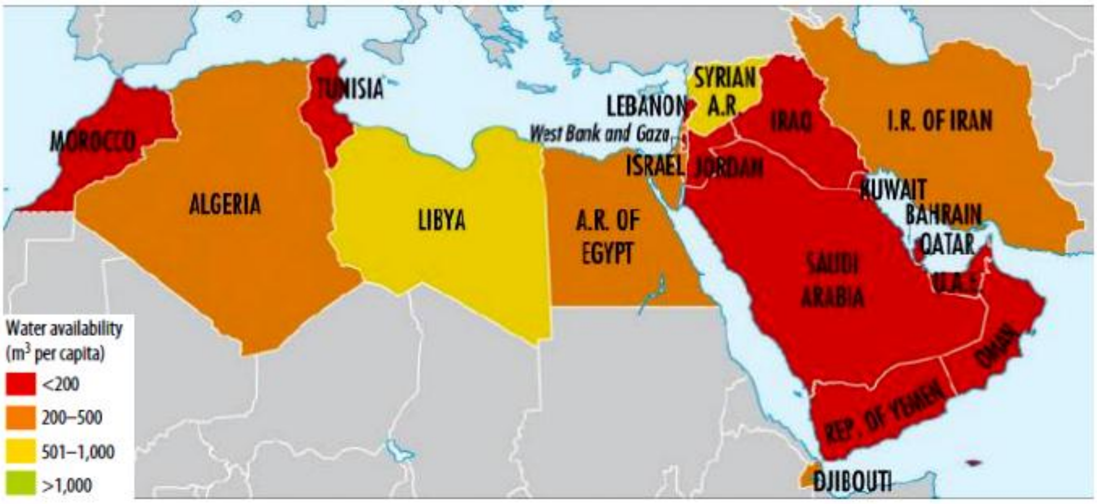

Figure 8. MENA's Water Availability by 2020-2030 (The World Bank, Washington, 2012)

In MENA, 80% of the region’s surface freshwater sources are stored in reservoirs. MENA’s rivers are the most heavily dammed in the world. Thus, the possibility to expand water supplies by building news dams is limited. This limited potential exists in high humid parts of the region such as north-western Iran and the Atlas Mountains of Algeria and Morocco. For this reason, the possibility to bridge the water demand gap must come from unconventional supplies such as desalination of seawater or brackish water and wastewater reuse.

4.2 Water demand in the MENA region

Current water demand in MENA region exceeds naturally available water suppliers by almost 20%. Future water demand is expected to increase due to population growth. Future water demand in the MENA region is expected to increase which is expected to reach 697 million by 2050 from a current 381 million. Thus, the water balance gap is expected to reach 37% of total demand in 2020-2030 based on an average climate scenario, reaching 51% by 2040-2050 as shown in "Fig.9"(The World Bank, Washington, 2012).

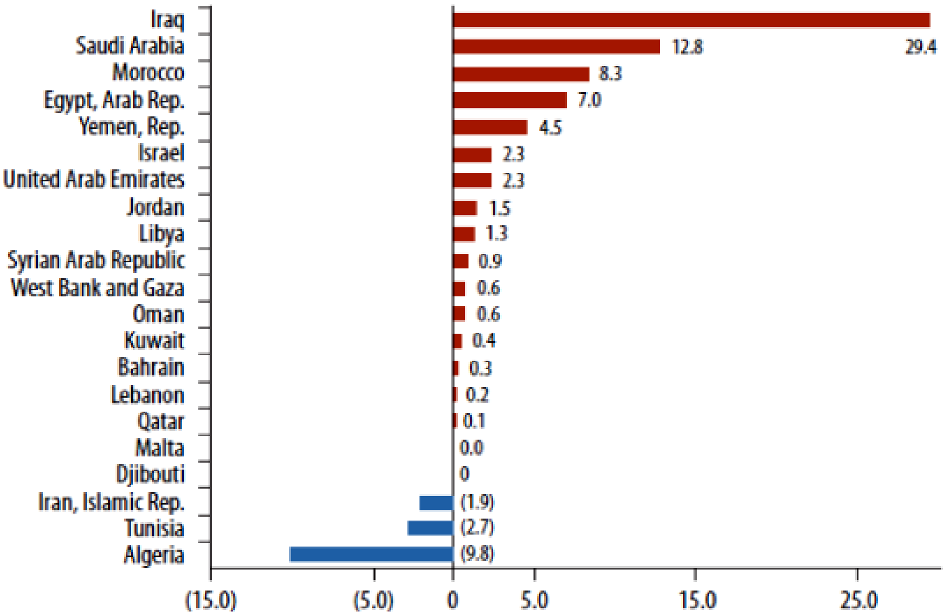

Figure 9. Demand Gap in MENA Countries by 2040-50 (The World Bank, Washington, 2012)

