ALI, D. and AL SAOUD, N. 2017. Solar powered desalination: zero carbon footprint water desalination plants in Qatar. Chișinău, Moldova: LAP [online]. Available from: https://www.lap-publishing.com/catalog/details/store/gb/book/978-620-2-05340-2/solar-powered-desalination

Solar powered desalination: zero carbon footprint water desalination plants in Qatar.

ALI, D. and AL SAOUD, N.

2017

© Dallia Ali, Noof Ali Al Saoud.

© 2017 International Book Market Service Ltd., member of OmniScriptum Publishing Group.

OpenAIR @RGU

This document was downloaded from https://openair.rgu.ac.uk

CC BY NC

Project-ID (164933) and the book's ISBN (978-620-2-05340-2)

Table of Contents

List of Figures

List of Tables

Abstract

This thesis attempts to interpret the implementation of Solar Photovoltaic Energy for powering Water Desalination Units in Qatar. The utilization of Renewable Energy in water desalination relates immediately to Qatar National Vision 2030 which with great priority ranks the development of sustainable energy practices towards ensuring water security.

The thesis starts with a summary of the existing water desalination practices together with an analysis of the different desalination methods. A more detailed research is then carried out on the existing seven Desalination Units operating in the country to discover Qatar's water desalination capacity, the associated energy requirements, together with the associated costs and environmental impacts. The research then looks into the implementation of renewable energy in powering water desalination plants and the associated costs and environmental impacts. A solar photovoltaic powered water desalination unit that is operating in one of Qatar farms is then presented as a case study. Investigating the case study system proves it to be an energy efficient system that stand as a landmark in the region for adopting alternative energy sources in powering water desalination practices. Towards this direction, the thesis finally concludes by suggesting the features of a similar larger-scale system for Qatar. Further installations for the optimal efficacy and efficiency of the unit, are proposed. Based on the current prices, an economic analysis of the proposed system is presented. Finally, the environmental impacts of the proposed system are discussed based on methods proposed in the existing literature.

Introduction

Qatar has managed within the last two decades to be ranked among the most developed countries in the world with the highest GDP per capita. Its expansion and consolidation as a first class energy player, has turned the country into a center of oil and gas production and consequently into a lucrative state regionally and internationally.

His Highness Sheikh Hamad bin Khalifa Al Thani has launched a pioneering national plan that addresses multiple perspectives of all citizens and residents lives. Qatar National Vision 2030 includes the four pillars of this plan that aims to '*'transform Qatar into an advanced society capable of achieving sustainable development by 2030''*. These pillars refer to economic, social, human and environmental growth that will assist the country to handle the rapid changes and challenges of the future.

Social and human developments include preservation of high moral ethics and promotion of the Islamic philosophy, humanitarian values and sense of community. Such actions is to enable Qatar's rapidly grown population to sustain a flourishing society with equal educational, employment and career opportunities. Further elimination of gender or other differences will assist the Qatari community to further incorporate Islam's values of peace, welfare and justice. Qatari students, the promising driving force of the country, are tomorrow's innovators and professionals boosting the State's economy, therefore high level educational and training opportunities followed by life-long learning programs will assist youth to meet current and future needs of the labor market.

Economic development is to be achieved through progressive diversification of the economy from an oil-based to a knowledge-based one. Such transition can bring wiser management in the business sector guaranteeing more stability. Stable business sector will attract profitable investments, adoption of new technologies and competition will be increased resulting into an overall improved quality of life with high living standards and expanded abilities of individuals, organizations and societies to improve talents and skills.

Environmental development refers to green growth policies and targets to set citizens' well-being as the top priority, with simultaneous ensuring of natural assets and resources preservation. Land and infrastructure development are to be in accordance to environmentally responsible methods for improving efficiency and efficacy of environmental impact assessment system across Qatar. The cooperation between social, economic and environmental developments can lead to an ambitious Sustainable Development scheme. Sustainability offers a vision of progress and growth that combine both mid-term and long-term objectives, locally and internationally, without compromising the needs of future generations. Its importance lays on both theory and policy, and only a multi-disciplinary approach will be effective. Sustainably development is not applied only by policies but must be adopted by society as well. It refers to meeting the needs of today's generation without jeopardizing and risking the wellbeing of future generations. This requires changes in ways of thinking, consuming, producing and acting. At the same time, social responsibility on behalf of industries, companies and government is considered as essential.

Towards this direction Qatar National Vision 2030, aims to human progress that is strongly intertwined with social, economic and environmental issues. A balanced development scheme including both economic prosperity and environmental preservation is set as a country milestone. Protection of the State's environmental heritage includes:

- Public environmental awareness through policies, campaigns and strategies
- Fair, strict and flexible legal system able to face efficiently all environmental challenges
- Responsible country planning with rational urban development
- Mitigation of all environmental issues arisen due to development activities
- Strategies for correct usage of natural sources with an eye on water
- Viable energy management planning
- Regional and global efforts for applying sustainable solutions towards all environmental challenges.

Environmental challenges include water and energy usage. The scarcity of freshwater sources over the last 20 years is becoming a problem that cannot be neglected. The rapid growth in population together with the continuously rising living standards, especially in industrial countries, have resulted into a higher per capita water consumption and global warming [where worldwide drought and desertification to expected to sharpen the problem]. The associated industrial and agricultural expansion has led into increased usage of freshwater, making the need for viable and environmentally friendly solutions for its retrieve more demanding. Water stress index has been introduced to describe the aforementioned water consumption, and is defined as the ratio of the average amount of water withdrawal to the amount of available freshwater resources. This index is higher and the problem becomes more important to address in arid areas and in regions where the population is high. Such circumstances are both present in Qatar and threats the future of humanity. Scientists and engineers have therefore started to look into advanced methods of water treatment. However, producing good quality water combined with minimum energy usage has proven to be a challenging field for researchers.

Their aim is to achieve progressive effectiveness of all applied methods by simultaneous reduction of energy requirements. Towards this direction, advanced interest has been shown towards oceans, since they represent the biggest water reservoir on earth; approximately 97% of the earth's water is seawater, with only 2% is locked in ice sources [1]. There is also an enormous fresh water presence under the earth, however the cost of extracting, because of the large depth, make the methods prohibitive. Difficult access to such resources, combined with the water lower quality deteriorate the present situation. Figure 1 describes the water distribution.

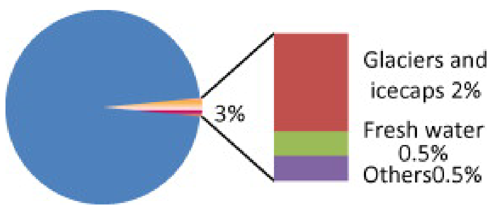

Figure 1. Water Distribution [2]

A competition for convenient water resources may arise between the agricultural, industrial and the public water users. This competition may lead to higher water prices, constricted economic development and social problems in regions with limited water access. As a result, the general welfare of a country under water stress conditions is threatened. Solutions require both national and international measures be taken, including resolution of water disputes and increased funding for desalination research and alternative technologies. One of the key tools to resolve future international water crises is the continued research into methods that will provide low-cost, energy-efficient and environmentally friendly desalination. Efforts have to be in depth since more than two-thirds of the world's population may experience water shortages by 2025, thus affecting practically every country in the world, including the developed, unless they reduce and/or develop additional water sources [3].

The motivation behind this research arises from the world's rising needs for water, together with the continuous global efforts to improve the desalination technologies to make them more efficient, rational, affordable, and with the least possible impact on the environment. The proposed study will be focused on Qatar, displaying the local efforts made to meet Qatar water needs and supply its population with high quality water at the least energy consumption, cost, and environmental impact.

Chapter 1. Desalination Processes

Desalination is the chemical process that removes minerals and salt from seawater to make it potable and suitable for human use. It is estimated that over 75 million people worldwide obtain fresh water by desalinating seawater or brackish water [1]. Desalination of seawater accounts for a worldwide water production of 24.5 million m^3/day with the "hot spot" of intense desalination activity to be the Arabian Gulf, among other regional centers, such as the Mediterranean Sea and the Red Sea [4]. The largest number of desalination plants are at the Arabian Gulf with a total seawater desalination capacity of approximately 11 million m^3 /day, with the main producers to be the United Arab Emirates [26% of the worldwide seawater desalination capacity] followed by Saudi Arabia [23%]. Figure 2 displays all desalination plants located in the Arabic Gulf.

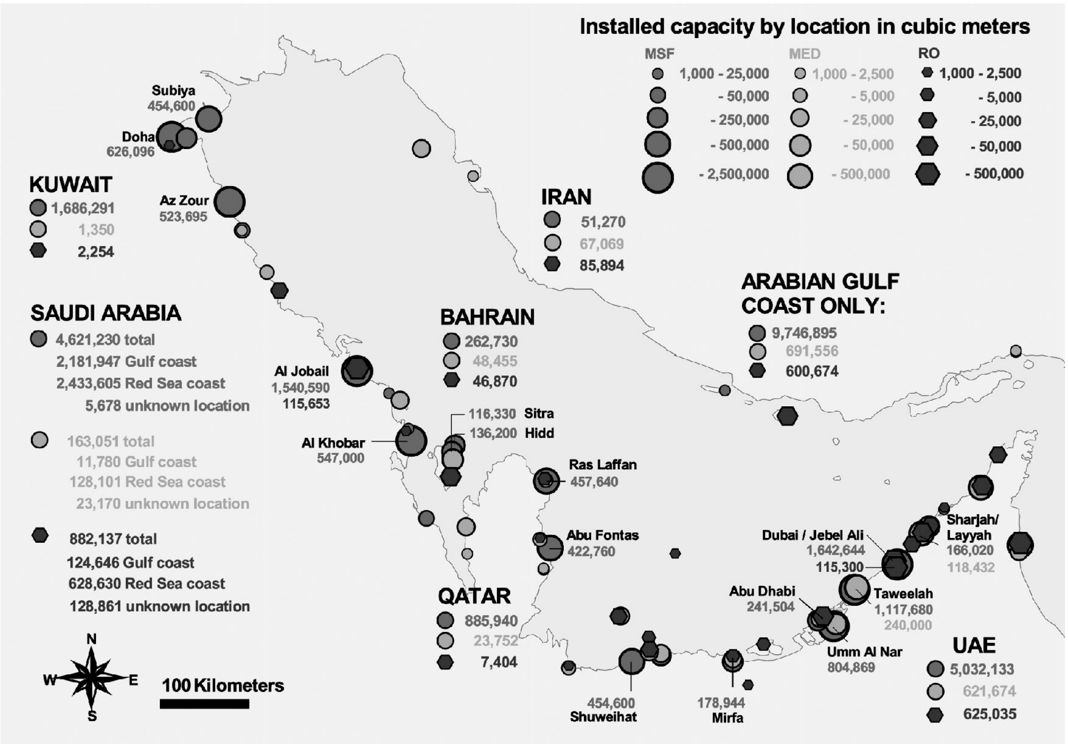

Figure 2. Seawater Desalination in the Arabian Gulf [4]

In Qatar, the operating desalination units are mainly located in the north part of the country in Ras Laffan industrial area and in Abu Fontas. Until 2008 the total installed desalination capacity was measured to be approximately 1,1million cubic meters.

The growth in the desalination capacities over the past ten years has been huge. According to a study [5], the Mediterranean countries growth rate at 2005-2015 period was predicted to be approximately more than doubled [179%]; and for the GCC countries [Arabian Gulf] the growth rate from 2005 to 2015 was estimated to be lower when compared with the Mediterranean [94%]. Asia then followed with a growth rate prediction of 76% and the American continent as the last one with an expected growth rate of 59%. When referring to the desalination capacities though, as aforementioned, GCC countries display the largest capacity globally; approximately 30million m^3/d; Mediterranean follows with almost 16million m^3/d with Americas and the Asia to rank at the last seats with 11million m^3/d and 8million m^3/d respectively.

