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INYUVESI YAKWAZULU-NATALI

RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION

BY

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30th AUGUST 2022

As the candidate's supervisor, I have approved this dissertation for submission.

Signed: _____ Date: **30th APRIL 2022**

Name: **Professor Freddie Liswaniso Inambao**

DECLARATION 1 –PLAGIARISM

I, Ojo Olufisayo Emmanuel declare that:

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DECLARATION 2 -PUBLICATIONS

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The following papers have been published, accepted, or are under review:

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1. **Ojo E. Olufisayo** and Professor Freddie Inambao*, A Review Of Seawater Membrane Desalination, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) (Accepted for publication)
2. **Ojo E. Olufisayo** and Professor Freddie Inambao*, A Review Of Renewable Energy Powered Reverse Osmosis System For Seawater Desalination, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD), ISSN (P): 2249–6890; ISSN (E): 2249–8001, Vol. 11, Issue 6, Dec 2021, 73–90
3. **Ojo E. Olufisayo** and Professor Freddie Inambao*, Modeling, And Simulation For A Seawater Reverse Osmosis System**,** International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) (Accepted for publication)
4. **Ojo E. Olufisayo** and Professor Freddie Inambao*, Lifecycle Cost (LCC) Analysis And Evaluation Of The Economics Of Seawater Reverse Osmosis Desalination: Current And Future Challenges For Better Water Supply Sustainability, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) (Accepted for publication)
5. **Ojo E. Olufisayo** and Professor Freddie Inambao*, Experimental And Data Analytical Study Of A Reverse Osmosis Desalination Plant, International Journal of Mechanical and Production Engineering Research and Development (IJMPERD) (Accepted for publication)

For all the publications the candidate is the main author while Prof. Freddie L. Inambao is the supervisor.

DEDICATION

This work is dedicated to the Almighty God for the gift of life and strength to complete this study, and to my beloved wife Fisayo-Ojo Helen, and my daughters, Fisayo-Ojo Inioluwa Angela and Fisayo-Ojo Mofetoluwa Kimberly for their love, understanding, and for standing by me through it all.

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Thank you all.

ABSTRACT

Desalination is one of the most successful procedures for freshwater supply from seawater in the world. Reverse osmosis (RO) is a major technology in the business of seawater desalination because of its ability to produce excellent potable water of highest quality from the seawater source with low energy consumption compared to other technologies. Freshwater is a prerequisite for life and procreation. Water as an essential commodity is used in every phase of human life, ranging from domestic activities such as drinking, cooking, washing, etc., to innumerable industrial and agricultural purposes such as power generation. Today's increasing demands for freshwater by the world population cannot be met by the available fresh water in our ecosystem. This is why numerous technologies for seawater desalination have been established and advanced over the years to augment/satisfy the ever-increasing global demand for freshwater. One such technological development is the use of computer-based modeling for the design and system analysis of the RO treatment process for optimum performance. The hands-on modeling of an efficient full-scale reverse osmosis (RO) system may be daunting work due to the RO systems' operating conditions which continually fluctuate due to cyclical variations in seasons and progressive fouling of the membrane during long-term filtration. The RO plants design, the cost of capital estimation (CAPEX), and operation expenses (OPEX) for large projects have become important factors for potential investors and consulting engineers to bear in mind for pre-construction planning and proper evaluation.

This study reviews existing seawater reverse osmosis (RO) desalination protocols, covering key areas such as pretreatment, RO treatment, and post-treatment of seawater desalination for best performance, with emphasis on solar energy powered RO systems for seawater desalination. This study also models an RO desalination plant using ultrafiltration and IX polishing for feed water pretreatment and post-treatment respectively using the W.A.V.E. software program for design efficiency. The success of seawater desalination using RO technology is predicated upon an efficient feed water pretreatment and post-treatment regime. The use of an ultrafiltration system in combination with filtration has been tested and adjudged to generate excellent quality feed water for the RO system, notwithstanding the quality of the raw seawater. The model framework depicted in this study can serve as a guide for design engineers in providing effective tools for the design of an efficient RO system while maintaining an acceptable balanced hydraulic performance

with considerable cost savings. For the experimental study, the physical experiment was conducted at the Victoria and Alfred (V & A) Waterfront Desalination Plant in Cape Town, South Africa. The experiment was aimed to investigate and quantify the effects of feed water temperature, pressure, salinity, and pH parameters on RO membrane elements. The raw data collected were processed and analyzed to establish the working principle of SWRO, and at the same time develop a relationship model based on the identified system parameters for a better understanding of SWRO operation. The modeling results are validated against the experimental result to evaluate RO system performance. This financial analysis covering capital expenditures CAPEX and operational expenditure (OPEX) of a traditional seawater reverse osmosis (SWRO) desalination plant was conducted. The key parameters involved in the determination of life cycle costs of seawater desalination were listed and analyzed. The parameters include water quality characteristics, production or plant capacity, location, energy consumption, materials, maintenance, operation, RO module costs, chemicals, and award year. For clarity, a 2 MGD SWRO plant was designed using WAVE software, and the design result was used to calculate the lifecycle cost of producing a unit (m^3/d) of potable water in Lagos, Nigeria, deploying a curve fit approach and pertinent water economic analysis tools to develop a reliable life cycle cost for RO systems with acceptable levels of accuracy, based on verifiable and practical parameters.

Keywords: Water, Seawater reverse osmosis (SWRO), Osmosis, Desalination, Seawater, Brackish water, RO membrane, WAVE, Ultrafiltration, Pretreatment, RO Model, Lifecycle cost, CAPEX, OPEX, TWC.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ACRONYMS/ABBREVIATIONS

RO	-	Reverse Osmosis
SWRO	-	Seawater Reverse Osmosis
LCC	-	Lifecycle Cost
CAPEX	-	Capital Expenditure
OPEX	-	Operational Expenditure
TWC	-	Total Water Cost
UF	-	Ultrafiltration
RR	-	Recovery Rate
TDS	-	Total Dissolved Solids
MED	-	Multi-Effect Distillation
MSD	-	Multi-Stage Flash
VCD	-	Vapour Compression Distillation
ED	-	Electro Dialysis
EDR	-	Electro dialysis Reversal
EDI	-	Electrode Ionization
PV	-	Photo Voltaic
HPP	-	High-Pressure Pump
CIP	-	Clean in Place
SDI	-	Silt Density Index
TMP	-	Trans Membrane Pressure
EPC	-	Engineering – Procurement - Construction
ERD	-	Energy Recovery Device
RES	-	Renewable Energy Source

VFD - Variable Frequency Drive

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Water is an important factor in the sustenance of a healthy environment in today's society. About one-third of the earth's total surface area is occupied by water, and about 97% of all water comes from the sea (Ceribasi et al., 2018). Natural sources of water are categorized into surface and sub-surface water. Surface waters such as lakes, rivers, etc., which account for the majority of global freshwater supply, have been seriously depleted due to below normal rainfall in recent years. Sub-surface water sources which are supposed to be more reliable have also failed due to the shortage or gradual reduction in global annual rainfall (Pangarkar et al., 2011). Over 1 billion people are estimated to be without potable water, which has resulted in over five million deaths annually from water-borne diseases, of which four million are children (Pangarkar et al., 2011). Water supply has become a serious problem due to population growth and increasing water demand (Greenlee et al., 2009; Pangarkar et al., 2010). Water is considered to be abundantly available, but freshwater cannot be reached easily in its unbounded cradle. Many countries globally today are suffering from immense scarcity of potable water. According to Ceribasi et al. (2018), the World Health Organization (WHO) reported that a quarter of the global population lives in regions that are not capable of accessing potable water due to a lack of the basic infrastructure needed to abstract and process this water for treatment from watercourses and underground natural reservoirs. Water scarcity is common around the world today, particularly in Africa and Arab countries which are the most affected regions of the world. This region is home to 6.3% of the world's total population, but contains only 1.4% of the world's renewable freshwater (World Health Organization). Desalination addresses the ceaseless problem of ever increasing potable water demand with limited supply. According to Karagiannis and Soldatos (2008), more than 67 % of the world’s populace may be exposed to a shortage of water by 2025, spanning all continents of the world, including the advanced and the under-developed countries alike, unless water demand is reduced and/or alternative/additional water sources are developed. The authors commented that considering the enormous volume of seawater available, the supply capacity of any desalination system seems to be without limits. Seawater requires thorough processing to make it suitable for human

consumption. Khawajia et al. (2008) estimated that more than 75 million of the world's population presently has access to potable water through desalination of seawater and brackish awater. The IDA Desalting Inventory (2004) reported that the total number of seawater and brackish desalination plants globally at the end of the year 2002 was 17 348 with a daily capacity of 37.8 mil/m^3 of potable water. According to [Ioannis C et. al], water is considered one of the key commodities that support and nourish our lives on earth. Its availability improves life quality and enhances the economy of a community. However, while water is a natural resource that occupies three-quarters of the earth's surface, only about 3% of all available water sources are suitable for drinking. According to [Ceribasi G. et. al 2018], the growing cost of desalinating seawater and the need to find an efficient method of desalination has become a matter of great concern to the scientific community, and consequent upon this, many of recent researches in seawater desalination are concentrating on evolving cost-effective methods of producing freshwater for human consumption. [Azevedo, F. D. A. S. M. 2014] reported that even though data on water precipitation is readily obtainable, the river runoff and groundwater levels are challenging and costly to track. Figure A shows the actual state of renewable water resources in 2011 [Azevedo, F. D. A. S. M 2014]. Renewable water is the total quantity of surface water and groundwater of a country's water resources generated through the hydrological cycle, while Non-renewable water resources are deep aquifers that have a negligible rate of recharge on the human time-scale (*This data was collected from AQUASTAT - water information system, developed by the Land and Water Division of the United Nations) [*Azevedo, F. D. A. S. M 2014*]*

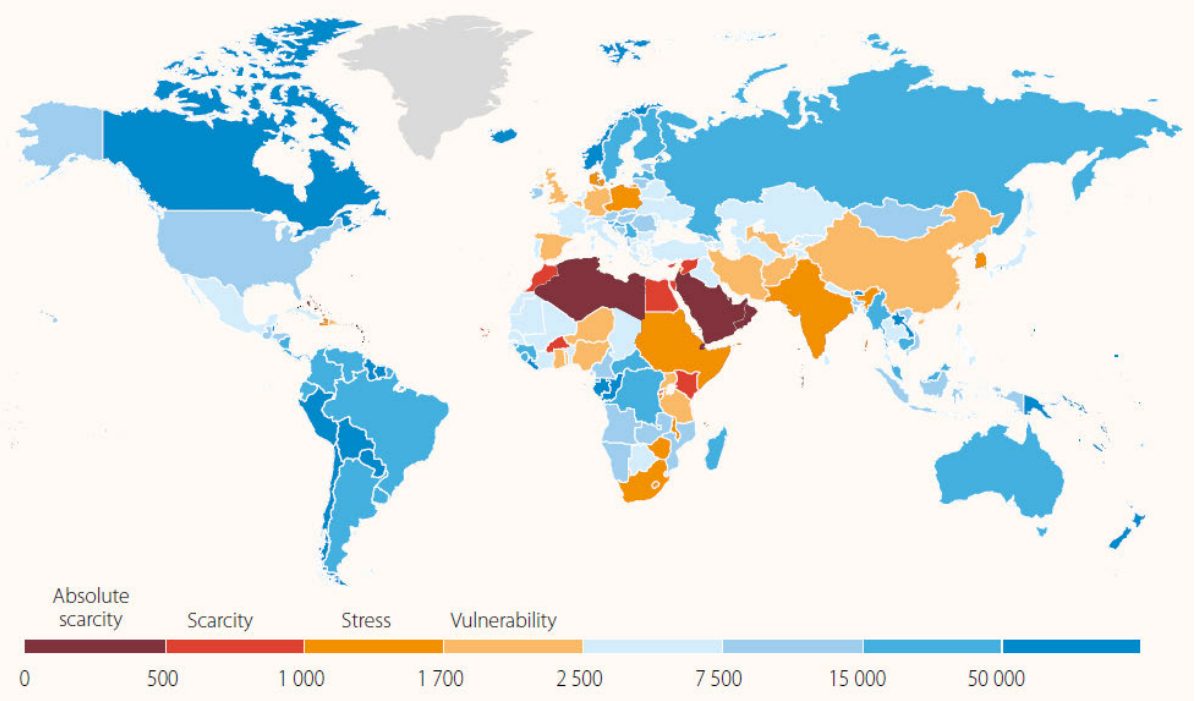

Figure A: Actual renewable water resources (in m^3) per capita and year, in 2011

Reverse osmosis is the fastest evolving desalination method due to its high productivity, rejection of excessive salt (> 99.7%), and moderately inexpensive membranes (Tan et al., 2012). In the design of a reverse osmosis systems, the feed flow is the feed water in gallons per minute (gpm) or cubic meters per hour (m^3/h) supplied to the membrane element or system, while the permeate is a desalinated product water from the RO membrane system. Flux is the rate of permeate transmitted per unit of membrane area and is generally measured in gallons per square foot per day (gfd) or liters per square meter an hour (l/m^2h) (Raju and Ravinder, 2018). Concentrate flow is the flow rate of the impermeable feed water which is formed in the membrane element. The concentrate contains some of the solutes initially introduced into the membrane element from the feed source. In membrane desalination processes, one of the biggest problems encountered is scaling and polluting the membranes. Polluting occurs due to insufficient pre-treatment operations to reduce particulate, colloidal, or organic substances to a bearable level, and due to biological growth in the membrane pressure vessels. Scale formation stems from the precipitation of poorly dissolved salts in the system and tends to be less of a problem with desalination of seawater than

in brackish water systems, which operate at higher recoveries. Compounds, such as silicate, calcium sulfate, calcium carbonate, barium sulfate, and strontium sulfate in the feedwater can limit the rescue of the RO process. The addition of scale/acid inhibitors (also known as antiscalants) will diminish the alkalinity and prevent scale formation, thereby paving way for higher recovery than would otherwise be possible. Because of the aerobic state of seawater and the high presence of particulates, any SWRO system will need extensive pretreatment and feed water chemical conditioning for an efficacious operation (American Water Works Association, 2011). The reverse osmosis (RO) feed water pretreatment system eliminates all suspended solids or flocs to prevent salt rain or microbial growth from taking place in the membranes. Pre-treatment may involve orthodox methods like coagulation/flocculation/sedimentation and sand filtration or membrane processes like ultrafiltration (UF). Ultrafiltration has been adjudged to be more efficient and effective when compared to the conventional system of RO feed water pretreatment. Post-treatment systems occur after the desalination operation to polish the desalinated water from the RO system and increase the water quality characteristics of the throughput so that it is suitable for drinking. This process may involve refinement of the pH and water disinfection to achieve the best water quality.

1.2 PROBLEM STATEMENT

Water withdrawal can be defined as the overall volume of water exploited from a river, lake, or any aquifer for any reason, while water consumption is defined as the segment of withdrawn water which disappears due to the activity of vaporization, absorption, or chemical conversion, transmission, or made inaccessible for additional purposes due to human usage (Azevedo, 2014). Presently, agricultural activities account for almost 70 % of global clean water withdrawals, whereas the commercial and domestic sectors are responsible for 20 % and 10 % respectively (United Nations, 2014). Industry accounts for a much larger percentage of freshwater withdrawals in developed countries, while agriculture takes the lead in water consumption in less-developed countries, accounting for over 90% of their freshwater withdrawals. Most of the statistics on freshwater withdrawal and consumption are founded on estimations rather than real measurements; according to OECD, global water withdrawals are anticipated to rise by 55 % as a result of the upsurge in manufacturing demand (400 % growth), domestic use (130 %) and thermal electricity

generation (140 %) (United Nations, 2014). Currently, about 2.8 billion people around the world live in areas affected by water scarcity, and of this figure, 1.2 billion reside in parts that are already suffering physically from water scarcity, while half a billion people are fast closing in on this situation. The remaining 1.1 billion people going through water scarcity are suffering from commercial water scarcity. This population of people lives in parts of the globe where water is naturally accessible but their access to it is limited by infrastructural distribution, institutional or financial issues, even though the available water deposit is sufficient to satisfy their water demand. This is the case in sub-Saharan Africa. Physical water scarcity arises when a water deposit in a particular locality or community is inadequate to cope with the demand of such a community, and this type of water scarcity is common in arid regions. Scarcity in other areas which are going through human-made physical water scarcity as a result of over-advance in their water withdrawal, which in turn leads to ecological degradation e.g. of groundwater tables and rivers.

