UNIVERSITI PUTRA MALAYSIA

APPLICATION OF INTEGRATED SOLAR POND WITH EVAPORATION SYSTEM FOR HEAT GENERATION TO RECOVER MINERALS IN REJECTED BRINE

ABDULSALAM ABDULLAH N. ALREWASHED

APPLICATION OF INTEGRATED SOLAR POND WITH EVAPORATION SYSTEM FOR HEAT GENERATION TO RECOVER MINERALS IN REJECTED BRINE

By

ABDULSALAM ABDULLAH N. ALREWASHED

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

August 2016

DEDICATIONS

This thesis is dedicated to my family and the Saudi government

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

APPLICATION OF INTEGRATED SOLAR POND WITH EVAPORATION SYSTEM FOR HEAT GENERATION TO RECOVER MINERALS IN REJECTED BRINE

By

ABDULSALAM ABDULLAH N. ALREWASHED

August 2016

Chairman: Profesor Azni Idris, PhD
Faculty : Engineering

Desalination plants are known to discharge large value of brine as waste from the distillation process which is increasing globally over time. Although the desalination techniques has a positive impact to the eco-socio and industrial sector by solving the problem of water shortage, it also contributes negatively to the environment during discharge of the concentrated brine back to the sea or landfill. However, the treatment of the brine could be effectively utilized by converting it into by-products via solar pond technology. Generation of heat using solar pond technology has certain limitations, but in case of Saudi Arabia all these limitations can be effectively addressed.

This research focused on the use of a solar pond with the integration of heat, power and the concentrated brine. The result from the characteristics of seawater and brine demonstrated that the level of mineral and salt in brine was very high compared to sea water. With respect to economic value of the minerals, it was found that a potential revenue of 18.46 billion USD/per year in brine at AL-Khobar desalination plant is from Na^{+}, Mg^{2+}, K^{+}, Ca^{2+} and Cu^{2+}. To recover minerals, evaporation pond used to evaporate water from brine with the integration of solar pond for heat generation. For the designing and fabrication of the solar pond, it was found that the maximum temperature of about 65ºC could be generated from solar pond. The experiment on evaporation rate using the evaporation pond showed that the best temperatures were from 45 °C to 70 °C, where evaporation rate increases linearly over the increment of temperature. This temperatures are used for faster evaporation to make brine more concentrate which have about 5% moisture content. This moisture need to be dried further to meet salt market specification over the world, and produced salt could be used for multiple purpose.

This research used microwave oven for salt drying process which was powered by solar PV technique. For harvesting maximum radiation of PV tracking surface, it should be determine the angle of PV setup to use the output power for powering microwave

which required 700 watts power for operation. The gain made by this tracker relative to flat plate collector was 35% and 81% in the summer and winter solstice days, respectively. Four solar panels were set at 27 degree to obtain maximum output to operate the microwave. It was found that, microwave drying process achieved faster drying by 16 times compared to the conventional heating on an average. The research has shown the best concept of recovering minerals from brine, using the integrated solar pond with evaporation pond by utilizing a PV panel to powering microwave.

Abstrak tesis ini dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

APLIKASI INTEGRASI KOLAM SOLAR BERSAMA SISTEM EVAPORASI BAGI MENJANA HABA UNTUK MENGGAMBIL GALIAN-GALIAN DALAM AIR GARAM BUANGAN

Oleh

ABDULSALAM ABDULLAH N. ALREWASHED

Ogos 2016

Pengerusi : Profesor Azni Idris, PhD
Fakulti : Kejuruteraan

Kilang-kilang desalinasi sangat terkenal dengan pembuangan air garam dengan kuantiti yang besar sebagai sisa dari proses yang mana ia semakin bertambah di seluruh dunia dari masa ke semasa. Walaupun teknik desalinasi ada impak positif kepada sosio-ekonomi dan sektor industri dalam menyelesaikan masalah kekurangan air bersih tetapi ia juga menyumbang secara negatif kepada alam sekitar semasa pembuangan sisa kelaut atau tanah penambakan. Walau bagaimanapun, rawatan air garam boleh dibuat secara berkesan dengan menukarkan cara penghasilannya melalui teknik kolam solar. Penjanaan haba melalui kolam solar ada batasnya tetapi di Saudi Arabia semua batasan ini boleh di atasi dengan berkesan.

Kajian ini memfokus dalam penggunaan kolam solar untuk mengintergrasi penjanaan haba, tenaga, dan air garam pekat. Keputusan yang diperolehi dari ciri-ciri air laut dan air garam di dapati panas garam galian-galian yang sangat tinggi. Dari segi nilai ekonomi ,galian-galian seperti Na^+,Mg^{2+}, K^+, Ca^{2+} dan Cu^{2+} yang didapati dalam air garam di kilang desalinasi Al-Khobar boleh menjana pendapatan sebanyak USD 18.46 Billion setahun. Untuk mengambil galian-galian ini, kolam evaporasi telah digunakan untuk mengeringkan air dari air garam dengan integrasi kolam solar untuk menjana haba. Dalam rekaan dan fabrikasi kolam solar, didapati suhu lebih kurang 65 deg C boleh dijana dari kolam solar. Eksperimen berhubung dengan kadar eveporasi menggunakan kolam evaporasi menunjukkan suhu yang paling baik ialah dari 45 deg C sampai ke 70 deg C di mana kadar evaporasi meningkat secara lurus dalam peningkatan suhu tersebut. Suhu ini telah diguna pakai untuk peningkatan evaporasi dalam menjadikan air garam lebih pekat di mana kelembapan adalah lebih kurang 5%. Kelembapan ini perlu dikeringkan lagi untuk mencapai spesifikasi pasaran dunia dan garam-garam yang diperolehi boleh dipelbagai gunaan.

Kajian ini mengunakan ketahur gelombang mikro untuk mengeringkan garam dengan menggunakan tenaga yang dijana dari penggunakan teknik PV solar. Untuk menuai radiasi maksima dari penjejakan lapisan PV, ia mesti menetapkan sudut letak PV untuk menggunakan kuasa luaran sebagai penjana tenaga bagi gelombang mikro yang

memerlukan 700 watt. Nilai tambah yang diperolehi dengan cara ini berbanding dengan dari menggunakan piring rata masing-masing 35% and 81% di musim panas dan sejuk. Empat panel solar telah digunakan dengan sudut 27 darjah untuk menghasilkan keluaran maksima dan mengoperasi gelombang mikro. Proses penggeringan menggunakan gelombang mikro dapat mencapai kekeringan 16 kali ganda lebih cepat jika dibandingkan dengan cara biasa. Kajian ini telah menunjukkan konsep yang paling baik untuk mengambil galian-galian dari air garam adalah dengan mengintegrasikan kolam solar bersama kolam evaporasi dengan menggunkan panel PV untuk menjana gelombang mikro.

ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude to Allah and after this to my supervisor, Prof. Dr. Azni Idris, for his invaluable guidance and support throughout my candidature. His scholarly criticisms, scrutiny and suggestions kept me going against all odds. In addition, I would like to thank Prof. Dr. Thamer Ahmad, who always provided me valuable consultation. Dr. Amimul Ahsan was also very helpful throughout my study. The prompt replies and value adding comments from my supervisory committee helped me to retain the quality of research and complete it on time.

This research journey would not have been successful without the moral support of my mother and my immediate family. I would like to thank my wife Lamya, for her loyalty, love, emotional support and endurance. Appreciation also goes out to my friends for their support and caring throughout my academic career. Special thanks and appreciation also goes to the Saline Water Conversion Corporation (SWCC) and the Research and Development Center in Al-Jubail desalination and power plant, Saudi Arabia. They provided me the required facilities, financial support and the permission to conduct experiments in Al-Khobar power and desalination plant. I also express my deepest gratitude to King Abdullah Foreign Scholarship Program for supporting me during my PhD.

Finally, I would like to thank everybody who helped me in anyway to make my PhD, a journey of success.

I certify that a Thesis Examination Committee has met on 11 August 2016 to conduct the final examination of Alrewashed, Abdulsalam Abdullah N on his thesis entitled "Application of Integrated Solar Pond with Evaporation System for Heat Generation to Recover Minerals in Rejected Brine" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Helmi Zulhaidi bin Mohd Shafri, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Salmiaton binti Ali, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Luqman Chuah Abdullah, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Monzur Alam Imteaz, PhD
Associate Professor
Swinburne University of Technology
Australia
(External Examiner)

ZULKARNAIN ZAINAL, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 28 September 2016

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy.

