Dear Dr. Kassam,

We are enclosing our multi-disciplinary engineering report entitled *Desalination: Breaking the Energy Barrier*. The report outlines work involving team members from various engineering disciplines. The project aims to decrease the energy consumption associated with seawater desalination by implementing energy-efficient desalination techniques on the industrial scale and by hybridizing renewable energy sources with the desalination process.

The report contains a collaborative work from civil, mechanical and electrical engineering disciplines. The current situation of the nexus of water and energy has been discussed. The problems of water scarcity and energy intensive nature of the conventional desalination methods have been highlighted. Several alternative desalination methods have been presented as viable solutions to the posed problems. At the end, all the alternative desalination techniques presented have been evaluated based on the energy and cost savings as well as the environmental benefits.

We would like to pay our gratitude to Dr. Hamada Kassam for his encouragement and guidance. His constructive criticism and remarkable comments have significantly contributed to the improvement of our project. We would also like to thank Mrs. Alanna Ross for introducing us to engineering databases. We are also obliged to Dr. Kazi Fattah and Dr. Maruf Mortula from the civil engineering department who helped us in understanding the need of energy-efficient desalination techniques.

The secondary sources for conducting our research were obtained from the AUS library. These sources included books, journal articles and databases, and graduate theses. The *Compendex* database was used to access the abstracts of all the scientific articles related to desalination. In addition, *Science Direct*, *Access Science*, and *IEEE Xplore* were used to retrieve full text published articles.

We hope that our report meets all the criteria for constructing a multi-disciplinary engineering project report. Any queries or concerns will be welcomed via email by contacting Fatima Iqbal at g00041551@aus.edu.

Yours sincerely,
Fatima Iqbal

*Desalination: Breaking the Energy Barrier* Team

Encl.: Desalination: Breaking the Energy Barrier Project Report
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Executive Summary

The problem of fresh water scarcity and increasing fresh water demand has intensified in many countries as a result of unchecked population growth and the expanding industrial and agricultural sectors. In order to alleviate water scarcity in dry regions of the world, a variety of desalination technologies have been developed that use the ocean as a source of producing pure drinking water. Among these desalination technologies, multi-stage flash evaporation and reverse osmosis represent the conventional desalination methods that have been employed on a global commercial scale. The objective of this report is to decrease the cost and energy consumption associated with the production of pure drinking water by examining energy-efficient alternatives to seawater desalination. The main methodology for this project was document searching using databases, books, and graduate theses. This type of methodology provides up-to-date information and ongoing scientific research on the topic of desalination.

The problems associated with the conventional desalination technologies are two-fold. First, both multi-stage flash evaporation and reverse osmosis are expensive and energy intensive. These two conventional desalination techniques use large amounts of thermal or electrical energy that significantly increases the cost of seawater desalination. Secondly, the conventional desalination methods result in the formation of a highly concentrated brine solution. The high temperature as well as the high salt content of the brine result in a disturbance in the aquatic environment once it is discharged into the ocean.

With regard to the aforementioned problems, the team has proposed the following feasible solutions: the hybridization of renewable wind and solar energy with the seawater desalination process, and the introduction of forward osmosis as an energy-efficient and sustainable desalination technique.
The energy consumption in the conventional desalination technologies can be reduced by the production of either thermal or electrical energy from solar energy using solar panels or photovoltaic cells. The solar generated thermal or electrical energy can then be used to operate the conventional desalination processes at a reduced cost. Similarly, electrical or shaft power can be generated from wind energy that can be used to operate reverse osmosis at a reduced cost. In addition, forward osmosis can be used to extract water from the saline feed into the aluminum sulfate draw solution without use of any energy. After the extraction of water into the draw solution, pure drinking water can be produced by the reaction of the aluminum sulfate solution with the calcium hydroxide solution to remove all the soluble salts as insoluble precipitates.