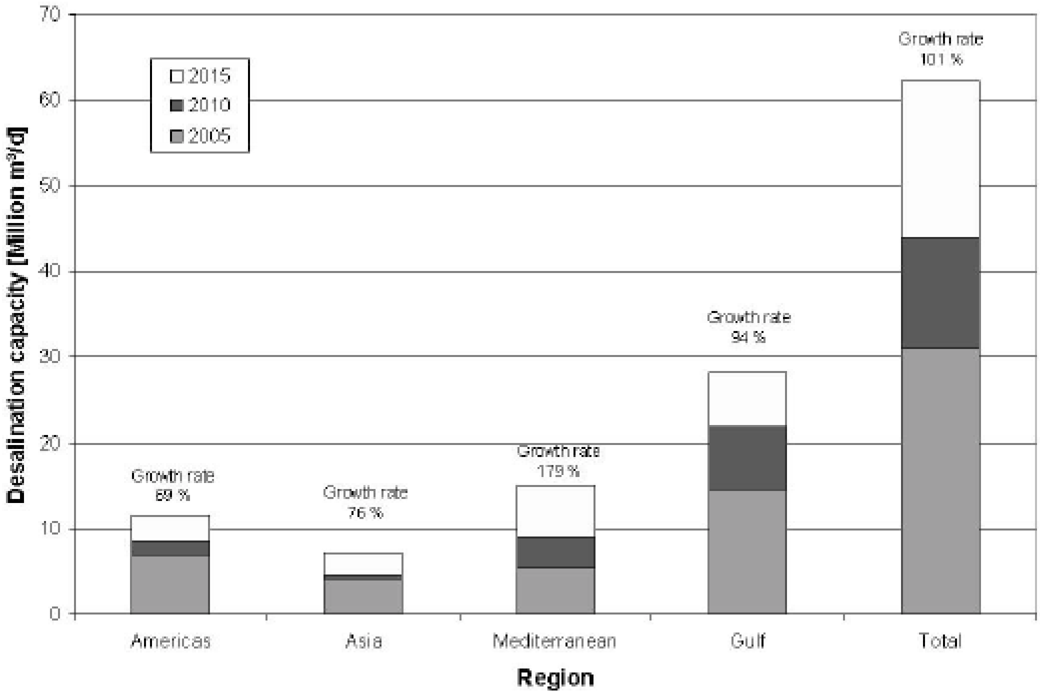

Figure 3. Expected Growth in Desalination Capacities [5]

Desalination is applicable in both brackish and seawater. Brackish water desalination is expected to grow at higher rates than seawater desalination in the near future.

Delivery of the fresh water produced from seawater desalination plants demands piping and pumping systems to transport the product water from coastal regions to residential areas, which increase cost. The high availability of brackish water in residential areas makes the expensive delivery piping and pumping unnecessary. However, one restricting problem in brackish water desalination is the discharge of brine, because disposal options are limited, disposal is associated with high additional costs, and environmental damage has to be expected. Desalination processes and technologies can generally be classified by their separation mechanism into thermal and membrane based desalination. Thermal desalination separates salt from water by evaporation and condensation, whereas in membrane desalination water diffuses through a membrane, while salts are almost completely retained. Thermal desalination is more energy intensive than membrane based desalination, but can better deal with more saline water and delivers even higher permeate quality [3]. The decision for a certain desalination technology is influenced by feed water salinity, required product quality as well as by site-specific factors such as labor cost, available area, energy cost and local demand for electricity. Current desalination technologies are, however, prohibitively expensive and energy intensive.

Energy is indisputably the most significant contributor to the cost of desalination [6]. Hence, reduction in energy usage is the primary objective to making desalination more affordable. Reverse osmosis [RO] and multi-stage flash [MSF] are the most widely used techniques. Methods of desalination, can be classified into two categories, phase change processes and single phase processes. Thermal methods, as it will be discussed further, are more effective than membrane methods in terms of efficiency in the desalination of very salty seawater.

1.1. Thermal Desalination Technologies [phase change processes]

1.1.1. Multi-stage Flash Desalination [MSF]

Multi-stage flash desalination [MSF] is the most frequently applied thermal desalination technology and the more preferred in the Middle East [5], where it benefits from the low energy price and high feed water salinity. Large MSF units with production capacity that ranges between 50,000–75,000 m^3/d are being installed in several countries, including Kuwait, Saudi Arabia, and United Arab Emirates. The large unit capacity contributes further to the reduction of the unit product cost.

The most important disadvantage of MSF is the low performance ratio, limited at about 11. This results into a much higher energy consumption, which makes MSF a comparatively expensive technique. Performance Ratio of a desalination system is the ratio of the mass of distillate to the energy input [7]. The Performance Ratio in metric units is often defined as the number of kg of water per M Joule of heat input [8]. A dimensionless Performance Ratio though is also used [9]. The higher the ratio is, the less affordable the desalination system is.

1.1.2. Multi-effect Distillation [MED]

MED is based on the heat transport from condensing steam to seawater or brine in a series of stages or effects. In the first effect, primary steam is condensed for the evaporation of preheated seawater. The secondary steam that is generated in this way is brought to a second effect, operated at slightly lower temperature and pressure; the primary steam condensate is recycled to the steam generator. High heat transfer rates can be achieved in the MED process due to the thin film boiling and condensing conditions. Such installations are present in the UAE, in Umm al Nar MED plant with a unit capacity of 15,911 m^3/d and in Sharjah plant with a unit capacity of 22,730 m^3/d. Problems related to MED method are related to corrosion and scaling of organic or mineral substances. Corrosion can be identified as the degradation of membrane's properties due to interactions with other materials. Such gradual decay can lead to lower membrane efficiency and efficacy. Scaling or fouling is the blocking of the membrane's pores from components such as dust, suspended or colloidal matter [10] or by biological growth, resulting into membrane's permeate flux reduction. An existing fouling layer adds to the overall resistance to mass transfer of the membrane and the overall performance drops significantly. Some of the most common scaling substances are Calcium Carbonate [$CaCO_3$], Calcium sulfate [$CaSO_4$] and silica. Membrane fouling on the other hand, is caused either by convective and diffusive transport of suspended or colloidal matter [10] or by biological growth, the so called bio-fouling.

1.1.3. Vapor Compression Distillation [VCD]

Vapor compression Distillation [VCD] is a technique that is used for small-scale plants. The technique is comparable to MED, but it is based on compression of the vapor generated by evaporating water instead of condensation, so that the latent heat of the vapor can be efficiently reused in the evaporation process. Vapor compression can be seen as a variation of MED, but technically somehow more complex, so that application is limited to smaller plants. The system constitutes of the condenser tubes and evaporator which are connected to the vapor compressor. The inlet feed seawater recovers close to 90% of the sensible heat in the brine and distillate stream leaving the evaporator. This feature enhances considerably the process efficiency.

1.2. Membrane based Desalination Technologies [single phase processes]

1.2.1. Reverse Osmosis [RO]

Reverse osmosis is the most common membrane based desalination option for seawater and brackish water, dominating in the area around the Mediterranean Sea. Reverse osmosis is by far the most widespread type of membrane based desalination process. It is capable of rejecting nearly all colloidal or dissolved matter from an aqueous solution, producing a concentrate brine and permeate of almost pure water. Although reverse osmosis has also been used to concentrate organic substances, its most common use lies in seawater desalination applications. It is based on a property of certain polymers called semi-permeability. While they are very permeable for water, their permeability for dissolved substances is low. By applying a pressure difference across the membrane, the water contained in the feed is forced to permeate through the membrane at a fairly high feed pressure [55-68 bars for seawater desalination]. Operating pressures for the purification of brackish water are lower due to the lower osmotic pressure caused by lower feed water salinity. A flow sheet of a reverse osmosis based desalination plant is shown in Fig. 4. The process includes the following stages:

- Water abstraction

- Pre-treatment
- Pumping
- Membrane separation
- Energy recovery
- Post-treatment C Control

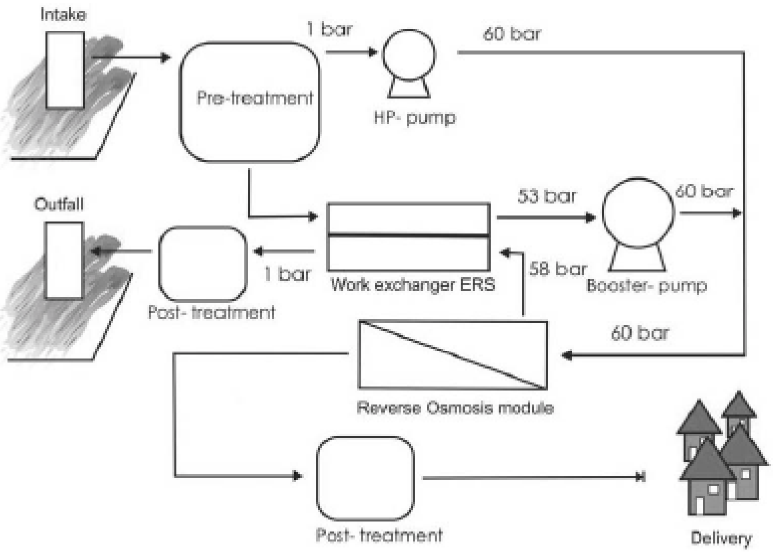

Figure 4. RO Simplified System [5]

RO is described as a [differential] pressure driven separation technique. By applying a pressure difference, the permeating component[s], in most applications nearly exclusively water, are forced through the membrane. The operating law of Reverse Osmosis occurs when a semi-permeable mem- brane [permeable to water and not to the solute] separates two aqueous solutions of different concentration. At equal pressure and temperature on both sides of the membrane, water will diffuse ["permeate"] through the membrane resulting into a net flow from the dilute to the more concentrated solution until the concentrations on both sides of the membrane become equal. Beside its application for the production of drinking water, reverse osmosis is also applied in the treatment of effluent water and in the separation of organic and inorganic compounds from aqueous solution for industrial applications. The method's disadvantage is the gradually deterioration of the membrane due to corrosion and fouling incidents, as discussed before at the MED method.

The cost of RO seems to be decreasing from 1980 to 2004 as can be seen in Figure 5 with the energy consumption rates to become 4 times less from the 80's until 2004.

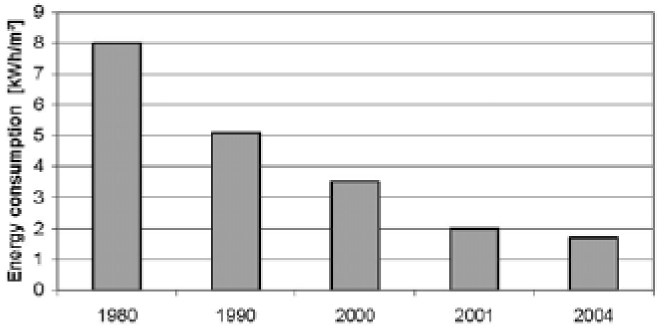

Figure 5. Development in achieving RO Cost Reduction[11]

1.2.2. Nano-filtration [NF]

The Nanofiltration [NF] membrane is a type of pressure-driven membrane made of polymeric films with pores size between 1-10 nm, or with a molecular weight cut off [MWCO] between 300-1000 [12]. MWCO is a unit of expressing the size of the pores. NF offers several advantages such as low operation pressure, high flux, high retention of multivalent anion salts and an organic molecular above 300, relatively low investment and low operation and maintenance costs. Disadvantages of NF membranes are similar to those of RO and MED.