The members of the Supervisory Committee were as follows:

Azni Idris, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Thamer Ahmad, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Amimul Ahsan, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

BUJANG KIM HUAT, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________________ Date: __________________________

Name and Metric No.: Abdulsalam Abdullah N. Alrewashed, GS28417

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ____________________
Name of Chairman of Supervisory Committee: Prof Dr Azni bin Idris
Jabatan Kejuruteraan Kimia dan Alam Sekitar
Fakulti Kejuruteraan
Universiti Putra Malaysia

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

Signature: ____________________
Name of Member of Supervisory Committee: ____________________

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

APC	Arab Potash Company
BCRS	Brine Concentration and Recovery System
BOD	Biological oxygen demand
CCS	Carbon dioxide Capture and Storage
CET	Cylindrical electro-conductivity-temperature
GCC	Gulf Corporation Council
GI	Galvanized Iron
ISP	Integrated SP
LCZ	Lower convective zone
MSF	Multi-Stage Flash
MSFD	Multi-Stage Flash Distillation
MED	Multi effect distillation
MFD	Microwave freeze drying
MSSP	Membrane stratified solar pond
NR	Not Reported
NCZ	Non-convection zone
PVC	Polyvinyl chloride
RO	Reverse Osmosis
SWCC	Saline water Conversion Corporation
SGSP	Salinity gradient solar pond
SSP	Shallow solar pond
SCZ	Storage convection zone
SP	Solar pond
TDS	Total Dissolved Solids
UCZ	Upper convective zone
ZLD	Zero liquid discharge

CHAPTER 1

INTRODUCTION

Recently, the rapid growth in human populations, increasing urbanization, industrial escalation, and commercial developments are causing some concern, and has resulted in a significant demand for potable water worldwide. This global development has led to the pollution of available water resources, degradation of natural sources, deforestation and climate change, resulting the global warming, all of which play a significant role to reduce average rainfalls (Apps and Price, 2013).

Many semi-arid and arid regions in the world are suffering from regular water shortages, which is detrimental towards economic, social, and human developments. However, the shortage of water is already prevalent in many regions around the globe, where more than one billion people do not have access to the potable water. It was also documented that 90% of infections and diseases in developing countries are transmitted through polluted water (Devabhaktuni et al., 2013). Furthermore, severe ecosystem damage may inquire if water abstraction rates exceed natural renewal rates, leading to a depletion or salinization of stocks, and land desertification (Lattemann and Höpner, 2008a). These have become a leading environmental concern, both at national and international levels. Therefore, to meet increasing demand and prevent damage to the ecosystems and the aquifers, water management practices need to be employed to mitigate water scarcity worldwide. In coastal regions, the desalination of seawater is the technology that is generally employed to alleviate the water shortage. It also should be in consideration that the worldwide production capacity is more than 74.8 million m^3/d (19,762 MGD) (Pankratz, 2013).

Desalination of seawater separates saline seawater into two streams: a fresh water stream containing a low concentration of dissolved salts, and a concentrated brine stream (Khawaji et al., 2008). Hence, the desalination process has emerged as an essential source of fresh water, especially in the arid region. The highest number of seawater desalination plants could be found in the Arabian Gulf, which is a region responsible for 57% of the global daily production (DesalData, 2012). The maximum amount of desalinated water is produced in the Kingdom of Saudi Arabia (KSA) comparing other countries over the world which is about 18%, while the Gulf Corporation Council (GCC) produces 41% of total production in the world. Desalinated water production by KSA reaches 10 million cubic meters per day (Mm^3/d). In the future, 1.6 Mm^3/d need to be added on top of the current 9.8 Mm^3/d. Thermal-based desalination processes, especially the Multi-Stage Flash (MSF) desalination, with a capacity of 5.6 Mm^3/d, still play a dominant role in KSA, however, Multi Effective Desalination (MED) and Reverse Osmosis (RO), both consuming lesser amounts of energy, are fast becoming more popular (Ghaffour et al., 2014).

Despite the fact that the desalination of seawater is responsible for the provision of quite a number of benefits to people and the environment via its constant supply of high quality drinking water without damaging natural freshwater ecosystems, there is an underlying negative effect, especially to the environment, due to concentrated (brine) and chemical discharges, capable of decreasing the quality of coastal water and the marine ecosystem (Vidalis, 2010). Brine has the comparatively higher value of salinity, alkalinity, and temperature gradient compared to the seawater, and these factors are especially detrimental to the development of marine species, survival of larvae, and reproductive traits and breeding of marine organisms (Chang, 2015).

This research investigated the best alternative that could minimize the potential environmental impact caused by brine disposal and other chemical concentrates. It has been established that the use of solar pond could be an alternative towards the effective management of brine, energy generation, and desalination.

1.1 Demand for fresh water

The human population has been recorded significant growth in the past few decades, which could be attributed to the enormous supply of provisions such as food, discovery of new resources for fresh water, and increased number of settlements. This unexpected population growth creates problems, amongst them shortages of potable water, which is projected to be the most prevalent problem in the near future (Li et al., 2010).

The world average baseline consumption of fresh water is 300 L per day per person, which is equivalent to about 100,000 L of fresh water per person annually. However, higher demands from the Arabian Gulf region have always been common. For example, the demand for fresh water in Saudi Arabia was estimated to be over 3,000 million cubic meters of potable water per annum for 2010. This alone entailed that there is an urgent need to find new alternative sources of fresh water, which lead to desalination technology being employed extensively in KSA in particular, and the gulf region in general (Raut and Kulkarni, 2012).

The solutions to the water challenges involve the creation of alternatives to water sources, preferably inexpensive ones. Dams and artesian wells have traditionally been used to provide fresh water, but these sources of water could only produce insufficient or unpredictable quantities of water (Danoun, 2007). The creation of alternative sources of water is a significant issue at the global level. In this context, desalination plants are one of the most vital and valuable alternative resources for many countries around the globe.

1.2 Desalination

The need for fresh or potable water in many countries due to the shortages of natural resources. It is therefore necessary to plan and create new methods, such as desalination technologies, which will provide fresh water that is potable for humans and animals, and irrigation for agriculture (Raut and Kulkarni, 2012). Desalination plant removed salt from seawater, in order to making the water potable (Linares et al., 2014).

The identification of desalination as an alternative supply strategy for fresh water helps meet the ever-increasing demand of water. Desalination describes the removal of salts and non-ionic minerals from sea water sources to a level suitable for human consumption. The desalination process can treat a variety of existing water with 5,000-10,000 mg/L total dissolved solids (TDS) and seawater (~35,000 mg/L TDS) from different sources (Bashitialalshaeer et al., 2011).

Desalination is made up of two main processes, which are evaporation and condensation via the application of heat. Reverse osmosis (RO), multi-stage flash (MSF), and multi effect distillation (MED) technologies are used by the desalination plants. In the Gulf region, the thermal processes (MSF: multi-stage flash; MED: multi effect distillation) account for 90% of production, while the main process in Spain is reverse osmosis (RO), where 95% of plants utilizing this technology (Latteman and Höpner, 2008a). It was envisaged that RO and MSF accounted for 83.7% of worldwide desalination capacity in 2004 (McCormick, 2007). Basically, the technique behind desalination plants is to separate saline into two streams: the first produces low concentrations dissolved salt and inorganic material suitable for human consumption, while the second produces unwanted concentrated dissolved salt solution called brine. Desalination is currently recording an annual increment of 9.5%. However, rejected brine is a common problem encountered from desalination process, as it kills many marine organisms and pollutes the sea. It was discovered that reject brine has the potential of increasing the salinity of water and soil when disposed into both water and soil (El-Naas, 2011).

1.3 Reject Brine

Brine is the waste fluid discharge from a desalination plant, containing high concentration of salts and dissolved minerals. It is a highly concentrated waste product, consisting of everything that was removed from seawater to produce potable water (Danoun, 2007). Generally, brine might be rejected directly either in the ocean alongside or in the form of a combination of other byproducts. The discharged brine has the ability to change the salinity, alkalinity, and temperature (El-Naas, 2011), and it is much harmful to a marine environment (Latteman and Höpner, 2008b).

