Water, Water, Everywhere, and Not a Drop to Drink[1]
Desalination Technologies in the U.S., Australia, and Israel: a Comparative Analysis

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Abstract

Desalination Technologies have become an increasingly viable option to provide drinking water to people by desalting brackish and seawater. It is an extremely energy intensive process that creates a large impact on the environment, economy and local communities. Since the amount of energy required for breaking the salt and water bond is large, the best way to reduce the carbon footprint of the desalination plant is to use renewable resources as the energy source. This study examines three large-scale desalination plants in Australia, Israel and the United States in order to better understand how renewable resources could possibly be used to power the desalination plants. It compares factors among the three different desalination projects that impact the production of fresh water. The investigation concludes that using renewable resources as a source of power with current technologies is best utilized on smaller scales, but can also be used to offset the environmental impacts of large scale operating desalination plants. The investigation recommends the Sorek desalination plant in Israel as the best candidate of the three case studies to implement renewable energy because of unique governmental characteristics and opportunities for investments.

Preface

I originally became involved in this project summer of 2016 while I was in the Central Valley of California studying the sustainability of almond farming, more specifically water usage. I quickly learned how valuable and political water rights are in California for agricultural purposes and human consumption. A few farmers I spoke with joked that there should never be a shortage of water because of California's proximity to the ocean, which was the first time I had given any thought to desalination. I began researching the feasibility of purifying seawater to fresh water for the purpose of agriculture, but found that it was much more common to desalt water for the purpose of drinking water. Before I started this honors thesis I had no experience with desalination, but I was very excited to explore this topic because every form of life uses water and it is such a rapidly growing industry. It has been a challenging but inspiring experience to create this document, and has taught me how important water scarcity is on a global level.

Acknowledgements

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Introduction

This project is an honors thesis that examines the use of desalination technology as a source for fresh water and the policies relating to this technology. My honors thesis is an analysis and comparison of three seawater desalination projects across three continents: Carlsbad Desalination Project in California, Sorek Desalination Plant in Israel, and Adelaide Desalination Project in Australia. It addresses the successes and frustrations of the projects, as well as the factors unique to each plant that could have contributed to those difficulties, including social, economic, governmental, and environmental elements. Numerous arid areas do not have fresh water capitals made up of groundwater or surface water such as rivers and lakes to meet demand. Numerous developed countries have invested in desalination technology that converts seawater into fresh water to make up for a lack of surface and ground water supply, as well as to offset even more limited water supplies during cyclical droughts. At the onset, my goal was to determine how currently operating desalination projects compare across three different regions in the world, all in need of a greater water supply. Furthermore, I asked would renewable resources be a viable source of energy to power the desalination plants.

Now, more than ever there is a great need for fresh water. The world is on the brink of a global water crisis, and "water scarcity already affects every continent. Around 1.2 billion people, or almost one-fifth of the world's population, live in areas of water scarcity, and 500 million people are approaching this situation" (Scarcity, 2015). As the global population rises, so does the demand for water, which puts strains on the finite amount of potable water. Because of the changing climate, many aqueducts around the world have been running dry, forcing people to find new sources of fresh water. As we know, the oceans cover 70% of the globe, and offer an inexhaustible seawater supply, but unfortunately, it is unfit to drink or use for agricultural purposes.

As an environmental studies major, I've taken particular interest in issues concerning water scarcity, and I feel this is a great opportunity to learn more by doing an honors thesis research project. I hope this qualitative research will use analytical skills to compare three different desalination plants around the world in terms of environmental impact, economic growth, and social equity. Through this project, I will contribute to sustainable environmental, economic, and social system development for the global desalination market.