1.2.3. Electrodialysis [ED]

Electrodialysis or electrodialysis reversal [EDR] is recommended for brackish water applications and introduces a membrane technology that competes with reverse osmosis. It can be used for the concentration or removal of charged species in aqueous solutions. ED has been used on an industrial scale since the 1960s. The process is based on the movement of charged species in an electrical field using Anion Exchange Membranes [AEM] and Cation Exchange Membranes [CAM]. Among the other techniques for seawater or brackish water desalination, electrodialysis is still the most promising technique especially for water with low salt concentrations, and is considered to be the most advantageous technique [13].

1.3. Cost of Desalination

The cost of desalination differs with the desalination method used, with the type of the initial water used [brackish or seawater], and with the capacity of the unit under operation due to the economics of scale.

The US Congress estimations for year 1988 cost of RO water desalination, without mentioning the plant capacity though, to range from 0.26-0.35€ [0.32-0.44$] per m^3 for brackish water and 1.26-2.84€ [1.57-3.55$] per m^3 for the seawater which contains ten times the number of contaminates [14]. 16 years later the same source estimated that the prices of desalination for seawater have fallen to a range of 0.18-0.22€ [0.22-0.28$] per m^3. The cost of desalination based on the plant capacity is depicted in Table 1 [14].

Table 1. RO desalination Cost based on the Plant Capacity [14]

Type of Water	**Daily Plant Capacity [m^3]**	**Cost per m^3**	**References**
Brackish Water	<1000	0.63-1.06€ [$0.78-1.33]	[14–17]
	5,000-60,000	0.21-0.43€ [$0.26-0.545]	[18–21]
Seawater	<1000	1.78-9€	[21], [22–25]
	1000-5,000	0.56-3.15€	[21], [26–30]
	12,000-60,000	0.35-1.3€[$0.44-1.62]	[21-21], [31–39]
	>60,000	0.40-0.80€[$0.50-1.00]	[32, 33, 36], [40–44]

In summary, results show that brackish water treatment costs monetary units than that of seawater, this is due to the different quality of water treated. The cost of desalination based on the type of energy used for powering the RO desalination plant, including conventional sources such as fossil fuels and RES, can be seen in Table 2.

Table 2. Cost of Desalination based on the Energy Used for Powering the Plant [14]

Type of Water	**Energy Used**	**Cost per m³**	**References**
Brackish	Conventional[fossil fuels]	0.21-1.06€ [$0.26-1.33]	[15–17], [18–21],
	Photovoltaics	4.50-10.32€	[45]
	Geothermal	2.00€	[45]
Seawater	Conventional[fossil fuels]	0.35-2.07€	[8-10, 12, 15, 18, 22, 29, 35, 36]
	Wind	1.00-5.00€	[24, 26, 28, 45]
	Photovoltaics	3.14-9.00€	[23, 26]

From table 2, it can be seen that Fossil fuels powered RO Desalination plants are more economic when compared with the Renewable Energy Sources [RES] powered ones. This should be due to the predominant establishment of fossil fuels; their usage in industry has been much longer than renewables and so the industrial sector does not have to further invest on them. Additionally there have been multiple R&D innovations in fossil fuels, managing to improve their efficiency. Moreover, fossil fuels are more subsidized than PV, solar and wind energy. Regarding brackish water RO desalination, geothermal energy proved to be the least expensive method when compared with other RES [46].

From table 2, Fossil fuels still prove to be cheaper than RES when desalinating seawater, followed by Wind Energy then PV as more expensive methods.

Chapter 2. Desalination in Qatar

Desalination is the main technology for coping with water scarcity in Qatar and in the Gulf region, with thermal and membrane processes being the most common methods. Multi Stage Flash (MSF) Desalination and Multi Effect Distillation are the predominant desalination technologies used in Qatar sharing 80.6% and 19.4% respectively [48], although MSF presents adverse environmental effects due to GHG emissions [49].

Kahramaa is the national company of Qatar that operates electricity and water grids. Qatar's water supply system, includes 2 desalination plants, 5400 km of water transmission and distribution lines, 290m gallons of reservoir storage capacity, and 22 water pumping stations [48]. The organization has set a strategy that will help the water sector to continue operating correctly within the following years. The targets set by the organization are as follows:

- Maintaining a 24h uninterrupted water supply to customers
- Increasing the water storage reserve to 7 days
- Studying/implementing alternative energy resources for water production [ex. nuclear-solar]
- Reducing the water losses.

According to Kahramaa, desalinated water is around 99.9% of the total water produced in Qatar while merely 0.10% comes from ground water; the average annual increase in water supply up to 2008 was 10.3%, while the average annual increase in water demand was 9.9%. Predictions for 2017 [from 2009] are indicating an increase in demand by 82% and in supply by 60% due to the rapid expanding population [48].

Figure 6 depicts the location of some of the water plants in the country.

Figure 6. Desalination Plants in Qatar [50]

Ras Abu Fontas plant can be seen in Figures 7 and 8, while Ras Lafan plant is depicted in Figures 9 and 10.

Figure 7. Ras Abu Fontas Site [50]

Figure 8. Ras Abu Fontas Station [50]

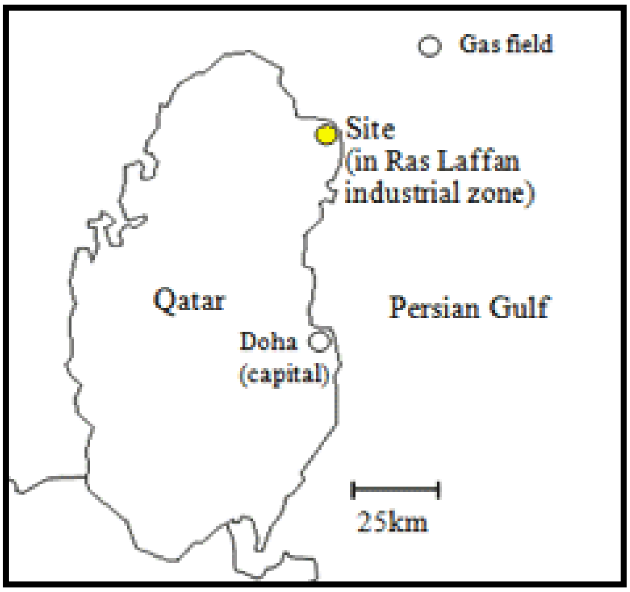

Figure 9. Ras Lafan Water Plant Location [50]

Figure 10. Ras Lafan Water Plant Site [50]

2.1 Water Production in Qatar and the associated Energy Requirements

In Qatar, there are seven operating Desalination Plants. Table 3 shows the water and the electric power capacity of each plant.

Table 3. Qatar's Main Power and Water Desalination Plants and their Capacities [51]

Desalination Plant	Electric Power Plant Capacity [MW]	Total Water Capacity m³/d	Total Water Capacity Million Imperial Gallons/Day	Plant Starting Date

RAF A	497	318,226	70	1980
RAF B	609	150,000	33	1995
RAF B1	377	240,000	53	2002
RAF B2	567	136,000	30	2003
Ras Laffan A	756	181,843	40	2006
Ras Laffan B	1,025	272,760	60	2009
Ras Girtas	2,730	286,400	63	1983
Total	6,561	***1,585,229***	***349***	

The largest desalination plant in Qatar is located in Ras Abu Fontas [RAF], in southern Doha while the rest are in Dukhan, Ras Laffan, Mesaieed, Umm Bab, Abu Samra, and in Al Shamal, all aiming to produce fresh water for the population needs and for the agriculture industries. The oldest plants are Ras Abu Fontas A and Ras Girtas, operating since 1980 and 1983 respectively. Despite the fact that they were the first plants in Qatar, their Total Water Capacity [TWC] is still the highest among all the rest with Ras Abu Fontas A producing 70 Million Imperial Gallons per Day [MIGD] and Ras Girtas 63 MIGD. 15 years later [in 1995], the Ras Abu Fontas B plant started operating producing 33 MIGD. The remaining four plants were then established after 2000, with the first to be Ras Abu Fontas B1 in 2002 with a 53 MIGD and Ras Adu Fontas B2 one year later in 2003 with a 30 MIGD. The most recent plants include Ras Laffan A in 2006 and Ras Laffan B in 2009 with 40 and 60 MIGD respectively. The total water production in Qatar is estimated to be 349 MIGD, which is equivalent to 1,585,229 cubic meters per day. However, the rapidly expanding population of the country creates a big challenge for the Qatari authorities, not only to maintain the water security but also to maintain water reservoirs for a larger period.

Looking into the electric power consumption of each Desalination plant, table 3 shows Ras Girtas to be the largest with 2,730 MW although it was the second operated desalination plant in the country [51]. Then comes Ras Laffan B with less than half of Ras Girtas capacity followed by Ras Laffan A, consuming respectively 1056 and 756

MW. Then comes Ras Abu Fontas B Plant with 609 MW followed by Ras Abu Fontas B2 with 567 MW. The two plants with the lowest energy consumption are Ras Abu Fontas A with 497 MW and Ras Abu Fontas B1 with 377 MW.

During the first decade of the desalination plants operation in Qatar, the total energy consumption by the only two operating plants at that time [RAF A and Ras Girtas] was 3,227 MW which is almost half that of the plants operating to 2006 (6,561 MW) [51]. This value indicates the advance in the desalination technology in the country.

2.2 Cost of the Currently Implemented Desalination in Qatar

The National electricity Company of Qatar (Kahramaa) has evaluated the total cost of producing the desalinated water to be $2.74 per cubic meter [52]. This involves the production cost ($1.64) and the distribution cost ($1.10) per cubic meter. It is obvious that the production cost for the desalinated water stands for approximately 70% of the overall cost. An interesting calculation method for this cost which depends on the different prices of the Natural Gas has been applied in 2016 [53]. Table 4 shows the desalination costs for both Multi-Stage Flash Desalination and Seawater Reverse Osmosis methods (SWRO) at different prices of the Natural Gas. The Total Cost given in the table has considered the production costs plus the transportation costs, where the transportation cost has been set for all the GCC countries to be $1.1/m^3 [52].

Table 4. Cost of Desalinated Water (DW) Production at Different National Gas (NG) Prices [52]

Natural Gas Production Cost ($/MMBtu)	DW (MSF) Production Cost ($/m^3)	Total Cost ($/m^3)	DW (SWRO) Production Cost ($/m^3)	Total Cost ($/m^3)	Cost Difference (%)
0.75	1.04	2.14	0.62	1.72	67.74194
1	1.10	2.2	0.63	1.73	74.60317
2	1.33	2.43	0.68	1.78	95.58824

3	1.57	2.67	0.72	1.82	118.0556
4	1.81	2.91	0.77	1.87	135.0649
5	2.04	3.14	0.82	1.92	148.7805
6	2.28	3.38	0.87	1.97	162.069
7	2.52	3.62	0.91	2.01	176.9231
8	2.75	3.85	0.96	2.06	186.4583
9	2.99	4.09	1.01	2.11	196.0396
10	3.23	4.33	1.06	2.16	204.717
11	3.46	4.56	1.10	2.2	214.5455
12	3.70	4.8	1.15	2.25	221.7391
13	3.94	5.04	1.20	2.3	228.3333
14	4.17	5.27	1.24	2.34	236.2903
15	4.41	5.51	1.29	2.39	241.8605
16	4.65	5.75	1.34	2.44	247.0149
17	4.88	5.98	1.39	2.49	251.0791
18	5.12	6.22	1.43	2.53	258.042
19	5.36	6.46	1.48	2.58	262.1622
20	5.59	6.69	1.53	2.63	265.3595

Where; MMBtu stands for a million British thermal units. Btu is a unit for work which is equal to approximately 1055 joules.