This thesis seeks to enhance the overall performance of the RO system through experimentation and optimization of the plants that are already in use.

1.3 RESEARCH MOTIVATION

Today's increasing demand for freshwater by the world population cannot be met by the available fresh water in our ecosystem. This is why numerous technologies for seawater desalination have been established and advanced over the years to augment/satisfy the ever-increasing global demand for freshwater. Water scarcity depends largely on the rate of global water withdrawal and water consumption. It was recorded by Azevedo (2014) that water scarcity is related to local requirements, which differ globally depending on the location. Ceribasi et al. (2018) reported that nearly 80 % of the world’s population may be affected by water scarcity as shown in figure 1. According to Karagiannis and Soldatos (2008), about 25 % of the worldwide population is faced with serious water scarcity problems, and this is expected to result in many not having access to potable water. Desertification, global warming, and drought are expected to aggravate the problem to the extent that even countries that are not currently facing water scarcity may be faced with scarcity of potable water shortly. It was further established, according to the Worldwatch Institute, more than 67% of the global's community could be affected by water scarcity by 2025, including developed countries, with more than 80 countries projected to be affected, unless there is a

reduction in the average daily water usage/demand and/or more water sources are developed. Pangarkar et al. (2011) argued that the difference between global water demand and supply has widened to the extent that in some areas this has become a severe threat to human existence. Pangarkar et al. (2010) explained that the problem of freshwater scarcity is an emerging problem globally as just a minor percentage of the total water on earth is of non-saline water origin, and suitable for human consumption. Similarly, Greenlee et al. (2009) reported that a geological survey in the United States established that 96.5 % of the global water source is precipitated in seas and ocean, while only 1.7 % is contained in the ice. The residual percentage is constituted by groundwater in salty aquifers, brackish water, and weakly saline water. Ceribasi et al. (2018) concluded that owing to the overwhelming presence of saline water in over 97% of the global water which is distributed in seas, oceans, and other saline sources, desalination of seawater has gained prominence and found acceptance as a viable substitute source of water in countries where freshwater sources are inadequate or overused. Global freshwater demand is at the top of the international agenda for the critical issues facing the world.

1.4 AIM AND OBJECTIVES

This project aimed to study, extract data and develop a model and simulations of an RO system. It also aimed to develop a life cycle cost (LCC) and optimize an SWRO desalination plant through experimentation on an already existing plant.

The objectives of this research are:

1. To develop a stable predictive model for the all-encompassing seawater reverse osmosis (SWRO) membrane desalination system
2. To presents financial analysis on CAPEX and OPEX, and estimate/calculate the unit cost of producing potable water from seawater by RO desalination process
3. To carry out an experimental study on an existing SWRO plant;
4. To recommend effective design/for best performance parameters values for an SWRO plant with optimum conditions for potable water production.

1.5 THESIS STRUCTURE

This thesis contains eight chapters that are in line with the aims and objectives of the research conducted. Most of the chapters are in the form of journal articles and publications through various publishing houses. The thesis comprises seven chapters.

Chapter 1: The Introduction: The chapter provides a background of the research, the research significance, aim and objectives, problem statement, outline, and scope of the thesis.

Chapter 2: A review of seawater membrane desalination: This chapter provides a critical review of the desalination process using RO.

Chapter 3: A review of renewable energy powered reverse osmosis system for seawater Desalination: The chapter provides a critical review of the renewable energy-powered RO desalination process.

Chapter 4: Modelling and simulation for a Seawater Reverse Osmosis System using WAVE: Provides modeling and simulation results for several correlations of specific energy and input temperature, feed temperature and permeate temperature, feed and permeate TDS.

Chapter 5: Lifecycle Cost (LCC) Analysis and Evaluation of the economics of Seawater Reverse Osmosis Desalination: Current and future challenges for better water supply sustainability**,** financial analysis on CAPEX and OPEX, and estimate/calculation of the unit cost of producing potable water from seawater by RO desalination process are presented in this chapter.

Chapter 6: Experimental and data analytical study of a Reverse Osmosis Desalination plant: presents experimental and data analytical findings from work conducted at the Victoria and Alfred (V&A) Waterfront desalination unit, a seawater desalination plant located in Cape Town, South Africa, a city on the Atlantic Ocean. Extracted data from experiments were collected and statistically analyzed using Microsoft Excel and different relationships of parameters were plotted.

Chapter 7: Discussions: Presents the discussions of the thesis.

Chapter 8: Conclusion and Recommendation: provides a summary of the research and recommendations.

1.6 SCOPE

This thesis covers work related to modeling and simulation, lifecycle cost, and optimization of an SWRO desalination plant.

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CHAPTER 2: A REVIEW OF SEAWATER MEMBRANE DESALINATION

This chapter provides a critical review of the research carried out by other researchers and scientists in the field of Seawater membrane desalination. The article was accepted for publication in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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A REVIEW OF SEAWATER MEMBRANE DESALINATION

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ABSTRACT

Freshwater is a prerequisite for life and for reproduction. Water is an important commodity used at every stage of human life, from household activities such as drinking, cooking and washing to countless industrial and agricultural purposes such as power generation, and by our ecosystems. For this reason, many techniques for seawater desalination have been established and further developed over the years to cover or meet the ever-increasing demand for freshwater around the world. This article reviews and summarizes recently published seawater desalination studies, explores reverse osmosis (RO) protocols, and covers key areas such as seawater, desalination, osmosis, and RO osmosis.

Key words: Water, Reverse osmosis, Osmosis, Desalination, Seawater, Brackish water, RO membrane.

1. INTRODUCTION

Osmosis is a fundamental process of nature in which two liquids alienated by a semi-permeable membrane permits the passage of a general flush but inhibits the route of the dissolved solids. Water flow direction is predicated upon the force, heat and absorption of the melted solids (Tan et al., 2012). In simple terms, osmosis is the movement of water from a lower concentration solution to a higher-concentration solution through a semi-permeable membrane, while reverse osmosis (RO) is the reversal of the process, and it happens when external pressure is brought upon the higher-concentration flank of the membrane, thereby forcing the diffusion of the higher-concentration solution into a lower-concentration solution. Reverse osmosis was designed in order to overcome the principle of osmotic pressure that occurs when a semi-permeable membrane separates two solutions with dissimilar concentrations of ions,. The osmotic pressure developed by the difference between two concentrations solutions channels the running water through the watery solution to the intense solution, till the evenness of the chemical becomes the reality. If the osmotic pressure is less than the applied external hydraulic force (pressure), this flow can be reversed. To overcome the osmotic pressure of salt and minerals, higher pressures are generally demanded, as well as the membrane material resistance and other related system losses (American Water Works Association, 2011). Figures 1 and Figure 2 show the concepts of osmosis and reverse osmosis.

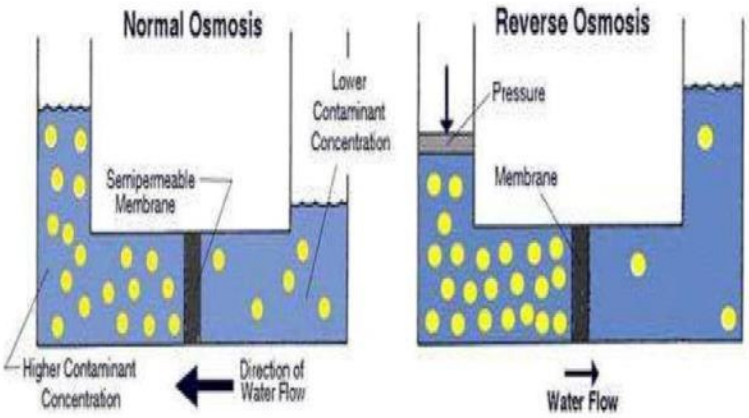

Figure 1 Overview of osmosis.

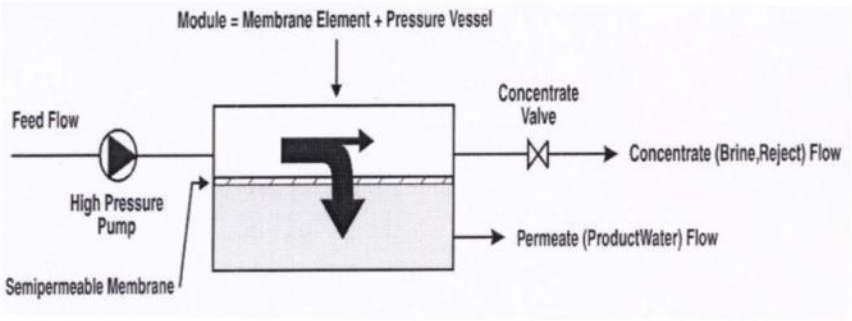

Figure 2. Reverse osmosis process.

Reverse osmosis is the fastest evolving desalination method due to its high productivity, rejection of excessive salt (> 99.7%), and moderately inexpensive membranes (Tan et al., 2012). In the design of a reverse osmosis system, the permeate is the desalinated water product, produced by the RO membrane system, while the feed flow is the feed water in gallons per minute (gpm) or cubic meters per hour (m^3/h) supplied to the membrane element or system. Flux is the rate of permeate transmitted per unit of membrane area, and is generally measured in gallons per square foot per day (gfd) or liters per square meter an hour (l/m^2h) (Raju and Ravinder, 2018). Concentrate flow is the flow rate of the impermeable feed water which is formed in the membrane element. The concentrate contains some of the solutes initially introduced into the membrane element from the feed source. In membrane desalination processes, one of the biggest problems encountered is scaling and polluting of the membranes. Polluting occurs due to insufficient pre-treatment operations to reduce particulate, colloidal, or organic substances to a bearable level, and due to biological growth in the membrane pressure vessels. Scale formation stems from precipitation of poorly dissolved salts in the system and tends to be less of a problem with desalination of seawater than brackish water systems, which operates at higher recoveries. Compounds, such as silicate, calcium sulfate, calcium carbonate, barium sulfate, and strontium sulfate in the feedwater can limit the rescue of the RO process. Addition of scale/acid inhibitors (also known as antiscalants) will diminish the alkalinity and prevent scale formation, thereby paving way for higher recovery than would otherwise be possible. Because of the aerobic state of seawater and the high presence of particulates, any SWRO system will need extensive pretreatment and feed water chemical conditioning for an efficacious operation (American Water

Works Association, 2011). The reverse osmosis (RO) feed water pretreatment system removes all suspended solids or flocs to prevent salt rain or microbial growth taking place in the membranes. Pre-treatment may involve orthodox methods like coagulation/flocculation/sedimentation and sand filtration or membrane processes like ultrafiltration (UF). Ultrafiltration has been adjudged to be more efficient and effective when compared to the conventional system of RO feed water pretreatment. Post-treatment systems occur after the desalination operation to polish the desalinated water from the RO system, and increases the water quality characteristics of the throughput so that it is suitable for drinking. This process may involve refinement of the pH and water disinfection to achieve the best water quality.

The common factors that can affect reverse osmosis include:

- ✓ Types and sizes of membrane, the number of modules used and their preparation.
- ✓ Operating conditions such as permeate recovery, feed pressure and temperature.
- ✓ Raw water state and effectiveness of the pre-treatment processes.
- ✓ Efficiency of pumps and energy recovery systems.
- ✓ The rate and degree of fouling, and the ease of cleaning.

The working parameters of a seawater RO system depends mainly on the salinity/temperature of feed water. The RO water transfer procedure is controlled mainly by diffusion and not by convection as in ultrafiltration. RO recovery refers to the rate (percentage) by which membrane system feed water exits the system as product or permeate water. The relationships between the quantity of permeate generated by the RO and the quantity of feed water that is fed into the RO is known as the recovery ratio (RR). The recovery ratio is of immense importance in terms of RO performance (Gabr, 2007). The system design (membrane) is based on the anticipated feed water quality. Recovery is defined by the first settings of the regulators in the concentrate stream. In order to maximize permeate flux and prevent the domination of super-saturated salts within the membrane scheme, recovery is always set at its highest level. Prior to the osmosis process, a high degree of recovery saves seawater treatment costs and a low degree of recovery saves energy costs for desalination. Rejection is the percentage of solute concentration that the membrane removes from the system feed water. High rejection of total dissolved solids (TDS) is key in reverse osmosis, while solutes of concern are defined in nano filtration, for example, high rejection is desired for organic material, and low rejection for hardness. Passage, which is the reverse of rejection, is the percentage of dissolved components (impurities) in the feed water that is permitted to pass through the membrane. Permeate flux and salt rejection are the key performance parameters of reverse osmosis or nano filtration process which are considered under certain reference conditions as to be the intrinsic properties of membrane performance. The flow and rejection characteristics of a membrane system are commonly influenced by variable parameters such as:

Pressure - As the effective feed pressure increases, total dissolved solid (TDS) contents of the permeate decreases while the permeate flux increases.

Temperature - If the temperature increases and all other parameters are held constant, the permeate flux and the salt passage will also increase.

Recovery - As recovery increases, the permeate flux decreases and stops when the salt concentration reaches a level where the osmotic pressure of the concentrate is as high as the applied feed pressure. The salt rejection will then decrease with increasing recovery.

Feed water salt concentration – An increase in salt concentration inside feed water leads to higher salt rejection, while permeate flux decreases (Raju and Ravinder, 2018). If the standard WHO water quality for potable water is not met for the product water, consideration may be given to a further treatment consisting of two-pass where part of the permeate generated in the principal pass is treated again in a subsequent pass. Therefore, an optimized SWRO design will depend on the feed water, operating conditions of the system, and definite water quality requirements.

2. WATER SOURCE

'Water source' in the context of desalination means sources of water from where water treatment plants take their supply. Water can be sourced from lakes, streams, reservoirs, rivers, springs, and groundwater. Water on the surface of the Earth is distributed through the hydrological cycle. The continuous circulation of water between oceans, atmosphere and land, is what is known as the water (hydrological) cycle. This is evaporation precipitation of water from the sea, surface and transpiration (by plants). Transpiration is the process of water movement in plants and its evaporation through aerial parts, such as pores in leaves, stems and flowers. The evaporated water condenses into a cloud which is then carried by the wind to different locations and eventually released in the form of rain or snow. Precipitation that falls on land can flow over the surface as run-off into rivers and streams, and percolates (trickles down) through the soil into underground rocks to become groundwater. The cycle is continuously repeated and powered by solar energy (Gabr, 2007). The water gathered by land rainfall is known as surface water. Water falls through the atmosphere; absorbing gases, fine particles such as soot and emissions. When it reaches the surface of the earth, water will absorb organic matter, minerals and clay. Surface water is affected by seasonal changes. There are two types of surface water, flowing and still water. Still surface water are lakes, reservoirs and ponds. This water has the ability to settle suspended solids acquired during rainfall. Algae and bacterial development are normally high. The flowing surface water on the other hands are streams and rivers. The flowing water picks up debris in its path, and has less bacterial development than still water with high turbidity tendency due to lack of settling time. Factory waste generated from industries which are pumped into this flowing water completely alters its composition. Surface water typically has the following features: high organic matter content, high turbidity, changes in seasonal fluctuations and variable low mineral content. Groundwater is water that permeates the ground by infiltration. Some of this water is used by trees and vegetation for development and released back into the atmosphere. During infiltration into the soil, groundwater is gathered into an underground formation called the aquifer which has small openings for water storage. In aquifers such as sand and gravel, the water is stored in the space between the particles. The other prevalent type of aquifer is made of fused rock material, and water in this type are stored in the cracks or shell layer of the rock formation. The two main features of aquifers that control the yield and usefulness of formations are internal storage capacity, and recharge/replenishment rate. The two properties are fundamental in predicting the pumping rate from the aquifer. The configuration and temperature of groundwater resources are typically steady when appropriately extracted. The main concerns in well exploration are pollution and intrusion. Compared to surface water, typical groundwater contains low levels of turbidity, high mineral content, and low levels of organic matter. Saline intrusion into ground water can take place if the aquifer is in close proximity to saltwater areas such as the sea, and if groundwater is withdrawn below the sea water level. Because several factors affect the quality and reliability of the ground water, cautious preparation and adequate planning is required before exploring a water source (OpenLearn Create, 2021).