There are many brine disposal alternatives that are widely acceptable today. Most of them are being used or currently under investigation, however, these alternatives are site-specific. Hence, all disposal methods, from an environmental and economical point of view, have to be assessed based on their respective sites (Vidalis, 2010). Examples of disposal methods are included (Vidalis, 2010) deep aquifer injection, deep well injection, aquifer re-injection, discharge to wastewater treatment plants, discharge of sewage system, discharge to open land, reuse for agriculture or landscaping, discharge of inland surface water, and solar gradient ponds. Among these techniques, the solar gradient pond, also known as solar pond, seems to be the best option, based on the fact that it leads to many important applications while reducing damage to the environment. Remarkable research has been done on a solar pond for the last 50 years (Saifullah et al., 2012), and it is now applied in many countries, such as Israel, China, USA, India, and Australia (Akbarzadeh et al., 2009). Meanwhile, countries such as KSA and other Gulf nations are also actively engaged in solar ponds research.

1.4 Solar Ponds

A solar pond is a shallow body of water that serves as a solar collector, equipped with an integral heat storage that supplies thermal energy. There are two types of solar ponds, convective and non-convective. The former permits convection, but prevent evaporation, and is exemplified in a shallow solar pond. It consists of a large bag with a blackened bottom, and a sheet of plastic or glass on top. Solar energy heats the bag during the day, while at night hot water is pumped into a large heat storage tank to minimize heat loss

(Saifullah et al., 2012). A non-convective solar pond is a large shallow body of water with an average depth of 3 - 4 m, set up in a way that its temperature gradient is opposite to the ones normally observed, which allows for the collection of radiant energy into heat, up to 95 °C in the system.

There are three types of non-convective solar ponds, these are salinity gradient solar pond (SGSP), membrane solar pond, and polymer gel layers solar pond. SGSP is a pool of water ~1-5 m deep containing dissolved salts that stabilizes the density gradient. This is further divided into three layers, the upper layer which is known as the upper convective zone (UCZ) of the clear fresh water, it serves as the solar collector or receiver, followed by the lower convective zone (LCZ) with the highest salt concentration, also serving as the heat storage zone, and finally the non-convective zone (NCZ), which is much thicker and occupies more than half of the depth of the pond (Saifullah et al., 2012).

SGSP is the most eco-friendly of solar energy desalination systems, as it can be used for electricity generation, heating, and cooling. Generally, solar ponds could be used for thermal applications, due to its ability to store thermal energy for long periods of time. This stored energy can be used for low-temperature thermal applications, such as thermal desalination (Lisa, 2009; DSE Capital Projects, 2008; Bashitialalshaeer et al., 2011), greenhouse heating (Benli, 2013), process heating (Devabhaktuni et al., 2013), space heating (Raut and Kulkarni, 2012), and agricultural applications.

1.5 Recovery of minerals from the sea water desalination

The recovery of minerals from seawater desalination resulted in reduced production costs and increased revenues. The extraction of materials and brine conditioning for surface storage is another advantage of desalination plants, as it makes them environmentally friendly (IAEA, 2007). Brine rejected by the desalination units contained the concentrate form of all the sixty elements from the periodic table. The utilization of brine in appropriate processes could yield calcium, magnesium, sodium, potassium, chlorine, sulfate, and bromine, as well as sodium chloride (Husain and Al-Rawajfeh, 2009).

It is therefore preferable to have a mineral recovery process in the reverse osmosis (RO), multi-stage flash (MSF), and multi effected desalination (MED) techniques. Minerals recovery of such resources will be considered very attractive in KSA and the Gulf region, due to its limited natural resources. There are deficiencies in the quantities of a majority of these elements on the land, as they are expensive, especially potassium and sodium salts.

1.6 Problem Statement

As pointed out previously, the tremendous population growth and increasing pressure on the available water resources, mostly in the arid regions, led to the establishment of desalination technologies. These technologies are a step-forward towards the mitigation of the scarcity of water resources worldwide. The introduction of desalination technology and the increases in the number of desalination plants around the world due to the rising shortage of fresh water source has been associated with several negative environmental impacts, the most important of which is the discharge of concentrated brine into land or marine environment, resulting damage in arable land, coastal water quality, and marine life, and air pollutant emissions attributed to the energy demand of the processes (Das et al., 2014; Ahmad & Baddour, 2014; Naser, 2013).

However, limited efforts had been made to characterize large quantities of and assess the impacts of brine discharge into an ambient environment. A feasible approach, which holds considerable promise, is a salinity gradient solar pond (SGSP), because it is a form of renewable energy source that collects solar radiation and stores it in the form of thermal energy for long periods of time (Sakhrieh & Salaymeh, 2013). SGSP is a cost effective method with a considerably lower technical know-how. Therefore, this research was intended to highlight the treatment of discharged brine from desalination plants based on solar pond application, identify potential mineral recovery and enhancement options alongside the cost reduction considerations. Figure 1.1 shows the summary of the problem statement.

From the integrated solar pond in the evaporation process, important salts could be recovered which has potential economic value. Daily disposal of brine globally reaches 571.8 million m^3/day which could be turn into revenue. However, this salt is not usable due to the moisture content in the salt, which not complies with the market standard (Geise et al., 2014). Due to this, it is necessary to dry moisture from the salt. If we use the dryer or heater for drying moisture, it needs a power source to operate the dryer but need to the expensive energy to dry. Using renewable sources to power up the dryer could reduce environmental impact (Devabhaktuni et al., 2013). This study used renewable energy for evaporation pond to speed up the evaporation of brine using heat exchanger and also microwave for salt drying which is more economical. It is necessary develop a model to know the maximum radiation to determine the PV setup angle and estimate output power for microwave. Choosing a method for fast drying makes it more practical for commercialization.

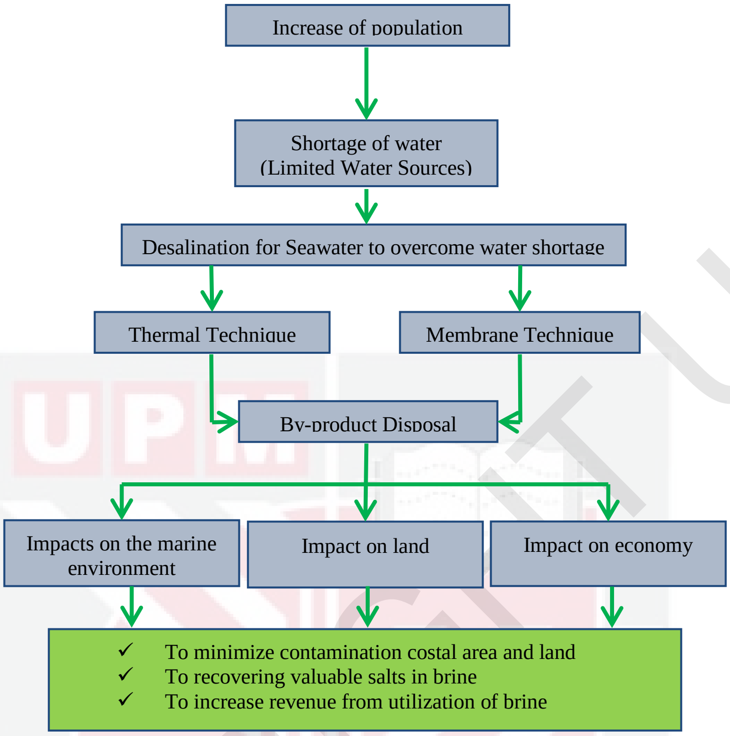

Figure 1.1: Summary of the problem statement

1.7 Research Objectives

The objectives of the research are:

1. Characterization of the sea water and the rejected brine from AL-Khobar desalination plant and update detailed assessment of the economic value of the rejected brine,
2. Assessment and evaluation of the integrated solar pond, fabrication, operation, and testing solar pond,
3. Simulation of the impact of generating heat in the integrated solar pond in the evaporation process with and without heat exchanger,
4. Radiation modeling and performance evaluations of fixed, single and double axes tracking surfaces: A case study for AL-Khobar city, Saudi Arabia,
5. Drying the remaining moisture in the salt after the evaporation by using a PV-powered microwave device.

1.8 Case Study

The study is conducted in KSA, because it has a large capacity of desalination inventory and sources for raw waste brine. The work was carried out at the Saline water Conversion Corporation (SWCC) at Al-Aziziyah, which is 10 km away from the city of Al-Khobar at the phase 3 section, in the coastal area of the eastern province in KSA.

1.9 Research Scope

This research explained the concept of the application of solar pond for the disposal of treated brine from desalination plants. Characteristics of seawater and disposal brine, and the economic value of rejected brine was investigated as well. A solar pond was designed, fabricated, operated, and tested to determine the stable temperature of generating heat. The effect of heat generated from solar pond in the evaporation process was investigated as well. A simulation that models a small-scale solar pond that comes equipped with a heater that was fabricated as the requirements of this work.