It can be seen from the table that MSF proves to be a more expensive desalination method than reverse osmosis. At the lowest NG production cost ($0.75/MMBtu), desalinated water from MSF is 67% more expensive than RO. The percentage in cost difference is continuously rising up to reach 265% when Natural Gas cost is $20/MMBtu. This means that in terms of expensive NG exploitation, RO continues to be an affordable and recommendable method of producing desalinated water.

2.3 Environmental Impacts of Desalination

Seawater desalination technologies manage to provide Qatar with potable and high quality fresh water reducing the exploitation of the already scarce ground water resources. However, desalination presents some disadvantages in the form of environmental impacts [2, 53].

The outflow water returned to the marine ecosystem after the desalination process is changed by three different ways. It presents different properties from the original inflow; its thermal energy is increased, the chemical composition is altered (advanced carbon, oxygen and nitrogen, inorganic salts and possible presence of heavy metals due to corrosion) and finally the microbial profile is changed (bacteria and fungi) [54].

The first environmental impact of desalination is related to their land usage [52]. Since the desalination plants' intake is mainly seawater, they are located at coastal sites which present sensitive eco-systems of high environmental interest. The seawater intake can lead to entrapment of marine organisms, disturbing the regional marine biology and habitats and thus affecting the overall sustainability of the coastline.

The second impact is related to the total energy consumption involved with the desalination plants since they are proving to apply energy intensive processes. The vast majority of the energy used in desalination is taken from fossil fuels resulting into increased production of greenhouse gases emissions, especially CO_2. In areas where the fossil energy is of low cost and abundant, such as the Middle East, this environmental impact on air quality is emerging more. The total CO_2 emitted for desalination processes in Qatar was estimated to be 7.04 Mega Tons [52]. This is equal to 14.67 kg of CO_2 released in the atmosphere for producing 1 m^3 of desalinated water.

The third environmental impact is related to the brine discharges of desalination. The outcome of the desalination process is water with increased salinity and high concentration of brine. The brine may consist of heavy metals such as Ni, Cr and Zn [55], or additive substances components like anti-scaling which is used to prevent carbonate and sulphate scaling to delay crystal-growth at the Reverse Osmosis membranes through pH controlling and antifouling [56]. The procedure of chlorination also affects the ecosystem since it presents high concentration while excessive insertion of ammonia affects the pH values further burdening the ecosystem [57]. The brine can be up to three times denser than saltwater and toxic [57]. Oxygen depletion is a hazard of reverse osmosis (RO)-derived brine, because of sodium bisulphite; the lack of dissolved oxygen can be dangerous to marine organisms, while some by-products of chlorine are carcinogenic. Brine may also contain residual chemicals from the pre-treatment process, heavy metals or cleaning agents. Figures 11 and 12 show the salinity as observed from Qatar Meteorology Department on the surface of the sea and in 5 meters-depth.

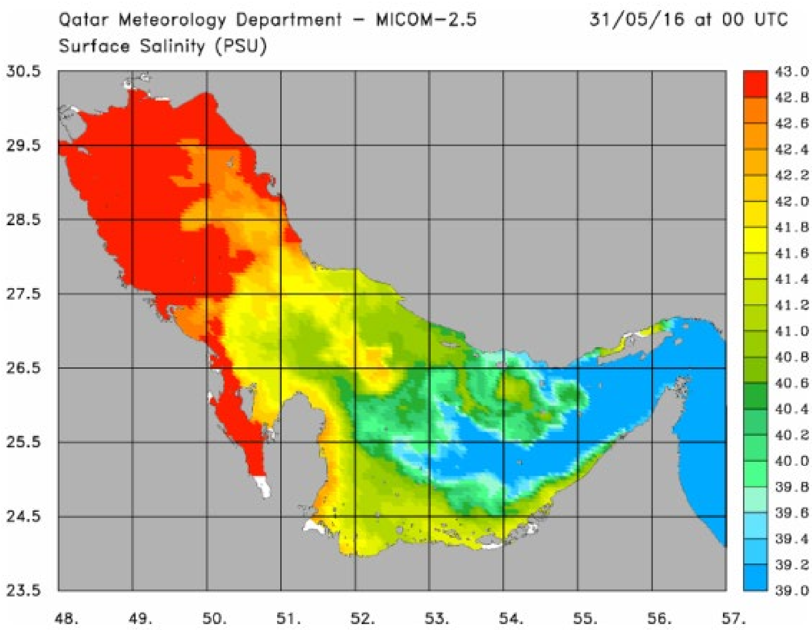

Figure 11. Salinity at the Surface [58]

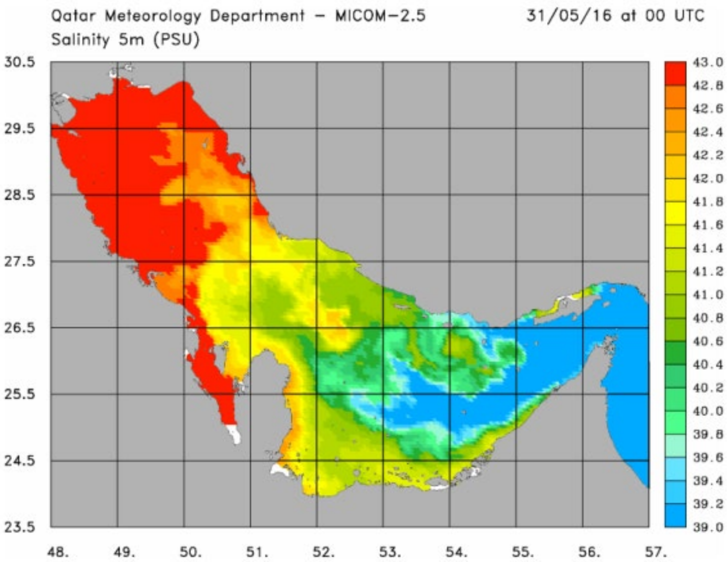

Figure 12. Salinity at 5m Depth [58]

Regarding the natural factors, high salinity around the coastline of the country can be explained with three processes; advanced evaporation of the water especially during summer periods, very low precipitation rates and little fresh water inflow from the inlands. According to the United Nations Environment Program [UNEP] and the Convention on Biological Diversity [CBD] measurements, the nearshore salinity of Qatar has been found to range between 39 ppt and 41 ppt at the surface. However, the salinity has also been observed to be around 60 ppt in some areas [59], while others determined the values at the Gulf of Salwah to be from 53 ppt at Dukhan up to 58 ppt towards the south at Abu Sanura [60]. Increased water salinity values can play either a positive or a negative role to the biodiversity of the water. It has been argued that through the high values of salt in the seawater, acidification of the Arabian Gulf has become smaller [61]. On the other hand, it has also been suggested that high levels of salinity enhances the water bleariness which in turn can disturb photosynthetically the procedures [62]. Lower lighting admittance will reduce the biodiversity of the Gulf and affect the plankton formation, resulting into the extinction of aquatic species. Additionally, the chemical alterations due to the impaired salinity can lower the amount of dissolved oxygen in the seawater threatening marine life [54]. Regarding the levels of the oxygen, further reduced values in the returning seawater can result from de-aeration, which is a procedure for lowering corrosive incidents in the desalination plants [63].

Chapter 3. Solar Powered Desalination Plants in Qatar

Qatar's boost in financial and demographic fields has brought the country in front of many challenges. Research and Development is continuously providing diverse and effective solutions that can help the country to face these challenges and achieve its missions. Food security issues combined with energy savings and renewables applications for less air pollutant emissions, have managed to bring local food production with innovative energy saving technologies into the country. Moreover, Qatar's solar energy future is steadily developing with its average daily sunshine of around nine-and-a-half hours and its low cloud cover conditions.

3.1 Introduction to Renewable Power Generation Applications in Qatar

According to Qatar 2030 vision, efforts are initiated to place Qatar's Resources Management on a Sustainable Path for the Future Generations. Based on the Ministry of Environment Intended Nationally Determined Contributions (INDCs) Report, November 19th 2015; Qatar is in the process of achieving energy efficiency and despite of the abundance of gas, Qatar is investing in clean renewable energy resources.

With Qatar's solar energy capability, there is great scope for small, medium as well as large-scale solar power projects in the country. The following facts were introduced by Dr Govina Rao during Qatar Solar Summit that has been organized by Qatar Petroleum in Doha in 2013.

- Each square Km of land in Qatar receives solar energy (per year) that is equivalent to 1.5 million barrels of oil.
- A Daily Net Irradiance (DNI) of 1800 kWh/m^2/year is considered enough for powering CSP (Concentrated Solar Power) plants, and a DNI of 2000 kWh/m^2/year is considered as a feasible amount of radiation.
- The DNI of Qatar is 2008 kWh/m^2/year

- The country's average daily sunshine is around nine-and-a-half hours, with low cloud cover conditions and plentiful space.

Qatar's potentials in investing on other RES such as wind, biomass and tidal energy is not as high as in solar energy but however it still cannot be considered as insignificant [64]. The Aeolic profile of the country presents promising advantages for investing in wind turbines for water drilling or electrifying in remote areas. Additionally, treatment of household waste is already in operation at Domestic Solid Waste Management Center, situated south of the country, for producing biomass.

Among all the RES, the solar sector holds the lion's share for research. Local educational institutions such as Qatar Foundation (QF) and Qatar Science and Technology Park (QSTP) along with governmental companies like Kahramaa, attempt to make the country as the solar capital of the region. Qatar Foundation has managed to produce more than 80% of the overall solar energy of the country. Research has also extended in producing materials for photovoltaic panels, so QStech plant is scheduled to produce $8 \cdot 10^6$ kg of polysilicon [65]. The QF campus in Qatar Education City is currently partly electrified by PVs at a total energy production of 1.68MW. In addition to installing rooftop solar panels, Kahramaa planning includes a solar power venue with an expected capacity of 15MW. The company target is to generate a total of 10,000MW by 2020 from Photovoltaic Panels that occupy approximately 10^6 square meters. This amount is almost 5% of the overall 200,000 MW power required by that time [66]. Such investments are proving adequate for future expansion in large-scale power generation for industrial and commercial purposes. One of the useful applications that solar power generation can contribute to, is water desalination. Concentrated Solar Power (CSP) generation can efficiently energize seawater thermal or membrane desalination processes. Seawater desalination can contribute towards the water scarcity problem that the country faces. Water production apart from industrial and municipality needs is also valuable for the agricultural sector. The National Food Security Programme (NFSP) targets that Qatar becomes food self-sufficient country by 2023, with only a small percentage of fruits and vegetables importing. Internal agriculture production is expected to increase so as to cover the population's needs.

Seawater desalination can accordingly assist the NFSP aim, by producing water for irrigation and agricultural purposes. Therefore, it can be concluded that promoting the Photovoltaic power generation is highly suitable for the country needs.

In summary, Solar power generation has multiple advantages for Qatar in the form of energy security, improved air quality, reduced greenhouse gas emissions, employment opportunities, as well as augmenting water and food security.

3.2 Costs involved with Solar Powered Water Desalination

In this section, the economic feasibility of solar powered desalination processes in arid environments like Qatar, is investigated. The investigation will mainly focus on the Photovoltaic Panels and the RO desalination units' costs.

For the RO desalination units, the fixed capital cost includes the costs of the following items: the raw water intake system, the intake pipeline, the raw water storage system, the pre-treatment and post treatment units, the low and high-pressure pumps, the disposal pumps and pipelines, the fresh water storage system, the land and buildings, the laboratory, the engineering and legal services as well as the insurance of the whole unit [67].