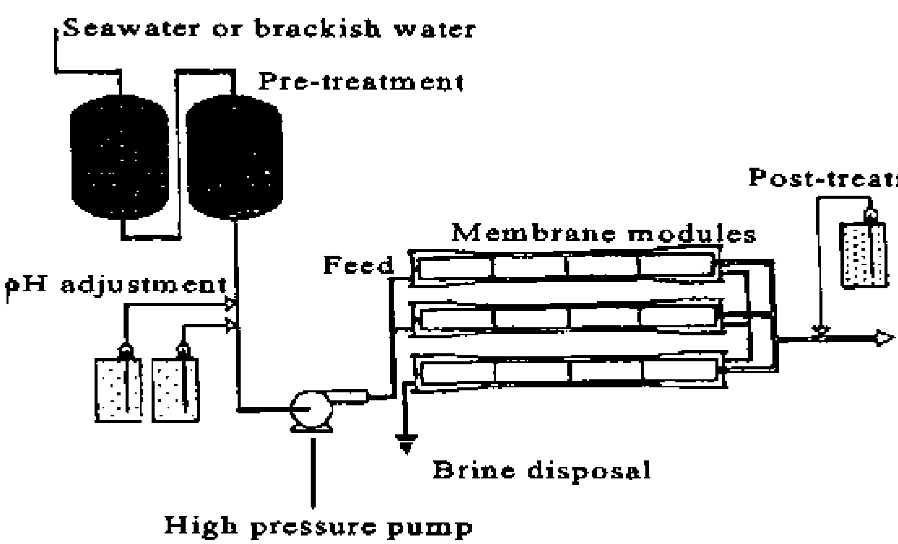
Background

"Seawater desalination has long been used in regions all over the world where fresh water is in short supply. Today, there are more than 15,000 desalination plants worldwide in 150 countries, producing more than 18 billion gallons of fresh drinking water per day. An estimated 70 million people around the world rely on desalinated water for their daily water needs" (Seawater, 2016). The oceans constituting 70% of the globe, offer an inexhaustible seawater supply. Unfortunately, it is unfit to drink (Seawater, 2016).

In numerous arid regions of the world, the need for additional water supplies will become ever more relevant due to the already critical levels of fresh water stocks. Desalination is process to remove salts and other minerals from a resource, with the potential to generate drinking quality water (Gude, 2016). "There has been an exponential increase in desalination capacity both globally and nationally since the 1960s, fueled in part by growing concern for local water scarcity and inadequate fresh water supply, both of quality and quantity" (Wittholtz, 2008). "Considering water shortage concerns about 80 countries and has caused some serious results in many places, the water shortage phenomenon is becoming a serious global problem that affects people's daily life and hindered the social development” according to a report on megascale desalination by Talbot. Because of the increasing population and development of both industrial and agricultural activities, the water required to meet demand will increase swiftly in a very near future (Talbot, 2016). It is apparent that the modern fresh water supply structure cannot meet the requirement any more in arid regions. An alternative water supply option is needed to help us deal with this problem (Crisp, 2012). Seawater desalination is considered by many to be the only true drought proof water supply available.

“There are about 15,000 desalination plants around the world. The biggest plants are in the United Arab Emirates, Saudi Arabia and Israel. Desalination plants have been constructed in major Australian coastal cities to produce large amounts of drinking water for urban populations” (Water, 2000). Israel used to have an insufficient water supply and fear of drought, buy now have an abundant supply and independence from climate conditions, thanks to the 70 years of planning leading up to the construction of desalination plants (Gude, 2016).

The most basic desalination involved heating salt water, gathering the steam, and condensing the steam for drinking water. “Today’s plants pump water at high pressure through



This figure shows the elements of the desalination process. (2.1 Desalination, 2016) membranes with hair-thin fibers that filter out the salt, producing fresh water that can be used for drinking" (Talbot, 2016). As innovation in technology continues to improves, the cost will be more affordable.

Water desalination has its critics. "Environmental issues related to desalination are a major factor in the design and implementation of desalination technologies. An acceptable desalination plant is expected to meet environmental regulations; be cost-effective in terms of construction, operation and management, as well as the costs associated with monitoring and permit fees" (Wittholtz, 2008). A few main environmental concerns consist of issues related to placement of desalination plants and water intake structures, and concentrate management and disposal. Seawater that is desalinated normally costs about $2,000 per acre foot worldwide—approximately the amount of water a family of five uses in a year. "The cost is about double that of water obtained from building a new reservoir or recycling wastewater," according to a 2013 study from the State Department of Water Resources (Sahin, 2015).

With respect to the environment, the construction process of the infrastructure for facilities can be laborious, loud, and disruptive. Ideally there would be as little construction as necessary. One way to maximize efficiency in the construction process is to locate the desalination plant nearby the water connection and electricity connection so that construction impacts are minimized. (Krishna, 2006). "Construction of water intake structures and pipelines to carry feed water and concentrate discharge may cause disturbances to environmentally sensitive areas. Concentrates are high in salinity and may contain low concentrations of chemicals as well as elevated temperatures. These properties of concentrate can pose problems for the marine habitats and receiving water environments" (Berktay, 2011). At present, there are no federal or state salinity discharge limits in the US and worldwide (Seawater Desalination Processes, 2011).