Solar radiation was studied in order to design a suitable PV system that provide electrical power to the microwave device that will be responsible for removing the moisture from the acquired salt post-evaporation. Furthermore, the performance of the solar tracking systems for the electrical power generated by the PV system was investigated for future works, as it might be a commercial endeavor at larger scales. However, in the context of this work, a tilted PV panel was fixed due to the small size of the solar pond, which helps keep the cost of the project low.

1.10 Contributions

The salinity gradient solar pond (SGSP) is an alternative solution to the indiscriminate disposal of brine onto land and sea by desalination plants, as it is a cost effective method with a considerably low technical know-how. Recent work involves the employment of solar ponds on its own to increase the evaporation rates of seawater, while the generated heat is utilized elsewhere. However, using the solar pond to increase the evaporation rate of the rejected brine from the desalination plant has not been under intense scrutiny. Drying these minerals are also a time consuming process, and afterwards, it still requires further refinements. This study reported the results of the application of solar pond for heat generation to enhance the rate of evaporation of rejected brine in the evaporation pond, which is novel in the context of the desalination plants of KSA. This part of this research aims to address objectives 2 and 3.

The recovered mineral was totally dried by a microwave device, powering from a PV system, as pointed out in objectives 4 and 5. Following objective 1, the characteristics of the minerals were analyzed by acquiring rejected brine from desalination plant as well as seawater, and also the economic value of the minerals from the rejected brine was calculated. Generally, this strategy will result in a significant economic advantage via the creation of jobs and decreasing the total cost of the desalination technique.

1.11 Thesis Organization

This thesis is divided into 9 chapters. Chapter 1 briefly introduces desalination and solar ponds, the global need for fresh water, the desalination technique, and its impact on the environment. Then, the application of solar pond for minimizing brine disposal is explained, followed by the possibility of mineral recovery from desalination plants, problem statements, objectives, scopes of the study, and the contribution of the work is presented.

Chapter 2 presents the reviews of the literatures associated with the general concepts of desalination, brine disposal and management, solar pond, mineral recovery, evaporation pond, solar radiation, and PV and microwave applications. Moreover, the modeling and simulation of solar pond equipped with an evaporation pond are presented.

Chapter 3 presents a detail of the materials and methods employed in this work. It also discusses the modeling, simulations, and experimental procedures and the subsequent analyses of the data.

Chapter 4 analyses the specifications of seawater, as well as rejected brine from the desalination plant and discuss the economic value of the minerals present in the brine.

Chapter 5 shows the results of operation of the fabricated small-scale solar pond for 60 days and 2-day tests.

Chapter 6 presents the impact of generated heat of the solar pond in the evaporation process simulated by a heater at different temperatures. The evaporation rate of a normal evaporation process and the one with the extra heat from the solar pond is compared.

Chapter 7 shows the results of solar radiation modeling and the amount of solar energy that can be harvested via fixed, single, and double-axes tracking surfaces in Al-Khobar city, Saudi Arabia.

Chapter 8 describes the assembly of a PV system that could power a microwave device that used to remove the remaining moisture in the salt post-evaporation.

Chapter 9 concludes the work and recommends future work in the context of industrial applications. The references and appendices are compiled at the end of the thesis, description about modeling, simulations, calculations and pictures of the different steps of practical sections of the work is illustrated in the appendices section.

REFERENCES

Abdul-Wahab, S. A., Al-Weshahi, M. A. (2009). Brine management: substituting chlorine with on-site produced sodium hypochlorite for environmentally improved desalination processes. *Water Resources Management* 23(12):2437-2454.

Abu-Hamatteh, Z., & Al-Amr, A. (2008). Carnallite froth flotation optimization and cell efficiency in the Arab Potash Company, Dead Sea, Jordan. *Mineral Processing & Extractive Metallurgy Review* 29(3):232-257.

Aerstin, F., & Street, G. (2012). *Applied Chemical Process Design*. Springer Science & Business Media.

Agee, J. T., Obok Opok, A., & de Lazzer, M. (2007). Solar tracker technologies: market trends and field applications. Paper presented at the Advanced Materials Research.

Ahmad, M., & Rahman, A. (2011). The stimulating role of NGOs in Bangladesh. *Climate of Coastal Cooperation*. Coastal & Marine Union, The Netherlands, 62-63.

Ahmad, N., & Baddour, R. E. (2014). A review of sources, effects, disposal methods, and regulations of brine into marine environments. *Ocean & Coastal Management*, *87*, 1-7.

Akbarzadeh, A., Johnson, P., Singh, R. (2009). Examining potential benefits of combining a chimney with a salinity garadient solar pond for production of power in salt affected areas. *Solar Energy* 83: 1345-1359.

Akinde, S. B., Obire, O. (2011). In-situ Physico-chemical properties of the deep Atlantic Ocean water column and their Implications on heterotrophic bacterial distribution in the Gulf of Guinea. *Advances in Applied Science Research* 2:470-482.

Akridge D. G. (2008). Methods for calculating brine evaporation rates during salt production. *Journal of Archaeological Science* 35:1453-1462.

Al-Faifi, H., Al-Omran, M.A., Nadeem, M., El-Eter, A., Khater, A.H., El-Maghraby, E.S. (2009). Soil deterioration as influenced by land disposal of reject brine from Salbukh water desalination plant at Riyadh, Saudi Arabia. *Desalination* 250: 479–484.

Al-Mutaz, I. S., Al-Mojjly, A., Abashar, M. (2006). *Thermal and brine Dispersion from coastal MSF desalination plants*. Paper presented at the 4th International conference on marine wastewater discharges and coastal environment (MWWP) Antalya Turkey.

Al Neaimi, A., Al Shamsi, A., Kanji, R., Al Naqeeb, W., Abu Eishah, S. (2011). Design of a Solar Pond for Solar Energy Storage/Recovery and Salt Production in Coastal and Rural Areas of the UAE. Paper presented at the *UAE-Swiss Research day on: The Future of Energy and Sustainability Lausanne*, 22-23 June, 2011.

Al-Tahaineh, H., Al-Busoul, M. (2013). Numerical investigation of the effect of salt-gradient solar pond dimensions on the pond performance and energy storage. *Journal of Energy Technologies and Policy* 3(10):45-57.

Alenezi, I. (2012). Salinity Gradient Solar Ponds: Theoretical Modelling and Integration with Desalination. Doctoral Thesis. University of Surrey.

Apps, M. J., & Price, D. (Eds.). (2013). *Forest ecosystems, forest management and the global carbon cycle* (Vol. 40). Springer Science & Business Media.

Aref, M. A., Basyoni, M. H., & Bachmann, G. H. (2014). Microbial and physical sedimentary structures in modern evaporitic coastal environments of Saudi Arabia and Egypt. *Facies*, *60*(2), 371-388.

Arshed, U. (2012). *Numerical Modelling And Performance Analysis of Salt Gradient Solar Ponds*. Final Project Report ACME.

Askari, G.R., Emam-Djomeh, Z.A.H.R.A., Tahmasbi, M. (2009). Effect of various drying methods on texture and color of tomato halves. *Journal of Texture Studies* 40:371-389.

Awan, U.K. (2012). *Experimental Analysis of Variable Capacity Heat Pump System Equipped with Vapour Injection and Permanent Magnet Motor*. Masters of Science Thesis, Stokholm, Sweden.

Bashitialalshaeer, R.A.I., Persson, K.M. Aljaradin, M. (2011). Estimated future salinity in the Arabian Gulf, the Mediterranean Sea and the Red Sea consequences of brine discharge from desalination. *International Journal of Academic Research* 3:133-140.

Babalola, P.O. (2010). Non-convective solar pond as a thermal energy source. Retrieved from: *http://www.scribd.com/doc/39657995/Solar-Pond-Scribd*. [Last accessed: 12th December, 2012].

Bai, S. B., Vaithyanathan, C. (2012). A Correlative study of the rates of artificial evaporation of the brines of various saltpans of Kanyakumari District, Tamil Nadu, India. *Journal of Chemical & Pharmaceutical Research* 4(10):665-670.

Bardi, U., Lavacchi, A. (2009). A simple interpretation of Hubbert's model of resource exploitation. *Energies* 2:646–661.

Bardi, U. (2010). Extracting Minerals from Seawater: An Energy Analysis. *Sustainability* 2:980-992.

Benghanem, M. (2011). Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia. *Applied Energy* 88(4):1427-1433.

Benli, H. (2013). A performance comparison between a horizontal source and a vertical source heat pump systems for a greenhouse heating in the mild climate Elaziğ, Turkey. *Applied Thermal Engineering*, *50*(1), 197-206.