The solar energy-based desalination is projected to become a major process for water production in MENA, accounting for about 16% of total water production in 2030 and 22% in 2050.This scenario involves the availability of surface- and ground-water according to mild-to-average climate change and desertification scenarios. On the other hand, careful assessment is needed to match the appropriate types of desalination technologies. Membrane based desalination technologies are not well suited to in regions where salinity is higher such as seawater because they require energy-intensive pretreatment to avoid fouling "Fig. 10".

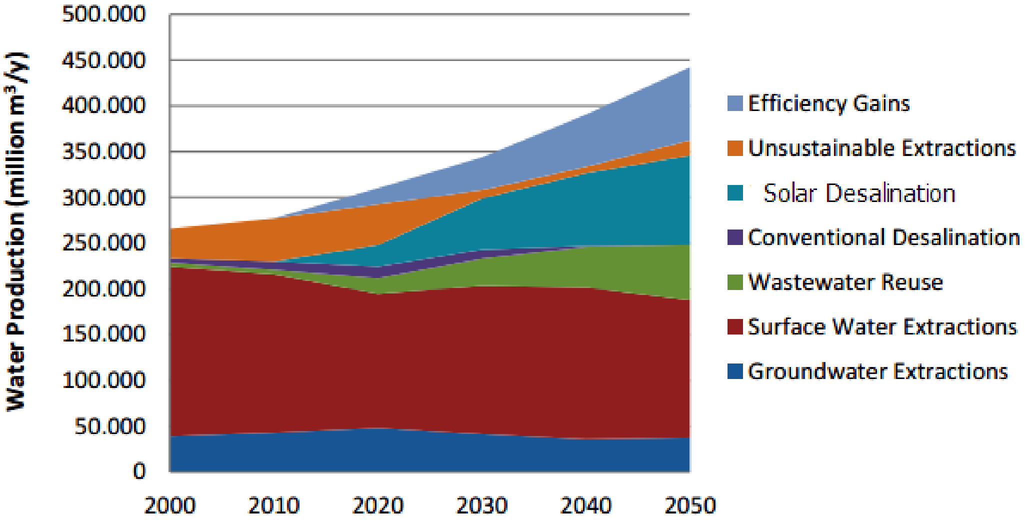

Figure 10. Water demand scenario in MENA, 2000–2050 (Triebet al., 2011)

Desalination will also be crucial in countries such as Egypt, which faces serious water deficits as a result of population and economic growth. The growing water demand, in Egypt, can no longer be met by the Nile water supply (Yousef et al., 2007). In 2025, Egyptian water demand might reach an amount of 130 billion m^3/year, with more than 80% used for agriculture, while water supply is currently expected to remain at 73 billion m^3/year (Yousef et al., 2007).

5 DESALINATION COSTS

The energy cost is the major factor affecting the cost of desalination. Therefore, the economic feasibility of desalination depends mainly on the local availability of energy and its cost (Zejli et al., 2002). The Comparisons between differenttechnologies of desalination should be based on identical local conditions. Capital. operation and maintenance cost is concerned for a comparison between two conventional desalination systems, i.e. RO and MSF, to be installed in Libya (Al-Karaghouli, 2011)shows that the MSF plant requires higher capital costs while the RO plant requires higher operation and maintenance costs due to the plant complexity.

Generally speaking, desalination based on renewable energy resources is still expensive when compared to conventional desalination. Both investment and generation costs of renewable energy are still higher. However, under certain circumstances – e.g. installations in remote areas where distributed energy generation (heat and power) is more convenient than centralized energy generation, transmission and distribution – renewable desalination could compete with conventional systems.

Costs of desalinated freshwater from most common desalination processes based on renewable energy are shown in "Table 4" (Papapetrou et al., 2010) and (European Union 2008). Most of such technologies have already been demonstrated, except for Solar/CSP-MED. With the rapid decrease of renewable energy costs, technical advances and increasing number of installations, renewable desalination is likely to reduce significantly its cost in the near future and become an important source of water supply for regions affected by water scarcity.