2.1 Salinity and the Main Salt Ions

The composition ratio of the salts in seawater are always the same, with the salinity difference occasioned by either evaporation of freshwater or addition of freshwater from the river. Freezing and thawing also play a role. The main salt ions that make up 99.9 % of salinity are listed in Table 1 (Anthoni, 2000; 2006).

Table 1. Salt ions in seawater.

chemical ion	valence	concentration ppm, mg/kg	part of salinity %	molecular weight	mmol/ kg
Chloride Cl	-1	19345	55.03	35.453	546
Sodium Na	+1	10752	30.59	22.990	468
Sulfate SO4	-2	2701	7.68	96.062	28.1
Magnesium Mg	+2	1295	3.68	24.305	53.3
Calcium Ca	+2	416	1.18	40.078	10.4
Potassium K	+1	390	1.11	39.098	9.97
Bicarbonate HCO3	-1	145	0.41	61.016	2.34
Bromide Br	-1	66	0.19	79.904	0.83
Borate BO3	-3	27	0.08	58.808	0.46
Strontium Sr	+2	13	0.04	87.620	0.091
Fluoride F	-1	1	0.003	18.998	0.068

2.2 Density

According to the World Health Organization (WHO) (2007), the allowable salt content in water is 500 ppm and 1000 ppm in special cases, but most water available on earth has a maximum salt content of 10,000 ppm. Seawater usually contains salts (about 35 000 ppm to 45000 ppm of total dissolved salts). Extreme brackishness will lead to taste and stomach problems. Desalination systems are designed to solve these problems by purifying seawater or brackish water and provide clean water with allowable limits of 500 ppm or less (Kalogirou, 2005). The density of freshwater is 1.00 (grams / ml or kg / liters), which can be increased by adding salt. The more salty water is, the higher its density. Water will expand and becomes less dense when it becomes hot. The colder the water, the higher the density. Figure 3 show the relationship between temperature, salinity and density. The Pacific Ocean has most of the lightest water with a density of less than 26.0; the Atlantic has most of the densest of between 27.5 and 28.0. Antarctic bottom water is densest for the Pacific and Indian Oceans, but not the Atlantic [Anthoni 2000, 2006].

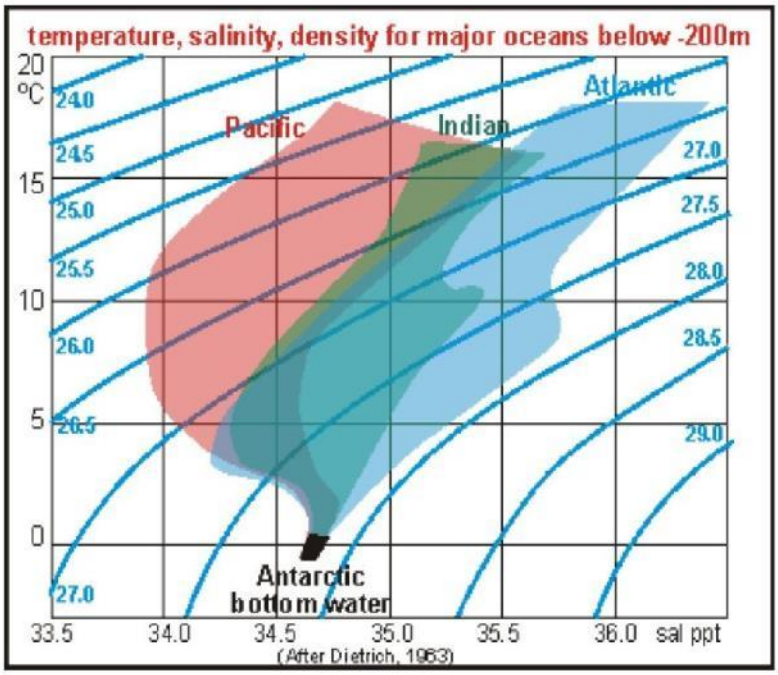

Figure 3. Relationship between temperature, salinity and density.

2.3 Dissolved gases in seawater

Gases dissolved in seawater are always in equilibrium with the atmosphere, but their relative concentration depends on the solubility of each gas, as well as on salt and temperature. As the salt content increases, more water molecules are immobilized by salt ions, which reduces the amount of dissolved gas. As the water temperature rises, the mobility of gas molecules increased, and facilitates their discharge from the water, which reduces the quantity of gas that dissolves. Table 2 shows the salt ion content of different sea water sources.

Table 2. Ion composition of Seawater (WHO, 2007)).

Constituent	Normal Seawater	Eastern Mediterranean	Arabian Gulf At Kuwait	Red Sea At Jeddah
Chloride (Cl^{-1})	18,980	21,200	23,000	22,219
Sodium (Na^{+1})	10,556	11,800	15,850	14,255
Sulfate (SO_4^{-2})	2,649	2,950	3,200	3,078
Magnesium (Mg^{+2})	1,262	1,403	1,765	742
Calcium (Ca^{+2})	400	423	500	225
Potassium (K^{+1})	380	463	460	210
Bicarbonate (HCO_3^{-1})	140	--	142	146
Strontium (Sr^{+2})	13	--	--	--
Bromide (Br^{-1})	65	155	80	72
Boric Acid (H_3BO_3)	26	72	--	--
Fluoride (F^{-1})	1	--	--	--
Silicate (SiO_3^{-2})	1	--	1.5	--
Iodide (I^{-1})	<1	2	--	--
Other	1	--	--	--
Total Dissolved Solids	34,483	38,600	45,000	41,000

-- – not reported

3. DESALINATION TECHNOLOGIES

Desalination of seawater can be defined as the extraction of clean (fresh water) from salt water, or the removal of salt saline water. Many technologies have been developed over time to do this, but only a few are commercially viable. Table 3 shows the two most widely used desalination methods. Desalination of sea water is accomplished by using several techniques, including industrial desalination techniques that employ phase changes or use a semi-permeable membrane to isolate solutes from inherent solvent. As mentioned above, desalination techniques have two major categories: phase change/thermal process and membrane/single-phase processes. All desalination processes include pretreatment of raw brine to prevent membrane fouling, foaming, corrosion, scaling, organic progression etc., and post-desalination treatment to render the water potable for safe consumption (Kalogirou, 2005).

Table 3. Desalination classification.

Phase-change processes	Membrane processes
1. Multi-stage flash (MSF)	1. Reverse osmosis (RO)
2. Multiple effect boiling (MEB)	–RO without energy recovery
3. Vapour compression (VC)	–RO with energy recovery (ER-RO)
4. Freezing	2. Electrodialysis (ED)
5. Humidification/ dehumidification	
6. Solar stills	
–Conventional stills	
–Special stills	
–Cascaded type solar stills	
–Wick-type stills	
–Multiple-wick-type stills	

3.1 Thermal Technologies

Thermal technology is the boiling of water which contains salt and harvesting the condensed steam (distillate) to generate purified water. Due to the high cost of desalting brackish water, thermal technology has rarely been used, but it has been adopted for the desalination of seawater. Thermal technologies are divided into three sub-groups namely Multi-Effect Distillation (MED), Multi-Stage Flash Distillation (MSF), and Vapor Compression Distillation (VCD) [Krishna et al.].

3..1.1 Multi-Stage Flash Distillation (MSF)

Distillation is achieved in this process through several (multi-phase) chambers as shown in Figure 4, with each subsequent phase of the system operating at continuously lower pressures. The feed water to the system is subjected to elevated pressure and fed into the first "flash chamber" where the pressure is allowed to drop, which leads to the water boiling rapidly and causing sudden evaporation also known as flashing. This process is designed to continue in each of the subsequent phases because the subsisting pressure in each phase is less than the previous phase. The steam produced from each stage is passed

through heat exchanger tubes for conversion to fresh water. Typically, multistage flash distillation (MSF) systems can have 15 to 25 stages, but generally, their capacities are not more than 15 mgd. A MSF system is designed to have either a "once through" or "recycle" process and configured as either a "long tube" or "cross tube" structure. Unless stainless steel is used for the construction, MSF systems are prone to rust. Similarly, MSF systems are also exposed to corrosion and impact attack as a result of the water supply turbulence in the expansion chamber due to water movement from stage to stage.

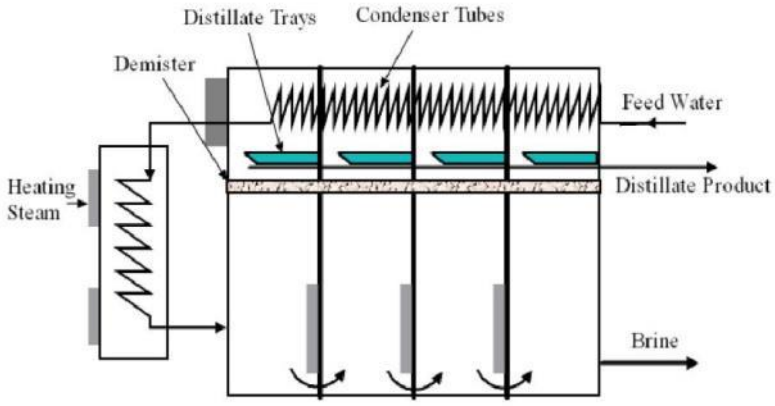

Figure 4: Schematics of multi-stage flash desalination system

3.1.2 Multi-Effect Distillation (MED)

The multi-effect distillation (MED) procedure for saltwater purification was used in the late 1950s and early 1960s. This technology takes place in a sequence of vessels and adopts the basic phenomenon of evaporation and condensation at abridged ambient pressure. A series of evaporation effects produces water at gradually reduced pressures. As the pressure drops, the water gets boiled at a lower temperature to allow the water vapor from the initial vessel or effect serve as the heat medium for the second vessel. The more vessels or effects are involved, the greater the performance ratio of the system. MED units can be categorized into two namely, horizontal tubes and vertical tubes/vertically stacked tube bundles contingent on the placement of the heat exchanger tubes (Zhao, 2006).

3.1.3 Vapor Compression Distillation

Vapor compression distillation (VCD) technology can be designed for usage with another process like MED or be used alone. The heating to evaporate is normally from the compression of steam (Figure 5). Compressing water vapor raises the temperature and generates steam. The heated steam flows through the water tank and then rises to the top of the collector and returns to the compressor. This permits heat to be recycled in a single distillation process. Hot steam powers and drives the compressor in thermal vapor compression, and such a system is popular for moderate desalination because it is simpler than MSF. In mechanical vapor compression, a diesel engine or an electric motor is used to drive the compressor. The VCD units are developed in different dimensions. Mechanical compressor types are deployed to produce heat for the vaporization. VCD units are characteristically low on delivery/volume and are mostly used for some industrial applications and in hotels and

resorts. A heat exchanger is usually configured to provide heat for the feed solution, and coupled with the residual heat from the resulting water will increase the system efficiency. Furthermore, increasing the surface area of the evaporator tube with a reduced compression ratio can also increase the system productivity.

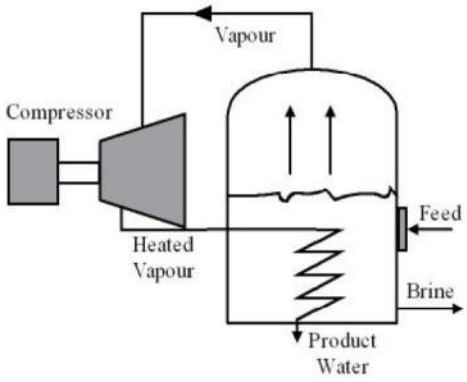

Figure 5. Diagram of the vapor compression system.

3.2 Membrane Technology

Membrane technology can be classified into two types, namely: reverse osmosis / nanofiltration and electrodialysis / electrodialysis reversal.

3.2.1 Electrodialysis (ED) and Electrodialysis Reversal (EDR)

Electrodialysis (ED) is a voltage-controlled membrane process that allows passage of salt ions via a membrane, thereby producing fresh water as final product. An ED system requires two types of membranes; one allows anions to pass but not cations, and the other one works in the opposite way. ED uses an electrical tendency to produce fresh water from saline through a membrane process. Electrodialysis deploys the general principles of similar poles repel and dissimilar poles attract. Appropriate membranes can be selected to selectively pass either cations or anions. In salt water, soluble ions such as in sodium chloride (Na^+ and Cl^-) can pass through some membranes that allow either anions or cations (but not both) to the opposite electrode. Depending on the polarity of the membrane, the soluble salt ions are attracted to the membrane. As water exits to the other side of the stack, they alternate into fresh water and concentrate in the spacer layer. Alternating the polarity of the voltage will reverses the freshwater and concentrates production in the layer. The membranes in the ED system are typically organized in an alternating form with the cation-selective membrane following the anion-selective membrane. A concentrated solution and a dilute solution are produced in the gap between the two alternating membranes, and this gap between two membranes is called a cell. The EDR system is based on similar principles as the ED, except in the configuration of product and concentrate channel which is identical. The polarity of the electrodes is reversed severally per hour, so that the attraction of the ions across the membranes are in the opposite directions. The reversal process helps to break down and wash away intracellular scales and debris before they accumulate. Flushing helps reduce membrane fouling problems. Due to the unique properties of the electrical processes used in the ED device, it is typically used for brackish water desalination instead of

high salinity water such as seawater. Electrodialysis was developed on a commercial scale in the 1960s, and since then it has gained wide application for desalination of brackish water. Electrodialysis is rarely used for seawater desalination because the energy consumption is highly dependent on the concentration of water supply.

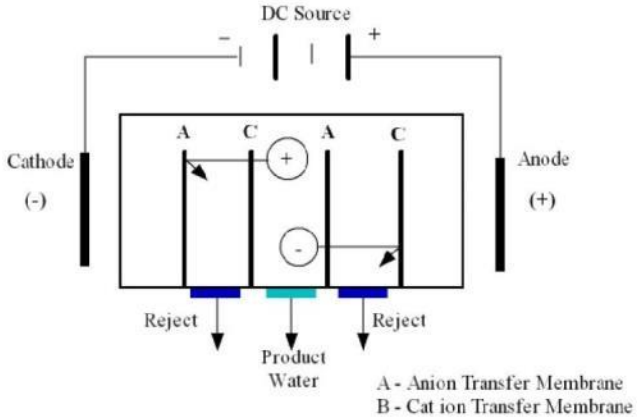

Figure 6. Schematic diagram of electrodialysis system.