Bernad, F., Casas, S., Gibert, O., Akbarzadeh, A., Cortina, J. L., & Valderrama, C. (2013). Salinity gradient solar pond: Validation and simulation model. *Solar energy*, *98*, 366-374.

Blackam, M. (2014). Source, fate and water-energy intensity in the coal seam gas and shale gas sector. *Water: Journal of the Australian Water Association*, *41*(1), 51.

Bollinger, M. L., Durch, N. M., & Lee, R. S. (2015). *U.S. Patent No. 8,951,305*. Washington, DC: U.S. Patent and Trademark Office.

Bozkurt, I., Karakilcik, M. (2012). The daily performance of a solar pond integrated with solar collectors. *Solar Energy* 86(5):1611-1620.

Brutsaert, W. (2013). *Evaporation into the atmosphere: theory, history and applications* (Vol. 1). Springer Science & Business Media.

Castillo, P., Beyers, M. (2010). New solar initiatives in super tall buildings: The spire at Ras Al-khaimah. Retrieved from: *http://www.ctbuh.org/LinkClick.aspx?fileticket=p3nOEUVj4HQ%3D&tabid=749&language=en-US*. [Last Accessed: 17 October, 2012].

Chang, J. S. (2015). Understanding the role of ecological indicator use in assessing the effects of desalination plants. *Desalination*, *365*, 416-433.

Chang, T. P. (2009a). The gain of single-axis tracked panel according to extraterrestrial radiation. *Applied Energy* 86(7):1074-1079.

Chang, T. P. (2009b). Output energy of a photovoltaic module mounted on a single-axis tracking system. *Applied Energy* 86(10): 2071-2078.

Cipollina, A., Misseri, A., Staiti, G. D. A., Galia, A., Micale, G., & Scialdone, O. (2012). Integrated production of fresh water, sea salt and magnesium from sea water. *Desalination and Water Treatment* 49(1-3):390-403.

Culligan, S.A. (2012).Report on the evaluation of existing methods on brine treatment and disposal. Retrieved from: *http://uest.ntua.gr/solbrine/uploads/files/Deliverable_1.1.pdf*. [Last accessed: 13 September, 2012].

Darwish, M. A., & Mohtar, R. (2013). Qatar water challenges. *Desalination and Water Treatment*, *51*(1-3), 75-86.

Danoun R. (2007). Desalination Plant: Potential impact of brine discharge on Marine life. *The Ocean Technology Group*. University of Sydney, Australia.

Das, R., Ali, M. E., Hamid, S. B. A., Ramakrishna, S., & Chowdhury, Z. Z. (2014). Carbon nanotube membranes for water purification: a bright future in water desalination. *Desalination*, *336*, 97-109.

Date, A., Yaakob, Y., Date, A., Krishnapillai, S., & Akbarzadeh, A. (2013). Heat extraction from Non-Convective and Lower Convective Zones of the solar pond: A transient study. *Solar Energy* 97:517-528.

Dawoud, M. A. (2012). Environmental impacts of seawater desalination: Arabian Gulf case study. *International Journal of Environment and Sustainability (IJES)*,1(3).

Dehwah, A. H., & Missimer, T. M. (2013). Technical feasibility of using gallery intakes for seawater RO facilities, northern Red Sea coast of Saudi Arabia: The king Abdullah Economic City site. *Desalination and Water Treatment*, *51*(34-36), 6472-6481.

Delzeit, L., Fisher, J. W., Pace, G., & Shaw, H. (2012). Brine Evaporation Bag Design Concept and Initial Test Results. In *42nd International Conference of Environmental Systems, San Diego, CA. Paper AIAA-2012-3525*.

DesalData (2012). Global Water Intelligence, Retrieved from: *http://www.DesalData.com*, [Last accessed: 14 September, 2012].

Devabhaktuni, V., Alam, M., Depuru, S. S. S. R., Green, R. C., Nims, D., & Near, C. (2013). Solar energy: Trends and enabling technologies. *Renewable and Sustainable Energy Reviews*, *19*, 555-564.

Davison, P., Lara-Lopez, A., & Koslow, J. A. (2015). Mesopelagic fish biomass in the southern California current ecosystem. *Deep Sea Research Part II: Topical Studies in Oceanography*, *112*, 129-142.

DSE Capital Projects (2008). DSE capital projects division victorian desalination project ees reference project overview. Retrieved from: http://www.dtpli.vic.gov.au/. [Last accessed: 12 February, 2012].

Duan, X., Zhang, M., Li, X., Mujumdar, A. S. (2008). Ultrasonically enhanced osmotic pretreatment of sea cucumber prior to microwave freeze drying. *Drying Technology*, 26(4):420-426.

Duffie, J. A., Beckman, W. A. (2013). *Solar Radiation. Solar Engineering of Thermal Processes*, Fourth Edition, John Wiley and Sons, New York, NY.

Dumont, M. (2009). Canadian Minerals Yearbook (CMY). Retrieved from: *http://www.nrcan.gc.ca/mining-materials/markets/canadian-minerals-yearbook/2009/8462*, [Last accessed: 24 July, 2012].

Dupavillon, J. L., Gillanders, B. M. (2009). Impacts of seawater desalination on the giant Australian cuttlefish Sepia apama in the upper Spencer Gulf, South Australia. *Marine Environmental Research* 67(4):207-218.

El-Naas, M. H., A. H. Al-Marzouqi, O. Chaalal. (2010). A combined approach for the management of desalination reject brine and capture of CO_2. *Desalination* 251:70–74.

El-Naas, M.H. (2011). Reject Brine Management, Desalination, Trends and Technologies. *INTECH Open Access Publisher*. Michael Schorr (Ed.).

El-Sebaii, A. A., Ramadan, M. R. I., Aboul-Enein, S., & Khallaf, A. M. (2011). History of the solar ponds: a review study. *Renewable and Sustainable Energy Reviews*, *15*(6), 3319-3325.

Environmental Protection Agency (EPA). 2006, Voluntary estuary monitoring manual, Chapter 11: pH and Alkalinity, Retrieved from: *http://www.epa.gov/owow /estuaries/monitor/*, [Last accessed: 13 January, 2013].

Fritzmann, C., Löwenberg, J., Wintgens, T., Melin, T., (2007). State of-the-art of reverse osmosis desalination. *Desalination* 216:1–76.

Gang, P., Jie, J., Wei, H., Keliang, L., & Hanfeng, H. (2007). Performance of photovoltaic solar assisted heat pump system in typical climate zone. *J Energy Environ* 6:1-9.

Gao, W., Liang, H., Ma, J., Han, M., Chen, Z. L., Han, Z. S., & Li, G. B. (2011). Membrane fouling control in ultrafiltration technology for drinking water production: a review. *Desalination*, *272*(1), 1-8.

Garg, H. P., Mullick, S. C., & Bhargava, V. K. (2012). *Solar thermal energy storage*. Springer Science & Business Media.

García-Quismondo, E., Santos, C., Palma, J., & Anderson, M. A. (2016). On the challenge of developing wastewater treatment processes: capacitive deionization. *Desalination and Water Treatment*, *57*(5), 2315-2324.

Gasulla, N., Yaakob, Y., Leblanc, J., Akbarzadeh, A., & Cortina, J.L. (2011). Brine clarity maintenance in salinity-gradient solar ponds, *Solar Energy* 85(11):2894-2902.

Geise, G. M., Paul, D. R., & Freeman, B. D. (2014). Fundamental water and salt transport properties of polymeric materials. *Progress in Polymer Science*, *39*(1), 1-42.

George, A., Olah, A.G., Surya Prakash, G.K. (2009). Chemical Recycling of Carbon Dioxide to Methanol and Dimethyl Ether: From Greenhouse Gas to Renewable, Environmentally Carbon Neutral Fuels and Synthetic Hydrocarbons. *Journal of Organic Chemistry* 74:487-498.

Ghaffour, N., Lattemann, S., Missimer, T., Ng, K. C., Sinha, S., & Amy, G. (2014). Renewable energy-driven innovative energy-efficient desalination technologies. *Applied Energy* 136:1155-1165.

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination, 309*, 197-207.

Gudiño-Ayala, D., & Calderón-Topete, Á. (2014). Pineapple drying using a new solar hybrid dryer. *Energy Procedia*, *57*, 1642-1650.

Gunerhan, H., Hepbasli, A. (2007). Exergetic modeling and performance evaluation of solar water heating systems for building applications. *Energy and Buildings* 39(5):509-516.