One of the biggest problems is that “the desalination of water requires a lot of energy. Salt dissolves very easily in water, forming strong chemical bonds, and those bonds are difficult to break. Energy and the technology to desalinate water are both expensive, and this means that desalinating water can be pretty costly” (Harmful, 2010). The burning of fossil fuels to meet the energy requirement for the function of a desalination plant boosts the process of global warming and is a major indirect environmental impact because of the release of CO_2. (Sadhwani, 2005). The running of these desalination plants incurs a cost due to the energy they consume. The International Atomic Energy Agency (IAEA) has developed the Desalination Economic Evaluation Program (DEEP) to perform economic analysis of desalination using nuclear energy versus alternative sources of energy (Younos, 2004). “Moreover, opponents say, removing salt from ocean water requires major power consumption; electricity accounts for as much as half of the cost of operating a plant. The resulting greenhouse-gas emissions are so high that desalination plants are required to aggressively seek ways to offset the carbon output” (Fears, 2015).

According to a study done on the impacts of desalination on marine life, the “environmental costs of desalination entail sea life getting sucked into desalination plants, killing small ocean creatures like baby fish and plankton, upsetting the food chain. Also, there's the problem of what to do with the separated salt, which is left over as a very concentrated brine. Pumping this extremely salty water back into the ocean can harm local aquatic life” (Harmful, 2010). Reducing these impacts is possible, but it adds to the costs. Perhaps the most significant and extreme limitation in the U.S. desalination market is environmental worry.

In 2003 the California Coastal Commission warned that “allowing desalination plants to proliferate could threaten marine life and turn what had long been considered a common good- the ocean- into a commodity” (Wittholz, 2008). Most impacts on the marine environment arise as a consequence of the brine discharge and their effects could be worse in the Mediterranean sea than in other areas because the salinity concentration is already very high (Sadhwani, 2005). There is always an impact on towns nearby operating plants because of the noise pollution produced by the plant.

Australia Background

In the past desalination has been “too expensive for major application in Australia and the world, but rising costs of developing remaining water resources (partly due to climate change), coupled with a growing demand for water supplies of varying quality for domestic, mining and industrial purposes, are making Australia look more closely at the rapidly developing desalination technologies. Water agencies in Australia have increasingly become involved in desalination initiatives” (Crisp, 2012). “In response to its worst drought ever- a decade long parching that the government says was deepened by climate change- the country launched one of the biggest infrastructure projects in its history. Australia’s five largest cities are spending $13.2 billion on desalination plants, which will draw up to 30 percent of their water from the sea” (Onishi, 2010).

A report on the potential role of renewables in water desalination described that typically low rainfall coupled with high variability in rainfall has meant that Australia has had to invest in significant water storage infrastructure. At present, the opportunities for expansion of existing water storage infrastructure or new infrastructure are limited. For example, due to environmental concerns, the difficulty in constructing new catchments and the financial costs involved, Melbourne has ruled out the construction of any new dams and reservoirs until at least 2055 (Rowlinson, 2012).

"Australia, the driest inhabited continent, has the highest per capita surface water storage capacity of any country in the world with over 84,800GL available storage" (Adelaide, 2016). Until recently Australia's water supply was almost entirely from precipitation even though the rainfall was very capricious. Because of the variability of rainfall, most cities rely heavily on dams and water storage mechanisms with a large capacity to provide water to their residents (Sahin, 2015).

> "Desalination provides a stable, high-quality, and climate-independent water source. As discussed, the desalination process is inherently energy intensive. And if energy for desalination comes from fossil fuels as it currently does in Australia, it is also very intensive in terms of greenhouse gas emissions. In a potentially carbon constrained Australian economy in the medium to long term, for desalination to be considered a sustainable water resource, it needs to utilize energy in a sustainable way. In this context, renewable energy can play an important role in the future in desalination of water" (Rowlinson, 2012).

Israel Background

"In 1999, the Israeli government initiated a long-term, large scale SWRO (Seawater Reverse Osmosis) desalination program. The program is designed to provide for the growing demands on Israel's scarce water resources, and to mitigate the drought conditions that have characterized most years since the mid-1990's" (Tenne, 2010). Prior to that, water was a national security issue for Israel from the beginning, when it was founded in the wake of World War II. Periodic droughts struck the country as its population and its industrial and agricultural sectors grew rapidly. A severe drought in the 1990s led to a water crisis and to technological innovation (Freemark, 2016). “Israel’s desalination facilities are essential to sustainable potable water supplies in the State, since they supplement the severely limited natural resources to a level that meets existing national potable water demands” (Tenne, 2010).

A dry spell lasting from 1998 to 2002 drastically depleted the country’s major underground aquifers. In response, the government banned washing cars with garden hoses and encouraged people to take shorter showers. It focused on recycling sewage and wastewater to irrigate farm fields (Talbot, 2015). Israeli seed companies became leading developers of hybrid crops that required less water to grow. It also launched a $2 billion program to build five massive seawater desalination plants, the most recent one going online in 2015 (Freemark, 2016).