Table 4. Comparative costs for common renewable desalination (Papapetrou et al., 2010) and (European Union 2008)

	Technical Capacity	EnergyDemand (kWh/m^3)	Water Cost (USD/m^3)	Development Stage
Solar stills	< 0.1m^3/d	Solar passive	1.3–6.5	Application
Solar-Multiple Effect Humidification	1–100 m^3/d	thermal: 100 electrical: 1.5	2.6–6.5	R&D Application
Solar- Membrane Distillation	0.15–10 m^3/d	thermal: 150–200	10.4–19.5	R&D
Solar/CSP-Multiple Effect Distillation	> 5,000 m^3/d	thermal: 60–70 electrical: 1.5–2	2.3–2.9 (possible cost)	R&D
Photovoltaic-Reverse Osmosis	< 100 m^3/d	electrical: BW: 0.5–1.5 SW: 4-5	BW: 6.5–9.1 SW: 11.7–15.6	R&D Application
Photovoltaic-Electro Dialysis Reversed	< 100 m^3/d	electrical: only BW:3–4	BW:10.4–11.7	R&D
Wind- Reverse Osmosis	50–2,000 m^3/d	electrical: BW: 0.5–1.5 SW: 4–5	Units under 100 m^3/d, BW:3.9–6.5 SW:6.5–9.1 About 1,000 m^3/d,2–5.2	R&D Application
Wind- Mechanical Vapor Compression	< 100 m^3/d	electrical: only SW:11–14	5.2–7.8	Basic Research
Wind-Electro Dialysis	-	-	BW: 2.0–3.5	-
Geothermal-Multi Effect Distillation	-	-	SW: 3.8–5.7	-

6 CONCLUSIONS

The use of renewable energy for desalination in MENA appears nowadays as a reasonable, economically and technically mature option towards the emerging and stressing energy and water problems. The main conclusions are summarized:

- Solar-powered desalination technologies are suitable and may be the only technically and economically competitive alternative for small desalination capacities up to 10 m^3/day to provide drinking water in remote areas where access to fuel, electricity, and technical expertise is not available.
- For MED, the total electrical power consumption varies between 14.45- 21.35 kWhe/m^3, considering a power-plant efficiency of 30%. The electrical power consumption in MVC varies between 7-12 kWhe/m^3, while in TVC is about 16.26 kWhe/m^3.
- For membrane desalination processes, the average power consumption of RO ranges between 3.7 to 8 kWh/m^3 for seawater. For SWRO unit with energy recovery the power consumption varies between 4 to 6 kWh/m^3 at 24.000 m^3/day capacity. For BWRO unit's the power consumption ranges between 1.5 and 2.5 kWh/m^3. Also, for ED, the electrical consumption varies between 0.7-2.5 kWh/m^3 for low salinity feed water and 2.64-5.5 kWh/m^3 for salinity between 2500-5000 ppm.
- The water balance gap might reach 37% of total demand in 2020-2030 on an average climate scenario, reaching 51% by 2040-2050.

- The solar energy-based desalination is projected to become a major process for water production in MENA, accounting for about 16% of total water production in 2030 and 22% in 2050.
- In 2025, Egyptian water demandmight reach a level of 130 billion m^3/year, with about 85% used for agriculture, while surface water supply from the Nile is expected to remain at 55.5 billion m^3/year and may be less.
- The economic analyses conducted so far was not able to provide a strong basis for comparing economic viability of each desalination technology. The economic performances expressed in terms of (i) cost of water production was based on different system capacity, (ii) system energy source, (iii) system component, and (iv) water source. These differences make it difficult, if not impossible, to assess the economic performance of a particular technology and compare it with others.
- Areas of current and future research on solar thermal desalination focus on the following three aspects: (1) enhancing solar-energy collection, (2) improving the technology of desalination techniques, and (3) better matching the solar field and desalination unit. These areas of investigation directly relate to the economic performance improvement of the system.

ACRONYMS AND ABBREVIATIONS

CSP	Concentrating Solar Power
CSP/MED	Solar powered multi-effect desalination
CSP/RO	Solar powered reverse osmosis
MCV	Multi-vapor compression
ED	Electro dialysis
MD	Membrane distillation
MENA	The Middle East and North Africa
MED	Multi-Effect-Desalination
MSF	Multi-Stage-Flash Desalination
PV	Photovoltaic
RO	Reverse osmosis
TVC	Thermal vapor compression

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