For the Photovoltaic Panels, the production cost has been decreasing over the past 30 years. Current prices are found to be $1.25 (=4.55QR) per Watt with the industry aiming to push the prices down to be lower than $1(=3.6 QR) per Watt [68]. Possible further decrease in prices can mainly come from advances in technology and limitations of middlemen when it comes to distribution [69].

For Qatar, such investments may prove cheaper because of the possible subsidy from the government. The RO membranes purchase cost will depend on the amount of flowrate to be handled, the frequency of membranes replacement (where a higher replacement frequency lead to higher hardware costs [70] and the operation energy costs [71].

Investments in energy storage systems (like batteries) are also important for storing the excess in the produced solar energy to be used later when needed [72].

Logistic nature investment is another important expense that cannot be neglected. Since the system may be installed in remote areas, therefore the costs of transportation of membranes and PV panels have to be also taken into account [73].

Operation and maintenance cost are regarded as approximately 1/50 (=2%) of the total investment [74]. Maintenance cost is mainly focused on the feed water pretreatment and the membranes post treatment. The inflow water must be filtered for silica, organic matter and sand while the chlorination, addition of coagulants, flocculants, antiscalants and sulphuric acids also increase the overall cost [75]. Manpower cost is mainly dependent on the scale of the project and the level of automation [76]. ***For Qatar,*** unskilled laboring is generally paid lower than EU countries and probably the workforce cost may be lower.

3.3 Environmental Impacts Involved with Solar Powered Water Desalination

Seawater desalination powered by fossil fuels is an energy intensive method. It is estimated that a daily production of 1000 m^3 per day of freshwater requires 10^7 tonnes of oil annually with a consequent environmental burden of 156 metric tons of CO_2 per day [77]. The desalination process powered by RES though, is considered to lower the environmental impact by up to 85% when compared with desalination coupled with fossil fuels [78].

The environmental impact on the marine ecosystem still exists with solar powered desalination due to the brine disposed in the sea, as has been referred to in section 2.3. This brine presents a higher salt concentration and is at higher temperature than the seawater and this results into disruption of the Arabian Gulf neutrality. Low quantities of antiscale and antifoam additives can make the brine polluted-free, thus not disturbing the ecosystem [79].

The environmental impact on the air quality coming from greenhouse gas emissions is less with solar powered desalination. In Abu Dhabi, the installation of photovoltaic panels of 10 MW total power production has managed to produce 24GWh energy without burdening the environment with more than 10^7 kg of greenhouse gases emissions., this reduction in the air pollution is equivalent to $47 million [80]. In

Australia, the greenhouse gas emissions from solar powered RO Desalination plants were found to be ~90% lower than that from a similar unit electrified by coal-fired generators [81].

In conclusion, utilizing Solar Driven RO desalination in Qatar can reduce the anthropogenic emissions from desalination processes while keeping the oil and gas reserves of Qatar for alternative usages.

3.4 Solar Powered Desalination Plants in Qatar

3.4.1 The "Ruwais" Installed Pilot Plant

A promising fully automated water desalination plant that is powered by Zero-Carbon Solar Energy source, has been installed in a local Qatari farm. The RO desalination plant is located in Al-Ruwais, at the northern part of the country, and is considered to be a pioneering reverse osmosis water desalination plant that is fully powered by solar energy. The plant has been installed in Al Sada family farm to avoid the high costs associated with the transportation of water to the farm. The plant utilizes the solar energy for powering the Reverse Osmosis desalination plant at low maintenance costs while achieving sustainable energy generation. The official launching of the project was on the first quarter of May 2016. The overall budget of the project was $250,000 and the payback period was estimated to be 4.5 years. The RO desalination unit that has been installed in the farm is a small-scale one, and the Photovoltaic Units used are Polycrystalline supplied by Jurawatt Vertrieb GmbH, which is a German leading supplier of high-performance solar modules. These Photovoltaic panels are especially designed to tolerate ambient temperatures of up to 125 ^{0}C, and this feature makes them suitable for arid and semi-arid areas where temperatures elevate extremely high. The installed units are 100% Potential Induced Degradation (PID) free. PID is responsible for the aging mechanism of modules which lead to the decrease of PV module power. The specifications and technical characteristics of the installed PV units are given in Table 5.

Table 5. Specifications of the Photovoltaic Panels [82]

Characteristics	Dimensions	(L) 1650 mm x (B) 991 mm x (T) 35 mm;
	Weight	20.5kg
	Number of cells	60
	Cell Size	156 mm x 156 mm
	Cell material	Polycristalline Si
	Cable length	1000 mm
	Front cover	Solar glass
	Backside film:	Polymer
	Frame material	Aluminum
	Connector type	MC4 Compatible Bypass
	Number of diodes	3
Electric Data	Rated output/nominal power/Peak Power or Pmax (Pmpp)	250 W
	Rated current at maximum power (Impp)	8,30 A
	Rated output Voltage (Umpp)	30,12 V
	Short circuit current Isc	9,02 A
	Open circuit voltage Uoc	37,10 V
	Efficiency	15.30%
	Sorting	+4,99 / 0 W
	Maximum voltage	1000 V
Temperature Coefficient	-0,38 %/K -1,002 W/K	
	-0,32 %/K -0,121 V/K	
	-0,001 %/K -0,001 A/K	
	-0,318 %/K -0,118 V/K	
	0,077 %/K -0,006 A/K	

The design of this plant is owned by Monsson Group, a pioneering company in wind and solar applications, established in 1997. Monsson is in close collaboration with three research institutes; two in Sweden [*IVL Swedish Environmental Research Institute* and *KTH Royal Institute of Technology*] and one in Switzerland [*Geneva State University HEPIA*]. The company is specialized in Reverse Osmosis plants that are powered by solar photovoltaic panels without additional electricity demand. According to its official website, Monsson has focused on renewable energy since 2004 and became a major energy developer with more than 2400 MW projects in its portfolio. The company highlights the importance of developing sustainable energy solutions in Qatar in terms of environment and gas and oil reserves, following the Ministry of Environment Intended Nationally Determined Contributions (INDCs) Report, 19 November 2015. The biggest challenge that Monsson has faced on implementing this pilot project was the amount of sand found in the input water, rather than the amount of salt. The membranes of the desalination units, due to such high concentrations, will therefore have to be changed every 3 years since their performance is 40% deteriorated.

A. Power Production of Al Sada Farm Installed PV Plant

The PV plant which has been installed to power the water desalination plant in Al Sada farm includes 80 photovoltaic units at a total length of 50 m as can be seen in Figure 13. Each unit produces 250W with an overall production of 20kW.

Figure 13. The Photovoltaic Panels installed in Al Sada farm [82]

The plant presents low energy consumption. During the daytime, the performance of the panels is adequate enough for producing the electricity needed for powering the desalination unit, and no extra energy contribution is needed from Kahramaa grid. In addition, the electricity produced from the installed Photovoltaic Units is also enough to power other facilities within the farm and their energy capacities can be further extended if needed. Currently, 60% of the energy produced by the installed PV units is used for powering the desalination unit and the remaining 40% are used for powering the farm internal energy needs. The energy storage unit used within this system is 50% of the energy produced, assisted by a back-up Generator for emergency conditions. The batteries installed can provide electricity for half an hour at a power of 10 kW full service on the operating units is agreed for further 10 years, indicating that the technology is not under an experimental stage but is 100% stably operational. The installed desalination system is entirely remotely operated and monitored on a daily non-stop basis.

B. Water Production of Al Sada Farm Installed Water Desalination Plant

According to an interview with the Chief Executive Officer of MONSSON, the desalination units of the farm can deliver 100m^3 of freshwater per day. The farm is equipped with large water tanks for the storage of the desalinated water.

The installed desalination plant is able to deliver water to the farm at lower prices than the desalinated water sold in the commercial markets. The company has calculated the cost to be almost three times lower than that of the transported water bought from the market. The cost of the transported water to the farm is approximately \$1.42 per m^3 while the cost of the water produced by the desalination units installed in Al-Sada farm is \$0.49 per m^3. The reasons behind this lower cost comes from:

a) No personnel costs since the plant is automatically operated.
b) Low energy consumption costs due to the integration of solar energy for powering the desalination plant. During the daytime, the desalination plant is running at zero energy consumption (i.e. no energy cost) since it is powered by the sunshine not with electricity from the grid.
c) Low running/maintenance costs; the components involved in this system needs no maintenance and are of high quality and reliability with low possibilities of frequent replacement.

C. The Cleaning Device Integrated within the Installed PV Panels

With prospect to the water scarcity problem that the country faces, the cleaning of the photovoltaic panels is dry. The installed PV panels system is equipped with an innovative robot designed fully automatic Dry Panel Cleaning Device [DPCV] as can be seen in Figure 14. A special rotating brush is equipped within the system to remove the dust form the panels' surface without damaging them and without using any water. The cleaning system is equipped with a sensor that allows the cleaning system to automatically operate when the accumulated dust affects the PV energy production efficiency, and can lead to an improvement of energy production up to 25%. This installed dry cleaning system does not require the installation of pipes and water tanks at all, therefore chemicals that may harm the PV surface or the environment are avoided. It can be operational at very high ambient temperatures [60 ^{0}C] at an approximate speed of 8m/min.

Figure 14. Dry Panel Cleaning Device [82]

The cleaning device structure can implement meteorological sensors that can collect data regarding atmospheric conditions. This data can be evaluated from the central unit to put the units in operation remotely.

D. Utilizing the Desalination Plant Water for Irrigation

The concept of solar driven desalination plants can be further expanded at very remote locations for fresh water supply and for irrigation at reasonable costs. Especially designed greenhouses for deserts can also be constructed to allow an all year round vegetable production without the need for special approvals. Future connection of such desalination plants with the existing water distribution grid, can assist into the supply of the population with potable water. Such water-grid connections can also help in increasing the capacity of the Qatari farming industry. According to Qatar's Minister of Energy and Industry, Dr. Mohammed bin Saleh Al Sada, the country's agricultural sector will require 750MW to 800MW of energy from renewable sources to deliver irrigation water and other production requirements such as cooling. Such investments will help Qatar to become independent from investing in lands abroad for producing and importing food. Such ''insurance policy'' as identified by Mr. Fahad Al Attiya, the chairman of the Qatar National Food Security Program, can help towards reclaiming land from the desert and turning it into cultivated areas. Since the country's natural aquifers are expected to be depleted within the next 20 years, then extended desalination is the only way for water supply.

With the agricultural sector consuming approximately more than 83% of the water in the Middle East region, the extension and continuous upgrading of the water desalination and its integration into the water grid, will be beneficial for the agriculture.

3.4.2 Monsson Target Desalination Plant

The company's target is to implement Reverse Osmosis on a very large scale aiming to deliver 336,000 m^3 of water on an annual basis to Qatar National Grid, powered only by wind and solar sources. Figure 15 shows the progress diagram of the target unit.

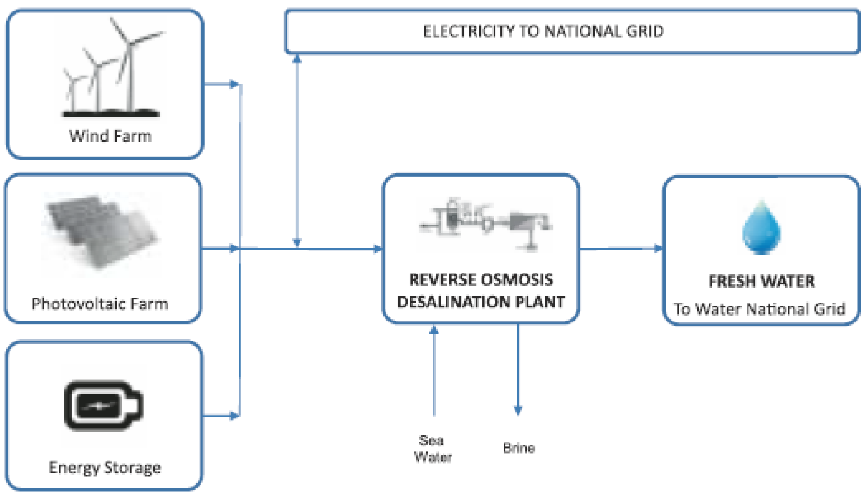

Figure 15. Process Diagram for Monsson Target Project [82]

This concept when applied on the targeted large scale, will not only contribute to the CO_2 emissions reduction but will also provide approximately one million people with clean and potable water and will create more than 800 new jobs [82]. This target plant can help the country in facing its biggest challenges for advancing the water security issues as its population is increasing and at the same time the high energy demands with perspective to the diminishing fossil fuels reserves.