3.2.2 Reverse Osmosis (RO) and Nanofiltration (NF)

When it comes to thermal processes, RO is a comparatively new technology that was developed into commercial scale in the 1970s (Buros, 2000). The most commonly accepted desalination technique globally is RO. The process capitalizes on pressure to drive salt water through a semipermeable membrane to generate a clean water stream and residual concentrated brine stream. Nanofiltration (NF) is another membrane technology commonly used to remove divalent salt ions e.g. calcium, magnesium and sulfate. RO is a process typically used to remove sodium and chloride ions from seawater, and can as well be used for the desalination of brackish water (TDS > 1 500 mg/l). RO is when the osmosis principle is forced to work in the opposite direction through the application of elevated pressure. Osmosis is a natural phenomenon in which a low-salt water passes through a semipermeable membrane into a more concentrated salt solution. The process becomes reverse osmosis when the pressure is applied to the high salt concentration solution which forces the water to flow in the opposite direction through the semipermeable membrane, leaving brine concentration as residue. A RO desalination plant is basically made up of four main systems: pretreatment system, high pressure pump, membrane system and posttreatment system.

Pretreatment as shall be seen later in this review is very significant because RO requires the membrane surface to be kept clean for efficient desalination process. Therefore, it is necessary to first remove all suspended solids and pre-treat the water to prevent salt precipitation and microbial development on the membrane. Pretreatment may include the conventional method of water treatment such as chemical feed followed by flocculation, coagulation, sedimentation and sand filtration. Alternatively, the pretreatment process can be a membrane method such as microfiltration (MF) or ultrafiltration (UF). The choice of specific pretreatment process depends on a number of factors which include: feed water quality properties, available space, RO membrane requirements, etc. A high-pressure pump provides the pressure required for water to be pushed through the membrane and have the salt rejected. The membrane assembly comprises a pressure vessel and an integral semipermeable

membrane that allows passage of water. There are generally two types of RO membranes for desalination: spiral wound membranes. and hollow fiber membranes. The spiral wound element is usually made from a flat sheet membrane material of cellulose acetate or other composite polymers. The membrane shell is wound around a central collection tube. The pressurized water supply spirals through the membrane shell and pure (desalted) water is collected in a central pipe. As part of the water passes through the membrane, the salinity of the remaining feed water continues to increase. Another type of membrane is a hollow fiber design, with a large number of hollow fiber membranes placed inside the pressure vessel.

4. RO DESALINATION PROCESS

4.1 Pretreatment

In reverse osmosis seawater desalination processes, pretreatment is a critical factor in achieving and maintaining the performance of RO desalination systems. The pretreatment system removes suspended solids from the feed stream and prevents the formation of salt precipitates or microbial growth on the membrane surface. Membrane surfaces must be kept in good condition and clean at all times (Oyo, 2006). There are two types of pretreatment methods for a RO desalination system: conventional pretreatment system and membrane pretreatment system, which includes microfiltration (MF) and ultrafiltration (UF). Conventional pretreatment methods include chemical feed/injection, clotting, flocculation, sedimentation, media filtration, and/or dissolved air flotation. The selection of pretreatment system for any reverse osmosis operation depends on the quantity of particles, silt, algae and organic substances present in the raw RO water, which, by extension is extremely reliant on the raw seawater quality. Chemical treatment coupled with media filtration are both conventional pretreatment processes, used in refining seawater to the best quality, suitable for a RO feedwater, thereby preventing biofouling of membrane elements. In contrast, an ultrafiltration (UF) membrane removes floating solids by visible filtration through a superficial elimination mechanism similar to a fine screen. Suspended elements that are bigger when compared to the biggest size of the UF membranes pore are disallowed and retained in the concentrate, while liquid and other floating particles that are smaller compared to the largest pore size of UF membranes penetrate to the permeate side of the membrane. The presence of flocs or suspended solids in raw seawater, if not properly disposed of, can cause serious damage to downstream process equipment such as pumps and membrane elements. Therefore, pretreatment procedures are strongly recommended to avoid sudden increases in silt and other particulates that can have devastating consequences for downstream processes. Organic compounds, which are also present in raw seawater in addition to suspended matter, are harmful, and foul membrane elements from downstream processes, thereby increasing the frequency of membrane element cleaning, reducing production capacity, reduces the durability of the membrane and increases operating costs (Tan et al., 2012). The development of external matter from feed water on the exterior of the dynamic membrane and / or in the feed spacer leading to operational problem is known as fouling. Membrane fouling, in turn, can be defined as the accumulation of several layers on the membrane surface and feed spacer which includes scaling. There are three common types of membrane fouling: colloidal, biological and organic fouling. Colloidal fouling describes the entrapment of colloidal substances or particles such as iron flocs or silt on the surface of the membrane, while biological fouling (biofouling) describes the development of biofilm substances on the membrane. Biological polluting is the adsorption of certain types of organic compounds like humic materials and oil on the exterior of the membrane. Scaling is the precipitation and deposition of poorly soluble salts within the system, which includes calcium sulfate, calcium

fluoride, barium sulfate, strontium sulfate, and calcium carbonate. A well designed and maintained pretreatment system will extend the life of a membrane and proffer a solution for impurities that cause deposits and fouling of the membranes. Major RO membrane failures are generally due to deficiencies in pretreatment systems. The silt density index of the feed stream must be monitored frequently to avoid the extreme presence of colloidal material, while excess colloidal material can be removed by proper coagulation and filtration. The right configuration and selection of the pretreatment system, which depends on the properties of raw saltwater, favors the useful life and efficiency of the membrane by reducing scaling, fouling and membrane degradation. RO feed water pretreatment should include a whole systematic approach for a continuous and reliable operation, because the cost of scrubbing, interruption, and the loss of system routine can be very high. The type of pretreatment system to be adopted at any time is highly dependent on the source of feed water (i.e. ground water or surface water). Groundwater is generally a constant source of feed source with little potential for fouling. Acidification and or anti-sealant dosing plus cartridge filter are a simple pretreatment for this water. On the order hand, surface water varies according to the seasonwith high potential for microbiological and colloidal fouling. Surface water pretreatment is usually more intensive than groundwater pretreatment (Raju and Ravinder, 2018). Most surface and groundwater in their natural state are practically saturated with CaCO3, whose solubility depends on the pH value, as shown in equation 1:

$$Ca^{2+} + HCO_3^- \leftrightarrow H^+ + CaCO_3 \qquad \text{Eq. 1}$$

The addition of H^+ as an acid shifts the equilibrium of the equation left keeping the calcium carbonate dissolved. The introduction of sulfate into the feed stream on the other hand, has the potential to cause sulfate deposits. The $CaCO_3$ is inclined to liquefy in the concentrate stream rather than precipitate. The tendency of $CaCO_3$ dissolution can be expressed by the Langelier saturation index (LSI) for salty water and the Stiff & 6 Davis stability index (S&DSI) for sea water. At saturation pH (pHs), water is in equilibrium with $CaCO_3$. The definitions of LSI and S&DSI are:

$$LSI = pH - pHs \text{ (TDS} < 10{,}000 \text{ mg/L)} \qquad \text{Eq. 2}$$

$$S\&DSI = pH - pHs \text{ (TDS} > 10{,}000 \text{ mg/L)} \qquad \text{Eq. 3}$$

It should be noted that the method used for predicting the PHs for LSI and S&DSI are different to regulate calcium carbonate scaling by acid addition; the LSI or S&DSI must be negative in the concentration stream. Acid addition is the only method used in the control of carbonate scale (Sami, 2014). Scale inhibitors, also known as anti-sealants, slow down the precipitation process of soluble salts as they are absorbed by salt crystals (after formation), to prevent the attraction of supersaturated salts to the crystal surfaces. Under these circumstances, crystals will never develop to a size or concentration sufficient enough to come out of suspension. In addition, many scale inhibitors have various dispersive properties that envelop suspended salt particles or organic solids with an anionically charged scale inhibitor. These anionically charged particles repel each other to prevent these particles from accumulating into a larger particle that can precipitate. Scale inhibitors are effective in controlling carbonate, sulfate and fluoride scale (Tan et al., 2012) Ultrafiltration [UF] membranes have smaller sizes compared to microfiltration [MF] membranes with approximately 0.01 µm to 0.02 µm, while MF membranes can contain particles with just about 0.1 µm to 0.2 µm size. Consequently, the UF membrane has a finer sieve capacity compared to the MF membrane, which justifies its use for this project. The UF membrane pretreatment benefits include less overall desalination

costs and improved water safety. The UF membrane pretreatment process capital cost has been reported to be 20 % to 50 % higher compared to conventional pretreatment processes. However, better quality permeate flow from a UF membrane pretreatment procedure can bring down the overall cost (initial and subsequent) of maintaining more recent RO operation as regards plant configuration size cutting and increasing manufacturing dimensions, but it depends on the saltiness of the spring water. Improved permeate flux from the UF pretreatment will also help bring down the cleaning frequency and element replacement of the RO membrane, thus cutting down on the cost of the operation. While this estimated cost reduction from UF is desirable, the actual benefit of UF pretreatment over conventional pretreatment is that it provides more stable and reliable treated water to the RO system, thereby reducing unplanned system downtime. However, the UF process has the limitation that organic substances easily penetrate the pretreatment process, which causes soiling of the membrane component which renders the pretreatment process ineffective. To counteract this scenario and reduce the number of organic substances that penetrate the RO process downstream, a coagulant pretreatment must be considered to reduce the natural burden on the UF compartment.

4.2 RO Membrane Process

The arrangement of the RO membrane operation largely depends on the following: manufacturing dimensions, the standard of the final product, and the specifications of the commercially available equipment. The designer needs to decide whether to use an acid/anti-scaling dose to inhibit the fouling of the membrane The next step is to choose the type and size of the membrane that will be deployed depending on type of feed source. The designer will calculate the estimated number of membrane elements to be used and the initial membrane configuration. The design of a reverse osmosis system generally includes:

- Determination of pretreatment requirement
- Selection of RO membrane
- Determination of system configuration
- Design for operational status

After initial model input, the computer model will generate an output in reference to the following parameters:

- Detailed analysis of permeate and water rejection
- Scaling tendency of the water
- Total pressure requirement
- Concentration polarization (Beta factor) (Raju and Ravinder, 2018)

The production capacity for each RO train up to 8 items per train is determined by the design, since every membrane constituent has a positive highest water manufacturing every day. The pressure drops across every element can reduce water production whereas the largest number of segments permitted per train creates the largest production of water. The operating force must therefore be adjusted accordingly. The quality of the permeate water is also influenced by the number of partition constituents inside every train and by the operating system. Characteristically, a RO unit has a solitary aggressive drive that supplies feed water to multiple RO trains. The choice of other secondary apparatus (force vessel, membrane element diameter, etc.) and high-pressure pumps are limited by the manufacturer's standard equipment. A second stage RO process can be used if

the overall objective of the RO installation is to increase water recovery. Second phase RO uses concentrate from the first phase RO and normally necessitates a support pump to increase the pressure of the feed water due to the quantity of water to be recuperated. The second phase RO normally operates with larger force when compared with the first phase unit, where concentrate from the preceding stage is used to feed the next stage. Multi-stage RO systems use multiple stages of operation. However, it cannot be applied in real design due to the huge capital involved. When multi-stage design is used, a two-stage operation is considered a credible design for seawater RO (Park et al., 2019). If the concern of the RO desalination system is to produce high quality product water, an RO unit an be used in the second pass to further purify permeate from the first pass, if the purpose of the RO salt removal structure is to make available high quality outcome water A second pass reverse osmosis unit will normally operate at a lower feed pressure as the feed water quality is of practical quality. For desalination of seawater for drinking water production, a RO unit is required in the second pass to lessen the boron concentration in accordance with the drinking water requirements (Tan et al., 2012). Water that penetrates through the RO membrane enters the permeate carrier, allowing water flow midway into the permeate channel. To dominate and bring down the concentration separation, the water recuperation of the membrane module is managed and restricted to 10 % to 20 %. Therefore, to achieve higher water recovery rates of say. 40 % to 50 % water recovery in salt water purification, this RO procedure is generally organized between three to eight modules / elements. membrane series in a pressure vessel. The concentrated salt water from the initial element is used to feed the close by constituent, etc. since every constituent is inside the force vessel.

4.3 Post-Treatment

Post-treatment is the process of stabilizing the water and preparing it for distribution. Since most alkaline mineral components in water appears bigger than the pores of normal RO and cannot pass through the membrane, permeate flux assumes an acidic status. Acidic water is not only harmful to humans if ingested, acidity can destroy the components of the RO system downstream of the membrane. In the case of such problems, naturally occurring alkaline minerals like lime and caustic soda are added to the permeate to restore its pH to an acceptable level. Post-treatment, which includes pH adjustment, also consists of disinfection to combat microorganisms during distribution and eliminate pathogens from the mixing process. In some cases, desalinated water can be mixed with water from other sources to enhance its taste, expand the supply, and also improve its quality for safe water consumption. Disinfection with ultraviolet radiation or chemical agents (chlorine) to ensure the elimination of bacteria or viruses that have passed through the membrane is an essential part of the follow-up treatment (Oyo, 2006). Also, if acid is added to the membrane feed water to control calcium carbonate scaling; the associated decrease in pH value will lead to the conversion of bicarbonate to carbonic acid in the stream (feeding the membrane). Decarbonization by means of an aeration process is regularly combined so as to eliminate surplus carbonic acid from membrane permeate; by so doing, the pH of the finished water will increase. Decarbonization is regularly used with chemical pH adjustment, to convert carbonic acid to bicarbonate alkalinity. The alkalinity can be complemented with chemical treatment by adding sodium carbonate or sodium bicarbonate. Adding hardness in order to control corrosion is another important aspect of the post-treatment. This can be achieved by mixing raw water, adding lime, and using limestone. Although a RO system is capable of removing 99 % of dissolved salts, protozoa, bacteria, viruses, and many chemical contaminants, post-treatment is proposed to guarantee that desalinated water is potable for drinking and completely free of contaminants that may have been present in the feed water. In order to reduce corrosivity, corrosion inhibitors can be added to the membrane permeates. Corrosion inhibitors

work by forming protective films on pipe walls (phosphate and silicate inhibitors) or reacting with metal ions to form a passivation layer (orthophosphates). Various computerized corrosion protection models are available to assess the total impact of any proposed model.

5. CONCLUSION

This paper reviewed various techniques for seawater and brackish water desalination to produce large quantities of standard/quality fresh water at reasonably competitive rates, and also identified some setbacks of the system. This paper also summarizes the comparison between the reviewed techniques as laid out below.

5.1 Comparison of The Three Major Desalination Technologies

Over the last decade due to the improved performance of the system in terms of dependability and energy consumption, RO technology remains widely accepted for the desalination of sea water. RO desalination is energy efficient when compared to thermal desalination technology. However, RO membranes are usually made of cellulose acetate or similar composite polymers which are prone to fouling. The cost of replacing a membrane is costly. Thorough seawater pretreatment is required to reduce membrane fouling and also to remove particles and organic matter, thereby increasing freshwater production costs. MSF is comparatively easy to use as it requires minimal pretreatment and requires less skill to operate the facility. It has the additional benefit of being able to treat large amounts of water and produce ultrapure water. However, MSF requires high energy input which is responsible for the most of the facility's operational costs. Due to the significant amount of thermal energy required, some desalination plants are built to take advantage of the excessive generated heat energy. In addition, MSF has a lower water recovery rate when compared to RO systems. MED was the first seawater desalination technology used. Like MSF, MED needs minimal seawater pretreatment and can produce ultrapure water. It has a higher water recovery rate than MSF. However, compared to RO technology, MED does not work well in that it consumes more energy and has a lower water recovery rate (Research Office, 2015). The strengths and weaknesses of the RO, MSF and MED technologies are summarized in Table 4.