Hepbasli, A., Alsuhaibani, Z. (2011). A key review on present status and future directions of solar energy studies and applications in Saudi Arabia. *Renewable and Sustainable Energy Reviews* 15(9):5021-5050.

He, X., & Boehm, R. F. (2009). Direct solar water splitting cell using water, WO 3, Pt, and polymer electrolyte membrane. *Energy*, *34*(10), 1454-1457.

Hoffman, D. (2009). Greening the Red Sea—Dead Sea Water Conveyance Project *The Jordan River and Dead Sea Basin* (pp. 213-234): Springer, The Netherlands.

Huang, W.N., Sun, X.N., Wang, X.K., Nie, Z., Bu, L.Z. (2008). Progress in industrialization for lithium extraction from salt lake. *Modern Chemical Industry* 28:14–19.

Husain, A.A, Al-Rawajfeh A.E. (2009). Recent patent on nanofiltration application in oil processing, desalination, wastewater and food industries. *Recent Patent in Chemical Engineering* 2:51-66.

Husain, M., Sharma, G., Samdarshi, S.K. (2012). Innovative design of nonconvective zone of salt gradient solar pond for optimum thermal performance and stability. *Applied Energy* 93:357–363.

Ibrahim, E. S. (2012). *Biomass Potentials for Bioenergy Production from built-up areas: Doctoral thesis Faculty of Geo-Information Science and Earth Observation*. University of Twente, Twente, The Netherlands.

IAEA. (2007). Economic of nuclear desalination: New development and site specific studies. Retrieved from: *http://www.pub.iaea.org/MTCD/ publications/PDF/te_1561_web.pdf*. [Last accessed: 11 September, 2012].

Islam, M. J., Hossain, M. S., & Mian, S. (2012). Nutritive value of dried and heat processed mola fish (Amblypharyngodon mola) products. *International Journal of Natural Sciences*, *2*(2), 43-48.

Jacob, C. (2007). Seawater desalination: boron removal by ion exchange technology. *Desalination 205*(1):47-52.

Jakhrani, A. Q., Othman, A.-K., Rigit, A. R., Samo, S. R., Kamboh, S. (2012). Estimation of incident solar radiation on tilted surface by different empirical models. *International Journal of Scientific and Research Publications* 2(12):1-6.

Kabay, N., Sarp, S., Yuksel, M., Arar, Ö., & Bryjak, M. (2007). Removal of boron from seawater by selective ion exchange resins. *Reactive and Functional Polymers 67*(12):1643-1650.

Kang, K. C., Linga, P., Park, K. N., Choi, S. J., & Lee, J. D. (2014). Seawater desalination by gas hydrate process and removal characteristics of dissolved ions (Na+, K+, Mg 2+, Ca 2+, B 3+, Cl−, SO 4 2−). *Desalination*, *353*, 84-90.

Karakilcik, M., Dincer, I., & Rosen, M. A. (2006). Performance investigation of a solar pond. *Applied Thermal Engineering* 26(7):727-735.

Karunamurthy, K., Kumar, K.M.M., Suresh, S. (2012). Enhancement of Heat Transfer in Pilot Simulated Solar Ponds using Modified Tube Inserts. *European Journal of Scientific Research* 91: 165-173.

Katzir, L., Volkmann, Y., Daltrophe, N., Korngold, E., Mesalem, R., Oren, Y., & Gilron, J. (2010). WAIV-Wind aided intensified evaporation for brine volume reduction and generating mineral byproducts. *Desalination and Water Treatment* 13(1-3):63-73.

Kedem, A., Gilron, J., & Kedem, O. (2007). Evaporation device, US Patent, U.S. Patent 7166188, January 2007.

Kepke, T.J., Lee F, Josef, C., Damian M. (2008). Hold the salt: innovative treatment of RO concentrate. *2nd International Salinity Forum Salinity, Water and Society–Global Issues, Local Action*, pp. 2619-2630

Khatib, T., Mohamed, A., Mahmoud, M., Sopian, K. (2011). Modeling of daily solar energy on a horizontal surface for five main sites in Malaysia. *International Journal of Green Energy* 8(8):795-819.

Khawaji, A.D., Ibrahim, K.K., Wie, J. (2008). Advances in seawater desalination technologies. *Desalination* 221:47-69.

Kim, D.H. (2011). A review of desalting process techniques and economic analysis of the recovery of salts from retentates. *Desalination* 270:1–8

Kim, J., Mun, S. C., Ko, H. U., Kim, K. B., Khondoker, M. A. H., & Zhai, L. (2012). Review of microwave assisted manufacturing technologies.*International Journal of Precision Engineering and Manufacturing*, *13*(12), 2263-2272.

Kogel, J. E. (2006). *Industrial minerals & rocks: commodities, markets, and uses*: SME.

Kostick, D. S. (2013). *Salt*. Retrieved from: *http://minerals.usgs.gov/minerals/pubs/commodity/salt/mcs-2013-salt.pdf*. [Last accessed: 23 July, 2012].

Koussa, M., Haddadi, M., Saheb, D., Malek, A., Hadji, S. (2012). Sun Tracker Systems Effects on Flat Plate Photovoltaic PV Systems Performance for Different Sky States: A Case of an Arid and Hot Climate. *Energy Procedia* 18:839-850.

Ladewig, B., Asquith, B. (2011). *Desalination Concentrate Management*: Springer Science & Business Media.

Lattemann, S., Höpner, T. (2008a). Environmental impact and impact assessment of seawater desalination. *Desalination* 220(1):1-15.

Lattemann, S., & Höpner, T. (2008b). Impacts of seawater desalination plants on the marine environment of the Gulf. *Protecting the Gulf's Marine Ecosystems from Pollution* (pp. 191-205): Springer, Birkhauser, Verlag, Germany.

Lara, J., González, L. E., Ferrero, M., Díaz, G. C., Pedrós-Alió, C., & Demergasso, C. (2012). Enrichment of arsenic transforming and resistant heterotrophic bacteria from sediments of two salt lakes in Northern Chile. *Extremophiles* 16(3):523-538.

Leblanc, J., Akbarzadeh, A., Andrews, J., Lu, H., & Golding, P. (2011). Heat extraction methods from salinity-gradient solar ponds and introduction of a novel system of heat extraction for improved efficiency, *Solar Energy* 85(12):3103–3142.

Lehmann, O., Nir, O., Kuflik, M., & Lahav, O. (2014). Recovery of high-purity magnesium solutions from RO brines by adsorption of Mg (OH) 2 (s) on Fe 3 O 4 micro-particles and magnetic solids separation. *Chemical Engineering Journal*, *235*, 37-45.

Lisa, H. (2009). The Current State of Desalination. Retrieved from: *http://www.idadesal.org/PDF/the%20current%20state%20of%20desalination%20remarks%20nov%2009%20by%20lisa%20henthorne.pdf*. [Last accessed: 11 July, 2012].

Li, C., Kosmadakis, G., Manolakos, D., Stefanakos, E., Papadakis, G., & Goswami, D. Y. (2013). Performance investigation of concentrating solar collectors coupled with a transcritical organic Rankine cycle for power and seawater desalination co-generation. *Desalination* 318:107-117.

Li, D. H., Lam, T. N. (2007). Determining the optimum tilt angle and orientation for solar energy collection based on measured solar radiance data. *International Journal of Photoenergy* 2007:1-9.

Li, Z, Boyle, F, Reynolds A. (2010). Rainwater harvesting and grey water treatment systems for domestic application in Ireland. *Desalination* 260:1-8.

Li, G., Zhang, F., Zhang, G., & Han, J. (2006). Recovery of Na 2 SO 4 from remediation of wastewater and reuse for preparation of sodium 4-nitrotoluene-2-sulfonate (NTSNa). *Desalination* 194(1):176-181.

Linares, R. V., Li, Z., Sarp, S., Bucs, S. S., Amy, G., & Vrouwenvelder, J. S. (2014). Forward osmosis niches in seawater desalination and wastewater reuse. Water research, 66, 122-139.

Liu, J., Yuan, J., Xie, L., & Ji, Z. (2013). Energy analysis of dual-stage nanofiltration seawater desalination. *Energy* 62:248-254.

Maatallah, T., El Alimi, S., Nassrallah, S. B. (2011). Performance modeling and investigation of fixed, single and dual-axis tracking photovoltaic panel in Monastir city, Tunisia. *Renewable and Sustainable Energy Reviews* 15(8):4053-4066.