Chapter 4. The Proposed Water Desalination Plant for Qatar

4.1 Features of the Proposed System

The system proposed for utilization in Qatar consists of a Seawater Reverse Osmosis (RO) desalination unit powered by a Solar Photovoltaic (PV) System. The RO desalination unit is operating by adapting to the solar photovoltaic power supply. The largeness of the RO desalinating unit is determined by considering the regional per capita consumption and the overall population that indirectly determine the daily operation of the unit [83]. The optimum RO system would present elevated recovery ratio (high outflow at the lowest salt content) with the lowest applicable pressure. This low feed pressure can increase the life cycle of the membrane, making their replacement more seldom. However, the seawater desalination requires high pressures as will be seen later.

The PV Unit suggested for the System proposed for Qatar consists of mono-crystalline PV modules, batteries, charge controller and converters. The system converts the solar energy into electrical energy to be used for pumping the water from the sea and for electrifying the operation of the membranes. The Mono-crystalline PV modules, are made from the highest-grade silicon and present the best rates of efficiency, ranging from 21.5% [84] up to 25% [85]. This type of solar cells produce the highest energy yield at the lowest space (space sufficient) with the longest warranty period of 25 years [86]. The cells perform efficiently in high and low light conditions [87]. BOSCH Company, with the ISO/CE/TUV/IEC certifications, manufactures such panels with cells of 250 Watt. The Direct Current (DC) produced by the PV panels is converted into Alternative Current (AC) by the power converter. The excess in energy production will be stored in a battery for providing stable power supply under all sunshine conditions. The cleaning of the panels will be carried out using a Dry Panel Cleaning

Device [DPCV] similar to the one used by MONSSON in Pilot Plant given in section 3.4.

The seawater desalination unit suggested for the System proposed for Qatar, includes a stainless steel pump to guide the water towards the Reverse Osmosis membranes and multilayer nets and filters to be suitable for Qatar sandy water. The biggest particles of the sand will not penetrate through the membranes, and therefore will not cause their fouling and deterioration. The factors considered for evaluating the size of the reverse osmosis unit are the per capita daily water production and the total operation hours per day [77]. An effective RO system should present high permeate flow at a low permeate salinity, at a low feed pressure (which can help in increasing the life span of the membrane). Usually the pressure applied for seawater is 55-70 bar [83]. Stainless steel high-pressure pumps will lead the seawater from the sea to the RO via pipes. The pipes will be enhanced with meshed nets and filters with thread diameter of less than 1mm [88]. The nets will be installed in the pipes at the intake of the seawater, as a first stage of pre-treatment, for removing the sand particles for the membrane protection. The second level of the seawater treatment includes chlorination, and the addition of antiscale and antifoam additives. Two non-alloy steel/aluminum storage tanks will be connected with the inflow (for storing the seawater that is ready for desalination), and with the outflow (for storing the desalinated water). Measuring systems for monitoring and recording the ambient temperature and humidity, the pressure, and the acidity of the water inflow and outflow are also suggested for the proposed System. Table 6 summarizes the suggested features of the proposed system and figure 16 depicts the suggested design of the desalination unit.

Table 6. The Design Characteristics of the PV-Powered RO System [24]

Specifications of PV-Seawater Reverse Osmosis (SWRO) Desalination Unit Components		
Component	**Brand**	**Specification**
PV modules	Bosch	250 W

Charge controller	Magnum Energy PT-100 Charge Controller	100A at 12/24/48V [89]
Inverter	GE	1500 VDC [90]
Battery	Toshiba	
Membrane types	Kubota	
Feed pump	GE	[91]
Aluminum Pipes	-	-
Nets	-	1 mm meshing

Figure 16 describes the operation of the Solar Powered Seawater Desalination Unit proposed for Qatar. The water is pumped from the Sea (1) towards the collection tank (2). The seawater is then filtered through 1mm-meshed nets (3) for removing the sand and the high diameter objects that can harm the membranes. The filtered seawater is then collected in a tank (4) where it is pretreaded (chlorination, addition of coagulants, flocculants, antiscalants and antifoams). The Photovoltaic Panels (5) converts the solar energy collected to electricity that powers the RO membranes (6). The desalinated water is finally collected in tank (7) to be distributed according to the local needs.

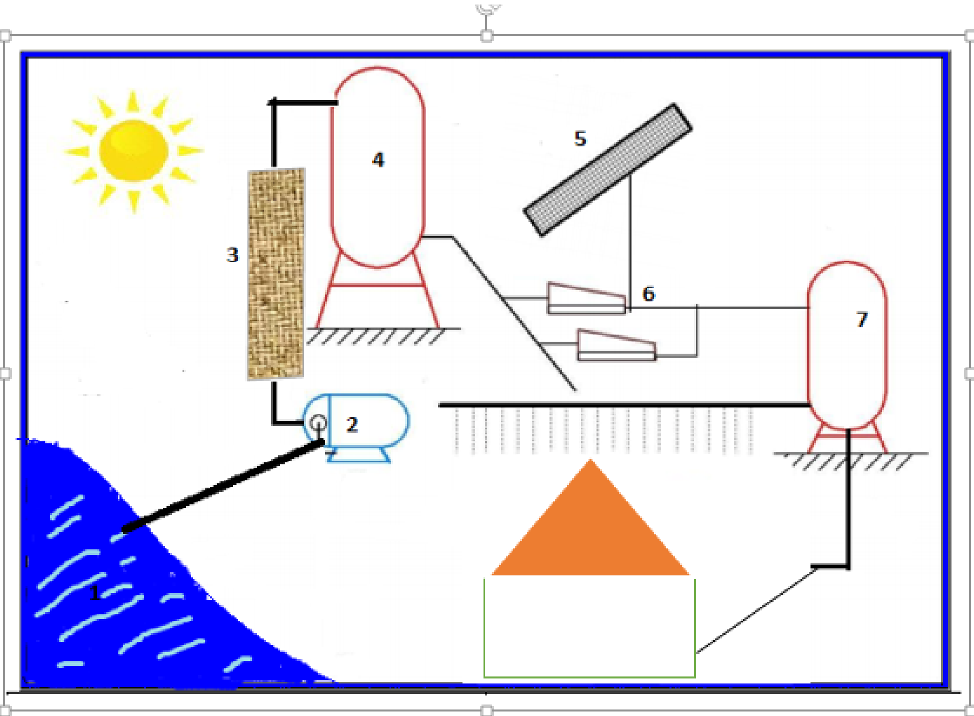

Figure 16. Design of the PV-RO Desalination Unit

4.2 Benefits of the Proposed System

The key benefits that the proposed System include:

1. It utilizes the solar energy, which is not only a free form of energy but is also an environmentally friendly one. Because Qatar presents high amounts of irradiance and the country location favors solar applications [92] therefore utilizing such a capability will be useful.
2. It offers a low constructive cost because of continues drop in the PV panels prices.
3. It offers low operational costs because of the no maintenance required for the PV panels with no moving parts, and because of the lower workforce cost in Qatar.
4. It allows the production of electricity and clean water with less Carbon Footprints.
5. It allows developments in rural and desert areas that has no access to the national power and water grids.

4.3 Challenges to the Proposed System

The primary concerns that may face the proposed solar-powered seawater desalination plant include:

1. The lack of renewable energy policy framework, legislations and grid access in Qatar. The domination of the state-utility Kahramaa may discourage the power producers from investing in developing such a system.

2. Qatar high reserves in gas and oil makes the cost of water desalination using the grid power less than solar-powered desalination. The water from Solar-powered desalination plants is approximately three times higher in cost than that from grid-powered plants [93].

3. The number of solar arrays needed to produce the required energy might consume a large land space. Therefore, the effective determination of the area required for the proposed project can prove more effective in terms of economical cost. Photovoltaic Panels of higher efficiency will occupy less space, making the investment more affordable [94].

4. Solar or renewably-powered water desalination Plants are currently still considered expensive for Qatar, however the plummeting prices of renewables can create opportunities for developing the proposed system.

5. Soiling of the Photovoltaic panels due to Qatar frequent sandstorms and lack of rain can result into to the accumulation of dust on the surface, this in turn affects the power production of the system and therefore the desalination process and additionally increases the operation costs.

6. The harsh Qatari climate, with high values of temperature and humidity, can affect the PVs' surfaces leading to an increase in their maintenance and replacement costs.

7. The fluctuations in the renewable sources power production can harm the desalination process and therefore the inclusion of effective energy storage is essential, thus adding to the overall cost of the proposed system [95].

4.4 Economic Evaluation of the Proposed System

The overall cost analysis of a solar driven desalination system includes three types of costs. Namely the investment costs that refer to the equipment, installation, work force and cost of the land purchase, the operational costs that include maintenance and replacements, and finally the energy costs that describe the energy needed for the operation of the system. The percentages of each cost within the overall budget of the project, for the solar driven desalination projects, can be seen in Table 7. The investment costs hold the largest part of the investment, while the energy costs can be considered typically zero since only solar energy is used [96].

Table 7. Costs in Solar Driven Desalination [96]

Solar Driven Desalination Costs		
Investment Costs (%)	Operational Costs (%)	Energy Costs (%)
30–90	10–30	0–10

The Capital Cost for the proposed system includes the cost of equipment, auxiliary equipment, land, installation charges and the water pre-treatment. The economical evaluation of the proposed system is given in Table 8. The Dry Panel Cleaning Device is evaluated to be at 1 % of the overall budget (as it was the case in Al-Sada farm). The prices for the PV modules were found according to their Watt characteristics [97].

A total of 160 PV units of 1,500 VDC are proposed here. The proposed 1,500 VDC (higher voltage) systems offer longer strings which allow for fewer combiner boxes, less wiring and trenching, and therefore less labor. Installing 1,500 VDC systems (instead of 1,000 VDC) can lower costs by as much as $0.05 per watt. By using the 1,500 V architecture in larger PV arrays, the maintenance and installation costs decreases delivering obvious benefits to the Engineering, Procurement, and Construction (EPCs) particularly the smaller ones, for reducing the overheads and increasing margins [98].

Table 8. Economic Evaluation of the Proposed System [47]

Specifications of the Proposed PV-Driven Seawater Reverse Osmosis Desalination Unit Components			
Component	**Units**	**Price per Unit (QR)**	**Total Cost (QR)**
PV modules Bosch 250W	160	2.26/Watt	90,400
Dry Panel Cleaning Device [DPCV]	1	9,100	9,100
Charge controller (Magnum Energy PT-100)	5	400 [99]	2000
Inverter GE	4	7,280 [100]	29,120
Battery	10	1950	19,500
Membranes	100	270	27,000
High Pressure Feed pumps GE	10	9,100	91,000
Aluminum Pipes	1	10,900/ton	10,900
Nets 1 mm meshing	30m^2	25/m^2	750
Man-hours	4000	25	100,000
Antiscale and antifoam additives	1 ton	12,740	12,740
TOTAL INSTALLATION COST			**392,510**

Maintenance Cost is a necessary operating expenditure that ensures the optimal operation of the system. The maintenance cost is the expenditure necessary for the replacement of parts and materials, and for the cleaning and protection of the system from corrosion and scaling. The annual operating and maintenance costs (AMC) are the total yearly costs of owning and operating the desalination unit, while including the amortization or fixed charges together with the operation, maintenance and parts replacement costs. Based on a consultation with Mr Lopu, the CEO of MONSSON, the replacement of the membranes is considered to be every 3 years. He has stated that the membranes' effectiveness and permeability get reduced by 40% after 3 years and thus they have to be replaced. The maintenance cost is considered to be at a 10 man-hours/week.