According to an article from *Desalination and Water Treatment* on the use of renewable fuels, “Israel currently has no other option for the expansion of its water supply. Israel would do best to increase its overall energy capacity for desalination through the development of renewable energy. The use of renewable energy for desalination has the potential to mitigate many of the negative effects of conventional desalination. The use of renewable energy guarantees a reliable supply of affordable water.” Desalination is the only choice for Israel. In that case, “it is important that the construction of every new desalination plant is accompanied by an Environmental Impact Assessment, in order to evaluate and minimize the negative effects of desalination plants on the environment” (Meindertsma, 2010).

United States/ California Background

California has a long history of drought and water supply shortages. Climate change and growing population will increase the demand for clean fresh water (Seawater Desalination., 2016). Historically, Southern California has relied heavily on water that is transported from the Sacramento- San Joaquin Delta and the Colorado River because of its particularly arid landscape and large population. Southern California continues to search for alternate sources of fresh water because most of the sources used thus far have been over extracted and has almost caused ecosystem collapse. (Grants, 2013).

"As of May 2016, there are nine active proposals for seawater desalination plants along the California coast, as well as two additional proposed plants in Baja California, Mexico that would provide water to southern California communities. This is down from an estimated 21 proposed projects in 2006 and 19 in 2012" (P.I. 2016). In order to expand their water portfolio, the California Water Authority wanted to shrink the districts dependence on the Colorado River and Bay Delta by starting the commercial operation of a seawater desalination plant. In doing so, the commercial plant provides a way for the region to be less vulnerable to droughts and natural disasters. It is the nation's largest seawater desalination plant. (Seawater Desalination The, 2016).

Physics of Desalination

There are currently two major types of desalination methods in use. The first is Thermal Distillation, which include the multi-stage flash method, as well as multiple effect distillation. These processes use excess heat from power plants to distill the water (Freyberg, 2013). The other method is reverse osmosis, which is the most popular method being proposed for future use. Reverse osmosis (RO) is a technology that “works by using a high pressure pump to increase the pressure on the salt side of the RO and force the water across the semi-permeable RO membrane, leaving almost all (around 95% to 99%) of dissolved salts behind in the reject stream” (Ultrapure, 2016). RO is an “energy-intensive process, requiring approximately 4 kWh of energy to desalinate one cubic meter of water” (Shalaby, 2017). 64% of world's desalinated water comes from multistage flash distillation (MFD) plants, though Reverse osmosis plants and other type of desalinators outnumber MFDs (Seawater, 2016).

Thermal Technology	Membrane Technology
Multi-Stage Flash Distillation (MSF)	Electrodialysis (ED)
Multi-Effect Distillation (MED)	Electrodialysis reversal (EDR)
Vapor Compression Distillation (VCD)	Reverse Osmosis (RO)

The main forms of desalination are split into Thermal Technology and Membrane Technology. The state of the art method is Reverse Osmosis and is used by all three case studies in this thesis. Figure from (Krishna, 2006)

The major energy requirement is for the initial pressurization of the feed water (Krisha, 2006). “In the RO process, water from a pressurized saline solution is separated from the dissolved salts by flowing through a water-permeable membrane. The liquid flowing through the membrane is encouraged to flow through the membrane by the pressure differential created between the pressurized feed water and the product water, which is at near-atmospheric pressure” (2.1 Desalination). “The theoretical absolute minimum amount of energy required by natural osmosis to desalinate average seawater is approximately 1 kilowatt-hour per cubic meter (kwh/m3) of water produced, or 3.8 kilowatt-hours per thousand gallons (kwh/kgal). The actual seawater reverse osmosis energy requirement in the 1970's was 7.0 to 9.0 kwh/m3 (26-34 kwh/kgal)" (Membrane, 2016)

Desalination and renewable energy

For the purpose of this thesis I will use the International Energy Agency's definition of renewable energy; all forms of energy produced from renewable sources in a sustainable manner, which include bioenergy, geothermal energy, hydropower, ocean, solar, and wind energy. In an evaluation of a multi-skid reverse osmosis unit operating at fluctuating power input, the most mature technology appears to be reverse osmosis driven by photovoltaics. The "power input originated from photovoltaics (PV) of capacity ranging from 10 up to 20kWp, showing that it is suitable to combine RO with renewable energy sources with strong intermittent power production" (Ntavou, 2016).

There have been remarkable developments in desalination technologies even though the uses of them are still limited because of the minimum energy requirements, which are normally met by using fossil fuels. Since renewable energy is used to produce electricity power, then is can be used to power desalination plants. Due to the upward demand for water desalination, alternate energy sources will need to be introduced (Ghaffour, 2015).