The report recommends the adoption of the three solutions mentioned above as viable alternatives to the current seawater desalination technologies. The proposed solutions will help supplying pure drinking water to the public at a cheap rate with increased energy efficiency.

The major limitation of this report is the lack of an economic analysis to estimate the capital cost of the alternative desalination technologies. Although the energy cost of the proposed solutions is less, the investment cost of the alternatives must be compared with the conventional seawater desalination processes.
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Glossary

AC: Alternating current

Brine: It is a solution of salt and water

Desalination: It is a process of separating salt particles from saline water to obtain pure water

DC: Direct current

Distillate trough: A container in which pure water is collected

Draw solution: High concentrated salt solution

FO: Forward osmosis

Heat Exchanger: It is a device through which heat energy is transferred efficiently from hot medium to cold medium.

kWh: Kilowatt per hour

MSF: Multi Stage Flash evaporation

Permeate: It is the penetration of liquid, vapor or gas particles through a solid medium

Photovoltaic: The process of converting solar radiation into direct current to generate electrical power

Potable water: Safe drinking water

RO: Reverse osmosis

Renewable Energy: Energy derived from sources which are replenished naturally such as sunlight and wind.

Semi-permeable: It allows only some molecules or ions to pass through, while the other particles are retained back

Solar collector: A device designed to collect heat energy from the sun

Thermal fluid: A fluid that has high heat storing capacity
1. Introduction

1.1. Situation

Pure drinking water is an essential resource for humanity and the rest of the living world to create a sustainable healthy environment. Water is also vital to the growth of a number of economic sectors including the industrial and agricultural sectors. Although approximately three quarters of the earth’s surface is covered with water, pure drinking water is a scarce resource since it accounts for only less than 1 percent of the total water present on the earth. Approximately 97 percent of the earth’s water is present in the sea while the remaining 2 percent is locked in the form of glaciers and icecaps [1]. Over the past few decades, alleviation of global water scarcity has become a challenge for the scientists and engineers since the scientific community has become increasingly aware of the role fresh water plays as a vital resource. In fact, the problem of fresh water scarcity and increasing fresh water demand has been acknowledged worldwide as a result of exponentially growing population and a continuous expansion in the industrial and agricultural sectors. According to statistics, about three billion people around the world have no access to satisfactory quality and quantity of safe drinking water [2]. In addition, with the increasing population and growing industrial and agricultural activities, the demand of water has intensified in many countries especially in the Middle East and North Africa [3]. According to statistical projections, more than two-thirds of the population may experience severe shortage of fresh water by the end of the year 2025, thus practically affecting every nation of the world [1].

In order to meet the increasing fresh water demand, a number of seawater desalination technologies have been developed to produce potable water from seawater. However, the conventional seawater desalination techniques that are of commercial importance are multi-
stage flash evaporation (MSF) and reverse osmosis (RO) [3]. Today, high energy consumption in the process of seawater desalination makes it a costly process for the production of pure drinking water. Therefore, alternative desalination techniques are required in order to meet the increasing fresh water demand and supply fresh water at a cheap rate.

1.2. Purpose

This report presents energy-efficient desalination technologies that will help reducing the energy consumption associated with seawater desalination. The objective of this multidisciplinary project is to economically meet the increasing fresh water demand and to provide drinking water to the public at a reduced cost. This report aims to address the following essential research question: How can the cost of seawater desalination be reduced by implementing energy-efficient desalination techniques on the industrial scale and by hybridizing renewable energy sources with the desalination process?

1.3. Scope

This engineering multi-disciplinary project combines knowledge of three engineering disciplines: civil, mechanical, and electrical. By coordinating all the three disciplines, energy-efficient alternatives to seawater desalination have been presented. The percentage reduction in energy consumption for each alternative has also been estimated. However, the report does not consider the investment cost of the alternative desalination technologies.
2. Background – Conventional Desalination Technologies

Seawater desalination technologies or processes are mainly classified into the following two types:

1. Thermal processes that are based on physical change in the state of the water or evaporation by application of heat
2. Membrane processes that employ a semipermeable membrane to separate the soluble salts present in the seawater

The thermal seawater desalination processes include multi-stage flash (MSF), multiple-effect distillation (MED), and vapor compression (VC) [4]. Membrane processes, on the other hand, include reverse osmosis (RO) and electrodialysis (ED) [5]. These desalination technologies are highlighted in Figure 1 [6].