Magarey, P., & Osei-Bonsu, K. (2008). Regional Disposal Strategy–Renmark Group Deep Injection: Phase II Feasibility Study.

Malik, N.S. (2011). *An investigation into the Chemistry and Biology of salinity gradient solar ponds in relation to their stability and inefficiency*. PhD Thesis RMIT University, Australia.

Malik, N., Date, A., Leblanc, J., Akbarzadeh, A., & Meehan, B. (2011). Monitoring and maintaining the water clarity of salinity gradient solar ponds, *Solar Energy* 85 (11):2987–2996.

McCormick, P. J. (2007). *A novel forward osmosis process for water recovery from all sources*. Master Thesis, ProQuest.

McMahon, T. A., Peel, M. C., Lowe, L., Srikanthan, R., & McVicar, T. R. (2013). Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. *Hydrology and Earth System Sciences*, *17*(4), 1331-1363.

Mellit, A., Kalogirou, S., Hontoria, L., & Shaari, S. (2009). Artificial intelligence techniques for sizing photovoltaic systems: A review. *Renewable and Sustainable Energy Reviews* 13(2):406-419.

Meral, M. E., Dinçer, F. (2011). A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. *Renewable and Sustainable Energy Reviews* 15(5):2176-2184.

Millero, F. J. (2013). *Chemical oceanography*. CRC press.

Mishra, V., Naveen, I. S., Purkayastha, S., & Gupta, S. (2013). Design of Adaptive Humidity Controller and Practical Implementation for Humidity and Temperature Exclusiveness. *International Journal of Advanced Research in Computer Science and Software Engineering*, *3*(6), 300-305.

Mohanraj, M., Chandrasekar, P. (2009). Performance of a forced convection solar drier integrated with gravel as heat storage material for chili drying. *Journal of Engineering Science and Technology* 4:305-314.

Moh'd A, A. N., & Al-Dafaie, A. M. A. (2014). Using nanofluids in enhancing the performance of a novel two-layer solar pond. *Energy*, *68*, 318-326.

Moore, J. W., & Ramamoorthy, S. (2012). *Organic chemicals in natural waters: applied monitoring and impact assessment*. Springer Science & Business Media.

Moreno, L., Ordóñez, J.I., Cisternas, L.A. (2014) *La industria salitrera y los recursos hídricos.* In: Editors Cisternas, L.A., Moreno, L. (Eds.). El agua de mar en la minería: Fundamentos y aplicaciones. RIL Editores. Santiago. Chile.

Morillo, J., Usero, J., Rosado, D., El Bakouri, H., Riaza, A., & Bernaola, F. J. (2014). Comparative study of brine management technologies for desalination plants. *Desalination*, *336*, 32-49.

Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K., Sharifi, A. (2009). A review of principle and sun-tracking methods for maximizing solar systems output. *Renewable and Sustainable Energy Reviews* 13(8):1800-1818.

Naser, H. A. (2013). Assessment and management of heavy metal pollution in the marine environment of the Arabian Gulf: a review. *Marine pollution bulletin*, *72*(1), 6-13.

Neelameggham, N. R., Sanchez-Segado, S., & Pistorius, P. C. (2015). Optimization of Microwave Drying of Salt with Response Surface Methodology. *Drying, Roasting, and Calcining of Minerals* 1:105.

New Zealand Institute of Chemistry., (2012). The Salt Recovery Process. Retrieved From: http://nzic.org.nz/ChemProcesses/production/1H.pdf, [Last accessed: 14 September, 2013].

Nie, Z., Bu, L., Zheng, M., Huang, W. (2011). Experimental study of natural brine solar ponds in Tibet. *Solar Energy* 85:1537–1542.

Nisan, S., & Dardour, S. (2007). Economic evaluation of nuclear desalination systems. *Desalination* 205(1):231-242.

Notton, G., Paoli, C., Vasileva, S., Nivet, M. L., Canaletti, J.-L., & Cristofari, C. (2012). Estimation of hourly global solar irradiation on tilted planes from horizontal one using artificial neural networks. *Energy* 39(1):166-179.

Osepchuk, J. M. (2012). PROSPECTS FOR EXPANSION OF INDUSTRIAL AND CONSUMER. *Fundamental and Applied Aspects of Nonionizing Radiation*, 411.

Omojaro, P., & Breitkopf, C. (2013). Direct expansion solar assisted heat pumps: A review of applications and recent research. *Renewable and Sustainable Energy Reviews* 22:33-45.

O'Reilly, D. (2009). *Evaporation Enhancement from Evaporation ponds Using Collector Plate Units*. Master Thesis submitted to RMIT University.

Oren, Y., Linder, C., Daltrophe, N., Mirsky, Y., Skorka, J., & Kedem, O. (2006). Boron removal from desalinated seawater and brackish water by improved electrodialysis. *Desalination* 199(1):52-54.

Orhan, M. F., Dincer, I., Naterer, G. F., & Rosen, M. A. (2010). Coupling of copper–chloride hybrid thermochemical water splitting cycle with a desalination plant for hydrogen production from nuclear energy. *International Journal of Hydrogen Energy*, *35*(4), 1560-1574.

Osterwald, C. R., Adelstein, J., del Cueto, J. A., Sekulic, W., Trudell, D., McNutt, P., Moriarty, T. (2006). Resistive loading of photovoltaic modules and arrays for long-term exposure testing. *Progress in Photovoltaics: Research and Applications* 14(6):567-575.

Oztekin, Y., Yazicigil, Z. (2007). Recovery of acids from salts forms of sodium using cation exchange membranes. *Desalination* 212:62–69.

Pacheco, R., Ordóñez, J., & Martínez, G. (2012). Energy efficient design of building: A review. *Renewable and Sustainable Energy Reviews*, *16*(6), 3559-3573.

Pala, R. A., White, J., Barnard, E., Liu, J., & Brongersma, M. L. (2009). Design of plasmonic thin-film solar cells with broadband absorption enhancements. *Advanced Materials*, *21*(34), 3504-3509.

Pankratz, T. (2013). IDA Desalination Yearbook 2012–2013. *Media Analytics Ltc*: Oxford, UK.

Parsons, T. R. (2013). *A Manual of Chemical & Biological Methods for Seawater Analysis*. Elsevier.

Pereira, M. C., Mendes, J., Horta, P., & Korovessis, N. (2007). Final design of an advanced solar dryer for salt recovery from brine effluent of an MED desalination plant. *Desalination* 211(1):222-231.

Pérez-González, A., Urtiaga, A., Ibáñez, R., & Ortiz, I. (2012). State of the art and review on the treatment technologies of water reverse osmosis concentrates. *Water Research* 46(2):267-283.

Peters, T., & Pintó, D. (2008). Seawater intake and pre-treatment/brine discharge—environmental issues. *Desalination* 221(1):576-584.

Peterskova, M., Valderrama, C., Gibert, O., & Cortina, J. L. (2012). Extraction of valuable metal ions (Cs, Rb, Li, U) from reverse osmosis concentrate using selective sorbents. *Desalination* 286:316-323.

Pretti, C., Chiappe, C., Baldetti, I., Brunini, S., Monni, G., & Intorre, L. (2009). Acute toxicity of ionic liquids for three freshwater organisms: Pseudokirchneriella subcapitata, Daphnia magna and Danio rerio.*Ecotoxicology and environmental safety*, *72*(4), 1170-1176.

Priyal, D. F., Toerien, A. (2010) The effect of salinity on evaporation rates of Brines resulting from the treatment of mine water. Retrieved from: *http://www.ewisa.co.za/literature/files/200_150%20Dama-87Fakir.pdf*. [Last accessed: 25 December, 2013].

Qian, W., Weinong, H., Malin, L., Mianping, Z. (2012). *Utilization of Solar Energy on Exploitation of Salt Lake Resources in Tibetan Plateau*. Power and Energy Engineering Conference (APPEEC), Asia-Pacific 1-5.

Ramalingam, A., Arumugam, S. (2012). Experimental Study on Specific Heat of Hot Brine for Salt Gradient Solar Pond Application. *International Journal of ChemTech Research* 4:956-961.

Raut, R. P., and Kulkarni, K. S. (2012). Desalination by membrane distillation. *International Journal of Advanced Engineering Research and Studies*, 1(3):115-121.

Ravizky, A., Nadav, N. (2007). Salt production by the evaporation of SWRO brine in Eilat: a success story. *Desalination* 205(1):374-379.

Reyes-Ruiz, M., Chavez, C. E., Aceves, H., Hernandez, M. S., Vazquez, R., & Nuñez, P. G. (2012). Dynamics of escaping Earth ejecta and their collision probabilities with different Solar System bodies. *Icarus*, *220*(2), 777-786.