> "An RO desalination unit can be powered by renewable energy sources such as wind and solar energy. However, the power that derives from these sources can strongly fluctuate, since it depends on the weather conditions and/or available solar radiation. As the available power production fluctuates, the water feed and the production of permeate also fluctuate. Therefore, flexibility concerning the RO unit is required, in order to operate

efficiently, ensuring the good quality (low salinity) of the produced fresh water" (Ntavou, 2016)

The photovoltaic (PV) powered RO desalination system is a practical method of providing fresh water. PV technology developed in the last decade has become available at a reasonable price. Most of the RO plants around the world are using PV systems due to its low price compared with solar thermal plants (Shalaby, 2017). "As such, renewable energy generation should be seen as a valuable economic investment that reduces external, social, environmental and operational costs" (Grubert, 2014).

Literature Review

Desalination technologies have received a lot of academic and new attention in the past years. However, the concept remains loose and many different conversations surrounding the projects emphasize either cultural, environmental or economic impact on the communities they are implemented in. The majority of the academic research refers to the actual technology such as reverse osmosis that is involved in desalination, and the economic implications associated with desalination.

There have been thousands of newspaper articles written about seawater desalination. It seems to be a topic of interest for many local and national newspapers, although only few of them discuss the potential environmental impacts of the desalination plants. Mostly, the dialog used for newspaper outlets is excitement and enthusiasm for the technology being developed that will help supply their water needs. There is mention of the costs of the desalination plants and the amount of energy required to power the plants.

Economic Research

There are many sources that summarize and compare the economics behind every desalination project. The academic research that has been done on desalination shows that there are several factors that affect desalination cost. Over all, cost aspects connected with employing a desalination plant are site specific and hinge on on several variables. A number of models exist for appraising desalination costs. Model applications are typically limited to site specific circumstances and provide ballpark estimates. “Cost models can be used as an indicator of potential costs for planning a desalination facility” (Younos, 2005). Despite some successes, one of the biggest concerns with desalination on a commercial scale is the cost effectiveness, which in turn depends on the design and implementation of the desalination plan and the region where it is implemented.

Social and Cultural Research

Finding academic research on the social and cultural implications of desalination projects is more challenging than research on the topics of economics or environmental associations, regardless of the country they are taking place in. Perhaps this is because it is harder to quantify this type of research for a government publication to be released to the public. Some reports make mention of how communities surrounding these projects could potentially be inconvenienced, particularly with noise, but none was written with the sole purpose to express social or cultural ramifications (Gude, 2016).

Environmental Research

The literature on the environmental aspect of desalination projects is best described by Sadhwani, Veza, and Santana in their article "Case studies on environmental impact of seawater desalination" showing "that there are several effects to be considered in desalination plants, such as the use of the land, the groundwater, the marine environment, noise pollution and the use of energy, amongst others" (Sadhwani, 2005). Many case studies demonstrate the equipment used in the desalination of seawater is complemented by adverse environmental effects.

Before any desalination projects begin the building process, an environmental impact assessment must be done first. The parameters of these assessments differ slightly depending on which country the desalination plant will be built, but their purpose is to assess and reveal potential impacts to the physical environment related with building and operation of the proposed project. The reports are often prepared by the city to quantify and analyze probable impacts on the surrounding geology, hydrology, air quality, noise, aesthetics and traffic.

Renewable Energy and Desalination

Most of the literature tying renewable resources to desalination is in peer reviewed journals and have been written by engineers. They focus on meeting the demand for energy in desalination through very specific types of renewables including different types of solar and wind technologies. Many of the articles are about desalinating brackish water because it is not as energy intensive, but there are a number of articles and reports connecting desalting water and renewables. There are many articles that cover the energy consumption desalination requires, and some articles compare them much like an article from *Chemical Industry Digest* (Seawater Desalination Processes, 2016). The research covering renewables seems fairly recent mostly in the last five years and largely focusses on the role that solar-aided desalination plays in current markets as well as the role technology will play in the future of desalination because at present that is the technology that is being most heavily invested in (Grubert, 2016).

Wrapping up

Given the current trends, the scale of desalination is likely to grow, creating new demands and circumstances for desalination to be utilized. Desalination is a promising concept that has potential to become a conventional water management tool, though it comes at a cost. “The planning, construction, and long-term operation of desalination facilities involve daily challenges, decision-making processes, and creative innovations that maximize the efficiency of each new (and always unique) facility. The desalination industry’s continuing success in overcoming each new challenge is the key to achieving sustainable national water use with independent national water resources” (Tenne, 2010).

