Energy Footprint of Water Desalination

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Abstract

Demand for the freshwater is growing due to the growth of world population that entails growing demand of freshwater for agricultural and industrial purposes. However, the fresh water availability on Earth is limited and many countries face severe water shortages. Water desalination could be a possible solution for this problem. Among the variety of existing water desalination technologies, three are particularly promising, these are: reverse osmosis (RO), multi stage flash (MSF), multi effect distillation (MED). Energy consumption of desalination processes are determined by factors like capacity of desalination plant (small, medium, large), the energy source (electricity vs thermal), type of feed water (brackish (BW) vs seawater (SW)), desalination method (thermal vs membrane), use of renewable energy sources (solar, wind, geothermal), and necessity of feed pretreatment (mechanical and/or chemical). In this paper, I compare the total energy consumption of different methods considering each influential factor and categorizing the existing desalination techniques. Results suggest that the membrane-based technologies are the least energy intensive. BW RO of medium and large scales require 1.9 kW h/m3. Then comes SW RO of medium size and SW RO of large scale with 4.3 and 4.4 kW h/m3 energy consumption. The thermal desalination techniques, primarily MSF and MED have much higher energy footprint, than the membrane ones. They consume 17.1 and 11.9 kW h/m3 respectively, however, thermal technologies are more efficient for desalination of very salty waters. Nevertheless, membrane-based desalination methods due to their less energy-intensive nature and small footprint became more popular than the thermal technologies and substantial efforts have been observed in integrating RO with renewable energy sources, mainly wind and solar. Energy footprint of this type of desalination techniques is in between the membrane and thermal routes. The energy consumption of renewable powered desalination plants ranges from 1.5 to 21.1 kW h/m3. Their main drawback is small capacity, which makes them non-competitive with conventionally powered plants. We could say that globally humanity spent 7 kW h energy for desalination of 1 m3 of water. For the most of developed countries desalination has large contribution to the total fresh water supply. However, the conventional energy sources are forecasted to be depleted in the near future. The main question is: can desalination satisfy the total fresh water demand at least in the coastal regions within 100 kilometers, where presently about 40% of the world's population live? And should we consider desalination only for municipal purposes or for industrial and agricultural purposes as well? Rough estimation was done regarding the land requirement for solar panels to be able to supply the energy demand from SW RO desalination that is based on solar energy. As a model for such a study I decided to choose a city with 1 million inhabitants located in the territory of Saudi Arabia. To supply 1 million people with fresh water, desalination plant should have 270 000 m3/day capacity for municipal purposes and 1 470 000 m3/day capacity for industrial and agricultural purposes as well. Desalinating freshwater to meet only the municipal purposes a 5.18 km2 of land is required for building a solar park or almost 700 modern soccer fields and for the industrial and agricultural purposes the land requirement increases to – 28.22 km2, which is 3804 soccer fields. The results change, if we change the location of desalination plant, owing mainly to the difference in the amount of radiance that earth surface receives. The sensitivity analysis of a land requirement dependency on radiance was further calculated.

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1 Introduction

1.1 Background

There is a rapidly increase of fresh water demand due to growth of world population, increasing use of water in the food production and homes. However, the fresh water availability on Earth is limited and many countries already face severe water shortages. Water desalination could be a possible solution for the water shortage problem.

There is a worldwide increase of need for more treatment plants of non-conventional water sources. Some water desalination technique, which are considered as traditional ways, during the half of century have been evolved to reliable and established processes (Bruggen et al., 2002). From majority of the existing water desalination technologies, three are of particular interest, these are reverse osmosis (RO), multi stage flash (MSF), multi effect distillation (MED). Many recent process improvements have been achieved on each of these methods for increasing the efficiency and reducing the energy consumption per one cubic meter of water (Bruggen et al., 2002).

However, the existing desalination methods are considered to be as a costly due to their large energy requirements. Moreover, they are quite expensive because of environmental pollution and in term of money (Karagiannis et al., 2007). Many efforts were done in order to combine desalination plants and “green” energy sources. During the last decades, several small brackish and seawater desalination units have been installed driven by renewable energy sources (RES) (Cipollina et al., 2014). However, conventional energy sources still remain more preferable for desalination because of small capacity, intermittency and restricted availability of renewable energy.

The energy consumption of water desalination per cubic meter of water varies from site and installation, because of the influence of the number of factors, like the uniqueness of each case, applied desalination method, the type of feed water, the energy source, the capacity of the desalting plant, and other site related factors (Karagiannis et al., 2007). Sometimes, the power consumption which is necessary for seawater desalination process is inaccurately represented, especially when it is compared to the other technologies, because of not considering many determining factors (SDPC, 2011). Major breakthroughs have been done in water desalination processes over the past 20 years due to less energy consumption and the price has significantly declined. In spite of this fact the energy footprint of water desalination remains high, not each country could afford it and there are unlikely to be any major further improvements in the near future (Cooley et al., 2012).

For the most of developed countries desalination has quite large contribution to the total fresh water supply. The main question is: will be able desalination to deal with the total fresh water demand in the coastal regions. And should we consider desalination only for municipal purposes or for industrial and agricultural purposes as well. The separation of water demand into different purposes is quite important, because industrial water usage could not be avoided. It does include water for drinking, bathing, cooking and washing. These are the needs of people that are obliged to be fulfilled. The usage of water for an industrial and agricultural purposes could be lowered to the possible minimum with recycling of water and water-saving technologies. So, it is very important to consider what we are expecting from desalination, should we go for every human need or only for the basic ones with it.

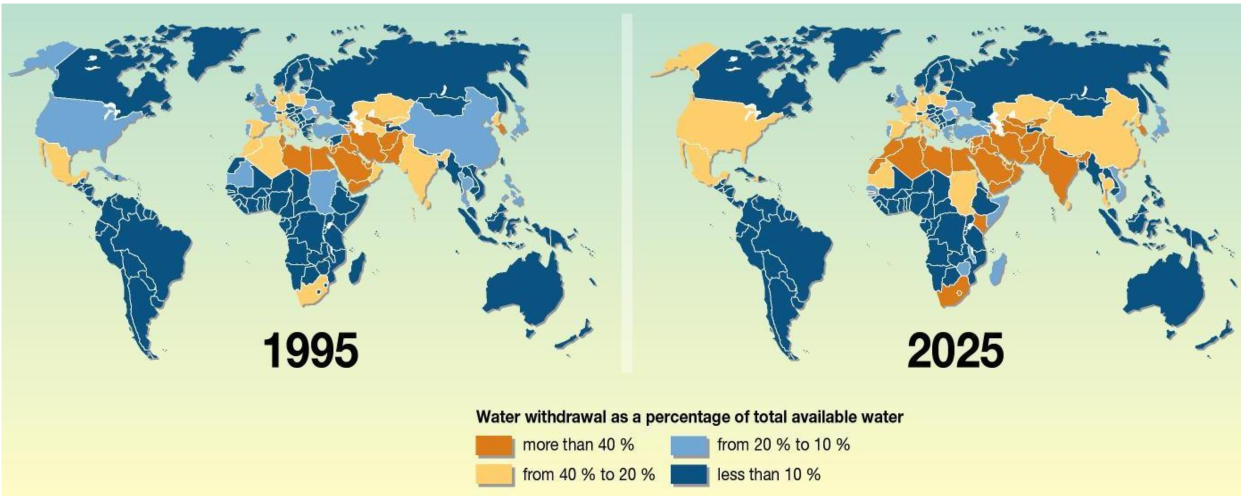

Figure 1 - Forecast of water scarcity in 2025 (PAI, 2009)

The figure 1 shows how water related issue were in 1995 and the forecast of how worse could it be in 2025. According to this source, the world will face severe water shortages. The countries that have water withdrawal as a percentage of total available water from 10% to 20% would become even more water stressed reaching to numbers from 20% to 40%. The situation would be even more rough with the countries that already were water stressed. As a solution to the problem could be water desalination from sea and oceans. More and more countries will rely on this method and supply desalinated water to the population.

1.2 Water desalination

Seawater or brackish water are not suitable neither for human consumption nor industrial and agricultural purposes. Nevertheless, there is a vast storage of seawater on Earth. Thus, by removing salt form practically unlimited seawater or brackish water, they could have become an important source of fresh water supply. The water desalination is a process of separation of saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts and a concentrated brine stream, which is the water containing high concentration of salts (Khawaji et al., 2007).

Since freshwater availability is limited, humanity should think about alternative sources of water to meet the water demand for the continuously growing population. The human needs for municipal, industrial and agricultural activities increase with each year. As a good solution to this problem could be water desalination form the vast reserves of water from seas and oceans. Even countries that currently do not face water shortages, they also could be exposed to the problem of fresh water scarcity in the near future. More than two-thirds of the world’s population may experience water shortages by 2025 according to the Worldwatch Institute, basically affecting every country in the world (Karagiannis et al., 2007).

1.3 Current desalination status

In the Middle East region, especially in Gulf Cooperation Council (GCC) countries, water is scares and desalination is the main sources of fresh water production. Countries, such as Saudi Arabia and United Arab Emirates, of this region are the largest water desalination producers in the world. The largest fresh water production through desalination process has Saudi Arabia, which produces 17% of total desalination capacity of the world (Figure 3). The second one is United Arab Emirates with 12%. The other countries of GCC have less desalinated water production, however together they contribute up to 10% of the global desalination capacity. GCC countries together produce 39% of total global desalination capacity (Fath et al., 2013). The figure 2 below shows the largest desalination regions and top 10 desalination countries of the world. As could be seen, Middle East takes the first and second places. The third place gets Spain and the fourth and fifth places are USA and China respectively.

Figure 2 – Top 10 desalination countries of the world (Water Desalination Report, 2014)

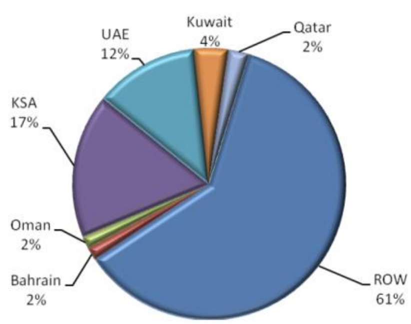

Figure 3 - Desalinated water productivity of GCC countries versus rest of the world (Fath et al., 2013)

1.4 Research objective

The research objective of this project is to determine the total energy demand for desalination. This research objective consists of two steps: 1. quantify factors that affect energy consumption of desalination; and 2. determine required energy per different desalination technologies, as well as the amount that is needed for desalination per unit of water. Current and future status of desalination is discussed and the possible further development regarding with integration of renewable energy sources. This is important because we need to consider how far could we rely on desalination of salty waters and could desalination be the solution of water related issues for human needs.

The emphasize is put on the main desalination technologies, like RO, MSF, MED, VC and ED. These technologies together take 96% of globally applied desalination capacity (Shemer et al., 2017). Energy footprint of desalination methods, which application is under 3% of total desalination capacity are not included for the two reasons. First, they have very small capacities, which make them not practical due to their non-competiveness with other ones. Second, their energy consumption is very little compared to the total energy footprint of water desalination globally. The same logic is applied regarding the renewable energy sources. Only two renewable energy sources are considered: solar and wind energy. The rest has minor practical implementation and their influence on the total picture is insignificant.

2 Literature review

2.1 Factors determining the energy consumption

Several factors that determine major energy consumption of water desalination process are outlined in this section to see how much energy does each of these factors require. Another purpose of doing so is to quantify how large there is variation of energy footprint depending on energy source and applied technology. We could theoretically find out which combination would have lowest energy footprint. This means that eventually there could be a range of possible variations of water desalination process, each of them have different energy footprint, however, not all combinations are considered, only those that have real application throughout the world. By real applied combinations, it is mean those, which already operate or under the construction. To consider all different possible variations, it is necessary to know how widely each of the existing methods are applied. After having the total energy footprint, we could compare different technologies with each other and to see which one has lowest energy consumption and which one has highest one.

Different factors have been searched through the existing literature that affect energy footprint of water desalination. Some of them have greater influence on energy footprint than others. These factors are: capacity of desalination plant (small, medium, large), type of required energy (electrical or thermal energy), type of feed water (brackish or seawater), desalination method (thermal or membrane), use of renewable energy sources (RES) (solar, wind, geothermal), necessity of feed pretreatment (mechanical and/or chemical). All these factors determine the total energy consumption of desalination plant. They are categorized in the figure 4 below.

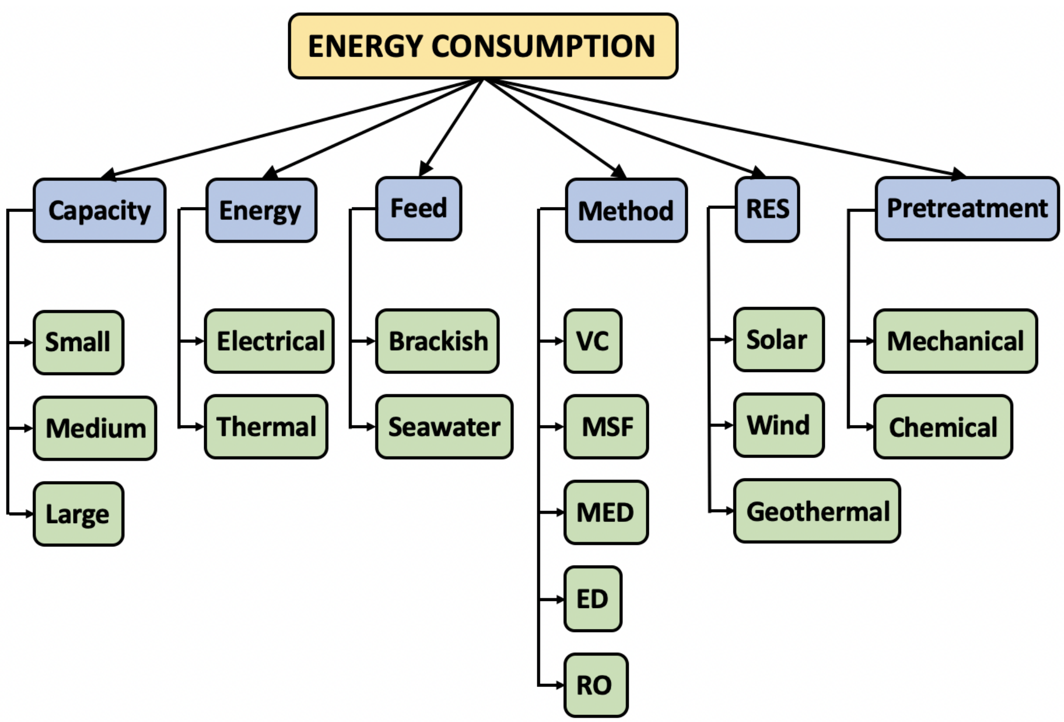

Figure 4 - Energy consumption break down for desalination process

Each of these factors affect the total energy consumption of the desalination plant. This means that for the main target of energy footprint reduction all these factors need to be considered. Environmental features, local area, design of desalination plant needs to be taken into account for the possibility to implement different types of technologies in order to create the most economically beneficial combination of these factors. Some combinations are widely applied, for example seawater reverse osmosis of large scale using electrical energy with pretreatment. Others are not, for example, seawater vapor compression of small scale using thermal energy without pretreatment. We discuss each of these decisive factors separately below.