![Seawater Desalination Processes](image)

**Figure 1: Main desalination processes [6]**
However, among all the seawater desalination technologies, multi-stage flash evaporation (MSF) and reverse osmosis (RO) dominate the desalination markets around the world. As depicted in Figure 2, the MSF process accounts for 26 percent of the total desalinated water produced in the world. On the other hand, RO is the most widely used desalination technology with 60 percent share in the desalination market [7].

![Figure 2: Total worldwide installed desalination capacities by technology, 2010 [7]](image)

Understanding the problems associated with seawater desalination requires a knowledge of the working principle of the MSF and RO processes. A brief description of the conventional seawater desalination processes is presented below.

### 2.1. Multi-stage Flash Evaporation (MSF)

The process of multi-stage flash evaporation is based on the principle of distillation. The pressurized seawater feed is heated using thermal energy obtained from steam. The steam is generally produced by burning fossil fuels such as coal and natural gas. When the heated seawater feed is discharged into a flash chamber maintained at a pressure lower than the vapor pressure of water, a fraction of the feed flashes to produce water vapors. The water vapors are subsequently condensed by the seawater feed flowing in heat exchanger pipes in
the upper section of the chamber to produce pure water. The partial vaporization of the seawater feed results in the formation of more concentrated brine solution. The brine solution flows to a second flash chamber where the pressure is further reduced to produce more water vapors. A typical MSF plant usually contains 4 to 40 flash chambers [8]. The condensed vapors from all the chambers are collected as pure product water. The MSF process also produces a highly concentrated brine solution as a waste stream that is discharged into the ocean. Figure 3 shows the schematic diagram of the MSF process [6].

![Diagram of a multi-stage flash distillation (MSF) unit](image)

**Figure 3: Diagram of a multi-stage flash distillation (MSF) unit [6]**

### 2.2. Reverse Osmosis (RO)

Today, reverse osmosis is the leading desalination technology around the world. The process of RO employs a porous semipermeable membrane that allows only water molecules to permeate though it. The seawater feed is pressurized up to a pressure of 40-82 bar (600-1200 psi) [9]. The application of a high pressure forces the water molecules to permeate through the pores present in the membrane. The membrane, however, does not allow the salts to pass through it and the permeate water is collected as the product. The working principle of the reverse osmosis process is shown in Figure 4.
In case of a continuous flow industrial RO process, the application of high pressure requires the use of a high-pressure pump. This is shown in Figure 5.

Figure 5: Continuous RO process

The process of RO is only able to permeate 35 to 60 percent of the water present in the seawater feed [9]. The remaining feed is discharged back into the ocean in the form of brine.
3. Problems Identification and Discussion

3.1. High energy consumption (MCE and ELE)

Historically, the conventional seawater desalination methods have been the most expensive way to produce commercial quantities of potable water because of the high energy costs. As described in the previous section, the process of MSF requires a large amount of heat energy to evaporate the seawater feed. Typically, an industrial scale MSF desalination plant requires 80.6 kWh of heat energy per cubic meter of desalinated water produced [10]. This high thermal energy requirement significantly increases the energy cost of the MSF process. In addition, the thermal energy cost is highly dependent on the price of the natural energy sources such as crude oil, coal, and natural gas. This is because the heat for the MSF process is usually obtained from steam which is produced by burning these fossil fuels. The increasing price of the natural energy sources further increases the energy cost of the MSF process. As depicted in Figure 6, the price of the crude oil is expected to increase at exponential rates over the coming decades [11]. The increasing fuel prices further intensifies the problem of high energy cost of the MSF process.
Similarly, in case of RO, the production of potable water requires large amount of electrical energy for the operation of the high-pressure pump. In fact, a typical industrial RO process requires 3.5-5 kWh of electrical energy per cubic meter of desalinated water produced [10]. This high electrical energy requirement makes, therefore, RO a costly process for producing commercial quantities of potable water.