Methods

My method is a comparative analysis of the leading desalination plants in Australia, Israel, and the United States using scientific reports and figures put out by the desalination plants themselves to determine which characteristics of the plants have made them so successful, and stand out on a global scale. The purpose is to collect complete, methodical and in depth information about each case of interest and introduce the idea of implementing renewable resources as a main energy source. By loosely following Bardach's 8 fold policy analysis procedure I will define the problem, assemble evidence, construct alternatives, select criteria, project outcomes, and confront tradeoffs, decide, and give my recommendation for three desalination projects around the world with regards to renewable energy. I will use the same criteria to examine each of the three case study plants, Carlsbad Desalination Project in California, Sorek Desalination Plant in Israel, and Adelaide Desalination Project in Australia. This will compare the effects of the plants on the environment and economy. After examining these characteristics I will condense them into a visual chart that will go in the results section.

This will compare characteristics including:

- cost of construction and operation
- energy consumption
- energy source
- emissions
- output of water (in mL)
- length of operation
- sources of funding
- recipients of water

Data		Claude Lewis Carlsbad Desalination Plant	Port Stanvac Desalination Plant Adelaide	Sorek Desalination Plant, Israel
	Date of Operation	December 2015	March 2013	October 2013
	Cost to build (USD)	$1 billion	$1.83 billion $328 million has been paid by the Australian Government	$500 million
	Production Size/ Plant capacity	190,000 m³/day	230,000m³/day	624,000m³/day, World's biggest seawater desalination plant.
	Percentage of needs met	~7% of San Diego county water supply 500,000 people ~ 38% according to Carlsbad's website	~50% of Adelaide's domestic water supply	~20% of Israel's municipal water demand. 1.5 million people
	Energy consumption	28.1 aMW, or 246,156 MWH per year.	3.47 to 3.70 kilowatt-hours of electricity per kilolitre of water produced	0.50 EUR/m3
	Source of energy	Encina Power Station (EPS)? large natural gas and oil-fueled electricity generating plant. Partner with them to use seawater for cooling power plant	AGL Energy one of Australia's integrated energy companies -natural gas	The Sorek plant has its own independent power plant to generate energy for operation. Excessive energy produced is sold to the national power grid. -natural gas
	Who owns it	South Australian (SA)Water Owned by South Australian Government	AdelaideAqua Pty Ltd, a company owned equally by ACCIONA -Investments from AU gov't	IDE Technologies 51% Hutchinson Water International Holdings Pte. Ltd: 49%

Carbon footprint (1.6kg CO_2 per m^3)	61,004 metric tons of CO_2 per year.	134,302 metric tons of CO_2 per year.	364,416 metric tons of CO_2 per year.
Percentage of total energy generated by renewable resources in country	14.27%	13.47%	2.5%

Discussion

The primary advantage of desalination is that seawater is an unlimited supply, and for some countries it is the only access to fresh water available. Disadvantages include the amount of energy required for reverse osmosis, high cost of investment and operation, and the environmental costs of brine discharge.

Relevant factors for the successes of these projects include the timing and placement of the desalination projects. These are perhaps the most influential factors because of the resources available at the time of planning for these projects. The next biggest factor in the success of these desalination projects is the demand for desalination. The demand for fresh water is the entire reason desalination is relevant at present time, and the desalination plants in these case studies have been placed in areas of high demand.

Unique Factors Case by Case Study

Carlsbad, California: Of the three case studies, Carlsbad was the least expensive to operate, though it also produces the least total amount of water for its region, meeting about 7% of San Diego's needs. To reduce the energy they consume, the desalination plant partners with the neighboring power plant, Encina Power Station to help cool the power plant. The seawater is warmed during this process and in turn the desalination process doesn't require as much energy as it would if the water were the temperature it was coming straight out of the ocean. The Carlsbad plant also gets their energy for desalination from Encina Power Station, so they have developed a symbiotic relationship. Carlsbad is the only case study that was planned to partner with an adjacent power plant that is not owned by the same company that owns the desalination plant, making it a unique scenario for the future of renewable energy powered desalination.

Lastly, this desalination plant was viewed as a pilot plant to see if seawater desalination could work at this scale in California. Since it is considered to be successful and the entirety of the demand for fresh water still isn't met, there are plans to build even more desalination plants similar to Carlsbad along the coast of California. Compared to Australia and Israel, California has only just begun the movement towards large scale desalination as a primary fresh water resource, meaning that there is plenty of room for renewable resources to be implemented into future plans. Carlsbad will likely be used as a model for future desalination projects throughout California and the country so they are setting the tone for how renewables can be utilized to help provide clean energy to a process that requires so much.