2.2 Desalination method

Desalination process requires some form of energy to desalinate, and there are several different technologies for separation and each of them require various amount of energy. There are two major techniques for water desalination: thermal and membrane. Historically, desalination has been performed by using thermal energy. The basic concept of thermal desalination has been implemented very well in today's thermal desalination processes, such as multi-stage flash (MSF), multiple-effect distillation (MED) and vapor compression (VC). Relatively recently, membrane techniques such as reverse osmosis (RO) and electrodialysis (ED) using electrical energy have replaced thermal desalination in many parts of the world, mainly due to their less energy intensive nature (Ali et al., 2017). In addition to energy saving, membrane processes also offer the advantages of compactness, light weightiness and high productivity which put these technologies in front of the old thermal methods. The main desalination technologies are presented in the table 1 below.

Table 1 - Major desalination technologies based on (Khan et al., 2018)

Thermal technologies	Multi Stage Flash (MSF) Multi Effect Distillation (MED) Vapor Compression (VC)
Membrane technologies	Reverse Osmosis (RO) Electrodialysis (ED)

In this research, five most popular water desalination methods were analyzed and discussed. More attention was being paid for RO, MED and MSF techniques, because they have broad implementation throughout worldwide. VC and ED have very small global application (Figure 5). However, these methods are also included in this work to show advantages and disadvantages of each one comparing with the primary desalination techniques.

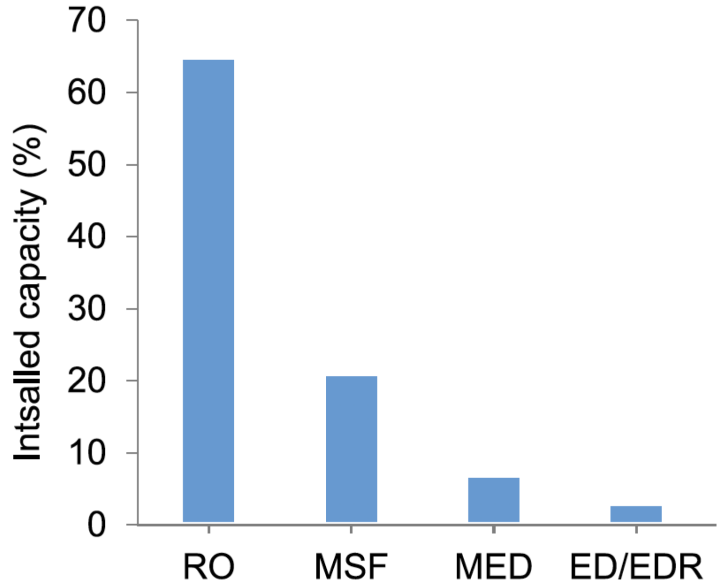

Figure 5 - Total worldwide installed desalination methods (Shemer et al., 2017)

Reverse Osmosis (RO)

In the reverse osmosis (RO) process, the osmotic pressure is overcome by applying external pressure higher than the osmotic pressure on the seawater (Figure 6). Thus, water flows in the reverse direction to the natural flow across the membrane, leaving the dissolved salts behind with an increase in salt concentration (Khawaji et al., 2007). The amount of fresh water that could be obtained from a seawater ranges between 30 and 75% of the volume of the feed water, depending on the initial water quality, the quality of the product needed, and the technology and membranes that is applied (Cipollina et al., 2014). There is no need for heating or phase separation change for this process. This is the main difference from the old thermal techniques, where desalination process is based on water heating. It means that RO process does not require thermal energy and all processes could be done using only electricity.

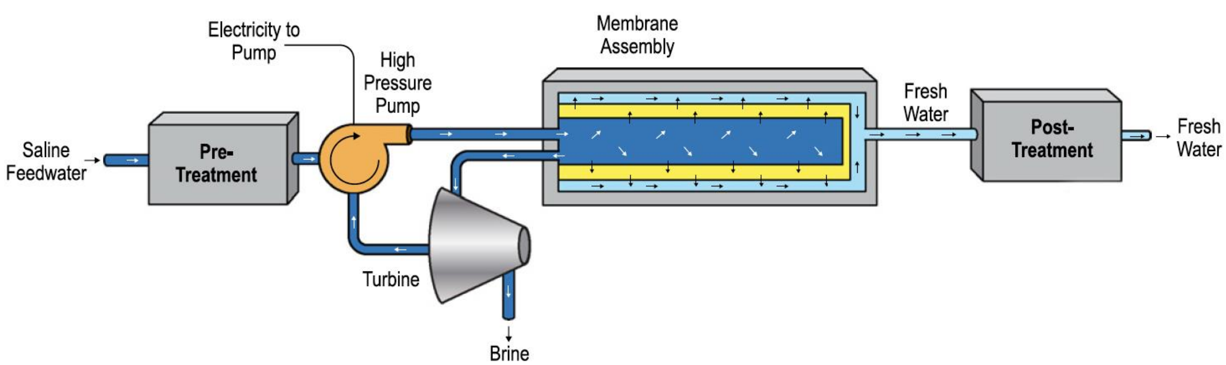

Figure 6 - Schematic diagram of RO system (Al-Karaghouli et al., 2013)

Thus, in RO desalination technique the major energy is required for pressurizing the seawater feed for desalting it. Two developments have helped to reduce the energy demand of RO plants during the past decade: the development of membranes that can operate efficiently with longer duration, and the use of energy recover devices (ERD) (Voutchkov, 2017). ERD transfers pressure energy from a high pressure fluid stream to a low pressure fluid stream. The ability to use ERDs reduces energy consumption of RO plant is approximately 6 – 8 kW h/m3 without energy recovery. Installing an ERD reduces the energy demand quite significantly to 4–5 kW h/m3 (Khawaji et al., 2007).

Multi-Stage Flash (MSF)

The multi-stage flash (MSF) distillation process is based on the principle of flash evaporation. The MSF includes the use of distillation through multiple chambers called stages (Figure 7). In this process, each following stage of the plant operates at relatively lower pressures. The process starts with heating of feed water under high pressure. The heated water enters into first stage, at lower pressure triggering the sudden evaporation called flashing. The flashing of a percentage of the feed water proceeds in each consecutive stage, because of the reduction of pressure in each successive stage. The heat exchanger tube bank that runs through each stage condenses the vapor and converts it into potable water (Khan et al., 2018).

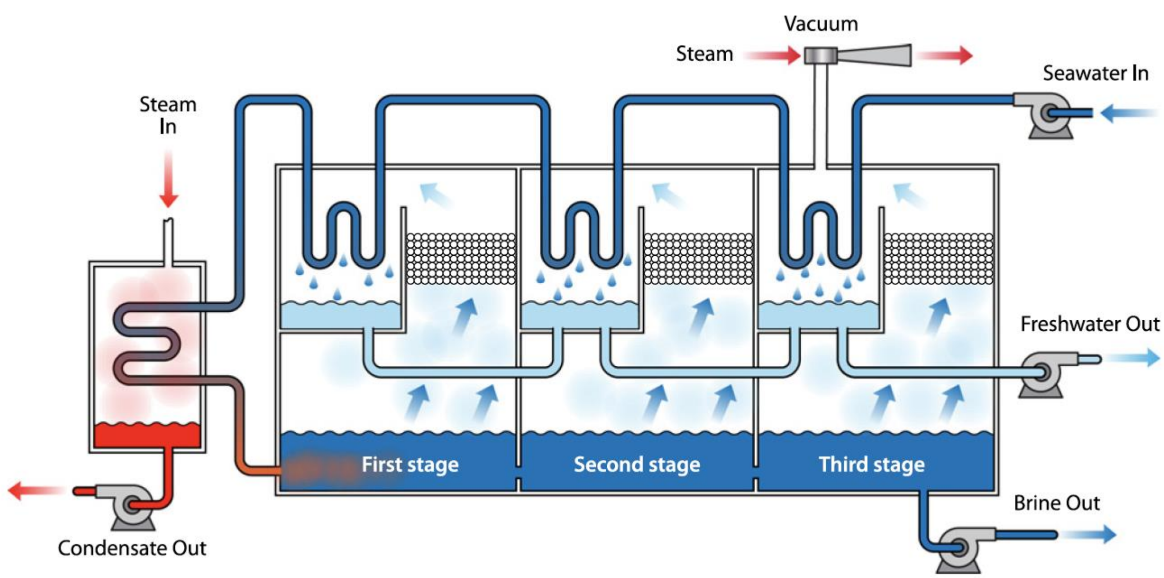

Figure 7 - Schematic diagram of MSF unit (Al-Karaghouli et al., 2013)

Multiple-Effect Distillation (MED)

The multiple-effect distillation (MED) process is the oldest desalination method and is very efficient thermodynamically. The MED process takes place in a series of evaporators called effects, and uses the principle of reducing the ambient pressure in the various effects (Figure 8). This process permits the seawater feed to undergo multiple boiling without supplying additional heat after the first effect. The seawater enters the first effect and is raised to the boiling point after being preheated in tubes. The seawater is sprayed onto the surface of evaporator tubes to promote rapid evaporation. The tubes are heated by externally supplied steam from a normally dual-purpose power plant (Khawaji et al., 2007).

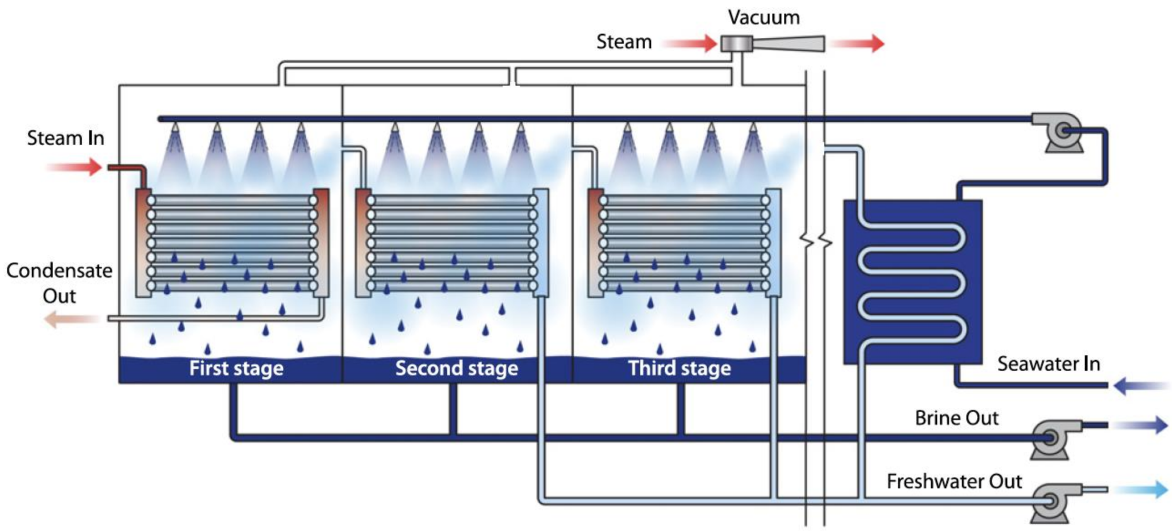

Figure 8 - Schematic diagram of MED unit (Al-Karaghouli et al., 2013)

Electrodialysis (ED)

Electrodialysis (ED) is a mass separation technique utilizing ion exchange membranes and an electrical potential difference for separation of ionic species from an aqueous solution and other uncharged components (Figure 9). ED is mostly applied for desalination of brackish water representing the main process for the production of potable water in some parts of the world (Ali et al., 2017). When a feed solution is pumped through these compartments and an electrical potential is maintained between the electrodes, the cations pass through the CEMs and migrate towards the cathode whereas the anions pass through the AEMs and migrate towards the anode. Consequently, the salts are depleted from the feed solutions to form a freshwater in dilute compartments and concentrated effluent in concentrate compartments. The cost for desalination largely depends on the concentration of salts to be removed. The process becomes uneconomical for large salt fractions, i.e. seawater, but is competitive for brackish water desalination. For water with low salt concentrations, ED is considered to be the most advantageous technique (Bruggen et al., 2002).

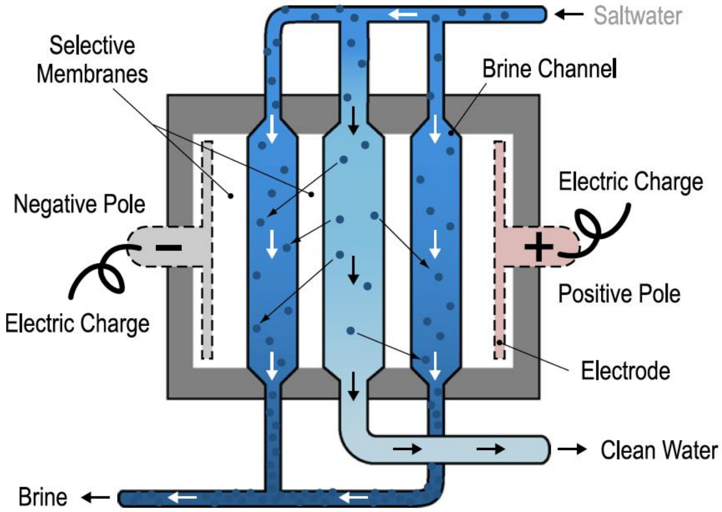

Figure 9 - Schematic diagram of ED unit (Al-Karaghouli et al., 2013)

Vapor Compression (VC)

Vapor compression (VC) 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 (Figure 10). Vapor compression can be seen as a variation of MED, but technically somewhat more complex, so that application is limited to smaller plants (Bruggen et al., 2002). VC is used mainly for small systems with production around 1000 m3/day (Karagiannis et al., 2007).