As a result, both of these conventional desalination methods are expensive since they require a large amount of either thermal or electrical energy in order to furnish potable water. In addition, the energy-intensive nature of these conventional desalination methods has resulted in huge economic spending in water-stressed countries including the Middle East and the UAE [3]. In fact, the UAE spends approximately Dhs 11 billion per year on desalination [11]. In short, the high thermal or electrical energy requirement in the conventional seawater desalination methods creates a room for the scientists and engineers to investigate alternative and energy-efficient desalination technologies that require less or no energy for the production of pure drinking water from seawater.

Figure 6: World crude oil price projection [11]
3.2. Environmental impacts of the brine (CVE)

The use of the MSF and RO processes on a global scale has been associated with several potential environmental impacts, the most important of which is the open discharge of the brine solution into the aquatic environment [12]. The brine solution is usually more saline that the raw seawater feed and is discharged into the ocean at an elevated temperature [12]. Upon discharge into the ocean, the brine solution has the potential to degrade the physical, chemical, and biological characteristics of the receiving water body [12].

The high salt concentration of the brine solution results in serious disturbances in the marine ecosystem. Usually, the salts present in the brine solution increase the salinity level of the receiving water bodies causing the salts to deposit at the bottom of the oceans and rivers. In many cases, the high temperature and salt concentration clog the gills of the fishes resulting in migration or death. Therefore, it becomes necessary to investigate sustainable and eco-friendly desalination techniques that allow for high pure water productivity and minimum production of the waste brine solution.
4. Solutions

4.1. Hybridization of seawater desalination with renewable energy systems

Using desalination technologies driven by renewable energy sources is a feasible method to produce pure drinking water with reduced cost and energy consumption. The two types of renewable energy sources that can be hybridized with the seawater desalination include solar and wind energy.

4.1.1. Desalination using renewable solar energy

Solar energy can be directly or indirectly harnessed for seawater desalination. Systems that use solar energy directly to produce pure water are called direct collection systems or solar ponds. On the other hand, indirect solar desalination involves generation of thermal or electrical energy from solar energy for use in the conventional desalination processes such as MSF and RO.

4.1.1.1. Solar stills

A solar still is a simple basin that is constructed using a support structure, transparent glazing, and distillate trough [6]. The working principle of a simple solar still is shown in Figure 6.
As depicted in Figure 6, a simple solar still will capture the solar radiation from the sun and the heat from exposure to the solar radiation will result in evaporation of the seawater feed. The vapors will then come into contact with a condensation dip where they will be condensed to give pure water. As evident from the working principle, solar stills will not require the use of either thermal or electrical energy for the production of pure water. The elimination of energy requirement will help reduce the cost of small-scale seawater desalination process.

4.1.1.2. Solar-assisted MSF and RO

Solar energy can be used to generate thermal and electrical energy which allows for the hybridization of these renewable energy sources with the conventional desalination processes such as MSF and RO. Figure 7 shows the possible combination of solar systems with the MSF and RO process [6].
The thermal energy required for the MSF process can be obtained from the solar energy by installing solar thermal plants next to the MSF desalination units. The solar thermal part of the MSF desalination plant will consist of a field of flat plate solar collectors as shown in Figure 8. These solar collectors will collect heat by absorbing the sunlight in the form of electromagnetic radiations. The collected heat will then be used to heat a thermal fluid between 70 and 120 °C. Finally, the heated thermal fluid will be used to vaporize the seawater feed in the MSF process. The proposed solution, as depicted in Figure 9 [7], will reduce the energy cost of the MSF process since the required thermal energy will be obtained from the renewable solar energy.
Figure 9: A field of solar collectors next to a desalination plant