Table 4. Comparison of the three major desalination technologies.

	RO (membrane-based technology)	MSF and MED (thermal-based technologies)
Strengths	• lower energy requirement • higher water recovery	• relatively simple to operate • capable of producing high-purity water
Weaknesses	• membrane susceptible to fouling • requirement for thorough seawater pre-treatment	• higher energy requirement • lower water recovery

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CHAPTER 3: A REVIEW OF RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION

This chapter provides a critical review of the research carried out by other researchers and scientists in the field of Renewable energy powered reverse osmosis seawater desalination. The article was published in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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Original Article

A REVIEW OF RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION

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ABSTRACT

Fresh water is a prerequisite for life and procreation. Water as an essential commodity is used in every phase of human life ranging from domestic activities such as drinking, cooking, washing etc. to innumerable industrial and agricultural purposes such as power generation etc. The increasing demand for fresh water by the world population today cannot be met by the available fresh water in our ecosystem. This is why numerous technologies for seawater desalination have been established and advanced over the years to augment/satisfy the ever-increasing global demand for fresh water. This paper reviews and summarizes recently published studies on desalination of seawater exploring reverse osmosis (RO) protocols, covering key areas such as seawater, desalination, reverse osmosis, RO membrane. The emphasis is on solar energy powered RO systems for seawater desalination.

KEYWORDS: Water, Reverse osmosis, Osmosis, Desalination, Seawater, Brackish Water & RO Membrane

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1. INTRODUCTION

Water is a critical factor in the sustenance of a healthy environment in today's society. About one-third of the earth's total area is occupied by water, with around 97 % of the total water originating from the sea (Ceribasi et al., 2018). Natural sources of water are categorized into surface and sub-surface water. Surface water such as lakes, rivers etc., which account for the majority of global fresh water supply, have been seriously depleted due to below normal rainfall in recent years. Sub-surface water sources which are supposed to be more reliable have also failed due to the shortage or gradual reduction in global annual rainfall (Pangarkar et al., 2011). Over 1 billion people are estimated to be without potable water, which has resulted in over five million deaths annually from water borne diseases, of which four million are children (Pangarkar et al., 2011). Increases in population and increased demand for water means that the supply of water has become a serious problem (Greenlee et al., 2009; Pangarkar et al., 2010). Water is considered to be abundantly available, but freshwater cannot be reached easily in its unbounded cradle. Many countries globally today are suffering from immense scarcity of potable water. According to Ceribasi et al. (2018), the World Health Organization (WHO) reported that a quarter of the global population lives in regions that are not capable of accessing potable water due to lack of the basic infrastructure needed to abstract and process this water for treatment from water courses and underground natural reservoirs. Water scarcity is common around the world today, particularly in Africa and Arab countries which are the most affected regions of the world. This region is home to 6.3 % of the total world's population while it holds only 1.4 % of the world's renewable freshwater (World Health Organization). Desalination provides a solution to the incessant problem of increasing demand for potable water with limited supply. According to Karagiannis and Soldatos (2008), more than 67 % of the world's populace may be exposed to a shortage of water by 2025, spanning through all continents of the world,

including the advanced and the under-developed countries alike, unless water demand is reduced and/or alternative/additional water sources are developed. The authors comment that considering the enormous volume of seawater available, the supply capacity of any desalination system seems to be without limits. Seawater requires thorough processing to make it suitable for human consumption. Khawajia et al. (2008) estimated that more than 75 million of the world's population are accessing potable water by desalination of brackish water and seawater. The IDA Desalting Inventory (2004) reported that the total number of seawater and brackish desalination plants globally at the end of the year 2002 was 17 348 with a daily capacity of 37.8 mil/m^3 of potable water.

2. WATER SCARCITY

Water scarcity depends largely on the rate of global water withdrawal and water consumption. It was recorded by Azevedo (2014) that water scarcity is related to local requirements, which differ globally depending on the location. Ceribasi et al. (2018) reported that nearly 80 % of the world's population may be affected by water scarcity as shown in figure 1. According to Karagiannis and Soldatos (2008), about 25 % of the global population are faced with serious water shortage problems, and this is expected to result in many not having access to potable water. Desertification, global warming and drought are expected to aggravate the problem to the extent that even countries that do not face water shortages at the moment may be faced with the scarcity of potable water in the near future. It was further established, according to the World Watch Institute, that more than 67 % of the global community may witness water scarcities by the year 2025, including developed countries, with more than 80 countries projected to be affected, unless there is a reduction in the average daily water usage/demand and/or more water sources are developed. Pangarkar et al. (2011) argued that the difference between global water demand and supply has widened to the extent that in some areas this has become a severe threat to human existence. Pangarkar et al. (2010) explained that the problem of fresh water scarcity is an emerging problem globally as only a small percentage of the total water on earth is of non-saline water origin, and suitable for human consumption. Similarly, Greenlee et al. (2009) reported that a geological survey in the United States established that 96.5 % of the global water source is precipitated in oceans and seas, while only 1.7 % is contained in the ice. The residual percentage is constituted by groundwater in salty aquifers, brackish water and weakly saline water. Ceribasi et al. (2018) concluded that owing to the overwhelming presence of saline water in over 97% of the global water which are distributed in seas, oceans and other saline sources, seawater desalination has gained prominence and found acceptance as a viable substitute source of water in countries where fresh water sources are inadequate or overused. The need for fresh water globally is uppermost in the international agenda of critical problems facing the world.

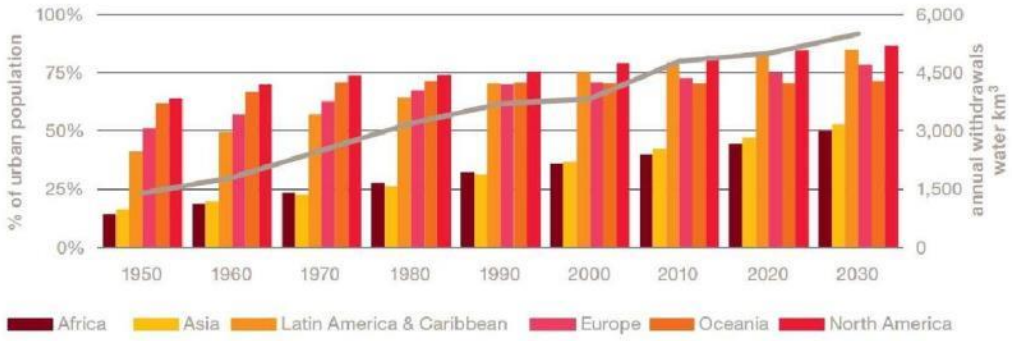

Figure 1: Population Density vs Water consumption.

Water withdrawal can be defined as the overall volume of water exploited from a river, lake or any aquifer for any reason, while water consumption is defined as the segment of withdrawn water which disappears due to the activity of vaporization, absorption or chemical conversion, transmission, or made inaccessible for additional purposes due to human usage (Azevedo, 2014). Presently, agricultural activities account for almost 70 % of global clean water withdrawals, whereas the commercial and domestic sectors are responsible for 20 % and 10 % respectively (United Nations, 2014). Industry accounts for a much larger percentage of freshwater withdrawals in developed countries, while agriculture takes the lead in water consumption in less-developed countries, accounting for over 90% of their freshwater withdrawals. Most of the statistics on freshwater withdrawal and consumption are founded on estimations rather than real measurements; according to OECD, global water withdrawals are anticipated to rise by 55 % as a result of the upsurge in manufacturing demand (400 % growth), domestic use (130 %) and thermal electricity generation (140 %) (United Nations, 2014). At the moment, about 2.8 billion of the world's population are living in areas that are prone to water scarcity, and of this figure, 1.2 billion reside in parts that are already suffering physically from water scarcity, while half a billion people are fast closing in on this situation. The remaining 1.1 billion people going through water scarcity are suffering from commercial water scarcity. This population of people lives in parts of the globe where water is naturally accessible but their access to it is limited by distribution infrastructure, institutional or financial issues, even though the available water resource is sufficient to meet their demand. This is the case in sub-Saharan Africa. Physical water scarcity arises when a water deposit in a particular locality or community is inadequate to cope with the demand of such a community, and this type of water scarcity is common in arid regions. Scarcity in other areas which are going through human-made physical water scarcity as a result of over-advance in their water withdrawal, which in turn leads to ecological degradation e.g. of groundwater tables and rivers.

3. SEAWATER AVAILABILITY

Water is an essential element of life. If water is available, life's quality and the community's economy are both enhanced. Water is one of the numerous gifts of nature. Water occupies more than half of the earth's ground surface, but, in spite of this, only around 3 % of this water is freshwater (Karagiannis & Soldatos, 2008). According to Ceribasi et al. (2014), the cost of desalinating seawater and the need to find an efficient method of desalination has challenged the scientific community to find a way out. As a result, many of the recent research studies in seawater desalination are concentrating on evolving cost-effective methods of producing freshwater for human consumption.

Azevedo (2014) reported that even though data on water precipitation are readily obtainable, it is very costly and difficult to monitor the levels of the groundwater and river runoff in many areas. Figure 2 shows 2011 regenerative water statistics (Azevedo, 2014). Regenerative water, otherwise known as renewable water, can be defined as groundwater and surface water, while deep aquifers with insignificant rate of recharging based on known human time scale are termed non-regenerative water sources (Azevedo, 2014).

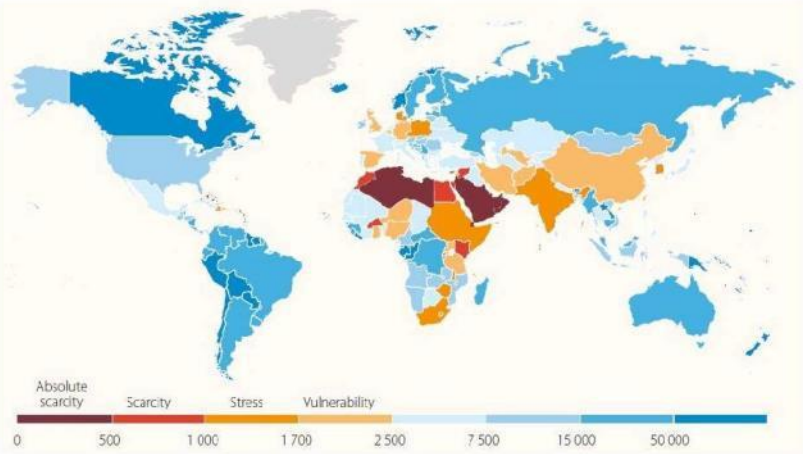

Figure 2: 2011 Statistics on Regenerative Water Resources (m3/c/yr).

4. DESALINATION

Numerous technologies or ways of desalinating seawater are being discovered and researched to augment the available fresh water supply. The techniques of desalination are divided into two classes based on the physical property of the process (Zhao, 2006). The classes are: thermal process and membrane process. Thermal technology employs the principle of liquid vaporization/evaporation to accomplish potable water separation from saline water, while membrane technology deploys the use of a filtration apparatus in bringing out potable water from saline water. Membrane technology can be further divided into reverse osmosis (RO) and electro dialysis processes, while the thermal technology is further divided into multistage flash distillation, freeze separation methods, multiple effect distillation, solar still distillation and vapor compression (Figure 3).

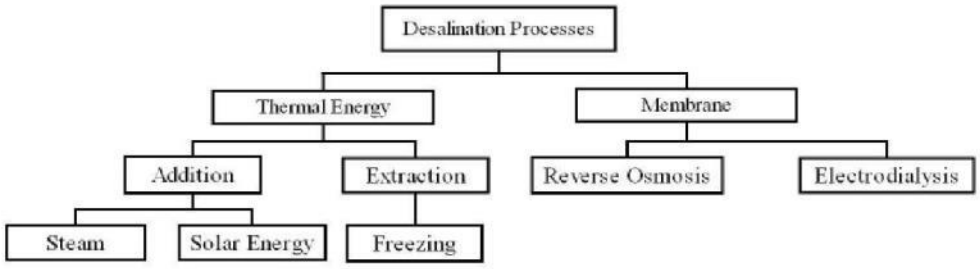

Figure 3: Desalination Technology.

Forward osmosis desalination is an evolving desalination technology which will change the overall concept of freshwater production from brackish water or seawater (Ceribasi et al., 2018). For this technology to move from the stage of laboratory research to real applications, researchers have to develop reliable novel forward osmosis membranes and draw solutes. Diverse osmotic membranes are being investigated for flux behavior. Novel draw solutes that have the capacity of easily regenerating, and which have no energy requirement for water recovery, are being researched. Kamble and Pitale (2015) examined different types of solar powered desalination systems ranging from MSF, MED, humidification-dehumidification desalination systems, electro dialysis desalination systems, solar still, and adsorption

desalination systems. and concluded that out of all these aforementioned desalination techniques, solar powered RO desalination systems predicated on solar photovoltaic technology is most commonly used and adopted, because both the PV and RO are modular and easily available. The universal installed seawater desalination capacity by technology is about 49 % and 35 % for thermal and membrane processes respectively (Pangarkar et al., 2011). According to Ceribasi et al. (2018), the development of desalination technologies has been predicated on membrane separation, thermal vaporization, electro-dialysis, etc. The authors went further to categorize desalination processes into two major types as shown in Figure 3 and Figure 4: namely: thermal desalination and membrane desalination processes.

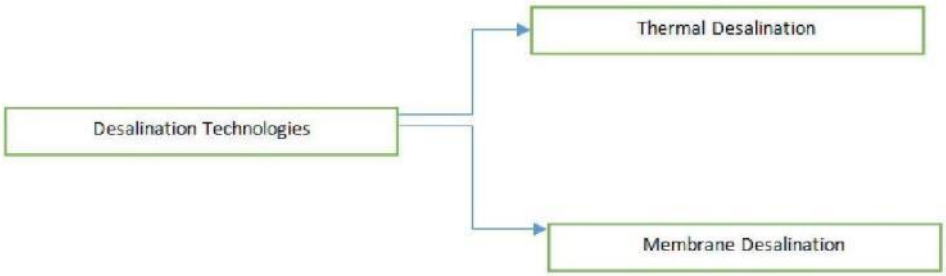

Figure 4: Desalination Processes.

The solar still is the cheapest and most affordable technique of desalination (Aybar, 2007). This is a modest device that can be used to extract potable water from dirty water, deploying solar energy as fuel. The basic principle of a solar still is that vaporized water from an open container that is left in an open area will condense back to water over a cooling surface (Figure 5).

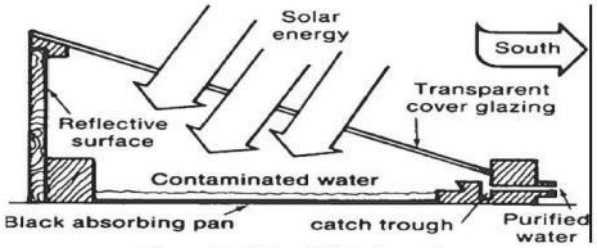

Figure 5: Solar Still Schematic.

4.1 Thermal Desalination Processes

Intake saline water from the sea or saline source is subjected to heat which produces steam that will later be cooled in order to obtain condensed water of reduced or low salt content (Ceribasi et al. 2018). Pressure is normally reduced in thermal desalination to reduce the quantity of heat required for saline water to evaporate. The Foundation for Water Research (2006) confirmed that thermal desalination processes can lower the salt content of saline water to as low as 10 milligrams per liter or even lower for TDS between 60 000 mg/L and 70 000 mg/L.