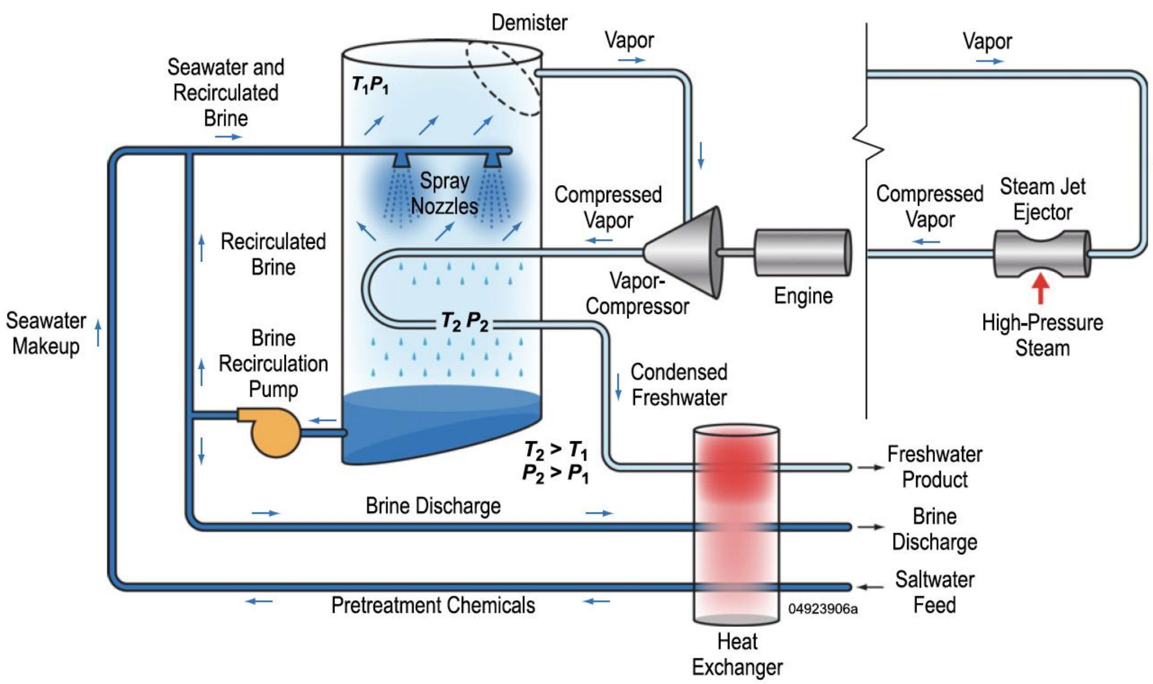

Figure 10 - Schematic diagram of VC unit (Al-Karaghouli et al., 2013)

2.3 Capacity

In the literature, the calculation of the desalination energy requirement is based on different assumptions, by different authors. There is for example significant variation of energy consumption of the same desalination technology with the same size. In most articles and published papers the energy consumptions are given in ranges. For the accurate comparison of the energy for one cubic meter of fresh water, all appropriate factors are needed to be included to get the correct and valid data. Thus, there should be a clear sub-division of existing desalination plants by various factors, which were discussed in the previous section.

The size of desalination installation has great impact on the energy consumption and cost of desalination process. With increase of desalination plant's capacity, it becomes more efficient in term of cost (Karagianis et al., 2007). The capacity of all desalination plants regardless of desalination technology, could be divided into three categories: small, medium and large. Each of the existing desalination method has its own range for its three sizes. Based on papers (Karagiannis et al., 2008) and (Shatat et al., 2014) was created table 2 with capacities of desalination plants. The numbers are presented below.

Table 2 - Sizes and methods of desalination plants based on sources (Karagiannis et al., 2008) and (Shatat et al., 2014)

		Desalination technology					
		SW RO	**BW RO**	**MSF**	**MED**	**VC**	**ED**
Capacity (m3/day)	**Small**	<1000	<1000	<23 000	12 000 - 55 000	1000 - 1200	<1000
	Medium	1000 - 5000, 12 000 - 60 000	5000 - 60 000	55 000 - 90 000	55 000 - 90 000	3000	1000 - 60 000
	Large	>60 000 - 320 000	>60 000 - 320 000	>90 000 - 528 000	>90 000	>3000	>60 000 - 145 000

The large desalination systems in many countries, such as China or those that in Middle East which can reach a daily production more than 500 000 m3, use mainly thermal desalination methods of large scales, sometimes combining additionally with the membrane ones. For medium size systems from 5 000 to 90 000 m3/day both thermal and membrane methods are possible. However, for small desalination units, with daily capacity of 1000–5000 m3 membrane technologies are the dominant way.

2.4 Type of required energy

Desalination processes require different types of energy, either thermal or electrical. Membrane technologies do not need thermal energy, all process steps are going using electricity. For RO plants, energy is needed to generate high pressure to force water to pass through the membrane. For ED plants, electrical energy is required to create electrical potential difference. Thermal technologies need both electrical and thermal type of energy to vaporize seawater in order to separate salts in them. Desalination techniques, such as MSF and MED, use thermal energy as a primary source and electricity to drive associated pumps as a secondary source (Al-Karaghouli, 2013). Thermal methods are more expensive than membrane ones because of the large quantities of fuel required to vaporize salt water. However, they are more efficient in terms of desalination of very salty waters than the membrane technologies. Electricity could be generated from fossil fuel like coal, oil, diesel, gas, renewable energy, and nuclear sources. Thermal energy could be produced from fossil-fuel-fired boilers, power-plant waste heat, renewable energy sources, and industrial-waste heat sources. Basically, high energy consumption is a critical factor that affects the economics of desalination. There is a need to make desalination processes as much energy efficient as possible by improving technology and equipment.

2.5 Type of feed water

Energy demand of water desalination strongly depend on the type of water, whether it is seawater or brackish water, especially for membrane technologies. The salinity content of brackish water is up to 10 000 parts per million (ppm) or 10 g/l and seawater normally has salinity in the range of 35 000 – 45 000 ppm or 35-45 g/l in the form of total dissolved salts making these waters unsuitable for drinking and most domestic uses (Ali et al., 2017). According to World Health Organization, drinking water quality permits a salinity of 500 ppm and 1000 ppm in certain cases.

As was discussed previously type of feed has great influence on energy requirements of desalination plants. The energy that is required for desalination of seawater is higher than for the brackish water one, because of higher concentration rate of salt in a seawater. Brackish water desalination requires less energy because of the lower salinity, which enable to apply lower pressure and to obtain much higher water recovery (Shemer et al., 2017). Thus, energy for desalination of seawater and brackish are different. Compared to seawater desalination, brackish water desalination requires around 0.5–2.5 kWh/m3 less energy. Thermal methods are more energy consumptive because of the large quantities of fuel required to vaporize salt water, however they seem to be more effective than membrane methods in terms of efficiency in the desalination of very salty seawaters.

2.6 Renewable energy sources (RES)

Desalination systems can be divided in two categories: systems that use a conventional energy source and those that are powered by renewable energy sources (wind, solar, geothermal). The cost of water produced from desalination systems depends on amount of energy that was used. It is lower when conventional source of energy is applied like gas, oil, electricity (Karagiannis et al., 2007). Desalination powered by renewable energy sources (RES), as opposed to conventional desalination, may be an attractive solution in terms of reducing environmental impact due to lower conventional energy consumption and lower gas emissions (Karagiannis et al., 2007). Renewable energy can be applied in desalination in form of electrical, thermal and mechanical energy. The conventional energy sources (gas, oil, fossil fuels) are prognoses to be depleted in the near future. This would make water related issues even more problematical. It means that in the near future humanity needs to produce more fresh water through desalination process relying less on conventional energy sources, but more on renewable energy sources. This section discusses the most promising renewable energy sources. These are solar and wind, which both quite abundant in many regions of the world. The correct combination of a renewable energy source with a desalination technology is crucial step for lowering the dependency on conventional energy sources and to produce desalinated water in an economically efficient and environment-friendly way.

Solar energy is the most abundant form of renewable energy across the world. It has been reported that many regions in Middle East and North Africa receive 5–7 kW h of solar insolation each solar day (Figure 11). For example, Saudi Arabia receives insolation of 5.5 kWh/m2/day (230W/m2). Most of these regions are rich of brackish or seawater but suffer from lack of sufficient freshwater, making them ideal for solar energy-driven desalination. Solar energy can be used directly to heat the saline water for desalination or indirectly by converting into electricity, which is needed for operation of high-pressured pumps. To convert solar energy into electricity generally applied photovoltaic (PV) cells. The cost-effectiveness, overall life time and energy storage issues, however, restrict the practical application of PV cells.

Geothermal energy is the form of renewable energy stored in the earth that can be pumped in form of steam and hot water which can further be used to generate electricity. Depending upon the quality of geothermal energy, it can be used either directly in the form of steam to run a turbine or to vaporize a low boiling point fluid. Geothermal energy is a proven technology for electricity production, although not spread out commercially (Ali et al., 2017). A high-pressure geothermal source allows the direct use of shaft power on mechanically driven desalination, whereas high-temperature geothermal fluids can be used to generate electricity to drive RO or ED plants. As compared to the other renewable energy resources, geothermal resource offers the uninterrupted thermal energy.

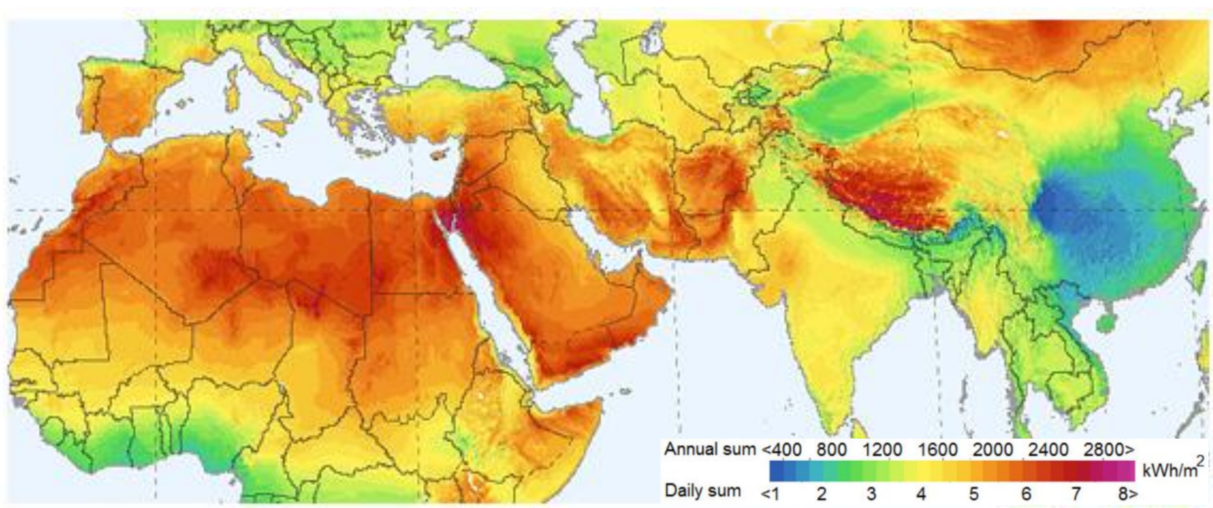

Figure 11 – Solar radiation distribution over the Middle East, Arabia and Gulf region (Sabry et al., 2015)

Wind energy is an abundantly available source of renewable energy in many regions in the world. Coastal areas, mountains and islands provide the large opportunities to use wind energy in desalination process. Many countries in the world has such areas enriched in wind resources. The energy from wind turbine (WT) can serve desalination plant by providing electricity or mechanical power. The growth of the installed wind power is hindered by a number of barriers. These are public acceptance, land requirements, visual impact, audible noise, telecommunication interference and various impacts on natural habitat and wild life (Ali et al., 2017). Most of these problems, however, are solved by the installation of offshore wind areas. Selection of location for wind operated desalination facilities is crucial for the correct and efficient way of desalination process.

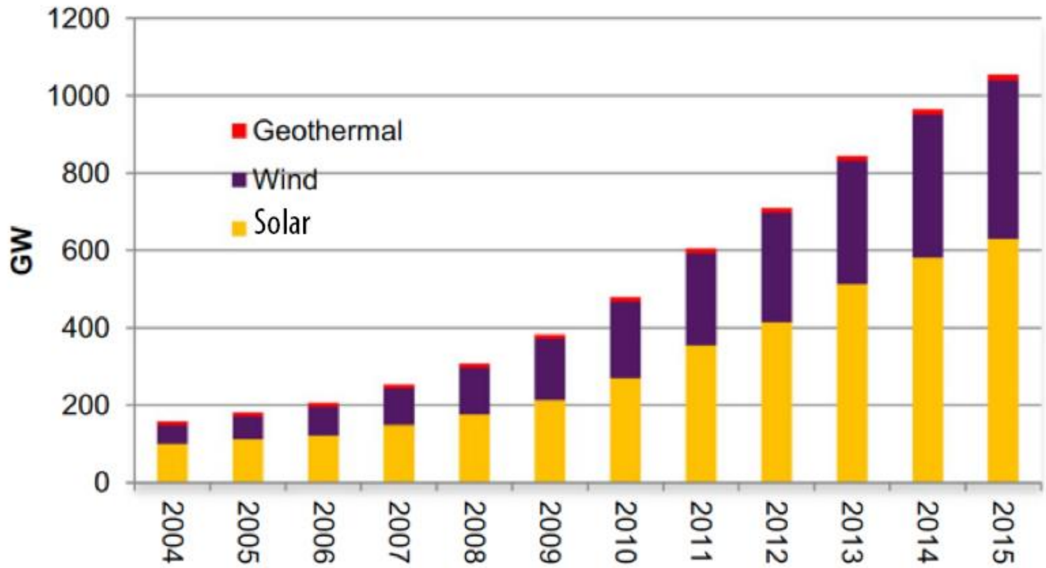

Figure 12 – The growth of global renewable energy capacity (Ali et al., 2017)

Figure 12 shows the annual growth of application of renewable energy sources for desalination processes. In this figure, summarized three main renewable energy sources, solar, wind and geothermal energy. As could be seen solar energy is the type of renewable energy that has the largest installation, more than a half of total. The second widely used renewable energy source is wind power. It does not have the same broad implementation as solar power, however it still has large share of the total application rate. The share of geothermal energy is very small and basically have no practical realization. The total use of solar and wind type of energy sources has been increased more than 5 times over ten-year period. For the geothermal source of energy, it remained mainly unchanged. According to another source (Alkaisi et al., 2017), solar electrical energy supply 43% and solar thermal energy 27%, in total 70% of the world renewably supplied desalination plants, the wind energy has 20% of total share and the rest 10% comes from other different type of renewable energy sources. Market share of renewable desalination is less than 1% of the global desalination capacity, which is in its turn based of 62% on RO powered. 43% of these plants are powered by PV (Abdelkareem et al., 2017).