4.5 Environmental Evaluation of the Proposed System

The proposed system is expected to produce 1000m^3 of water on a daily basis. Based on the Bahrain solar desalination units which produce 40million gallons of water (110,000m^3) daily and save 55 million m^3 of natural annually due to the solar energy utilization [101], the proposed system natural gas annual saving is therefore calculated to be approximately 50,000 m^3.

To investigate the environmental benefit of the solar energy utilization compared to the conventional electric energy, the reduction in the CO_2 emissions will be calculated according to the UK guidelines as follows [102]:

$$\textit{Reduction in Carbon emissions} = \textit{Annually Used Electricity (kWh)} * CO_2 \textit{ conversion factor}$$

The Annually Used Electricity of the proposed system if powered with conventional fuels is estimated to be ***2.98 kWh/m³ of produced water*** [103]**.**

The proposed system is expected to produce ***3.65*10⁵ m³ of water per year***, therefore:

$$\textit{The Annually Used Electricity is } 10.88*10^5 \textit{ kWh}$$

The CO_2 factor for the Middle East region, as defined by the US Energy Information Administration [102], is $\boldsymbol{0.616\ kg*kWh^{-1}}$. Thus, the carbon emission reductions will be:

$$\textit{Reduction in Carbon emissions} = 10.88 * 10^5 \times 0.616$$

$$\textit{Reduction in Carbon emissions} = 6.69*10^5 = 66{,}900 \textit{ kg } CO_2\textit{/year}$$

Chapter 5. Conclusion and Challenges

Although Qatar is the world's leading exporter of Liquefied natural gas, the diversification of its energy production to include renewables is needed to help the country in achieving its target for the national energy mix by 2022.

Although Reverse Osmosis (RO) is one of the most widespread water desalination methods in Qatar, it is mostly powered by the grid. The exploitation of fossil fuels though, enhances the environmental pollution by increasing the CO_2 emissions into the atmosphere.

The proposed Solar Powered Sea Water Desalination Plant is an innovative example of using solar energy in fully powering the RO water desalination units. Implementing such a system on a large scale basis ensures affordable, sustainable, secure freshwater supply and increased capacity for the local farming. Based on Al-Sada Farm Pilot System experience, the proposed system suggests the additional installation of nets in the inflow for removing the sea-sand and for protecting the RO membranes from fouling.

The proposed system has been economically and environmentally evaluated. Based on the economic evaluation that has been carried out here, it was found that the proposed system have a cost of approximately 400,000 QR, which can be considered as a low-risk investment. The proposed devices and instruments within the system present high efficacy and are considered to be of advanced technology. With the PV cost continuously dropping, the overall budget can be considered as more affordable in future. The proposed system presents low maintenance expenses due to the low workforce cost and the zero cleaning needs. Based on the carried out environmental evaluation, the proposed system was found to save almost 67 tons of CO_2 on an annual basis, thus confirming its effectiveness.

The challenges that face the solar applications in the country are the lack of renewable energy policy framework, legislations, institutional support, feed-in tariffs and grid access. Also, utilizing the solar power is still highly expensive in the country, however the potential plummeting in the prices can create the opportunity for solar applications expansion. Finally, the degradation of solar panels due to the harshness of the regional climate is another issue that must also be addressed before utilizing the solar energy in large-scale applications. High quality materials for optimizing the cell's performance should also be taken into consideration. Further research to update the proposed system is therefore strongly recommended.

The development of such large scale solar-powered Plants will help the country to obtain a visionary renewable energy policy that would help it to build clean, sustainable energy systems and to accelerate its regional as well as global emergence as a clean-tech country. The large scale implementation of solar energy will have multiple advantages for Qatar, this includes energy security, improved air quality, reduced greenhouse gas emissions, more employment opportunities in addition to augmenting the water and food security.

References

1. Khawaji AD, Kutubkhanah IK, Wie J-M. Advances in seawater desalination technologies. Desalination. 2008 Mar;221(1–3):47–69.
2. Saidur R, Elcevvadi ET, Mekhilef S, Safari A, Mohammed HA. An overview of different distillation methods for small scale applications. Renew Sustain Energy Rev. 2011 Dec;15(9):4756–64.
3. Global water intelligence Magazine. Global water intelligence [Internet]. Available from: https://www.globalwaterintel.com/research/global-picture
4. Lattemann S, Höpner T. Environmental impact and impact assessment of seawater desalination. Desalination. 2008 Mar;220(1–3):1–15.
5. Fritzmann C, Löwenberg J, Wintgens T, Melin T. State-of-the-art of reverse osmosis desalination. Desalination. 2007;216(1–3):1–76.
6. Mesa AA, Gómez CM, Azpitarte RU. Design of the maximum energy efficiency desalination plant (PAME). Desalination. 1997 Feb;108(1–3):111–6.
7. Buros OK. The ABCs of Desalting. Int Desalin Assoc Mass. 2000;(2):1–32.
8. Watson IC, Morin OJ, Henthorne L. Desalting Handbook for Planners. Desalin Water Purif Res Dev Progr Rep No 72. 2003;(72):1–310.
9. El-Nashar AM. The economic feasibility of small solar MED seawater desalination plants for remote arid areas. Desalination. 2001 Apr;134(1–3):173–86.
10. Alklaibi AM, Lior N. Membrane-distillation desalination: Status and potential. Desalination. 2005 Jan;171(2):111–31.
11. Stover RL, Ameglio A, Khan PAK. The Ghalilah SWRO plant: an overview of the solutions adopted to minimize energy consumption. Desalination. 2005 Nov;184(1–3):217–21.
12. Eriksson P. Nanofiltration extends the range of membrane filtration. Environ Prog. 1988;7(1):58–62.
13. Van der Bruggen B, Vandecasteele C. Distillation vs. membrane filtration:

overview of process evolutions in seawater desalination. Desalination. 2002 Jun;143(3):207–18.

14. Karagiannis IC, Soldatos PG. Water desalination cost literature: review and assessment. Desalination. 2008 Mar;223(1–3):448–56.

15. Karagiannis IC, Soldatos PG. Current status of water desalination in the Aegean Islands. Desalination. 2007 Feb;203(1–3):56–61.

16. Al-Wazzan Y, Safar M, Ebrahim S, Burney N, Mesri A. Desalting of subsurface water using spiral-wound reverse osmosis (RO) system: technical and economic assessment. Desalination. 2002 May;143(1):21–8.

17. Jaber IS, Ahmed MR. Technical and economic evaluation of brackish groundwater desalination by reverse osmosis (RO) process. Desalination. 2004 Aug;165:209–13.

18. Sambrailo D, Ivić J, Krstulović A. Economic evaluation of the first desalination plant in Croatia. Desalination. 2005 Jul;179(1–3):339–44.

19. Afonso MD, Jaber JO, Mohsen MS. Brackish groundwater treatment by reverse osmosis in Jordan. Desalination. 2004 Apr;164(2):157–71.

20. Rico DP, Arias MFC. A reverse osmosis potable water plant at Alicante University: first years of operation. Desalination. 2001 May;137(1–3):91–102.

21. Chaudhry S. Unit cost of desalination. CA Desali- nation Task Force Sausalito. 2003;

22. Avlonitis SA. Operational water cost and productivity improvements for small-size RO desalination plants. Desalination. 2002 Mar;142(3):295–304.

23. Hafez A, El-Manharawy S. Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study. Desalination. 2003 Feb;153(1–3):335–47.

24. Mohamed ES, Papadakis G. Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. Desalination. 2004 Mar;164(1):87–97.

25. Kershman SA, Rheinländer J, Neumann T, Goebel O. Hybrid wind/PV and conventional power for desalination in Libya—GECOL's facility for medium

and small scale research at Ras Ejder. Desalination. 2005 Nov;183(1–3):1–12.
26. Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. The effect of hydraulic energy recovery in a small sea water reverse osmosis desalination system; experimental and economical evaluation. Desalination. 2005 Nov;184(1–3):241–6.
27. Voivontas D, Misirlis K, Manoli E, Arampatzis G, Assimacopoulos D. A tool for the design of desalination plants powered by renewable energies. Desalination. 2001 Mar;133(2):175–98.
28. Abou Rayan M, Khaled I. Seawater desalination by reverse osmosis (case study). Desalination. 2003 Feb;153(1–3):245–51.
29. Voivontas D, Arampatzis G, Manoli E, Karavitis C, Assimacopoulos D. Water supply modeling towards sustainable environmental management in small islands: the case of Paros, Greece. Desalination. 2003 Aug;156(1–3):127–35.
30. Zejli D, Benchrifa R, Bennouna A, Zazi K. Economic analysis of wind-powered desalination in the south of Morocco. Desalination. 2004 Aug;165:219–30.
31. Atikol U, Aybar HS. Estimation of water production cost in the feasibility analysis of RO systems. Desalination. 2005 Nov;184(1–3):253–8.
32. Leitner GF. Total water costs on a standard basis for three large, operating , S.W.R.O. plants. Desalination. 1991 Jul;81(1–3):39–48.
33. Tian J, Shi G, Zhao Z, Cao D. Economic analyses of a nuclear desalination system using deep pool reactors. Desalination. 1999 Aug;123(1):25–31.
34. Poullikkas A. Optimization algorithm for reverse osmosis desalination economics. Desalination. 2001 Feb;133(1):75–81.
35. Wade NM. Distillation plant development and cost update. Desalination. 2001 May;136(1–3):3–12.
36. Andrianne J, Alardin F. Thermal and membrane processe economics: Optimized selection for seawater desalination. Desalination. 2003 Feb;153(1–3):305–11.
37. Wu S, Zhang Z. An approach to improve the economy of desalination plants with a nuclear heating reactor by coupling with hybrid technologies.

Desalination. 2003 Jun;155(2):179–85.

38. Agashichev SP. Analysis of integrated co-generative schemes including MSF, RO and power generating systems (present value of expenses and “levelised” cost of water). Desalination. 2004 Apr;164(3):281–302.
39. Ettouney H. Visual basic computer package for thermal and membrane desalination processes. Desalination. 2004 Aug;165:393–408.
40. AGASHICHEV S. Systemic approach for techno-economic evaluation of triple hybrid (RO, MSF and power generation) scheme including accounting of CO2 emission*1. Energy. 2005 Jun;30(8):1283–303.
41. Borsani R, Rebagliati S. Fundamentals and costing of MSF desalination plants and comparison with other technologies. Desalination. 2005 Nov;182(1–3):29–37.
42. Tian L, Wang Y, Guo J. Economic analysis of a 2×200 MW nuclear heating reactor for seawater desalination by multi-effect distillation (MED). Desalination. 2003 Feb;152(1–3):223–8.
43. Ophir A, Lokiec F. Advanced MED process for most economical sea water desalination. Desalination. 2005 Nov;182(1–3):187–98.
44. Tian L, Guo J, Tang Y, Cao L. A historical opportunity: economic competitiveness of seawater desalination project between nuclear and fossil fuel while the world oil price over $50 per boe—part A: MSF. Desalination. 2005 Nov;183(1–3):317–25.
45. Wu S. Analysis of water production costs of a nuclear desalination plant with a nuclear heating reactor coupled with MED processes. Desalination. 2006 Apr;190(1–3):287–94.
46. Tzen E, Morris R. Renewable energy sources for desalination. Sol Energy. 2003 Nov;75(5):375–9.
47. Mohamed ES, Papadakis G, Mathioulakis E, Belessiotis V. An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with an hydraulic energy recovery unit. Desalination. 2006 Jun;194(1–3):239–50.