4.2 Membrane Desalination Processes

The membrane desalination process is the most frequently used in general desalination of seawater (Ceribasi et al. 2018). Membrane technology has a wide range of applications in solving sea and brackish water desalination difficulties. This

technology can be categorized based on the variety of elements involved and the mode/prime moving input deployed. The principle of membrane desalination is based on a semi-permeable membrane's ability to selectively permit molecules of water through it. The membrane desalination process can be categorized into osmosis and RO, which are the two basic desalination techniques deployed in membrane type desalination. According to (Voutchkov, 2007), scientists discovered the principle of osmosis and RO several years ago. What is relatively new is the principle of the application of RO to the desalination process. The passing of water through a semi-permeable membrane from a low concentration solution to a higher-concentration solution is what is known as osmosis. The reverse process occurs when outside pressure is applied to the higher-concentration side of the membrane, thereby diffusing the higher-concentration solution into a lower-concentration solution. Ceribasi et al. (2018) described the process by which a semi-permeable membrane allows only pure water to pass through by rejecting salt, as RO desalination. To achieve a reverse water flow, the hydrodynamic pressure should be high enough to exceed osmotic pressure when the feed water is pressured on one side of a semi-permeable membrane. This is shown in Figure 6. Williams (2003) reported that RO has been adjudged to be the most acceptable desalination technique in the world.

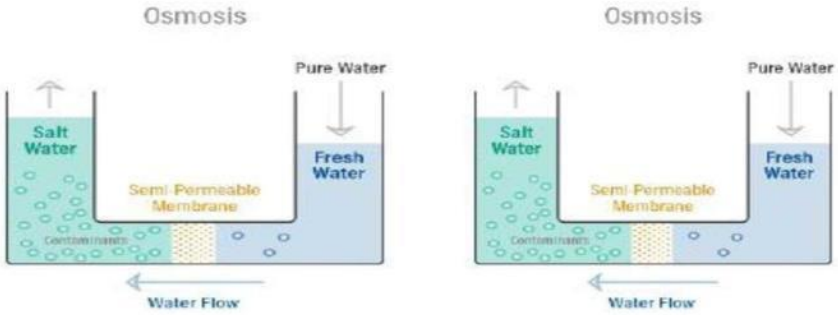

Figure 6: Reverse Osmosis.

Ceribasi et al. (2018) studied the non-stop movement of industrial RO procedures, where the application of outside force to the systems require the use of a high-pressure pump. This procedure requires the salt water to be delivered at an elevated pressure before dispensing it for membrane separation. Two diverse pressure collections are needed for saline water sources. In the case of seawater, the pressure of the intake feed needs to be raised to a pressure of 40 bar to 82 bar (600 psi to 1200 psi), and for brackish water, the intake feed pressure has to be elevated to a pressure of 2 bar to 17 bar (30 psi to 250 psi).

4.3 Reverse Osmosis Process

Saline water from the sea or brackish water sources are firstly treated with a hydraulic strainer where all floating solids that could cause a foul smell for the membrane are removed. Residual flow is then raised to the system functional pressure depending on the level of its salinity and later delivered into the desalination unit. A percentage of the water will infiltrate through the membrane and same are collected as a throughput invention after a suitable afterward treatment. The after-treatment phase will involve the normal water treatment process to ensure the potability of the treated water. Strohwald (1992) reported that RO systems in the desalination of sea-water has been studied, and adjudged to be effective. Emphasis during one of the studies was on the choice of a proficient pre-treatment system. The deployment of a low-cost tubular ultra-filtration system in combination with double media and cartridge filtration produced a very good RO residual water

with outstanding quality notwithstanding the raw water source quality. Even though fouling of ultra-filtration membranes may be noticed, the flux restoration can be achieved with the aid of sponge balls. Reverse osmosis reclamations in excess of 40 % can be achieved without harmful effects on the membranes by using a scale inhibitor. The quality of the residual water from the single stage RO unit is usually well within the endorsed SABS confines for domestic supplies with no RO membrane fouling.

4.4 Energy and Rate of Water Desalination

There are two main categories of energy sources for desalination systems: conventional sources, and renewable sources (Karagiannis & Soldatos (2008). Desalination driven by renewable energy sources may be the answer in terms of climate/ecological effect to lower energy consumption and lower CO_2 emissions. There are three major desalination systems that use renewable energy sources. These are: (a) wind, (b) solar (photovoltaics or solar collectors) and (c) geothermal. Systems powered by renewable energy sources can also be connected to a conventional source of energy (e.g., local electricity grid) in order to reduce the variations in the level of energy production and consequently water production.

Multi-effect distillation (MED) remains the most used thermal methods, i.e., vapor compression (VC) / multi-stage flash (MSF). RO is the most widely accepted membrane method. Thermal methods when compared to the membrane method seem to be more efficient in terms of effective desalinating of salty seawaters, but critical studies have found that thermal methods are more expensive due to the large quantity of fuel required for vaporization of the salt water. Membrane methods which are mainly RO have the ability to desalt brackish water more economically, and have substituted in popularity the use of thermal methods for desalination. However, due to the high cost of membrane replacement, membrane methods are not frequently used for desalination. The American Membrane Technology Association (2003) reiterated that technological development has aided the decrease in the total desalination cost, by refining the energy efficiency (multi-flash distillation or hybrid systems), and by improving the transfer processes or energy recycling (process of cogeneration).

5. REVERSE OSMOSIS

Desalination system technologies are an excellent technique for generating large volumes of standard potable water at a reasonably competitive cost, but the high energy consumption remains a major setback to the system (Pangarkar et al. 2011). The latest membrane technological discoveries, e.g., RO, nano-filtration (NF), and electro dialysis (ED), have in recent times gained recognition due to their reliable separation capabilities and potential for water treatment. RO membrane technology has been widely adjudged the lead technology for desalination installations, and is suitable for both brackish and seawater usage. Brackish water desalination (RO membranes) are typically identified with higher water flux, lower salt elimination, and require less operational pressures due to the reduced osmotic pressure (M'nif et al., 2007). However, this system is usually associated with some problems because of the creation of polarization films and by-products which may produce bacteria and pollution. According to Pangarkar et al. (2011), this problem can be overcome by deploying alternative membrane technology such as membrane distillation for underground water desalination. Generally, RO membrane treatment processes are designed to either use pressure or conventional electrical driven technologies. The pressure-driven membrane mode of operation can be divided into four categories, namely: RO, ultra-filtration (UF), micro-filtration (MF) and nano-filtration (NF). Nano-filtration process are considered to be efficient in salt desalination. Poullikas (2001) categorized a typical RO system into four major sub-systems: (a) pre-treatment system, (b) high-pressure pump, (c) membrane module, (d) post treatment system. The pre-treated feed water is channeled to flow

across the membrane surface, when a high-pressure pump is deployed. The operating pressure of RO ranges between 17 bars and 27 bars for brackish water and between 55 bars and 82 bars for seawater. According to Strohwald (1992), since the development of asymmetric cellulose acetate membranes by Loeb and Sourirajan in the early 1960s, RO membranes have been used commercially for sea water desalination. The author reported that most of the major membrane producers, e.g., DuPont (USA), Filmtec (USA), and Toyobo (Japan), manufacture membranes from synthetic polymers made specifically for the desalination of seawater. Water production from seawater through the RO technique gained significant popularity in the mid-seventies with new desalination installations springing up around the world. The author points out that the operating cost of RO desalination is lower than MSF evaporation since no phase change is involved. Economics, high energy consumption and improvements in the RO technology development caused a sharp decline in the market share of MSF evaporation from 67 % recorded in the early 1980s to 3 % in 1989, while RO made an equivalent rise from 23 % to 85 % during the same period (Ahmed, 1991). Water resources are speedily being depleted, and this has resulted in more attention being paid to desalination of sea and brackish water (Raju Yadala & Ravinder, 2018). In the present day, much energy is required for desalination, making it less cost friendly. According to Tzen (2006), RO is the most used and most economic method of desalinating brackish water. However, other methods exist but are seldom used. One example though, is on Kimolos island, Greece, where the MED process utilizes the abundant geothermal energy in the island to generate 80 m^3/day of potable water at 2.00 h/m^3.

The brackish total dissolved solids (TDS) can and do affect the cost of water produced per day which varies from 2000 ppm to 10 000 ppm. Raju Yadala and Ravinder (2018) compared the cost of 230 ppm brackish water desalination in Jordan that is as low as 0.21 h/m^3 (0.26 \$/m^3) to 5000 ppm brackish desalination in Florida at 0.22 h/m3 (0.27 \$/m3), and it was established that two similar systems that uses dissimilar water volume of TDS usually have a considerable cost disparity. Tzen (2006) argued that the desalination of 10 000 ppm brackish water using conventional sources of energy costs 0.43 \$/m3, while using renewable energy sources in similar situation will cost as high as 8.2\$h/m3 (10.32\$/m3].

The cost of water production from desalination schemes using conventional sources of energy, (gas, oil, electricity) is lower and cheaper when compared to renewable sources of energy over a short period, but when considered over a long period of time, renewable energy is practicably cheaper. The RO method of desalination as shown in figure 7 has become more prevalent past few years because the cost of membranes has become more affordable. Some years ago, RO was mainly utilized for desalination of brackish water, but of late it has become the most commonly used method for various kinds of desalination due to its lower energy demands. Therefore, RO is now being applied to larger units that have the ability to deliver daily production of 320 000 m^3.

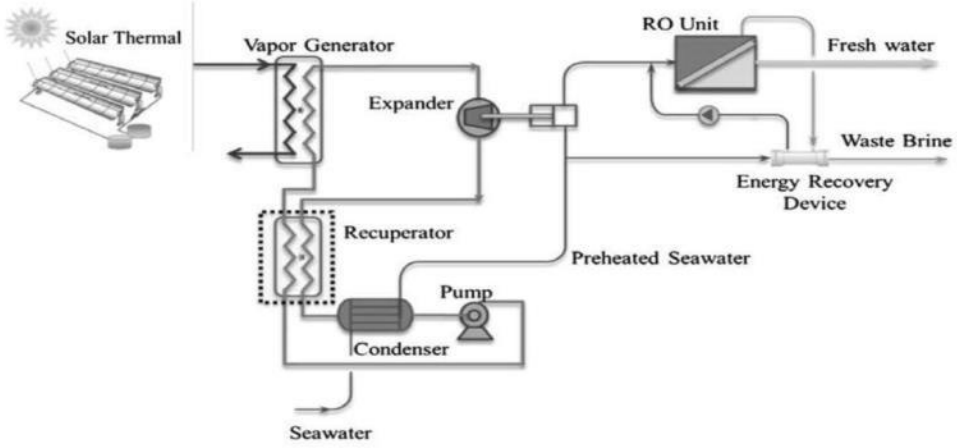

Figure 7: Reverse Osmosis.

5.1 Basic Principles of Reverse Osmosis Process

According to Greenlee et al. (2009), in RO and nano-filtration, osmosis is said to take place when water flows from a diluted salty solution, and passes over a semi-permeable membrane into a section of higher concentrated saline solution. A semi-permeable is penetrable to pure water but does not allow salty liquid to penetrate. On the assumption that a membrane can only allow passage of water and not salt, when there is a salt solution in one section and pure water in another section, a semi-permeable membrane will permit water to permeate through it to either side, but salt will not be allowed. Greenlee et al. (2009) defined osmotic pressure in RO as the ultimate height difference between water columns when water diffuses towards a higher concentration through a semi-permeable membrane from a region of lower concentration in order to equalize the solution strength, and RO reverses water flow direction when the applied pressure is in excess of the osmotic pressure. To achieve desalination, the system will try to maintain an equilibrium position by allowing water to flow from the clear water to salt solution compartment in order to equalize the level of concentration on both sides of the membrane and dilute it. An increase in the level of salt solution may be created by osmosis and will continue to increase until the water column pressure (salt solution) becomes so high that the force of the water column stops the inflow. The water level equilibrium point in terms of the pressure from the water against the membrane is called osmotic pressure (Figure 8 and Figure 9).

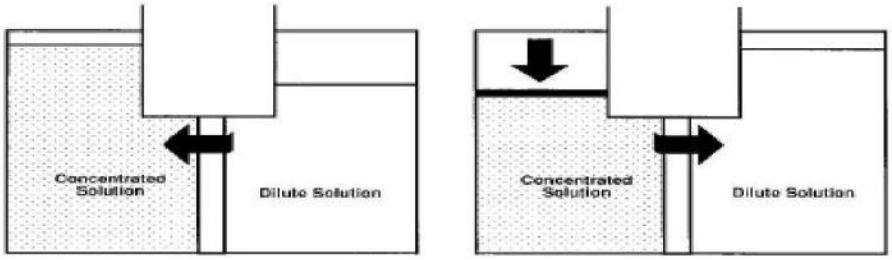

Figure 8: Overview of Osmosis.

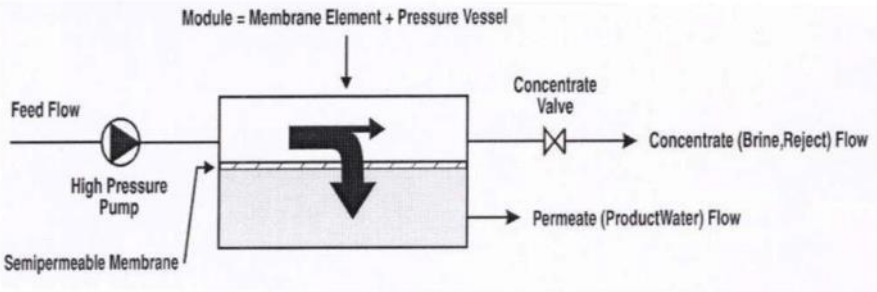

Figure 9: Reverse Osmosis Process.

When a force is applied to the column of water, and the direction of water flowing through the membrane is reversed, this process is known as reverse osmosis. It should be noted that since the membrane is not permeable to salt, the reversed flow produces pure water from the salt solution (Greenlee et al., 2009). Manolakos et al. (2005) described RO as a physical procedure that adopts the osmosis concept using osmotic pressure difference between the saline water and the clear water to remove salt from water. Raju Yadala and Ravinder (2018) also described RO as a process where an intake stream flows under a higher pressure through a semi-permeable membrane thereby segregating two aqueous streams, one brine (rich in salt) and other clear water (lacking salt). According to Tian et al. (1999), as the exerted pressure is higher than the osmotic pressure, clear water will permeate through the membrane and brine will be collected as a byproduct of the system. Consequently, water with low salt concentration stream, will permeate through the membrane and concentrated brine will remain inside the feed part of the system. According to Raju Yadala and Ravinder (2018), when compared to sea water, brackish groundwater usually has a much lower osmotic pressure, and as a result, its desalination process requires less energy. Low-cost plastic components are allowed in an RO system due to the lower pressure associated with brackish water. Tzen (2006) reported that RO membranes are made of a polymer material which forms a coated, web-like structure. Feeds with elevated pressure are made to run through a circuitous pathway to the membrane, and then to the permeated side. According to Maalouf (2014), RO membranes usually offer high salt rejection membranes for RO plants. Membranes are designed for a normal lifetime of 7 years with an effective pre-treatment. The salt passage through a membrane can be affected by the cleaning methods, salinity, temperature, and target recovery. TDS levels has to be reduced to convert seawater into safe drinking water (properties shown in table 1), and this can only be achieved by using either old desalting technologies or desalination processes which use newer technology such as sea water RO (SWRO), electro dialysis (ED), electrode-ionization (EDI) multi-effect distillation (MED) and multi-stage flash (MSF) distillation. A hybrid setup can be created by combining some of these desalination processes in some instances, to achieve the best desalination and also reduce energy consumption.