2.7 Pretreatment

Feed pretreatment is another factor determining the total energy consumption of desalination installation. This is particularly imperative for RO, but for distillation processes it is also highly important. Traditional pretreatment is based on mechanical treatment for removing from the feed debris and other unnecessary substances using screens and filters. Mechanical pretreatment supported by an extensive chemical treatment, including chlorination, flocculant dosing, dosing for scaling prevention. This process require energy, basically electrical for the pumps and mixing devices. Conventional intake system where the supply source is nearby the

SWRO facility, power consumption is in range from 15% to 20% of the total power consumed by the water desalination process (SDPC, 2011).

2.8 Theoretical and practical minimum energy

All desalination processes are energy intensive and share a common minimum energy requirement for deriving the separation of a saline solution into pure water and concentrated brine. The concept of minimal energy for the separation process is well established in thermodynamics. Different methods were used to calculate the minimum energy requirement of water desalination. The actual work required is likely to be many times the theoretically possible minimum. This is due to the extra work required to keep the process going at a finite rate, rather than to achieve the separation.

The theoretical minimum energy of desalination for seawater at 35 000 ppm salt and at a typical recovery of 50% is 1.06 kW h/m3 (Figure 13B). However, the actual energy consumption, is larger and additional 0.5 kW h/m3 energy is spent because desalination systems are finite and do not operate as a reversible thermodynamic process (Elimelech et al., 2011). The practical minimum energy for desalination of seawater at 50% recovery is 1.56 kW h/m3, which suggests potential for further improvement (Mazlan et al., 2015). This ideal energy consumption of 1.56 kW h/m3 is not too far off from reported energy consumptions of 2 kW h/m3 from well-designed SWRO systems (Elimelech et al., 2011).

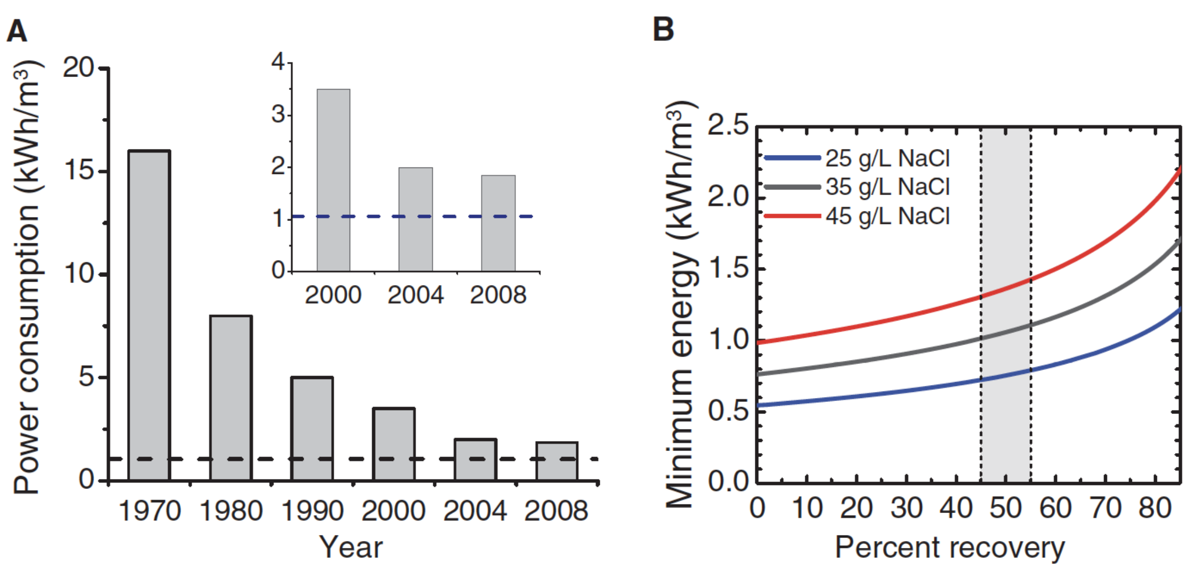

Figure 13 - A) The change in power consumption for RO plants over the certain time period, B) Theoretical minimum energy for desalination as a function of percent recovery (Elimelech et al., 2011)

According to the tables 5 and 6 of section 3.2, average energy consumption of SW RO desalination plant is of the order of 4 kW h/m3. Energy demand for the RO process itself depends on such factors as feed water salinity, the recovery ratio, the efficiency of the pumps and the efficiency of the energy recovery system and has a range between 1.7 and 2.5 kW h/m3. Additional steps such as pumping, pre-treatment, brine discharge require in total 0.3 – 1.5 kW h/m3 energy

(Shemer et el., 2017). Therefore, the overall energy consumption is 2.0 – 4.0 kW h/m3. Smaller installations, remote locations, inexperience in design and operation may increase the energy footprint. Thus, the energy demand of SW RO is within a factor of 2 greater than the theoretical minimum energy for desalination, and is only 25% higher than the practical minimum energy for desalination for an ideal reverse osmosis case. Yet, the overall energy consumption of new SWRO plants is three to four times higher than the theoretical minimum energy due to the need for extensive pretreatment and posttreatment steps (Elimelech et al., 2011).

The theoretical minimum for thermal desalination process is 190 kW h of thermal energy or 15kWh equivalent electrical energy per cubic meter of water (Gordon et al., 2016). The simplest desalination technique of a single stage evaporator requires tremendous amount of thermal heat per one cubic meter of seawater, depending slightly on the evaporation temperature. The main evaporation techniques (MSF and MED) have overcome this obstacle by reusing the energy consumption through multiple stages (Shemer et el., 2017).

3 Method

3.1 Subdivision of desalination plants

Despite its potential, seawater desalination requires large amount of energy. Energy footprint of desalination is very important to understand and analyze its applicability as a possible solution to the existing and forecasted water shortages. Calculating the energy footprint of water desalination is a complex, multi-step process as the energy footprint depends on a number of factors and we want to quantify these factors and determine global energy footprint associated with obtaining a given amount of freshwater through water desalination.

The energy consumption of desalination plants is separated considering decisive factors such as desalination method, capacity and type of feed water. Thus, the sub-division is done in accordance with desalination technology, whether it is thermal or membrane technology, with its capacity, whether it has small, medium or large scale and with type of feed, whether it is brackish or seawater. Energy demand is sub-divided into electrical and thermal energy requirement. If desalination process requires thermal energy as well, the latter is recalculated in terms of electrical energy in order to be possible to sum all electrical energy demand and compare with those that require one electrical energy without need of thermal one. The other factors, like pretreatment and use of renewable energy sources are just check points, either they are present or no. The biggest part of total energy consumption determines whether the desalination plant is thermal or membrane technology and the scale of desalination plant itself.

3.2 Energy consumption of reverse osmosis (RO)

Table 3 – The summary of RO with type of feed seawater of medium capacity

REVERSE OSMOSIS (RO)	Type of feed: SEAWATER Unit Size: MEDIUM				
Capacity (m3/day)	not specified	not specified	24 000	40 000	24 000
Electrical energy (kW h/m^3)	2.5 - 7.5	2 - 4	3 -7	2.5 - 4	4 - 6
Thermal energy (MJ/m^3)	none	none	none	none	none
Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none	none
Total electricity consumption (kW h/m^3)	2.5 - 7.5	2 - 4	3 -7	2.5 - 4	4 - 6
Recovery device	✓	✓	✓	✓	✓
RES	✕	✕	✕	✕	✕
Pretreatment	✓	✓	✓	✓	✓
Reference	(Rao et al., 2018)	(Shemer et al., 2017)	(Alkaisi et al., 2017)	(Voutchkov, 2017)	(Al-Karaghouli et al., 2013)
Total average electricity consumption (kW h/m3) for each reference	5	3	5	3.3	5
		Total average =	4.3	(kW h/m3)	

Table 3 represents the summary from several papers for RO with type of feed seawater of medium capacity. According to the literate the total energy consumption of this kind of desalination plants ranges from 2 to 7.5 kW h/m3. The average energy consumption is calculated for each reference and then is made the total average. For RO of seawater of medium size the average energy consumption is 4.3 kW h/m3.

Table 4 - The summary of RO with type of feed seawater of large capacity

REVERSE OSMOSIS (RO)	**Type of feed: SEAWATER Unit Size: LARGE**						
Capacity (m3/day)	**100 000 - 305 000**	**278 000**	**not specified**	**not specified**	**not specified**	**up to 128 000**	**up to 128 000**
Electrical energy (kW h/m^3)	**3.1 - 3.65**	**2.6 - 8.5**	**3 -4.5**	**3.5 - 5**	**3 -3.5**	**4 - 6**	**3 - 8**
Thermal energy (MJ/m^3)	**none**	**none**	**none**	**none**	**none**	**none**	**none**
Equivalent electrical to thermal energy (kW h/m^3)	**none**	**none**	**none**	**none**	**none**	**none**	**none**
Total electricity consumption (kW h/m^3)	**3.1 - 3.65**	**2.6 - 8.5**	**3 -4.5**	**3.5 - 5**	**3 -3.5**	**4 - 6**	**3 - 8**
Recovery device	✓	✓	✓	✓	✓	✓	✓
RES	×	×	×	×	×	×	×
Pretreatment	✓	✓	✓	✓	✓	✓	✓
Reference	**(Zarzo et al., 2018)**	**(Herrero-Gonzalez et al., 2018)**	**(Aminfard et al., 2018)**	**(Lee et al., 2018)**	**(Fane et al., 2017)**	**(Abdelkareem et al., 2017)**	**(Shahzad et al., 2017)**
Total average electricity consumption (kW h/m3) for each reference	**3.4**	**5.6**	**3.8**	**4.3**	**3.3**	**5**	**5.5**
			Total average =	**4.4**	**(kW h/m3)**		

The same is done for RO with seawater feed of large capacity. The summary is represented in the table 4. Energy consumption in this case is given in the range of 2.6 – 8.5 kW h/m3. And total average electricity consumption is 4.4 kW h/m3. This is a bit more than the energy demand for RO of medium size.

As was discussed in section 2.5, RO of brackish water requires less energy than RO of seawater due to less salinity, which in its turn means that less energy would be applied to desalinated it. This could be observed from the table 5, which is the summary of RO of brackish water of medium and large scale. It indicates that energy requirement for brackish water desalination is much lower than energy of seawater desalination. Total energy consumption for brackish water is given in the range of 0.5 – 3 kW h/m3. The average energy consumption for BW RO is 1.9 kW h/m3. In most papers, the capacities of brackish water RO desalination plants are not specified, because the availability of brackish water is limited. This is a reason that brackish water RO desalination plants are not constructed for very large scales. Basically, they are limited up to 100 000 m3/day.

Table 5 - The summary of RO with type of feed brackish water of medium and large capacity

REVERSE OSMOSIS (RO)	Type of feed: BRACKISH WATER Unit Size: MEDIUM & LARGE			
Capacity (m3/day)	**98 000**	**not specified**	**not specified**	**not specified**
Electrical energy (kW h/m^3)	**1.5 - 2.5**	**0.5 - 2.5**	**1.5 - 2.5**	**1 - 3**
Thermal energy (MJ/m^3)	**none**	**none**	**none**	**none**
Equivalent electrical to thermal energy (kW h/m^3)	**none**	**none**	**none**	**none**
Total electricity consumption (kW h/m^3)	**1.5 - 2.5**	**0.5 - 2.5**	**1.5 - 2.5**	**1 - 3**
Recovery device	✓	✓	✓	✓
RES	×	×	×	×
Pretreatment	✓	✓	✓	✓
Reference	**(Abdelkareem et al., 2017)**	**(Shemer et al., 2017)**	**(Shahzad et al., 2017)**	**(Aminfard et al., 2018)**
Total average electricity consumption (kW h/m3) for each reference	**2**	**1.5**	**2**	**2**
		Total average =	**1.9**	**(kW h/m3)**

3.3 Energy consumption of multi stage flash (MSF)

Table 6 is the summary of MSF desalination technique with seawater feed type and medium capacity. Total energy consumption for this method is given in range from 13.5 to 30 kW h/m3. The total average energy demand, which is required for this technology to desalinate one cubic meter of seawater is 17.1 kW h/m3.

Table 6 – The summary of MSF with type of feed seawater of medium capacity

MULTI STAGE FLASH (MSF)	Type of feed: SEAWATER Unit Size: MEDIUM				
Capacity (m3/day)	**50 000 - 70 000**	**50 000 - 70 000**	**50 000 - 70 000**	**not specified**	**not specified**
Electrical energy (kW h/m^3)	**2.5 - 5**	**4 - 6**	**2.5 - 5**	**3.5**	**not specified**
Thermal energy (MJ/m^3)	**190 - 282**	**190 - 390**	**191 - 290**	**not specified**	**not specified**
Equivalent electrical to thermal energy (kW h/m^3)	**15.83 - 23.5**	**9.5 - 19.5**	**15 - 25**	**12**	**not specified**
Total electricity consumption (kW h/m^3)	**19.58 - 27.25**	**13.5 - 25.5**	**20 - 30**	**15.5**	**15 - 20**
RES	×	×	×	×	×
Pretreatment	✓	✓	✓	✓	✓
Reference	**(Abdelkareem et al., 2017)**	**(Alkaisi et al., 2017)**	**(Shahzad et al., 2017)**	**(Ameen et al., 2017)**	**(Woo et al., 2018)**
Total average electricity consumption (kW h/m3) for each reference	**23.4**	**19.5**	**25**	**15.5**	**17.5**
		Total average =	**17.1**	**(kW h/m3)**	

3.4 Energy consumption of multi effect distillation (MED)

Table 7 represents the summary of MED desalination technique with seawater feed type and medium capacity. Total energy consumption for this method is given in range from 6 to 22.5 kW h/m3. The total average energy, which is required for this technology to desalinate one cubic meter of seawater is 11.9 kW h/m3.