Rice, E. W., Baird, R. B., Eaton, A. D., & Clesceri, L. S. (2012). Standard methods for the examination of water and wastewater. *American Public Health Association, Washington, DC*.

Roberts, W.C. (2010). *Extracting minerals from the Great Salt Lake: Great find or great fraud?* University of Utah working paper.

Rodríguez-DeLaNuez, F., Franquiz-Suárez, N., Santiago, D. E., Veza, J. M., & Sadhwani, J. J. (2012). Reuse and minimization of desalination brines: a review of alternatives. *Desalination and Water Treatment*, *39*(1-3), 137-148.

Roskill. (2007). *Salt: Global Industry Markets & Outlook*. Technical Report

Saifullah, A.Z.A., Iqubal, A.M.S., Saha, A. (2012). Solar pond and its Application on Desalination. *Asian Transactions on Science and Technology* 2:2221-4283

Sakhrieh, A., & Al-Salaymeh, A. (2013). Experimental and numerical investigations of salt gradient solar pond under Jordanian climate conditions.*Energy Conversion and Management*, *65*, 725-728.

Saleh, A., Qudeiri, J.A., Al-Nimr, M.A. (2011). Performance investigation of a salt gradient solar pond coupled with desalination facility near the Dead Sea. *Energy* 36: 922-931.

Sampathkumar, K., Arjunan, T., Pitchandi, P., Senthilkumar, P. (2010). Active solar distillation—A detailed review. *Renewable and Sustainable Energy Reviews* 14(6):1503-1526.

Samy A. Khalil1, M. Shaffie (2013). Performance of Statistical Comparison Models of Solar Energy on Horizontal and Inclined Surface. *International Journal of Energy and Power (IJEP)* 2(1):825.

Sanchez-Velasco, L., Lavín, M. F., Jiménez-Rosenberg, S. P. A., & Godínez, V. M. (2014). Preferred larval fish habitat in a frontal zone of the northern Gulf of California during the early cyclonic phase of the seasonal circulation (June 2008). *Journal of Marine Systems*, *129*, 368-380.

Saxena, A., & Goel, V. (2013). Solar air heaters with thermal heat storages. *Chinese Journal of Engineering* 2013:1-11.

Scarpa, F., Tagliafico, L., & Tagliafico, G. (2011). Integrated solar-assisted heat pumps for water heating coupled to gas burners; control criteria for dynamic operation. *Applied Thermal Engineering* 31(1):59-68.

Schober, B. *Membrane stratified solar ponds* [Master thesis], University of Gavle, Sweden, 2010.

Şencan, A., Kızılkan, Ö., Bezir, N. C., & Kalogirou, S. A. (2007). Different methods for modeling absorption heat transformer powered by solar pond.*Energy Conversion and Management*, *48*(3), 724-735.

Shahvari, A., & Yoon, J. (2014). Brine Discharge Load Design and Optimization Framework for Desalination Process Using Mixing Plume Criteria and Discharge Pipe Length Augmentation. In *World Environmental and Water Resources Congress 2014: Water Without Borders* (pp. 666-678). ASCE.

Singh, B., Gomes, J., Tan, L., Date, A., & Akbarzadeh, A. (2012). Small Scale Power Generation using Low Grade Heat from Solar Pond. *Procedia Engineering* 49:50-56.

Smith, B., & Carpentier, M. H. (2012). *The microwave engineering handbook: Microwave systems and applications* (Vol. 3). Springer Science & Business Media.

Sodaye, H., Nisan, S., Poletiko, C., Prabhakar, S., Tewari, P. (2009). Extraction of uranium from the concentrated brine rejected by integrated nuclear desalination plants. *Desalination* 235(1):9-32.

Soliz, D., Glenn, E. P., Seaman, R., Yoklic, M., Nelson, S. G., & Brown, P. (2011). Water consumption, irrigation efficiency and nutritional value of Atriplex lentiformis grown on reverse osmosis brine in a desert irrigation district. *Agriculture, ecosystems & environment*, *140*(3), 473-483.

Steinhauser, G. (2008). Cleaner production in the Solvay Process: general strategies and recent developments. *Journal of Cleaner Production* 16(7):833-841.

Sunliang, C. (2010). State of the art thermal energy storage solutions for high performance buildings. Master's Thesis, Norwegian University of Science and Technology.

Tanaka, Y., Reig, M., Casas, S., Aladjem, C., & Cortina, J. L. (2015). Computer simulation of ion-exchange membrane electrodialysis for salt concentration and reduction of RO discharged brine for salt production and marine environment conservation. *Desalination*, *367*, 76-89.

TATA. (2013). Industrial Salt. Retrieved from: *http://www.tatachemicals.com/products/industrial_salt.htm*, [Last accessed: 20 August, 2013].

Téllez, D., Lom, H., Chargoy, P., Rosas, L., Mendoza, M., Coatl, M., Macías, N., & Reyes, R. (2009). Evaluation of technologies for a desalination operation and disposal in the Tularosa Basin, New Mexico. *Desalination*, *249*(3), 983-990.

Tomson, T. (2008). Discrete two-positional tracking of solar collectors. *Renewable Energy* 33(3):400-405.

Tracstar, (2011). Should you install a solar tracker?. Retrieved from: http://www.helmholz.us/smallpowersystems/.

Tripp, T.G. (2009). Production of magnesium from Great Salt Lake, Utah USA. *Natural Resources and Environmental Issues* 15:55-67.

Tularam, G.A., Ilahee, M. (2007). Environmental concerns of desalinating seawater using reverse osmosis. *Journal of Environmental Monitoring* 9:805–813.

Tundee, S., Terdtoon, P., Sakulchangsatjatai, P., Singh, R., & Akbarzadeh, A. (2010). Heat extraction from salinity-gradient solar ponds using heat pipe heat exchangers. *Solar Energy*, *84*(9), 1706-1716.

UNBS. (2006). *Uganda Standard Edible salts — Specification*. Kampala, Uganda.

USGS. (2006). United States Geological Survey. Salt review; Available online: http://minerals.usgs.gov/minerals/pubs/commodity/salt/ (accessed on 23 July 20011).

USGS, (2009). United States Geological Survey. Mineral Commodities Summary; Available online: http://minerals.usgs.gov/minerals/pubs/mcs/index.html (accessed on 21 July 2009).

Velmurugan, V., & Srithar, K. (2008). Prospects and scopes of solar pond: a detailed review. *Renewable and Sustainable Energy Reviews* 12(8):2253-2263.

Venkatesan, G., Iniyan, S., & Goic, R. (2013). A prototype flash cooling desalination system using cooling water effluents. *International Journal of Energy Research*, *37*(9), 1132-1140.

Vidalis T. (2010). Development of an advanced, innovative, energy autonomous system for the treatment of brine from seawater desalination plants. Retrieved from: *http://www.wise-rtd.info/en/info/development-advanced-innovative-energy-utonomous-system-treatment-brine-seawater-desalination*, [Last Accessed: 8 September, 2012].

Viehmann, S., Bau, M., Hoffmann, J. E., & Münker, C. (2015). Geochemistry of the Krivoy Rog Banded Iron Formation, Ukraine, and the impact of peak episodes of increased global magmatic activity on the trace element composition of Precambrian seawater. *Precambrian Research*, *270*, 165-180.

Vishnu, G., Palanisamy, S., Joseph, K. (2008). Assessment of fieldscale zero liquid discharge treatment systems for recovery of water and salt from textile effluents. *Journal of Cleaner Production* 16:1081–1089.

Wang, H., Su, W., Zou, J. (2007). *Experiment and numerical simulation of sea water solar pond*. International Conference on Power Engineering, Huanghzou, China.

Yaakob, Y., Date, A., Akbarzadeh, A. (2011). Heat extraction from gradient layer using external heat exchangers to enhance the overall efficiency of solar ponds, in: IEEE First Conference on Clean Energy and Technology (CET).

Younis, S.M., El-Shakweer, M.H., Eldanasary, M.M., Gharieb, A.A., Mourad, R.I. (2010). Effect of some factors on water distillation by solar energy. *Misr Journal Agricultural Engineering* 27:586–599.

Zhang, W., Xue, S., Liu, S., Wang, J., Shen, B., & Zhai, J. (2014). Structure and dielectric properties of BaxSr 1− xTiO 3-based glass ceramics for energy storage. *Journal of Alloys and Compounds*, *617*, 740-745.