Table 1: Potable Water Organoleptic Properties (World Health Organization, 2003)

Concentration (MG/L)	Classification
TDS ≤ 300	Excellent
300 ≤ TDS ≤ 600	Good
600 ≤ TDS ≤ 900	Fair
900 ≤ TDS ≤ 1,200	Poor
TDS > 1,200	Unacceptable

5.2 Reverse Osmosis Membrane Fouling

Raju Yadala and Ravinder (2018) point out that RO membrane fouling has become a major problem in the application of RO in the potable water production industry, and this is more pronounced when high concentrations of organic matter and inorganic constituents occur. The authors also note that membrane fouling is generally triggered by organic components (humic acid) or melted inorganic (BaSO4, CaSO4, and CaCO3) suspended particles, bacteria, or floating solids. Turek and Dydo (2003) classified pollution into organic, inorganic, and biofouling, and the polluting deposits mainly comprise a mixture of organic matter, iron, phosphorous, and microorganisms, combined with chemical constituents in seawater or surface water. Pangarkar et al. (2011) concluded that the acute fouling problem associated with the brackish RO system is usually salt precipitation and membrane scaling. The authors also reported that concentration polarization is the key factor to be considered in membrane pollution of melted inorganic contaminants Fouling escalates resistance, which, as a consequence, reduces infiltrated flux. The resistance responsible for reducing the flux are: membrane resistance (*Rm*), concentration polarization resistance (*R*cp), cake resistance (*Rc*), and pore blocking resistance (*Rp*). The total resistance during membrane filtration can be taken as:

$$RT = Rm + R\text{cp} + Rc + Rp. \qquad \text{Equation (1)}$$

Membrane types can either be porous or nonporous, which is a key factor in defining the flux resistance triggered by inorganic fouling; *Rp* is not applicable to non-porous membranes. The primary technology/techniques always deployed in controlling fouling are the feed pretreatment and membrane cleaning. Reducing the fouling tendency of the water in the system is the main objective of any RO pretreatment system for seawater or brackish water.

5.3 Energy Requirements and Recovery

Raju Yadala and Ravinder (2018) confirmed that seawater or brackish water desalination technology is the best method for producing large quantities of potable water at a competitive cost, but the high energy consumption of this system remains a problem. Muthumariappan (2004) stated that a flow rate is proportionally related to the feed pressure required to pump the water; this same energy is the primary energy used in the RO system. High brine concentration in seawater requires high hydrostatic pressure of up to 7 000 kPa to produce the desired permeate flux; the higher the salt concentration, the greater the pressure and the pumping power required. The energy cost center in the RO process is the high-pressure pump set which is approximately 70 % of the total energy requirement, and the applied hydrostatic pressure must be higher than the osmotic pressure of the water feed segment of the membrane. The osmotic pressure on the feed compartment of the membrane continues to increase when the (RO) unit recovery work increases, thereby increasing the required feed pressure. The resultant brine waste from the system is characterized by high pressure and having shared a considerable percentage of feed pressure. This resultant brine pressure can be profitably utilized to enhance the feed pressure of the raw water by deploying an appropriate technology, and this process is called the energy recovery system.

6. DESALINATION ENERGY DEMAND

Azevedo (2014) confirmed in his study that the desalination process is considered to be an energy demanding process, as it consumes more energy per liter when compared to other water supply treatment options. The energy required for the desalination process varies and is hinged on other factors including facility design, deployed technology, feed water quality and temperature, the application of energy recovery devices / the quality of the projected water produced. Technological advancement has reduced the energy demands of desalination over the last 40 years, and this trend is expected to increase

because technology keeps evolving. The areas to develop in order to minimize energy consumption in desalination are: (a) Improved system design (b) High efficiency pumping (c) Energy recovery (d) Innovative membrane materials and (e) Advanced technologies. The energy consumption in membrane desalination processes depends mostly on the recovery rate and the feed water salinity. In the RO process, the energy required in the system is for pumping of the feed water. The average energy consumption of a RO process varies, ranging between 3.7 kWh/m3 and 8 kWh/m3 for seawater depending on the size of the facility. For a seawater RO unit of 24 000 m^3/day the average energy consumption varies between 4 kWh/m3 and 6 kWh/m3 with energy recovery devices. On the other hand, the brackish water RO unit average energy consumption ranges between 1.5 kWh/m3 and 2.5 kWh/m3 (Al-Karaghouli & Kazmerski, 2013).

7. RENEWABLE ENERGY-POWERED DESALINATION

All over the world, desalination of sea and brackish water has gained acceptance for supply of potable water. Some inaccessible villages in third world countries are isolated from the main cities and as such often lack access to the national electricity grid which has created a big vacuum in accessibility to potable water supply, which are usually powered by conventional electricity. Similarly, in order to reduce their environmental impact, desalination facilities require an energy source that is low in emissions and at the same time affordable. Renewable energy sources such as solar photovoltaic, wind, thermal or geothermal energy can be exploited to solve these problems. The International Energy Agency (2012) justified renewable energy for desalination in order to reduce greenhouse gases emission as the current capacity of desalination worldwide exceeds 70 million m^3/day. Similarly, renewable energy cost solutions are expected to further depreciate, the remote villages and locations with low population and poor infrastructures are expected to be attracted and gain access to potable water. Renewable powered desalination plants/facilities at present, represents less than 1 % of the global desalination capacity, and most of these desalination plants are RO based technology measuring about 62 % of the world capacity followed by MSF and MED. Solar photovoltaic (PV) is the leading renewable energy source for water desalination facilities, and it accounts for 43 % of the total desalination plants, followed by thermal and wind energy (Azevedo, 2014). The practicability of renewable energy plant depends largely on various factors, including feed water salinity, location, availability of renewable energy sources, plant capacity/ the availability of national electricity grid.

7.1 Solar Photovoltaic

Solar photovoltaic (PV) systems work to transform sun energy into direct current by using semi-conductors and PV cells. The PV modules are made up of PV cells which produce direct current that is accumulated and stored in batteries or directly fed into an inverter, which converts the direct current into alternating current (Azevedo, 2014). The solar PV systems are directly connected to RO desalination for the pumping system. The system is made up of a set of batteries for energy storage, and a charge controller that protects and regulates the charging of the batteries by circumventing deep discharges and overcharge. The battery set enables the membrane system to generate a certain quantity of water at the desired quality and avoid variations in pressure and flow. The effects of large variations relating to solar irradiance in battery-less membrane systems, is the major issue that necessitates an urgent need for research. Practical experiments have shown that the system can produce good quality water, although this will depend on the type of membrane used. Another significant issue in RO desalination is the ability of the system to function at variable capacities, based on the available energy. Ghafoor et al. (2020) discussed the new RO technology developed by ENERCON GmbH in which a piston system is used for energy recovery, and also permits variable levels of energy input. Reverse osmosis systems operating with this new technology can vary the production output between 12.5 % and 100 % of normal capacity by varying the piston speed

and regulating the production for available energy input or water demand. Other companies are also researching and developing systems that have this demand response capability. Ghafoor et al. (2020) conducted a feasibility on 500 L/h capacity solar powered RO desalination system and concluded that the productivity of any membrane appreciated with every increment in the temperature of the feed water resulting in a permeate productivity of 60 % and brine of 40 %. Helal (2008) conducted an economic analysis study and performance evaluation on a RO system using a PV system with no battery accumulator, just PV and a diesel generator. The results of the studies indicated that 20 m^3/d throughput was obtained using PV-RO combined with diesel, 20 m^3/d throughput deploying only the diesel generator, and 44 m^3/d water throughput was gained using solar based RO only on clear sunny days, Figure 10 shows a schematic diagram of a PV-RO system. Bilal (2016) conducted a study on a PV system with battery and without battery for operation of an RO system. The results showed that 5.9 L/h permeate productivity was produced with battery for 5 h and 3.8 L/h without battery. The fresh water throughput was 9.8 % higher with a battery dependent PV system in comparison without a battery system. The authors concluded that both types of PV systems were beneficial but battery-less was more economically suitable compared to battery-based systems.

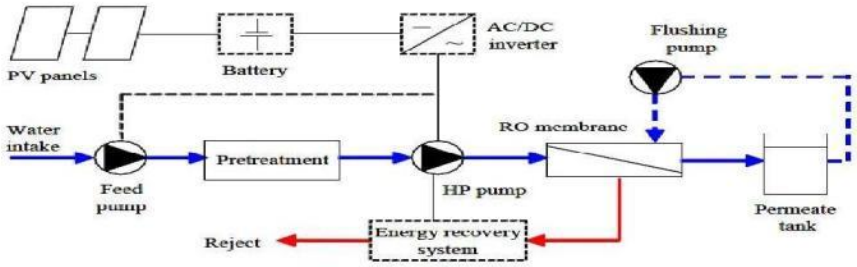

Figure 10: Schematic of PV-RO System.

Azevedo (2014) concluded that PV-RO system as shown in figure 10 has been considered one of the most robust options for renewable energy powered desalination, especially for remote areas, as both PV and RO are modular and accessible. The modularity contributes to the reduction in cost that has been achieved via economies of scale, and permits small-scale systems that can be achieved by attaching a DC output of PV modules directly to DC pumps and electronics, thereby increasing the overall efficiency of the system by 5 % to 10 % due to the prevention of losses in DC-AC power conversion and AC-DC rectification (Richards & Schafer, 2009). Figure 11 shows a schematic of a PV-ED system

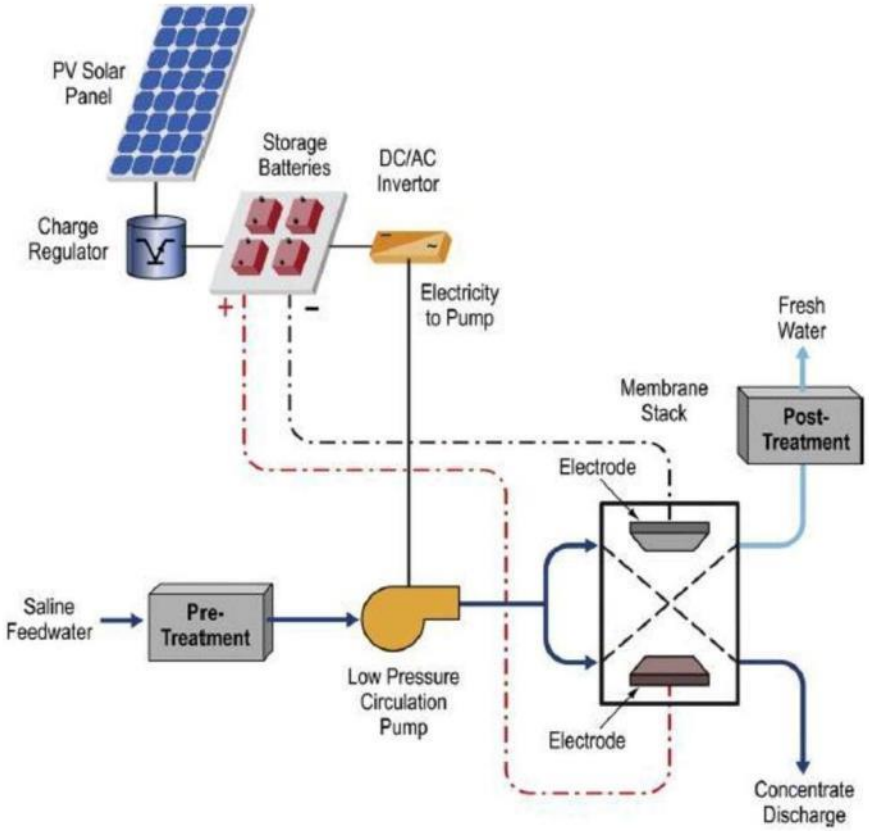

Figure 11: Schematic of PV-ED System.

8. HOW MANY COUNTRIES ARE PRACTISING RO DESALINATION

Strohwald (1992) reported that as of 1992, the installed world-wide RO capacity is estimated at 13 297 000 m/day This figure includes both seawater and brackish water desalination applications. Others are, 20 000 m^3/day plant at Ghar Lapsi, Malta (DuPont, 1986a) and the 46 000 m^3/day plant at Ras Abu Jarjur, Bahrain (DuPont, 1986b).

Up to 2009, many RO facilities, with different capabilities ranging from 100 m^3/day to 9 000 m^3/day, have been constructed in the Republic of South Africa for the desalination and treatment of brackish waters and industrial effluents. Greenlee et al. (2009) cited the new 36 m/g/d (136380 m3/day) seawater RO plant in Singapore as the largest in Asia and one of the largest in the world. The authors further confirmed that the RO systems for industrial and residential needs are being produced by various companies. The Saudi Arabian Saline Water Conversion Corporation (SWCC) has concluded a plan to upgrade the desalination plant in the country and build a new one with a larger capacity. Desalination has become a significant solution to Algeria's water demand. The Chennai Water Desalination Ltd. was established to produce a 100 m/l/d desalination throughput plant at Kattupalli village in Tamil Nadu, India (Water Today, 2006). Raju Yadala and Ravinder (2018) stated that 48 % of the total number of global RO plants are of brackish water source, while 25 % are of seawater source, and the remaining 27% desalination plants comprise other feed waters such as streams, wastewater, and unpolluted water.

9. WHAT ARE THE FUTURE CHALLENGES

Strohwald (1992) reported that RO units are capable of producing potable water of standard quality, but this technology always comes with the problem of premature decline in capacity and salt rejection performance. This can be attributed to an operational problem with pretreatment and maintenance systems, which may result in the membranes being subjected to the following:

- Chlorine escaping from the pretreatment section
- Bacterial contamination
- Membrane fouling which may not have been removed during pretreatment and could not be also detected by the plugging index determination
- Contamination by grease from pump

Based on a recent investigation of desalination of sea-water for potable water production in one of the naval applications, the following system design/operational problems were identified:

- *Pulsation and noise from high pressure pumps.* Several problems were reported with high pressure positive displacement pumps, ranging from failed bearings, cracked plungers, and valve pitting to water leaks past the plunger pump packing. It was also reported that incorrect sizing and routing of inlet plumbing and heavy vibration from pumps might have have initiated damage to some of the DuPont preemptors, which may cause high mechanical noise and cavitation. All the problems identified underline the need for right sizing of the suction and discharge piping, and also, the finest positioning of pulsation dampeners must be put into consideration at the design stage(Strohwald 1992).
- *High pressure pumps.* Wrong selection for the specific duty and operation of the pumps may result in excessive vibration and eventual breakdown, and also complications in the procurement of spares for imported pumps can cause problems. There is a need for selecting best fit pumps specifically designed and engineered for RO applications.
- *Pre-treatment.* Insufficient and unsuitable pretreatment equipment has led to premature RO membrane fouling with consequential reduction in capacity and product quality. These particular problems have led to the wrong perception of RO being unreliable and unnecessary expensive, even though the ability of the system to produce potable water from seawater and brackish water is unquestionable. This misconception can only be addressed by showcasing the competences of appropriately engineered plants in the market (Strohwald 1992).
- *Bacterial control.* Extreme precaution must be exercised when deploying chlorine as a bactericide to prevent a scenario of chlorine breakthrough from the pretreatment section. Although chlorine may be considered very effective in preventing bacterial development, RO membranes are very sensitive to chlorine, and as such, chlorine breakthrough is fatal to the performance of the RO membranes.

10. CONCLUSIONS

This paper reviewed RO as being an excellent desalination technology. It is the most popular membrane technology for seawater and brackish water desalination and can produce large quantities of standard portable water at an economical cost.

The main drawback, however, is that an RO system requires high energy consumption. Also reviewed is the economic viability of renewable energy powered RO systems and other desalination techniques for sea and brackish water, energy costs, properties of RO membranes and challenges facing RO membrane system construction.

This paper summarizes the solar powered RO processes and basic principles behind the RO membrane technology with the goal of establishing and promoting the advantages of photovoltaic (PV) RO membranes over other methods, and to bring to the fore the only shortcoming of the system (high energy consumption) with the aim of encouraging further studies to eliminate it.