Table 7 - The summary of MED with type of feed seawater of medium capacity

MULTI EFFECT DISTILLATION (MED)	Type of feed: SEAWATER Unit Size: MEDIUM				
Capacity (m3/day)	5 000 - 15 000	5 000 - 15 000	5 000 - 15 000	not specified	not specified
Electrical energy (kW h/m^3)	2 - 2.5	1.5 - 2.5	2 - 2.5	6 - 8	1.5
Thermal energy (MJ/m^3)	145 - 230	230 - 390	145 - 230	not specified	not specified
Equivalent electrical to thermal energy (kW h/m^3)	12.2 - 19.1	5 - 8.5	12 - 19	not specified	6
Total electricity consumption (kW h/m^3)	14.45 - 21.35	6.5 - 11	15 - 22	6 - 22.5	7.5
RES	✕	✕	✕	✕	✕
Pretreatment	✓	✓	✓	✓	✓
Reference	(Abdelkareem et al., 2017)	(Alkaisi et al., 2017)	(Shahzad et al., 2017)	(Rao et al., 2018)	(Ameen et al., 2017)
Total average electricity consumption (kW h/m3) for each reference	17.9	8.8	18.5	14.3	7.5
		Total average =	11.9	(kW h/m3)	

3.5 Energy consumption of electrodialysis (ED)

Table 8 - The summary of ED with type of feed brackish water of medium and large capacity

ELECTRODIALYSIS (ED)	Type of feed: BRACKISH WATER Unit Size: MEDIUM & LARGE				
Capacity (m3/day)	up to 145 000	up to 145 000	not specified	not specified	not specified
Electrical energy (kW h/m^3)	2.64 - 5.5	2.6 - 5.5	0.6 - 1	0.7 - 2.5	2.64 - 5.5
Thermal energy (MJ/m^3)	none	none	none	none	none
Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none	none
Total electricity consumption (kW h/m^3)	2.64 - 5.5	2.6 - 5.5	0.6 - 1	0.7 - 2.5	2.64 - 5.5
Salinity	between 2500 and 5000 ppm	between 2500 and 5000 ppm	< 2500 ppm	< 2500 ppm	between 2500 and 5000 ppm
Recovery device	✓	✓	✓	✓	✓
RES	✕	✕	✕	✕	✕
Pretreatment	✓	✓	✓	✓	✓
Reference	(Abdelkareem et al., 2017)	(Alkaisi et al., 2017)	(Shatat et al., 2014)	(Al-Karaghouli et al., 2013)	(Al-Karaghouli et al., 2013)
Total average electricity consumption (kW h/m3) for each reference	4.1	4.1	0.8	1.6	4.1
		Total average =	2.9	(kW h/m3)	

Table 8 represents the summary of ED desalination technique of medium and large scale with brackish type of feed water. Total energy consumption for this method is given in range from 0.6 to 5.5 kW h/m3. The total average energy consumption, which is required for this technology to desalinate one cubic meter of seawater is 2.9 kW h/m3.

3.6 Energy consumption of vapor compression (VC)

Table 9 represents the summary of VC desalination technique of small scale with seawater as a type of feed. Total energy consumption for this method is given in range from 7.5 to 17.5 kW h/m3. The total average energy consumption, which is required for this technology to desalinate one cubic meter of seawater is 12.8 kW h/m3.

Table 9 - The summary of VC with type of feed seawater of small capacity

VAPOR COMPRESSION (VC)	**Type of feed: SEAWATER** **Unit Size: SMALL**		
Capacity (m3/day)	**1000 - 1200**	**1000 - 1200**	**100 - 2500**
Electrical energy (kW h/m^3)	**7.5 - 17.5**	**1.6 - 1.8**	**7 - 12**
Thermal energy (MJ/m^3)	**none**	**227.3**	**none**
Equivalent electrical to thermal energy (kW h/m^3)	**none**	**14.56**	**none**
Total electricity consumption (kW h/m^3)	**7.5 - 17.5**	**16.3**	**7 - 12**
Recovery device	✓	✓	✓
RES	×	×	×
Pretreatment	✓	✓	✓
Reference	**(Rao et al., 2018)**	**(Al-Karaghouli et al., 2013)**	**(Alkaisi et al., 2017)**
Total average electricity consumption (kW h/m3) for each reference	**12.5**	**16.3**	**9.5**
	Total average =	**12.8**	**(kW h/m3)**

3.7 Energy consumption of renewably powered plants

Table 10 represents the summary of energy consumption of desalination plants powered by solar energy. The table is sub-divided into two main parts with the membrane and thermal technologies. Membrane methods require around 5 times less energy rather than the thermal methods. Consequently, it is economically more beneficial to combine renewable energy sources with membrane technologies, rather than with thermal ones. Solar energy mostly combined with RO of brackish water, RO of seawater and ED of brackish water. However, there are still some MED desalination plants that powered by solar energy. The energy consumption of these plants quite high from 18.2 to 25.8 kW h/m3. Energy demand of brackish water RO is in the range 0.9 – 29.1 kW h/m3. Here is a big range of energy requirement, which highly depends on the capacity of desalination plant starting from <100 m3/day to several 100 m3/day. However, the total average energy consumption is 10.2 kW h/m3. For seawater RO energy demand is also given in a big range from 2.4 to 17.9 kW h/m3, with the average energy consumption of 5.5 kW h/m3.

According to some sources form the table brackish water ED has the lowest energy demand from 0.8 – 3.2 kW h/m3, with average energy consumption of 2 kW h/m3. Without doubt, we could say that brackish water ED powered by solar energy has the lowest energy footprint among the other renewably powered desalination plants. The capacity of such a desalination installation could achieve to 200 m3/day.

Table 11 represents the summary of desalination techniques that are combined with wind energy. Here the sub-division is done as in the previous table, into membrane and thermal technologies. The total average electricity consumption for brackish water RO powered by WT is 1.5 kW h/m3 and for the seawater is 5.2 kW h/m3. Energy consumption of brackish water ED technology is given in the range of 2 – 19 kW h/m3 with the total average energy demand of 7.3 kW h/m3. Total energy demand for thermal desalination technique such as VC is 13.5 kW h/m3.

3.8 Calculation of capital energy costs for desalination technologies

Comparison of energy consumption of different desalination methods obviously quite important, however it doesn't give too much information to understand how efficient certain method and how economically beneficial, especially for those, who doesn't deal with idea of energy consumption. Another way to compare the desalination technologies and to reveal the most beneficial one from the economical perspective is to compare the capital prices of energy. According to the US Energy Information Administration 2019, the capital cost per 1 kW of energy obtained from gas or oil is 1000 US dollars. The capital cost of renewable energies like wind and solar is much higher than the conventional ones. They are 1600 and 1800 US dollars per 1 kW of energy for wind and solar sources. Having energy consumption numbers per different desalination technologies and type of supplied energy from tables 3 to 11 and using capital costs of energies from (EIA, 2019), we could calculate the capital cost of energy in $/m3. This is represented in the table 12 below.

Table 12 - Calculation of capital costs

Type of desalination	Energy consumption (kW h/m3)
SW RO medium	4.3
SW RO large	4.4
BW RO medium & large	1.9
MSF medium	17.1
MED medium	11.9
ED medium & large	2.9
VC small	12.8
PV BW RO	10.2
PV SW RO	5.5
PV ED	2
PV MED	21.1
WT BW RO	1.5
WT SW RO	5.2
WT ED	7.3
WT VC	13.5

×

Type	Capital cost $/kW
gas/oil	1000
wind	1600
solar	1800

US Energy Information Administration (EIA) 2019

=

Type of desalination	Capital cost of energy ($/m3)
SW RO medium	4250
SW RO large	4382
BW RO medium & large	1875
MSF medium	17083
MED medium	11880
ED medium & large	2918
VC small	12753
PV BW RO	18383
PV SW RO	9855
PV ED	3625
PV MED	37890
WT BW RO	2400
WT SW RO	8304
WT ED	11600
WT VC	21600

Table 10 - The summary of desalination technologies powered by solar energy

Powered by solar energy	Membrane												Thermal	
Desalination method	RO				RO				ED				MED	
Type of feed	brackish water				seawater				brackish water				seawater	
Capacity (m^3/day)	from < 100 m3 to sev. 100 m3/day	not specified	up to 60	20 - 30	20	from < 100 m3 to sev. 100 m3/day	up to 50	up to 24	1 - 200	not specified	1 - 200	200	5000	up to 3000
Electrical energy (kW h/m^3)	0.9 - 29.1	1 - 3	1.1 - 19.4	10.4 - 16.8	7 or 5	2.4 - 17.9	15	3.8 - 7.7	1.5 - 4	0.92 - 1.69	0.4 - 6	0.6 - 1	1.5 - 2	2 - 5
Thermal energy (MJ/m^3)	none	none	none	none	none	none	none	none	none	none	none	none	60 - 70	60 - 75
Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none	none	none	none	none	none	none	none	none	16.7 - 19.5	16.7 - 20.8
Total electricity consumption (kW h/m^3)	0.9 - 29.1	1 - 3	1.1 - 19.4	10.4 - 16.8	7 without ERD and 5 with ERD	2.4 - 17.9	15	3.8 - 7.7	1.5 - 4	0.92 - 1.69	0.4 - 6	0.6 - 1	18.2 - 21.5	18.7 - 25.8
Recovery device	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
RES	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Pretreatment	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Reference	(Ali et al. 2017)	(Albloushi et al. 2019)	(Abdelkareem et al., 2017)	(Cipollina et al. 2014)	(Cipollina et al. 2014)	(Ali et al. 2017)	(Albloushi et al. 2019)	(Abdelkareem et al., 2017)	(Cipollina et al. 2014)	(Albloushi et al. 2019)	(Fernandez-Conzalez et al. 2019)	(Ali et al. 2017)	(Abdelkareem et al., 2017)	(Cipollina et al. 2014)
Total average electricity consumption (kW h/m^3) for each reference	15	2	10.3	13.6	6	10.2	15	5.8	2.8	1.3	3.2	0.8	19.9	22.3
		Total average =	10.2	(kW h/m3)		Total average =	5.5	(kW h/m3)		Total average =	2	(kW h/m3)	Total average =	21.05 (kW h/m3)

Table 11 - The summary of desalination technologies powered by wind energy

Powered by wind energy	Membrane						Thermal	
Desalination method	RO		RO		ED		VC	
Type of feed	brackish water		seawater		brackish water		seawater	
Capacity (m^3/day)	50- 2000	50- 2000	8500	50- 2000	3 - 8.5	204	50 - 500	from 100 m3 to sev. 100 m3/day
Electrical energy (kW h/m^3)	1.5 - 2.5	0.5 - 1.5	5.88	4 - 5	4- 19	2 - 4	9 - 20	11 - 14
Thermal energy (MJ/m^3)	none	none	none	none	none	none	not specified	not specified
Equivalent electrical to thermal energy (kW h/m^3)	none	none	none	none	none	none	not specified	not specified
Total electricity consumption (kW h/m^3)	1.5 - 2.5	0.5 - 1.5	5.88	4 - 5	4- 19	2 - 4	9 - 20	11 - 14
Recovery device	✓	✓	✓	✓	✓	✓	×	×
RES	✓	✓	✓	✓	✓	✓	✓	✓
Pretreatment	✓	✓	✓	✓	✓	✓	✓	✓
Reference	(Al-Karaghouli et al., 2013)	(Abdelkareem et al., 2017)	(Cipollina et al. 2014)	(Abdelkareem et al., 2017)	(Ali et al. 2017)	(Fernandez-Conzalez et al. 2019)	(Cipollina et al. 2014)	(Abdelkareem et al., 2017)
Total average electricity consumption (kW h/m^3) for each reference	2	1	5.9	4.5	11.5	3	14.5	12.5
	Total average =	1.5 (kW h/m3)	Total average =	5.2 (kW h/m3)	Total average =	7.3 (kW h/m3)	Total average =	13.5 (kW h/m3)

3.9 Hypothetical case study of solar powered SW RO in Saudi Arabia

To understand how feasible combination of desalination plants of large scales with renewable energy sources for the water supply of many people, I decided to go with the imaginary city case of 1 million citizens. To supply water demand of 1 million people, desalination plant should be built. There should be the combination of less energy consumptive desalination method and the most promising renewable energy source. The lowest energy consumption, which has wide global application, is the seawater reverse osmosis (SW RO). There are some other combinations of desalination process like, reverse osmosis of brackish water or brackish water electrodialisys, however these combinations are not applied with large capacities due to some restrictions. As a renewable energy source would be solar power. Photovoltaic (PV) technology has wide application and nowadays broadly used for energy supply for different purposes. The Saudi Arabia in the Middle East is chosen as a location for the city, due to two main reasons. First, it has higher amount of solar radiance and long stretched access to the seawater. And the second reason is that Saudi Arabia is the leader of desalination water production, there are many real installed desalination plants, that later will be used as a comparison of real and imaginary cases.

To harness solar power mostly are used solar panels. They are mainly of two types: residential and commercial. The commercial one is larger and it has more surface to collect more solar radiance. The differences between these two are shown in the figure 14 below. The sizes of commercial solar panel are 1.96m x 0.99m making in total 1.94 m2 of surface.