48. Dreizin Y. Ashkelon seawater desalination project — off-taker's self costs, supplied water costs, total costs and benefits. Desalination. 2006 Apr;190(1–3):104–16.
49 Al-Malki A. Business Opportunities in Water Industry in Qatar (Qatar General Electricity and Water Corporation). 2008;
50. Desalination plants in Qatar [Internet]. [cited 2016 Feb 17]. Available from: https://www.google.com/search?q=desalination+plants+in+qatar&espv=2&biw=1242&bih=557&source=lnms&tbm=isch&sa=X&ved=0ahUKEwj888ujvcbQAhVL1SwKHXyLBLsQ_AUIBigB
51. Al-Mohannadi F. Presentation on Power & Water Plants in Qatar. 2010.
52. M. A. Darwish. Qatar water challenges. Desalin Water Treat. 2013;51(1–3):75–86.
53. Darwish MA, Abdulrahim HK, Hassan AS. Realistic power and desalted water production costs in Qatar. Desalin Water Treat. 2016;57(10):4296–302.
53. Darwish MA, Al Awadhi FM, Abdul Raheem MY. The MSF: Enough is enough. Desalin Water Treat. 2010 Oct 3;22(1–3):193–203.
54. Darwish MA, Al Awadhi FM, Abdul Raheem MY. The MSF: Enough is enough. Desalin Water Treat. 2010 Oct 3;22(1–3):193–203.
55. Hoover LA, Phillip WA, Tiraferri A, Yip NY, Elimelech M. Forward with osmosis: emerging applications for greater sustainability. Environ Sci Technol. American Chemical Society; 2011 Dec 1;45(23):9824–30.
56. Winters H, Isquith IR, Bakish R. Influence of desalination effluents on marine ecosystems. Desalination. Elsevier; 1979 Oct;30(1):403–10.
57. Hoepner T, Lattemann S. Chemical impacts from seawater desalination plants — a case study of the northern Red Sea. Desalination. Elsevier; 2003 Feb;152(1–3):133–40.
58. Qatar Meteorology Department, 2016
59. Bleninger T, Jirka GH. Modelling and environmentally sound management of brine discharges from desalination plants. Desalination. Elsevier; 2008;221(1):585–97.

60. Danoun R. Desalination plants: Potential impacts of brine discharge on marine life. 2007.
61. Areiqat A, Mohamed KA. Optimization of the negative impact of power and desalination plants on the ecosystem. Desalination. Elsevier; 2005 Nov;185(1–3):95–103.
62. Beltagy M. IMCO/UNEP Workshop on Combatting Marine Pollution from Oil Exploration and Transport in the Kuwait Action Plan Region. 1980;
63. Uddin S. Environmental Impacts of Desalination Activities in the Arabian Gulf. Int J Environ Sci Dev . 2014;5(2).
64. Münk F. Ecological and economic analysis of seawater desalination plants. Dr Thesis. 2008;Institute(April):119.
65. Group KT. Process Design of AIR COOLED HEAT EXCHANGERS (AIR COOLERS). Malaysia. [Internet]. 2015 [cited 2016 Oct 23]. Available from: http://www.tradearabia.com/news/IND_303158.html
66. TheEdge. Kahramaa announces first solar power facility to open next year - The Edge [Internet]. 2015 [cited 2016 Oct 23]. Available from: http://www.theedge.me/kahramaa-announces-first-solar-power-facility-to-open-next-year/
67. Hafez A, El-Manharawy S. Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study. Desalination. 2003;153(1):335–47.
68. Munsell M. Solar PV Prices Will Fall Below $1.00 per Watt by 2020 [Internet]. Greentech Media . [cited 2016 Nov 7]. Available from: https://www.greentechmedia.com/articles/read/solar-pv-prices-to-fall-below-1.00-per-watt-by-2020
69. Zhu A, Christofides PD, Cohen Y. Effect of Thermodynamic Restriction on Energy Cost Optimization of RO Membrane Water Desalination. Ind Eng Chem Res. American Chemical Society; 2009 Jul;48(13):6010–21.
70. Dakkak M, Hirata A, Muhida R, Kawasaki Z. Operation strategy of residential centralized photovoltaic system in remote areas. Renew energy. 2003;28(7):997–1012.

71. Taheri AH, Sim LN, Haur CT, Akhondi E, Fane AG. The fouling potential of colloidal silica and humic acid and their mixtures. J Memb Sci. 2013;433:112–20.
72. Adler PS. Managing Flexible Automation. Calif Manage Rev. 1988;30(3):34–56.
73. Nair M, Kumar D. Water desalination and challenges: The Middle East perspective: a review. Desalin Water Treat. Routledge ; 2013 Feb;51(10–12):2030–40.
74. Kasemset S, Lee A, Miller DJ, Freeman BD, Sharma MM. Effect of polydopamine deposition conditions on fouling resistance, physical properties, and permeation properties of reverse osmosis membranes in oil/water separation. J Memb Sci. 2013;425:208–16.
75. Harder E, Gibson JM. The costs and benefits of large-scale solar photovoltaic power production in Abu Dhabi, United Arab Emirates. Renew Energy. Elsevier Ltd;
76. Shahabi MP, McHugh A, Ho G. Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy. Renew Energy. 2014;67:53–8.
77. Tzen E, Perrakis K, Baltas P. Design of a stand alone PV - desalination system for rural areas. Desalination. Elsevier; 1998;119(1):327–33.
78. Zhao J, Wang A, Wenham SR, Green MA. 21, 5% efficient 47 μm thin layer silicon cell. In: Proc of the 13th European PV Solar Energy Conference,. Nice, France; 1995. p. 1566–9.
79. Saga T. Advances in crystalline silicon solar cell technology for industrial mass production. NPG Asia Mater. Nature Publishing Group; 2010 Jul;2(3):96–102.
80. Chandel SS, Nagaraju Naik M, Sharma V, Chandel R. Degradation analysis of 28 year field exposed mono-c-Si photovoltaic modules of a direct coupled solar water pumping system in western Himalayan region of India. Renew Energy. 2015;78:193–202.
81. Amin N, Lung CW, Sopian K. A practical field study of various solar cells on

their performance in Malaysia. Renew Energy. 2009;34(8):1939–46.
82. Monsson. We give you pure water anywhere.
83. Abdallah S, Abu-Hilal M, Mohsen MS. Performance of a photovoltaic powered reverse osmosis system under local climatic conditions. Desalination. Elsevier; 2005;183(1):95–104.
84. Tiwari GN, Mishra RK, Solanki SC. Photovoltaic modules and their applications: A review on thermal modelling. Appl Energy. 2011;88(7):2287–304.
85. P. Denholm, E. Drury, R. Margolis, M. Mehos. Solar energy: the largest energy resource. Generating Electricity in a Carbon-con-strained World. Acad Press Calif. 2010;271–302.
86. Invented for life Solar modules from Bosch Solar Energy [Internet]. [cited 2016 Nov 13]. Available from: http://www.bosch-solarenergy.de/media/en_us/bosch_se_serviceorganisation/product/datenblaetter_2/kristtalin/na_2/Bosch_Solar_Module_c_Si_M_60_NA44117.pdf
87. Reliable system – high yields. Bosch Solar Module µm-Si plus EU1410 [Internet]. [cited 2016 Nov 12]. Available from: http://www.bosch-solarenergy.com/media/en/bosch_se_serviceorganisation/product/datenblaetter_2/duennschicht_1/_m_si/Bosch_Solar_Module_m_Si_plus_EU1410.pdf
88. Almazroui M. Climatology and Monitoring of Dust and Sand Storms in the Arabian Peninsula. Center of Excellence for Climate Change Research.
89. Charge controllers from Wholesale Solar [Internet]. [cited 2016 Oct 27]. Available from: http://www.wholesalesolar.com/charge-controllers#BlueSky
90. GE. ProSolar Central Solar Inverter [Internet]. [cited 2016 Oct 30]. Available from: http://www.gepowerconversion.com/sites/gepc/files/product/ProSolar Central Solar Inverter_fact sheet.pdf
91. GE. Chemical Feed Systems | GE Water [Internet]. [cited 2016 Oct 30]. Available from: https://www.gewater.com/handbook/chemical_feed_control/ch_35_chemicalfeed.jsp

92. Radhi H. On the value of decentralised PV systems for the GCC residential sector. Energy Policy. 2011;39(4):2020–7.
93. The World Bank. Renewable Energy Desalination:An Emerging Solution to Close the Water Gap in the Middle East and North Africa. 2012.
94. Martin R. To Make Fresh Water without Warming the Planet, Countries Eye Solar Power [Internet]. MIT Technology Review . 2016 [cited 2016 Oct 23]. Available from: https://www.technologyreview.com/s/601419/to-make-fresh-water-without-warming-the-planet-countries-eye-solar-power/
95. Wei Qi, Jinfeng Liu, Christofides PD. Supervisory Predictive Control for Long-Term Scheduling of an Integrated Wind/Solar Energy Generation and Water Desalination System. IEEE Trans Control Syst Technol. 2012 Mar;20(2):504–12.
96. Shatat M, Worall M, Riffat S. Economic study for an affordable small scale solar water desalination system in remote and semi-arid region. Renew Sustain Energy Rev. 2013;25:543–51.
97. Bosch Brand Poly Solar Panel,Poly Solar Panel For Solar Home System,Bosch Solar Cells [Internet]. [cited 2016 Nov 8]. Available from: https://www.alibaba.com/product-detail/Bosch-brand-poly-solar-panel-poly_1618972470.html
98. PV Magazine. Higher voltage, lower cost [Internet]. [cited 2016 Nov 7]. Available from: http://www.pv-magazine.com/archive/articles/beitrag/higher-voltage--lower-cost-_100020830/630/#axzz4PObKuwMF
99. New Design 12v 24v 48v MPPT Solar Charge Controller [Internet]. [cited 2016 Nov 8]. Available from: https://www.alibaba.com/product-detail/NEW-DESIGN-12V-24V-48V-MPPT_60314002450.html?spm=a2700.7724838.0.0.DaXvMu&s=p
100. GENERAL ELECTRIC INVERTER IC3506A105A6 [Internet]. [cited 2016 Nov 12]. Available from: http://www.ebay.com/itm/GENERAL-ELECTRIC-INVERTER-IC3506A105A6-USED-/231605607975?hash=item35ecc51e27:g:oOgAAOSwu4BVjbmv

101. Al-Qahtani H. Feasibility of utilizing solar energy to power reverse osmosis domestic unit to desalinate water in the state of Bahrain. Renew Energy. Pergamon; 1996;8(1):500–4.
102. International Energy Agency. Benign energy? The environmental implications of renewables. 1998.
103. Mobile solar RO desalination unit claims 87% energy saving - WaterWorld [Internet]. [cited 2016 Nov 8]. Available from: http://www.waterworld.com/articles/2015/01/mobile-solar-ro-desalination-unit-claims-87-energy-saving.html
104. EIA-Voluntary Reporting of Greenhouse Gases Program - Emission Factors and Global Warming [Internet]. [cited 2016 Nov 6]. Available from: http://www.eia.gov/oiaf/1605/emission_factors.html