Figure 10: Schematic of solar assisted multi-stage flash desalination process [7]
On the other hand, the operation of the RO system requires a large amount of electrical energy for driving the high-pressure pump. Hybridization of the RO process with the solar energy requires generation of electricity from sunlight. Again, our proposed solution for generating electricity for the RO process from sunlight is the use of solar panels that convert sunlight into direct current (DC) electricity. In this case, the solar panels will be coated with a semiconducting material such as silicon. The exposure of the solar panel to the sunlight will result in flow of electrons due to atomic excitation of the semiconducting material. The flow of electrons will generate a direct current (DC) voltage. The produced DC voltage will be amplified by a DC/DC converter and finally converted to AC voltage using a DC/AC converter. The amplified AC voltage will then be used to drive the high-pressure pump of the RO process. The proposed solution, as depicted in Figure 10 [7], will reduce the energy cost of the RO process since the required electrical energy will be obtained from the renewable solar energy.

![Figure 11: RO pump operation using solar energy](image-url)
4.1.2. *Desalination using renewable wind energy*

The hybridization of the renewable wind energy is possible only with the process of RO since the wind energy is usually inefficient to produce thermal energy required for the MSF process. However, the wind energy can be used to supply power to the RO process using a suitable power production method.

4.1.2.1. *Wind-assisted RO*

Our proposed solution recommends the use of a synchronous generator (SG) system for the conversion of the wind energy into electrical energy. As shown in the Figure 11, the main components of the wind-assisted RO will consist of a synchronous generator (SG), a bridge diode rectifier, a DC/DC converter and a DC/AC converter which is also known as inverter. The blades of the turbine will rotate with the help of the incoming wind. The rotation of the turbine blades will produce mechanical energy which will be fed into the synchronous generator (SG). The synchronous generator will act to convert the produced mechanical energy into electrical energy.

The synchronous generator will contain three phases A, B, and C which will be separated from each other by 120 degree phase shift. Moreover, it will also contain a magnet that will create a magnetic field of its own. After receiving the mechanical energy, the magnetic field will rotate. This rotation of the magnetic field will create three phase alternating current (AC). These currents will then be separated by 120 degree phase shift. After producing the three phase currents, the currents will be received by a bridge diode rectifier. The bridge diode rectifier will then convert the alternating current (AC) to direct current (DC). Since the produced DC current will contain a very low voltage, it will be amplified to a large voltage using a DC/DC converter in order to meet the high electrical energy requirement of the RO pump. The DC current will be received by a DC/AC convert
which will convert the amplified DC voltage to AC voltage. Finally, the amplified AC voltage will be used by the high-pressure pump of the RO process.

Figure 12: RO pump operation using wind energy

Figure 13: Internal function of a synchronous generator
4.2. Forward Osmosis (FO)

Another solution to the high energy cost of the conventional desalination methods is the use of energy efficient desalination techniques such as Forward Osmosis. Recently, FO has been under investigation by the researchers as a potential means of desalinating sea water at reduced cost and energy \[13,14\]. Forward Osmosis is a natural process that involves movement of water molecules across a semi-permeable membrane under the driving force of concentration gradient. Our proposed energy-efficient FO desalination is shown in Figure 14.