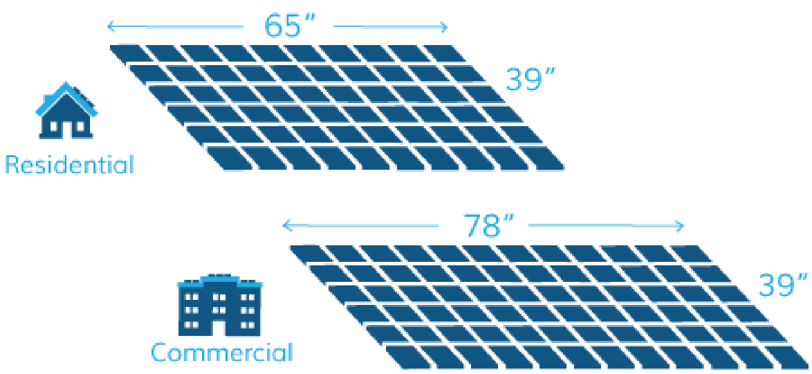

Figure 14 – Residential vs Commercial solar panel sizes comparison (Google search)

According to the figure 11 of the section 2.6 Saudi Arabia receives solar radiation ranging from 5 to 7 kW energy per 1m2 of surface per day. For my calculation, I took 5.5 kW/m2/day radiation. This amount of heat corresponds to the east coast of Saudi Arabia, where are located many desalination plants. It means that per hour 1 m2 surface receives around 230 W of energy. Now we could calculate how much surface is needed to produce the required amount of energy for water desalination. SW RO has 4.4 kW h/m3 energy demand. It means that to produce 4.4 kW h, we need to have 19.2m2 of solar panels' surface or 10 solar panels of commercial type. The average price per watt for solar panels ranges from 2.67$ to 3.43$ (Wikipedia).

To figure out what should be the capacity of desalination plant we need to define water consumption. Two cases are studied, first one – water consumption only for municipal purposes, and the second one – water consumption for municipal, industrial and agricultural purposes.

The average water consumption per capita in Saudi Arabia is 270 l/day for municipal purposes according to the Water Statistics Report in GCC Countries of 2018. It means that for 1 million citizens we need to build water desalination plant of capacity 270 000 m3/day. We considered only water demand for municipal purposes of one million people, but what if we include also the industrial and agricultural water demand. Obviously, the water consumption would be much more than in a previous case. Industrial and agricultural water demands have large ranges for different countries. Because our study case is an imaginary city case that is located somewhere in the Middle East, it would be more realistic if we look into the real water consumption data for the countries of that region. The figure 15 represents the total water consumption for agricultural, industrial and municipal purposes throughout the year per capita of 5 Middle East countries. The total water consumption per capita for these countries ranges from 282.3 to 907.5 m3 based on Our World in Data (Ritchie et al., 2019). The average for these countries is 535.8 m3 per one person. It means that per day for a one person is needed 1.47 m3 of water to supply all needs. It is equal to 1 470 000 m3/day. Knowing the amount of water that is required for one person, we could calculate the capacity of desalination plant.

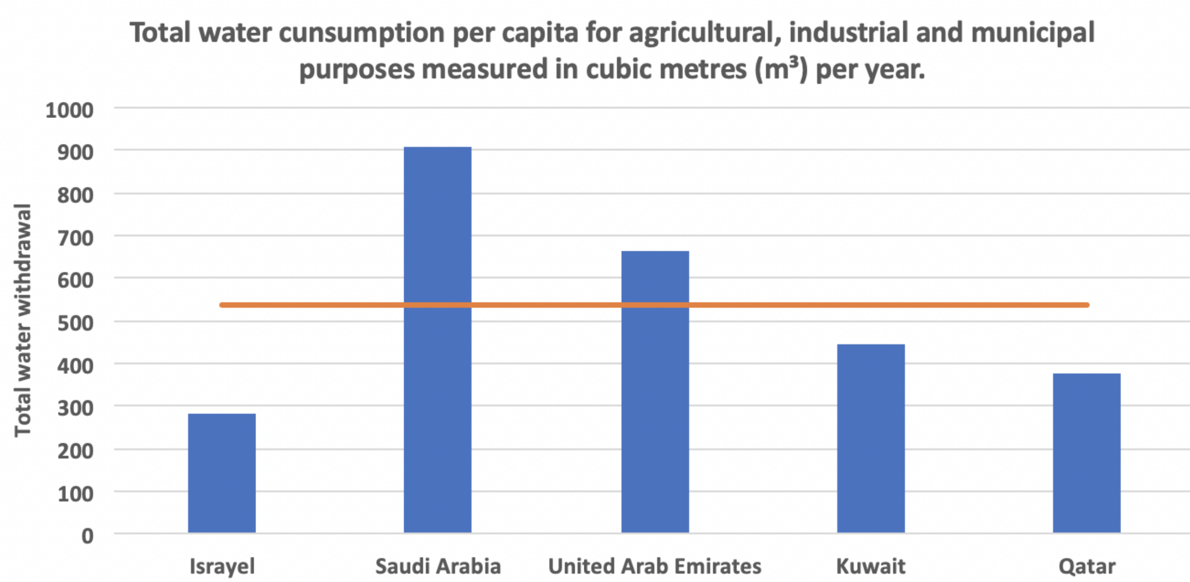

Figure 15 – Total water consumption per capita of Middle East's countries for agricultural, industrial and municipal purposes

4 Results and Discussion

From table 3 – 11 we could extract the capacities of each desalination method that are applied with conventional or renewable energy sources and combine with the table 2, which is subdivision of capacities of desalination plants. The results are presented in tables 13 and 14. It could be seen that for desalination plants of the medium and large sizes are typically used conventional energy sources, like oil, gas, diesel, fossil fuels. And it is vice versa for the renewable energy sources. They are mostly applied for desalination plants of small sizes and they desalinated water production in most cases not exceed 1000 m3/day. This is true basically for all main desalination technologies. An explanation to this could be the large amount of energy that is required for water desalination process. Renewable energy sources basically have low energy productivity (Shahzad et al., 2017), they are not able to supply the appropriate energy demand for medium and large scale desalination plants. Moreover, they are not able to deal with huge energy demand of thermal desalination processes as well. However, for some desalination techniques use of renewable energy could be possible. For example, for RO technology, the only power requirement is electrical energy, (for feed water pumping, dosing/filter pumps, permeate water pump, high-pressure pump), the RO technology can be easily driven by solar and wind systems (Cipollina et al., 2014).

Table 13 - Application of desalination plants with conventional energy sources. The table is based on sources (Karagiannis et al., 2008) and (Shatat et al., 2014)

		Desalination technology					
		SW RO	BW RO	MSF	MED	VC	ED
Capacity (m3/day)	Small	✗	✗	✗	✗	1000 - 1200	✗
	Medium	1000 - 5000, 12 000 - 60 000	5000 - 60 000	55 000 - 90 000	55 000 - 90 000	3000	1000 - 60 000
	Large	>60 000 - 320 000	>60 000 - 320 000	>90 000 - 528 000	>90 000	✗	>60 000 - 145 000

Table 14 - Application of desalination plants with renewable energy sources. The table is based on sources (Karagiannis et al., 2008) and (Shatat et al., 2014)

		Desalination technology					
		SW RO	BW RO	MSF	MED	VC	ED
Capacity (m3/day)	Small	<1000	<1000	<23 000	12 000 - 55 000	1000 - 1200	<1000
	Medium	✗	✗	✗	✗	✗	✗
	Large	✗	✗	✗	✗	✗	✗

4.1 Comparison of energy consumptions

Tables 3 – 11 in section 3 show the total energy consumption of different desalination methods of different sizes and energy sources. To understand how efficient certain method, it is good to compare desalination techniques with each other. Figure 16 depicts comparison of energy consumption of most applied desalination methods ranging from lowest to highest energy demand in kW h per 1 m3. Membrane technologies are shown with blue color, thermal ones – with orange color and desalination methods that use renewable sources as an energy supply are shown with green color. Membrane technologies powered by renewable energy sources are marked with light green and thermal technologies powered by renewable energy sources marked with dark green.

Membrane-based desalination methods due to their less energy-intensive nature and small footprint became more popular than the thermal ones. Substantial efforts have been observed in integrating membrane technologies, mainly reverse osmosis (RO) and electrodialysis (ED), and relatively green sources of energy (wind, solar). It could be observed that brackish water ED powered by solar energy and brackish water RO powered by wind energy have the lowest energy demand among the others renewably powered desalination plants. However, they application is limited due to several factors, like availability at the same location both the brackish water and enough solar radiance or wind capacity. So, practically their application is restricted up to 200 m3/day for BW ED and up to 2 000 m3/day for BW RO. This capacity is not enough for overcome the existing severe water shortages in many regions.

Next come membrane technologies powered by conventional energy sources. First come brackish water RO of medium and large scale and brackish water ED of medium and large scale with 1.9 and 2.9 kW h/m3 energy demand respectively. As was mentioned before availability of brackish water is somewhat limited, thus, although these technologies have relatively small energy demand per cubic meter of water, however they are not applied in large scales globally. The picture is quite different with seawater, which availability is practically unlimited because of seas and oceans. Seawater RO of medium size has energy consumption of 4.3 kW h/m3 and seawater RO of large scale has 4.4 kW h/m3 energy footprint. Due to selective nature of RO membrane, ions and other solute particles are rejected under the high pressure. Compared to its thermal counterparts, RO possesses the advantages of significantly less energy consumption, non-corrosive equipment, small footprints and relatively safer operation. Thus, seawater RO of medium and large scales are the most popular and economically efficient type of desalination method, making the installed share of SW RO of total globally installed desalination capacity more than 65%. It could be seen in the figure 17.

It is clear from figure 16 that membrane desalination plants powered by renewable energy sources are in between of conventional membrane and conventional thermal methods. They lose in energy demand to membrane technologies, but win the thermal ones. This could give a good incentive to continue improvements of implementation of renewable energy sources in desalination processes in the future.

The energy demand of thermal methods is quite large comparing with membrane technologies. They are more expensive because of the large quantities of fuel required to vaporize salt water. Thermal desalination now exists mainly in the regions enriched in petroleum resources such as Middle East (Ali et al., 2017). The power consumption of an MED plant is significantly lower than that of an MSF plant, and the performance ratio of the MED plant is higher than that of the MSF plant. MED technology has 11.9 kW h/m3 energy requirement and MSF has 17.1 kW h/m3. Therefore, MED is more efficient than MSF. However, there is a serious problem with corrosion in both thermal methods. Still the problem with corrosion is easier to solve with MSF compared to MED, because the design is less complex. This is the main reason that MSF has received wider global application than MED for desalination of very salty waters, despite the fact that energy demand for MSF higher than for MED. Thermal technologies powered by renewable energy sources have even more energy footprint. Wind VC has 13.5 kW h/m3 and solar PV MED has 21.1 kW h/m3, which make them extremely inefficient regarding with small plant sizes.

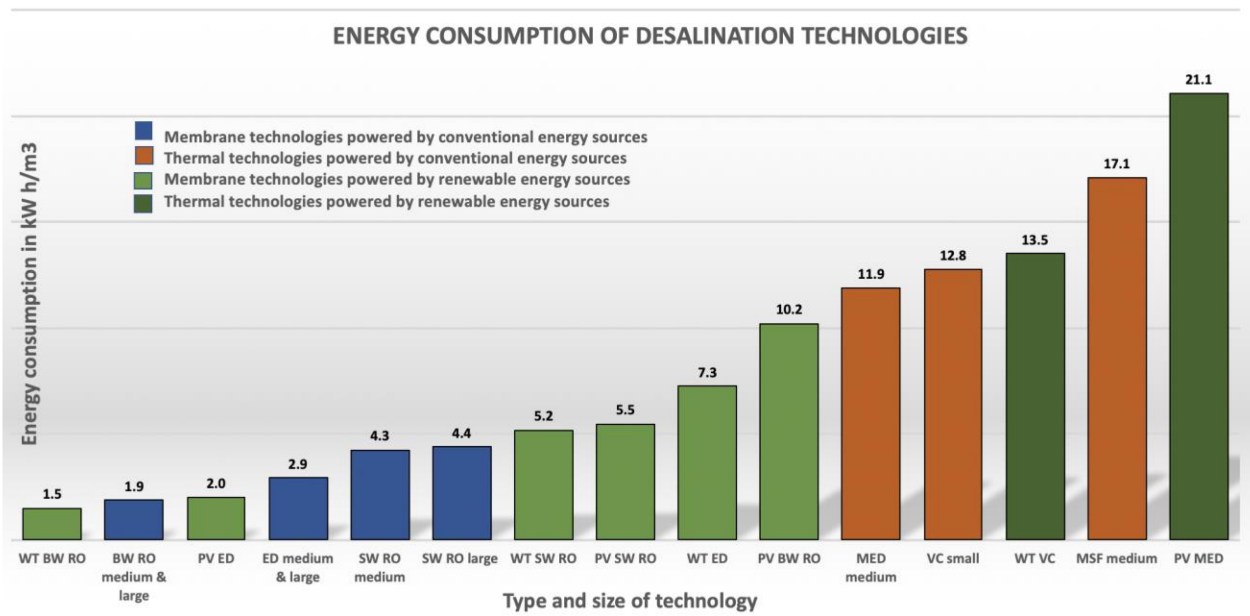

Figure 16 – Energy consumption of different type of desalination technologies

4.2 Global average energy consumption per unit of water

There are different desalination methods throughout the world powered by different energy sources. Each of them has its own energy requirements for desalination process. But how much energy do we spent globally per unit of water. To answer to that question, we need to calculate global weight average of energy consumption per unit of water. To do so, first we need to find out the global application rate of each methods. According to papers (Shemer et al., 2017) and (Abdelkareem et al., 2017) RO is applied to 65%, MSF – 21%, MED – 7%, ED – 4% and other desalination techniques applied to 4% globally. Brackish water is being used in RO method for desalination up to 41%, seawater is being applied for 59% (Shahzad et al., 2017). The main feed type for thermal desalination methods is seawater, thus, it is considered to 100%. For ED method, the main feed is brackish water only, thus it is applied for 100%.