Adelaide, Australia: This project is owned and operated by a Southern Australia's water supplier called South Australian Water (SA Water). It is the only plant of the three case studies that is completely owned and operated by the state. This is particularly interesting because the governments of the U.S.A. and Israel have invested in the initial construction of infrastructure but there is no further investment in the operational costs or function of the plants. This leads me to believe that the government of Australia considers desalination to be a vital part of the safety for its people and security for the future.

Acciona, a "Spanish conglomerate group dedicated to the development and management of infrastructure and renewable energy" has played a vital role in getting the desalination plant up and running (Acciona, 2017). Though Acciona does not have anything to do with the ownership or operation of this plant, they did invest quite a bit of money in the preliminary stages of this project. Since Acciona is so involved with renewable energy, perhaps they might invest even more into introducing sustainable solutions like renewables.

Adelaide's desalination plant is the only case study that buys all of its energy off the grid like any other commercial company would. This project does not partner with an energy plant to save energy, but Adelaide has a more intense pretreatment process that allows the desalinating process to be less energy intensive than if it didn't have the pretreatment process.

This plant is also unique because it gives 6GL per year to the Murray River, which is where Adelaide got its drinking water from before the installation of the desalination plant. They do this to help attempt to return the river to its normal flowing level since it has reduced in the past decades of drought. This reduces the plant's environmental impact and reliance on the river.

<u>Sorek, Israel</u>: This project is privately owned by two companies that have a long history with desalination projects. The neighboring energy plant is owned by the same companies, so the desalination plant works very closely with the power plant to meet everyone's needs. Together

they employ an energy recovery system for increased productivity and reduced energy consumption. This case is unique because of how closely they work with the government to provide drinking water, yet the Israeli government agency Water Desalination Administration does not actually have any part in ownership. It is also worth pointing out that the United States, nor Australia have a government agency entirely dedicated to desalination. Because of this I think Israel's government would be more willing and able to invest in renewables due to the governmental resources that are already present in order to progress desalination in Israel even further.

Conclusions & Recommendations

According to the International Renewable Energy Agency, "current information on desalination shows that only 1% of total desalinated water is based on energy from renewable sources. Renewables are becoming increasingly mainstream and technology prices continue to decline, thus making renewable energy a viable option" (Aroussy, 2016). Carlsbad, Adelaide, and Sorek are all located in arid regions where there is plenty of sun, so they could potentially utilize solar energy to contribute to the energy needed for desalination. Also since the desalination plants are right on the coast already, there has been talk of utilizing tidal energy or off shore wind power to self-generate electricity to support reverse osmosis. Renewable energy powered desalination could be a significant tool for sustained development, especially as countries scale down their use of fossil fuels.

Of the case studies I have presented I would recommend Sorek in Israel to be the best fit for implementing renewable energy powered desalination. From what I have collected, all of the stakeholders are enthusiastic and eager to be on the cutting edge of desalination technologies and confident in taking risks to move towards sustainable goals. Of the three country's governments, Israel seems to have the least "red tape" surrounding desalination policies, making it easier to implement and amend desalination projects. All desalination projects need to be well funded, but it appears that people are especially willing to push to get things done in this region. From what I can tell the biggest difference between Israel and the two other countries is that the people living in Israel have a huge appreciation for water and recognize how valuable desalination is for their people.

Of the energy Israel uses, 2.5% is from renewable resources as of 2014, so implementing renewable resources as a sources of energy would help them attain their goal of 10% from renewable resources by 2020 (Udasin, 2016). Since the Sorek plant already generates all of its own energy and sells back the extra to the grid, they could possibly introduce renewable resources as a another source of revenue since they already have the means to sell energy back to the grid.

Although I think Sorek would be the best fit for renewable resources to be employed on a large scale project, I also think renewables could be used at the desalination plant in Adelaide, Australia because at present they do not have any way of supplementing the energy they buy off the grid. The governing bodies in each country all invested in the initial infrastructure to employ the desalination plants, but Australia has the most involved government by far, meaning they could very well get the funding to be able to invest in renewables and not rely so heavily on energy bought from the grid, which is natural gas.

Perhaps the cost of implementing renewable resources to power desalination will be lower with intensive planning and proactive vision. While renewable resources have been successfully integrated elsewhere in the world, it might not be cost effective to apply renewables in any of my three case studies at present day, but it is definitely worth looking into for future desalination projects with proper planning. With government investment and subsidies to produce fresh water, it is a viable option to power desalination plants with renewables.