![Forward osmosis desalination process](image)

**Figure 14: Forward osmosis desalination process**

The process will consist of a storage chamber that will be divided into two parts using a semipermeable membrane. The sea water feed will be placed on one side of the membrane, while the other side of the membrane will face a highly concentrated aluminum sulfate solution (called the draw solution). This will result in permeation of water molecules through the membrane since the concentration of salts in the draw solution will be higher than that in the feed seawater. The semi-permeable nature of the membrane will not allow the salts to pass through it. After all the water molecules present in sea water permeate into the draw solution, the diluted draw solution will be reacted with calcium hydroxide solution. Upon adding calcium hydroxide solution to aluminum sulfate solution a double precipitation
reaction will take place resulting in removal of all the soluble chemicals as removed as insoluble aluminum hydroxide and calcium sulfate precipitates according to the following reaction:

$$\text{Al}_2\text{(SO}_4\text{)}_3\text{(aq)} + 3\text{Ca(OH)}_2\text{(aq)} \rightarrow 2\text{Al(OH)}_3\text{(s)} + 3\text{CaSO}_4\text{(s)}$$

The precipitates will be allowed to settle and the top water layer will be collected as the pure water product.
5. Evaluation

5.1. Desalination using renewable solar energy

- Hybridizing the conventional seawater desalination processes with the renewable solar energy reduces the energy requirement by 60% and 55% in case of MSF and RO, respectively. The savings in energy are summarized in Table 1 [15].

Table 1: Energy reduction using solar-assisted desalination [15]

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy requirement (kWh/m³)</th>
<th>Energy reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>1.5-2.5</td>
<td>60</td>
</tr>
<tr>
<td>MSF</td>
<td>14.45-21.35</td>
<td>55</td>
</tr>
</tbody>
</table>

- The use of solar energy to produce thermal or electrical energy for seawater desalination is highly suitable for hot and dry arid regions such as the UAE
- The use

5.2. Desalination using renewable wind energy

- Hybridizing the wind energy with the RO process results in significant savings in the electrical energy as shown in Table 2 [16]

Table 2: Energy reduction using wind-assisted desalination [16]

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy requirement (kWh/m³)</th>
<th>Energy reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RO</td>
<td>1.5-2.5</td>
<td>60</td>
</tr>
</tbody>
</table>
• The use of wind energy for desalination is only possible for regions with windy climatic conditions

• The hybridization of wind energy with the RO process is not suitable for the UAE since the region lacks windy weather conditions

5.3. Forward Osmosis (FO)

• Forward osmosis using aluminum sulfate draw solution is highly energy-efficient and does not require either thermal or electrical energy

• Forward osmosis produces a small quantity of brine solution. As a result, the adverse effects of high concentration of brine on the marine life is minimized

• Forward osmosis does not require heating and the brine solution is discharged into the sea at ambient temperatures. Hence, the adverse effects of the high temperature of the brine on the marine life is eliminated
6. Recommendations

6.1. Laboratory-scale evaluation

All the alternative desalination techniques presented in this project must be evaluated using laboratory experiments. The laboratory performance of each alternative must be compared with the conventional desalination processes.

6.2. Pilot-scale evaluation

In case if the proposed solutions perform well in the laboratory, pilot-scale desalination plants must be constructed. The pilot-scale experiments will help in evaluating the performance of the proposed solutions on a larger scale.

6.3. Investment cost

The project does not cover the investment cost of the alternative desalination technologies presented. It is recommended to estimate the investment cost of each alternative seawater desalination technique. In addition, the investment cost of the alternative desalination techniques must be compared with the investment cost of the conventional desalination processes.

6.4. Application on an industrial scale

In case if the laboratory and pilot scale experiments are successful, the alternative desalination techniques must be commercialized. Successful implementation on an industrial scale will help reducing the cost of seawater desalination and providing pure drinking water at a cheap rate.
7. Conclusions

Supplying pure drinking water at a cheap rate has become an important concern for the scientific community due to increasing water demand and the high cost of the conventional desalination processes. In addition, there is a pressing need to achieve breakthroughs in reducing the cost of seawater desalination by reducing the energy consumption. The proposed solutions tend to overcome the energy barrier associated with seawater desalination by hybridizing renewable solar and wind energy with conventional desalination techniques and by introducing forward osmosis as an energy-efficient desalination technology. The alternative desalination techniques presented will help reducing the cost of seawater desalination by reducing the required amount of thermal or electrical energy.
References