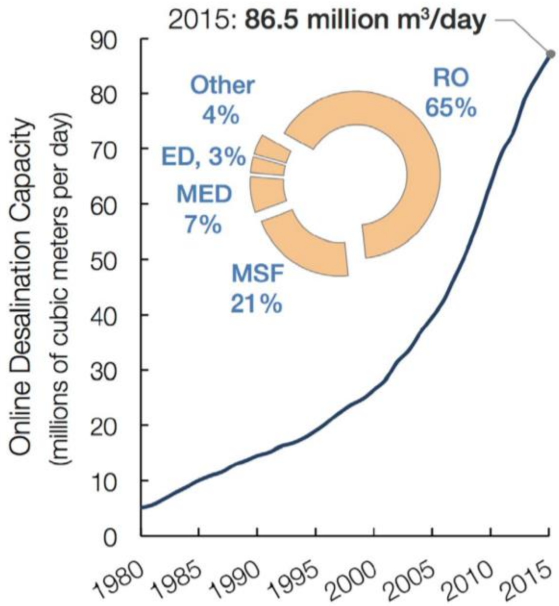

Figure 17 – Worldwide desalination capacity (Abdelkareem at al., 2017)

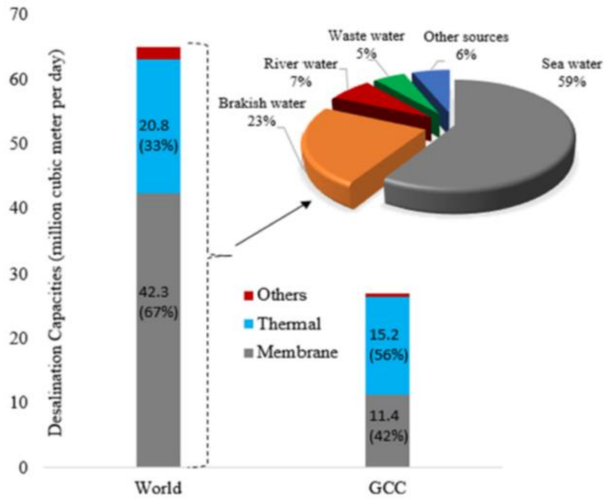

Figure 18 – Total desalination installed capacities and share of differnet technologies (Shahzad et al., 2017)

Table 15 – Global average energy consumption per unit of water

Method	BW RO	SW RO	MSF	MED	ED	other
Average energy consumption (kW h/m3)	1.9	4.3	17.1	11.9	2.9	8.8
Seawater application (%)	-	59	100	100	-	100
Brackish water application (%)	41	-	-	-	100	
Global application (%)	65		21	7	3	4

Weighted average energy consumption (kW h/m3)	2.15	3.59	0.83	0.09	0.35
Global average energy consumption (kW h/m3)	7				

Table 15 represents how calculation of total weighted average energy consumption is calculated. We could say that globally humanity spent 7 kW h energy for desalination of 1 m3 of water. If we compare our result with the numbers of the figure 16, we could see that total average energy consumption is somewhere in the middle of the range that was presented. It is higher than average membrane SW RO energy consumption, but it is lower than energy demand of thermal methods. The largest part of global average energy consumption comes from MSF, in spite of the fact that globally it has application of only 21%. Its energy consumption is the highest one, which make the total weighted average quite high as well.

4.3 Comparison of energy costs

How capital cost of different energies was calculated was discussed in section 3.8. The results could be sorted again from smallest to the largest capital cost of energy that were gathered from table 12. If we compare figure 16 with figure 19 we could see that the picture has many changes.

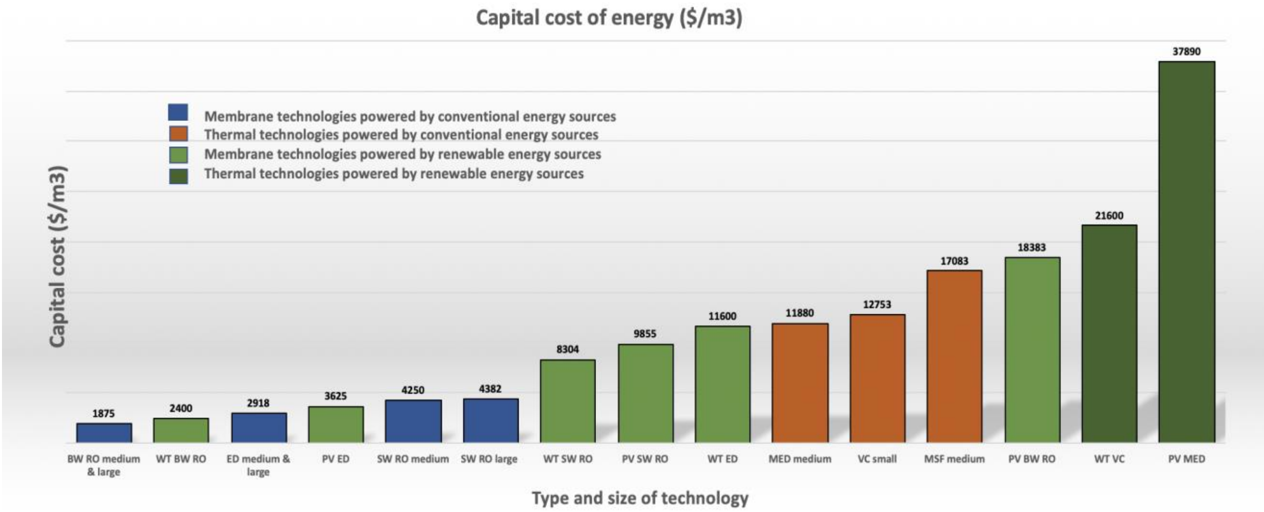

Figure 19 – Capital costs of energy for different desalination technologies.

From energy consumption point combining renewable energy sources with membrane technologies are good regarding with less energy demand for desalination of 1 m3 of water. And thermal technologies stand at the last place due to their large energy requirement (Figure 16). However, from the point of view of capital cost of energy, the renewable energy sources are shifted to the right, which make them more expensive, than the thermal ones and the latter came more to the middle of the graph (Figure 19). Moreover, the capacities of desalination plant powered by renewable energy sources are smaller several times than the thermal ones, which makes them even more non-competitive and economically not beneficial in comparison with conventional membrane or thermal desalination plants at least at this stage of their development.

The situation with membrane technologies quite stable. They are both economically efficient and less energy consumptive. These could be seen from figure 16, where membrane methods are located in the left side of the graph, which means that they are most energy efficient desalination techniques. And in the figure 19 they are also depicted in the left side, making them economically beneficial for investments. Obviously, these are the main triggers that push membrane technologies in front of others and their global application is increasing rapidly, leaving behind the thermal ones. But most efficient membrane technologies are powered by conventional energy sources as well, which would have been depleted in near future. The main question could the membrane technologies are efficiently combined with the renewable energy sources and could they supply the human fresh water needs in the future. We try to find answer to this question in the next section.

4.4 Hypothetical study case

Section 3.9 discusses how to calculate land requirement for solar powered SW RO desalination plant for two water demand cases. To supply energy requirement for the desalination plant with capacity of 270 000 m3/day for 1 million people for municipal purposes, we need solar park of size 5.18 km2. If the land required for this would be of square shape, its sides sizes would be 2.27 km each. Quite difficult to image the land surface of this size. To understand how big it is, I compare it with the surface of modern soccer field with sizes 106m x 70m. 699 soccer fields are needed to be covered with solar panel to supply the energy demand to desalinate 270 000 m3/day seawater. The installation cost only of solar park would be 3.62 billion US dollars. The territory of Amsterdam could contain 42 solar parks of this size (Figure 20 and 21). These numbers are summarized in the table 16 below.

Table 16 – Desalination for 1 million people for municipal purpose

The average municipal water consumption per capita in Saudi Arabia	270	l/day
The average municipal water consumption per capita in Saudi Arabia	0.27	m3/day
The number of inhabitants	1 000 000	people
The capacity of desalination plant	270 000	m3/day
The number of solar panels	2 672 165	pcs
The total surface area needed for solar park	5 184 000	m2
The total surface area needed for solar park	5.184	km2
The length and width of solar park if it is square	2.277	km
The surface of the modern soccer field	7420	m2
The number of soccer fields needed for the solar park	699	pcs
Energy demand for the certain capacity	1 188 000	kW h/day
The cost of solar park	3.62	Billion $
The surface of Amsterdam	219.3	km2
Comparison of solar park with Amsterdam	42.3	pcs

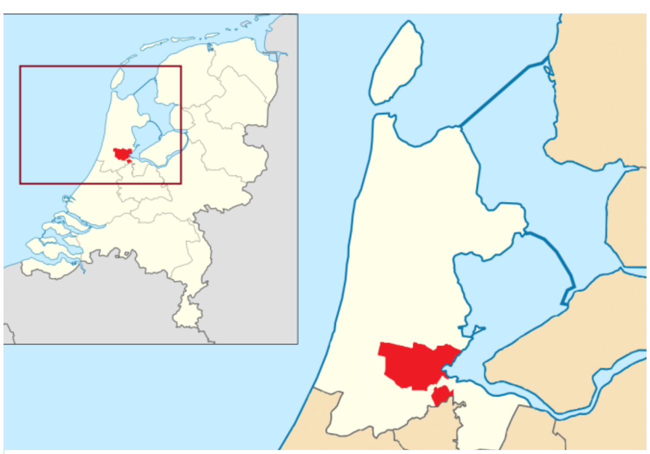

Figure 20 – The territory of Amsterdam (Google search)

Figure 21 – Solar park (Google search)

To supply the desalination plant with this capacity 1 470 000 m3/day for 1 million people for municipal, industrial and agricultural purposes with the given energy demand, we need solar park of 28.22 km2. If the land required for this would be of square shape, its sides size would be 5.31 km. 3804 soccer fields are needed to be covered with solar panel to supply the energy demand to desalinate required seawater amount. The installation cost only of solar park would be 19.72 billion US dollars. The territory of Amsterdam could contain more than 7 solar parks of this size (figure 20 and 21). These numbers are summarized in the table 17.

Table 17 - Desalination for 1 million people for municipal, industrial and agricultural purpose

Total water withdrawal for agricultural, industrial and municipal purposes per capita	1.47	m3
The number of inhabitants	1 000 000	people
The capacity of desalination plant	1 470 000	m3/day
The number of solar panels	14 548 454	pcs
The total surface area needed for solar park	28 224 000	m2
The total surface area needed for solar park	28.22	km2
The length and width of solar park if it is square	5.31	km
The surface of the modern soccer field	7420	m2
The number of soccer fields needed for the solar park	3804	pcs
Energy demand for the certain capacity	6 468 000	MW h/day
The cost of solar park	19.72	Billion $
The surface of Amsterdam	219.3	km2
Comparison of solar park with Amsterdam	7.77	pcs

In both cases the required land is being considered to be covered entirely with solar panels. However, in reality there would be even more space needed because some additional space should be left between the rows of solar panels. This is not calculated to make the results comparable with each other without the dependency of external factors such as the design of solar park and its geographical location. The shadow from the first row should not overlap on the solar panels of the second row. This depends on sun position in the sky and the throwing shadows length from panels. This is different in each location.

How real are these kinds of projects? We could understand comparing only with the existing real desalination plants. The world's first large scale solar powered SW RO desalination plant at Al Khafji, which has capacity of 60 000 m3/day is located in Saudi Arabia. PV plants provides 100% SWRO plant energy demand with 47.5 MW peak energy and it is connected to the local grid. It has been reported that the capacity is sufficient to supply 150 000 people. It means that per person there is 400 liters per day. That is much more than was reported in (www.water-technology.net), however if we calculate with 270 l/day, we get that this renewably powered desalination plant is able to supply even 222 000 people. 120 ha of land was needed for solar panels, which is 1.2 km2. If it has a square shape, it would have sizes 1095 m x 1095 m. 162 soccer fields are takes this size of solar park.

4.5 Sensitivity analysis

Knowing how much energy require desalination process and how much radiance receives Earth surface at the design location, it is possible to calculate the solar park sizes and the land that is required for its construction. If desalination plant would be located in hot countries, where ground surface receives large amount of radiation, then less square meters of land is needed to be covered by solar panels, because they would get more solar energy. And vice versa, if the location would be somewhere in the north countries, then more land is needed to be able to catch the same amount of solar energy to supply the desalination process. The question is how big would be increase of the required land for solar park with getting less radiance. To answer to that question, a sensitivity analysis is done. The result is being showed in the figure 22. According to it regions like Middle East that receives 5 – 7 kW of solar radiance would need around 5 km2 for municipal purposes water desalination and 25 km2 for all purposes. But let's imagine that these type of desalination plants are needed to be constructed in the Netherlands, where it receives less than 2 kW of solar energy with the same water demand per capita. The land requirement would be 15 km2 for municipal purposes and around 80 km2 for all purposes. It is 3 times more than for the countries of GCC.

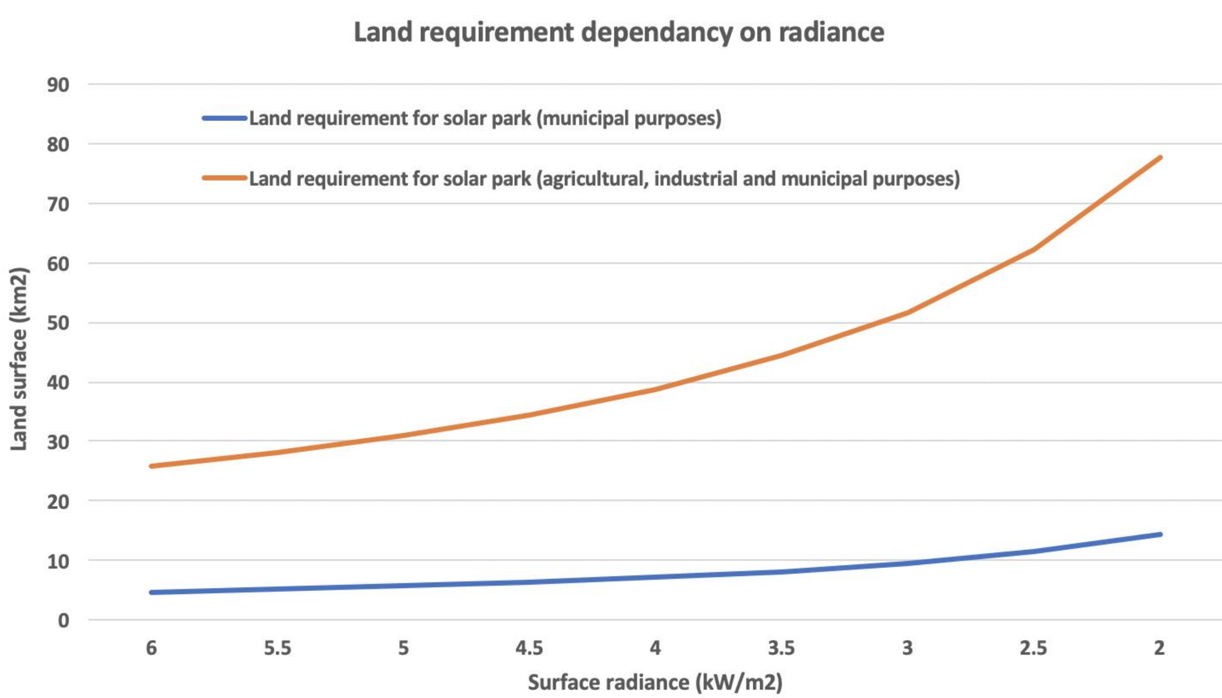

Figure 22 – Sensitivity analysis of land- radiance dependency

4.6 Future of desalination

Besides the energy consumption and land requirements for renewably powered desalination plants, it is important to think what would change in the near future. This is essential because we need to understand the trend of desalination, how fast it grows and which contribution desalination could have on global water demand. For this purpose, forecast of global water demand and desalination capacity are needed.