Desalination is comparable to the solar industry in the way that solar needed to be subsidized heavily in the beginning to bring the cost down and make it more affordable for anyone using it. This is also true for desalination so either investments need to be made in improving the membrane technology to improve the efficiency and lower the minimum energy required to break the salt water bond, or the investments need to be made in the supply of the energy. Either way the carbon footprint of the desalination plant would be reduced, but it would be more logical to invest in clean energy because the technology for that is already available, it just needs to be applied to the cause.

While brine discharge is the focus of a lot of the push back coming from environmental groups, the real environmental cost comes from the amount of CO_2 released in the process of providing energy to break the salt water bond. It seems the simpler solution to providing fresh water to these cities would be to recycle and reuse fresh water that is already in the system instead of introducing new water that after one use will end up as wastewater, and eventually end up in the ocean again. It is possible to strike a balance between the energy consumed by the process of desalination and the impact of the emissions from the process, but perhaps it might be even more effective to make the most with the water that is already salt free and find new ways to better utilize what it already available.

The way things function right now with the desalination plants getting power from fossil fuels seems to be counter intuitive to the system they are working in response to. The reason desalination plants at this scale are built in the first because long lasting droughts caused by climate change made water availability an issue, but by using non-renewable resources to power these plants they producing CO_2 and enhancing climate change. Desalination plants that are not using renewables are creating a positive feedback into the system that helps create the problem that large scale desalination stemmed from, so it doesn't make sense to continue building huge desalination plants in the future that emit so much CO_2 from the sources of energy. All three case studies are primarily fueled by natural gas, which compared to other non-renewable resources does not emit as much CO2, but since these desalination plants are producing on such a large scale they are also emitting carbon on a large scale as well. Based on this information, there should be a push to power desalination plants by renewable energy.

Is the brine usable or could it be treated for human consumption? It is similar to sea salt we can buy in stores. Maybe there is a different use for the brine, so that it doesn't need to be paid for to be taken back into the ocean. This way it would save energy from the desalination plant and they wouldn't face so much backlash from environmental groups concerning the negative effects of brine on marine life. According to the Carlsbad Desalination Plant's Webpage on process FAQs, the "amount of salt generated is too great to be processed at the project site while the amount of mineral is too small to justify the expense of additional processing" (Water S, 2016).

Another consideration is the human health effects from desalinated water. Since the process of desalination strips all minerals from H_2O, good or bad, it is necessary for some minerals to be added back into the water to meet drinking water standards. It would be interesting to explore whether or not there are any health consequences from drinking desalinated water. Since it is pumped throughout cities with the rest of the water supply I would assume it is well mixed with water from other sources that are trusted by people to drink, so if there are any adverse effects they would be minor.

Moving forward, desalination and renewable resources could be a viable option for providing fresh water to the global population, especially on small scale operations. It would take immense planning and development to implement renewables on desalination plants that already have operating infrastructure, particularly ones that were designed to work with adjacent power plants, though it is still possible. I have explored the option for implementing renewable resources into three different large scale desalination plants around the world and compared factors of success. The most compelling were investors, government involvement, and partnerships with adjacent power plants. Desalination is a growing industry for Australia, Israel, and the United States, so making a shift towards powering desalination plants by renewable resources to reduce their part in climate change only seems logical.

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Appendix

The source in each of these boxes corresponds to the facts in each of the boxes on the data table

SOURCES	Claude "Bud" Lewis Carlsbad Desalination Plant	Adelaide Desalination Plant	Sorek Desalination Plant, Israel
Date	(Seawater Desalination The Claude, 2016)	(Adelaide, 2016)	(Sorek, 2016)
Cost to build	(Seawater Desalination The Claude, 2016)	(Grants, 2013)	(Talbot, 2016)
Production Size/ Plant capacity	(Carlsbad, 2016)	(Water, n.d.)	(Talbot, 2016)
Percentage of needs met	(Seawater Desalination The Claude, 2016)	(Adelaide, 2016)	(IDE, 2014)
Energy consumption	(Seawater Desalination The Claude, 2016)	(Adelaide, 2016)	(IDE, 2014) (Talbot, 2016)
Source of energy	(Carlsbad, 2016)	(Water, n.d.)	(Sorek,2016)
Who owns it	(Seawater Desalination The Claude, 2016)	(Adelaide, 2016)	(Sorek, 2016)
Carbon footprint	Calculation based on (Cooler, 2013)	Calculation based on (Cooler, 2013)	Calculation based on (Cooler, 2013)
Percentage of renewable energy per country	(Total, 2014)	(Total, 2014)	(Total, 2014)

Title lines from "The Rime of the Ancient Mariner," by Samuel Taylor Coleridge, 1834.