In spite of the numerous improvements that seawater desalination methods already undergone and some of them are already proven techniques of fresh water supply, they still remain quite expensive. Large amount of energy footprint is the main reason that many countries could not afford it. Nevertheless, for some developed countries desalination vastly contributes to their water resources. Total globally installed desalination capacity was 92.5 million m3 per 2017 according to (IDA, 2017). This number is rapidly increasing during the last years due to continuous improvements of desalination techniques and annually average growth of desalination application is 8% as could be seen from the figure 23 (IDA, 2017). It means that in 2019 the total cumulative desalination capacity of the world is 107.9 million m3/day. Using Water Demand Projections, the current water demand of humanity is 4.5 billion m3 per day of fresh water (Amarasinghe et al., 2014). This means, that throughout the world through desalination process people supply 2.1% of the total water demand. Fresh water supply through desalination was less than 1% several years ago (Ali et al., 2017). Nevertheless, it contributes very little to the total.

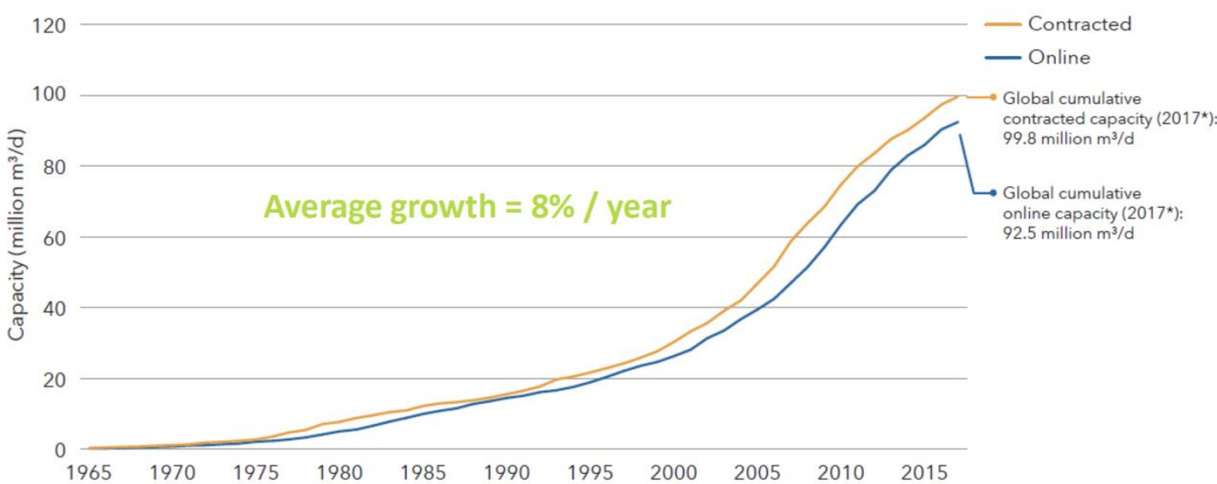

Figure 23 - Globally installed desalination capacity (IDA, 2017)

The figure 24 states that global installed capacity of desalination plants would be doubled in 2030 reaching the number 200 million m3 per year (IDA, 2017). This means, that in 2030 most probably desalination capacity throughout the world would contribute twice more than it does now. From 2.1% of contribution to total water demand it will increase to 4%.

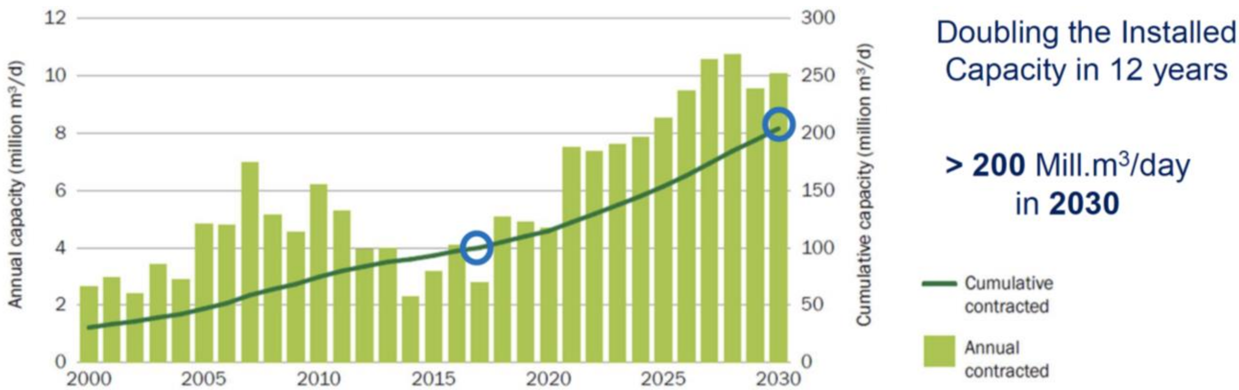

Figure 24 - Desalination capacity: history and forecast, 2000 – 2030 (IDA, 2017)

As we know from previous sections the most energy efficient desalination method is seawater reverse osmosis (SW RO) of large scale, which has energy consumption of 4.4 kW h/m3. What if we throw all the other existing desalination methods and keep only SW RO, how much would there be increase of desalinated water production now? And what would be the desalination water production if we change all existing methods in 2030 with the SW RO powered by renewable energy sources?

Table 18 – Calculation of changes in water desalination capacities in 2019 and 2010

		Energy consumption (kW h/m3)		Global desalination capacity (m3/day)	Desalinated water production (m3/h)	Percantage (%)	
2019	SW RO large	4.4		107892000	7193731	160	Increase by 60%
	Global average		7		4495500	100	
2030	PV SW RO	5.5		200000000	10673266	128	Increase by 28%
	Global average		7		8333333	100	

Table 18 represents calculation of changes in water desalination capacities for 2019 and 2030 years. Nowadays, in 2019 globally humanity spend 7 kW h energy to desalinate 1 cubic meter of water with total desalination capacity of around 107.9 million m3. If we desalinate this amount of water using only SW RO technology, which has energy of 4.4 kW h/m3, then we could produce by 60% more. And in 2030 if we take the forecasted global desalination capacity and try to desalinate the total desalination capacity only using already existing renewable technologies, we still would produce by 28% more than we do today.

However, these calculations are based on many assumptions. First, the cost of renewable energy is getting down due to continuous improvements in this area and it could not be the same as it is today. Second, there is a huge limitation regarding with the size of desalination plants powered by renewable energy. Most of the existing “green” desalination plants have small sizes and the capacities are not exceeding the 1000 cubic meter of water. To produce the same amount of desalinated water as humanity do today with renewable energy sources, would be a major challenge for now. And third, because reverse osmosis technology is less energy consumptive, it rapidly wipes out the other existing technologies like MED and MSF. The share of RO from the total applied rate is growing every year. Thus, most probably in the near future RO would be the single desalination method that is economically efficient and competitive with other water treatment methods.

4.7 Limitations

Comparison of energy consumption of the existing desalination technologies is very complicated task due to many aspects that needed to be taken into consideration. In this work, the most crucial and influential factors are assembled. The factors that have great impact on energy footprint of desalination plants are desalination method, capacity, type of feed, energy requirement and pretreatment. These factors determine the largest part of total energy demand of desalination process. However, there are still many factors that are not considered such as:

- Post-treatment; This is not being considered because it is somewhat out of the scope of this project. In this research, we are interested in energy footprint of core desalination process and the post-treatment is something that is going after the desalination process. There could be even no need of post-treatment at all. This highly depend on which purpose the desalinated water is going to be used. For example, the is no need for post-treatment if this water would be used for industrial or agricultural purposes, however in case of fresh water supply to people, there is need to do so.
- Age of desalination plants; This could lead to the decrease of efficiency. There is a serious issue of corrosion for thermal desalination technologies. The problem is that some parts, which are always in touch with salty water are subject of corrosion. This of course influence on efficiency of desalination plant. There is a need to replace them periodically. This is not a problem for membrane technologies, however another drawback is existing for them as well. Over the time the permeability of membranes decreases, which obviously leads to higher energy consumption due to higher pressure is needed to apply on them to supply the same amount of water to pass through the same membrane. There is a need to change these membranes over a period of time as well.
- Year of construction; The technologies are undergoing to many technical improvements and they are becoming less energy consumptive. As for an example, the energy consumption of reverse osmosis has been lowered by several times during the last decades. And no doubt, that desalination plant, which was constructed earlier is less energy efficient than the other one, which would be constructed in present time.
- Mixed-type of desalination plants; Renewable energy sources are actively being applied with the existing desalination methods. Renewable energy sources stand alone cannot supply vast amount of energy for large scale desalination plants. Thus, in many cases they are connected to the local grid. This is a way to reduce or to compensate some part of used electricity. The combination of renewable energy sources with the conventional ones for energy supply is called mixed-type. In this research they are not counted, but considered only conventional ones or renewable ones, because this would make research quite complicated and hard for comparing.

5 Conclusions and Recommendations

5.1 Conclusions

In spite of the fact that water desalination has been confirmed as a steady process of obtaining the fresh water and huge technological improvements throughout its history, it still has large energy consumption. Some membrane water desalination techniques like RO and ED has established as a less energy consumptive than the other ones. Two developments have helped to reduce the energy demand of membrane desalination plants during the past decades. These are the development of membranes that can operate efficiently with longer duration and the use of energy recover devices. Membrane technologies have become the most popular and economically beneficial way of water desalination with global application rate more than 65% of total world desalination capacity. The disadvantage of membrane techniques is the sensitivity of membranes to foaling by suspended solids and to damage. The energy footprint of thermal ones like MED, MSF and VC has from 6 to 9 times higher than the membrane technologies. Nowadays, they are mostly existing in the Middle East countries, which are abundant of conventional energy sources. Despite that thermal technologies require huge amount of energy, they are more effective in desalination of very salty waters.

Comparing energy consumption of widely applied desalination technologies, it was revealed that membrane techniques powered by conventional energy sources have the lowest energy footprint. BW RO of medium and large scales have 1.9 kW h/m3 energy demand. Then comes SW RO of medium size and SW RO of large scale with 4.3 and 4.4 kW h/m3 energy consumption. The thermal desalination techniques, primarily MSF and MED have much more energy footprint, than the membrane ones. They consume 17.1 and 11.9 kW h/m3 respectively. Thermal techniques powered by renewable energy sources have the highest energy footprint, for example PV MED has 21.1 kW h/m3 energy demand. Membrane technologies which are operated by renewable energy sources require more energy that the conventionally powered membrane ones, but less than conventionally powered thermal methods. This is a proof that combining renewable energy sources with membrane technologies is most promising way of water desalination in near future, after when conventional energy sources would be eventually depleted. However, from the capital cost comparison, it is obvious that renewably powered desalination plants are more expensive, especially if we consider the relatively small sizes of renewable desalination installations comparing with conventional thermal ones. From both energy consumption and capital cost points of view, conventionally powered membrane desalination plants are the most beneficial way of water desalination. Because some desalination technologies are globally applied more than others, it was calculated the global average energy consumption of desalination. We could say that globally humanity spent 7 kW h energy for desalination of 1 m3 of water.

Because of limited conventional energy sources, to meet the growing fresh water demand humanity should move toward the “green” energy sources. Essential progress was done during the last years of powering desalination plants by renewable energy sources. Rough estimation was done regarding the land requirement for solar panels to be able to supply the energy demand for SW RO desalination based on solar energy. As a model for such a study was decided to choose a city with 1 million inhabitants and geographical location in the territory of Saudi Arabia. To supply 1 million people with fresh water, desalination plant should have 270 000 m3/day capacity for municipal purposes and 1 470 000 m3/day capacity for industrial and agricultural purposes as well. For the first one 5.18 km2 of land is required for solar park or almost 700 modern soccer fields and for the second one – 28.22 km2, which is 3804 soccer fields. The results are quite different, if we change the location of desalination plant, in other words the amount of radiance that earth surface receives.

5.2 Recommendations

It is recommended for future works, take into the consideration even more factors that have influence on energy consumption of desalination process, take into account not only those factors that determine the largest parts of energy footprint but the smallest ones, that in total could have quite a detectable change on energy demand, which are discussed in section 2.1. This is a way how to expand this research and make the results even more up to date.

Another suggestion is to compare energy consumption of mixed type of desalination plants, where for energy supply are used both conventional and renewable energy sources. To calculate real renewable energy contribution to the total energy supply is quite a tough assignment because of intermittency of energy supply of renewable ones. In most cases there are considered as a supplementary energy source, but not the main ones. And the calculation how much they contribute to the energy demand of water desalination is complicated due to many aspects. However, it is recommended to take them into account as well.

Land that is needed for solar park in section 4.5 is being assumed to be covered entirely with solar panels. However, in reality there is a space needed to be left between the solar panels' row. This is not considered to make the results comparable with each other, making them dependent only on radiance amount that earth surface receives. This factor is dependent strictly on geographical location. Nevertheless, it is recommended for further researches include it also.

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