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CHAPTER 4: MODELING AND SIMULATION FOR A SEAWATER REVERSE OSMOSIS SYSTEM

In this chapter, Water Application Value Engine (WAVE) water solution modeling tool was used to develop a predictive model for a seawater reverse osmosis (SWRO) membrane desalination system comprising: the UF pretreatment, RO membrane desalination, and IX polishing post-treatment processes. The modeling result presented an extensive result of the simulation, tied to operational variables and the system key performance parameters. The modeling and simulation adopted the basic principles and equations of productive SWRO design. Profiles of feed pressure, feed concentration and feed velocity along with the UF membranes, RO membranes, and resins were modeled for these operations together with the relationship between recovery rate, pH, temperature, and feed pressure. The article was accepted for publication in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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MODELING AND SIMULATION FOR A SEAWATER REVERSE OSMOSIS SYSTEM

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ABSTRACT

Seawater desalination is one of the most successful procedures for fresh water supply in the world. Reverse osmosis (RO) is a major technology in the business of seawater desalination because of its ability to produce high quality water from seawater with low consumption of energy compared to other technologies [Ezzeghni et al., 2016]. The hands-on modeling of an efficient full-scale reverse osmosis (RO) system is a daunting work due to the RO systems' operating conditions which continually fluctuate due to cyclical variations in seasons and progressive fouling of the membrane during long-term filtration [Jeong et al. 2021]. This paper aims to model an RO desalination plant using ultrafiltration and IX polishing for feed water pretreatment and post-treatment respectively [Ezzeghni et al., 2016]. The success of seawater desalination using RO technology is predicated upon an efficient feed water pretreatment and post-treatment regime. The use of an ultrafiltration system in combination with filtration has been tested and adjudged to generate excellent quality of RO feedwater, notwithstanding the quality of the raw sea-water [Strohwald et al., 1992]. The model framework depicted in this paper can serve as a guide for design engineers in providing effective tools for the design of an efficient RO system while maintaining an acceptable balanced hydraulic performance with considerable cost savings.

Key words: WAVE, Ultrafiltration, Pretreatment, Reverse Osmosis, Desalination, Seawater, RO membrane, RO Model

1. INTRODUCTION

Reverse osmosis design software has been developed with a precise and technically optimized membrane system configuration to aid RO plant design. It assists the designer to swiftly assess diverse combinations of parameters and configurations as well as obtain details on accessories such as pump flow and pressure. One of the most popular reverse osmosis (RO membrane design) software is DuPont's water application value engine (WAVE) which was used for this RO modeling. The essential inputs in this software are:

1. Project details
2. Water Ssurce / analysis
3. Temperature / pH
4. Product water volume requirement

As a response to the above inputs, the software calculates the feed TDS and the scaling tendency of the water, and as a result of the above results, a decision is taken on the use of acid / anti-scalant dosage, and the type and size of the membrane to select. The approximate number of membrane elements and the initial membrane configuration are calculated. In general, for 5 m^3/hr, 8 inch membranes are preferred, and as soon as this data has been entered into the program, the system generates an output related to the following parameters:

1. Detailed analysis of the permeate and rejection water.
2. Tendency of scaling of the water.
3. Net head pressure requirement.
4. Concentration polarization (beta factor).

The listed membrane system computer models, if adopted in line with the respective manufacturer's guidelines, have proven to be effective tools. However, they are subject to various restrictions. It is important for the designer to understand these limits to ensure that data output from these models are deployed appropriately when designing a reverse osmosis membrane system. There are innumerable possible configurations of membranes, pumps and energy recovery mechanisms, etc. that could be considered for an SWRO desalination system [DeMichele et al., 2014].

2. DESALINATION SYSTEM CONFIGURATION

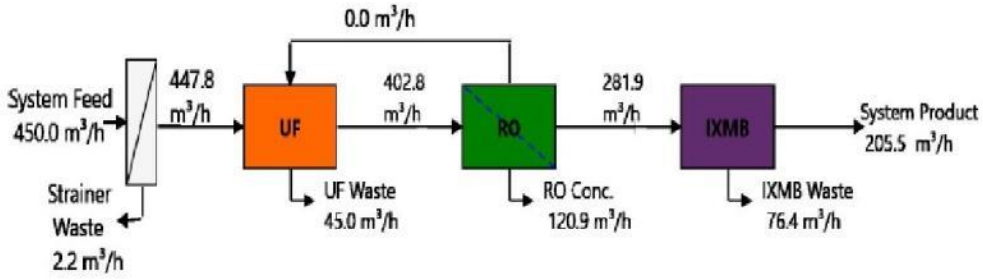

Figure 1: UF, RO, IX system configuration

This paper focuses on modeling of reverse osmosis (RO) desalination system using DuPont's WAVE water solution software. The reverse osmosis desalination process involved in this model is made up of four different stages, as shown in Figure 1 above. The water from the system feed source is first passed through a strainer with fine and coarse screens to remove any floating particles in the feed stream before entering into the ultrafiltration (UF) pretreatment system. The ultrafiltration unit consisted of six online trains, with each of the trains consisting of 34 Integralflux SFP-2860 XP modules of 1.86 m in length (Table 1), which are interlocked and branched internally in parallel. The module occupies a total area of 51 m^2 with a diameter of 0.225 m as shown in Table 1 to Table 3. The module provided a total volume of 35 liters. A CIP water source is provided from the RO permeate flux for the UF system.

Table 1: UF system overview

UF System Overview

Module Type		IntegraFlux SFP-2860XP			
# Trains		Online =	6	Standby =	0
				Redundant =	0
# Modules		Per Train =	34	Total =	204
System Flow Rate	(m^3/h)	Gross Feed =	450.0	Net Product =	402.8
Train Flow Rate	(m^3/h)	Gross Feed =	75.0	Net Product =	67.1
UF System Recovery	(%)	89.95			
TMP	(bar)	0.29 @ 10.0 °C		0.20 @ 25.0 °C	
Utility Water		Forward Flush:	Pretreated water	Backwash:	UF filtrate water
		CEB Water Source:	UF filtrate water	CIP Water Source:	RO permeate water

Table 2: System configuration options

Stream Name		Stream 1	
Water Type		Sea Water (10.0 - 40.0 °C)	
		Feed	**Expected UF Product Water Quality**
Temperature	(°C)	25.0	25.0
Turbidity	(NTU)	1.7	≤ 0.1
TSS	(mg/L)	10.0	-
Organics (TOC)	(mg/L TOC)	3.0	2.7
TDS	(mg/L)	29631	29658
pH		8.4	7.0

Table 3: UF System size and module details

UF System Size and Module Details

Trains		Module Details		
		Name: IntegraFlux SFP-2860XP		
Online Trains	6	Membrane Area	51 m^2	549 ft^2
Standby Trains	0	Length	1.860 m	73.2 in
Redundant Trains	0	Diameter	0.225 m	8.9 in
Total Trains	6	Weight (empty)	48 kg	106 lb
Max Offline Trains	1	Weight (water filled)	83 kg	183 lb
Modules/Train	34	Water Volume	35.0 L	9.2 gal
Total Modules	204			

The UF permeate is pumped at an elevated pressure with a high-pressure pump (HPP) as feed water to the RO desalination system, and the feed water flow across a semi-permeable membrane barrier as shown in Figure 2. The solvent flows through the membrane faster than the dissolved solids. The difference in this flow rate results in separation of the solids from the solvent. The solvent which in this case is pure water passes through the membrane with a very low salt concentration. The concentrated water or brine is left behind as waste to be disposed of.

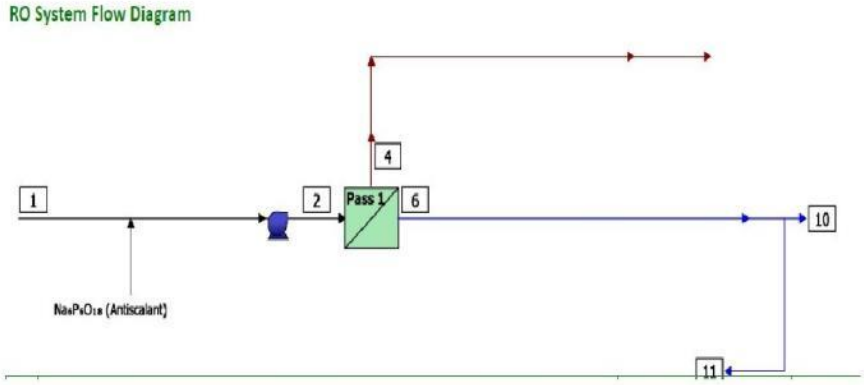

Figure 2: RO system configuration

The reverse osmosis system train is designed with a two-stage PV configuration (Table 4). The production capacity of the SWRO is 9 000 m^3 per day with a total recovery rate of 70%. The UF process is designed at a recovery rate of 90% while the IX polish (post-treatment) system is designed with a 72.9% recovery rate. The UF permeate in the pretreatment process maintained acceptable water quality conditions (TSS ≤ 10 mg/L, turbidity ≤ 1.7 NTU and SDI ≤ 2.5) for the feed water of the RO process. This feed water was pressurized, using a high-pressure pump (HPP). The RO process is classified into two PV stages, the first and second stages comprises of 36 and 18 PVs, respectively, with each PV having six seamaxx^{TM} - 440i elements installed. Specifically, it is important to note that the retentate from the stage 1 PV (i.e., the feed water from the second stage PV) in the RO process was not further pressurized by an interstage booster pump (IBP). This can be confirmed by the difference in the inlet feed pressures between the first stage and second stage PV. This inlet pressure difference was calculated as an average of 0.3 bar (i.e., pressure drops within the first stage PV) during the studied period of the RO operation. Sodium hypochlorite, hydrochloric and citric acids are used as chemical agents for the CIP to remove organic and inorganic foulants from the membranes separately.

Table 4: RO system overview

#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	402.8	29,646	0.0
2	Net Feed to Pass 1	401.5	29,739	71.2
4	Total Concentrate from Pass 1	120.5	98,094	68.6
6	Net Product from RO System	281.9	433.2	0.0
10	Net RO Product after UF Use	281.9	433.2	0.0
11	RO Permeate Used for UF	0.02	433.2	0.0

The configuration for the IX post-treatment is shown in Table 5 below.

Table 5: IX system configuration

IX Process		RO Permeate Polishing			
Layout		[MB]			
#Trains		Online =	1	Regeneration =	1
System Average Flow Rate	(m^3/h)	Feed =	282	Product =	205
Net Product Flow Rate per Train	(m^3/h)				205
Throughput per Train per Cycle	(m^3)	Gross =	286	Net =	213
System Recovery	(%)	72.9			
Estimated Run Time	(h)	1.04			
Estimated Regeneration Time	(h)	4.27			

3. MODELING AND SIMULATION

3.1 System Modeling

Post-treatment is the process of stabilizing water and preparing it for distribution. Since most alkaline mineral components in water are bigger than the pores of a normal RO membrane, these cannot pass through the membrane and permeate flux can, therefore, assume a very acidic status. Acidic water is not only very harmful for human consumption, it can also destroy components.

3.2 Model Input

The WAVE model tool is able to size new systems or evaluate the performance of existing systems. To design a new ultrafiltration system, it is important to understand the key inputs required for an accurate and optimized design. These inputs include information about the feed source, quality, temperature range, and required feed flow or net production of the system. For a given type and quality of a feed water source, appropriate design guidelines should be applied. These design guidelines are developed on the basis of wide-ranging experience and literature in similar waters. Design guidelines include effective operational flow, length of filtration cycles, or frequency of chemical cleaning. Once this information has been entered into the system design software, a detailed UF, RO, and IX system design report is created, showing an overall process flow diagram, module selection, size, and number of inhalations, the size of the water and chemical tanks, the process parameters and sequence tables, estimates, chemicals consumption among other things. The feed water quality shown in Table 6 was entered into the computer models, while the permeate water quality is the information output of the computer models. The actual total dissolved solids content of the raw water was obtained from the seawater database.

3.2.1 Input Justification

The model design is based on simulation and development of a movable solar-powered reverse osmosis membrane 2 MGD packaged facility that treats seawater and/or brackish water of high salinity. The feed source for this model is seawater from an inexhaustible source of the ocean, with its properties derived from the physicochemical analysis of the source work. Silt density index (SDI) of less than 1 was adopted because the seawater has been tested to have less fouling potential of

suspended solids, and this is further established with the selection of a 70 % recovery rate due to the low TDS of the system. A fouling factor that accounts for flow loss due to fouling of 1.00 was adopted for this model because the system vis-à-vis the membranes is still new with expected less fouling/scaling tendency. One online RO train with two stages of treatment comprising 36 PVs and 18 PVs respectively for stage 1 and stage 2 was selected to ensure a highly efficient desalination process by removing a considerable percentage of brine concentration and delivers improved permeate flow of WHO standard potable water.

Table 6: Input data table

Parameter	Unit	Value
Feed water classification	Not applicable	Surface water, Membrane
Pretreatment,	Silt density index	< 1
Permeate flow per train	Cubic meter per hour	289.1
Recovery rate	percent	70
Membrane fouling/flow factor	Not applicable	1.00
Stages	Number	2
Pressure vessels – first stage	Number	36
Pressure vessels – second stage	Number	18
Elements per vessel	Number	6
Membrane element selection	Not applicable	
Area per element	Square meter	40.9
Feed Stream pH adjustment	Not applicable	Hydrochloric acid

Figure 5: Design capacity input

From the Feed Water tab, the water type is selected. The solid content properties (NTU, TSS, SDI) and the organic content (TOC) are inputted together with the temperature and pH values. Please note that the pH value in WAVE is defined as –log10 of the H + concentration (mol / L). In the case of a solution of fixed composition, the concentration of H + cum the pH value is a function of temperature due to the temperature dependence on the equilibrium constants.

Table 7: RO solute concentration

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)						
		Concentrate		Permeate		
	Feed	Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.11	0.34	0.36	0.00	0.03	0.00
K^+	355.0	1,098	1,170	4.75	88.65	7.33
Na^+	9,100	28,174	30,059	102.6	1,856	156.5
Mg^{+2}	990.0	3,084	3,302	2.29	39.95	3.45
Ca^{+2}	395.0	1,230	1,317	0.89	15.91	1.35
Sr^{+2}	5.70	17.76	19.01	0.01	0.23	0.02
Ba^{+2}	0.03	0.09	0.10	0.00	0.00	0.00
CO_3^{-2}	1.66	15.02	16.71	0.00	0.02	0.00
HCO_3^-	151.5	448.2	476.5	2.31	34.92	3.27
NO_3^-	0.01	0.03	0.03	0.00	0.01	0.00
F^-	0.86	2.66	2.83	0.01	0.22	0.02
Cl^-	15,727	48,712	51,986	166.3	3,013	253.9
Br^{-1}	90.00	276.9	294.5	1.83	31.48	2.74
SO_4^{-2}	2,830	8,822	9,451	3.12	53.39	4.66
PO_4^{-3}	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	98.25	290.1	308.2	11.04	44.70	12.10
TDS[a]	29,646	91,881	98,094	284.1	5,134	433.2
Est. Cond. µS/cm	44,584	119,438	126,306	584	9,337	881
pH	7.0	7.5	7.6	5.5	6.4	5.7

Please note that in RO, TDS refers to "total dissolved solids" and excludes dissolved CO_2, but in the IX modules, TDS refers to "total dissolved solutes" and includes dissolved CO_2. Important design parameters for ion exchange systems are the quality of the water, the quantity and cost of the chemicals and the amount and geometry of the containers. There is no one-size-fits-all solution to design, as several trade-offs can be made. This bears some resemblance to the UF system designs.

3.3 Model – UF, RO, IX polishing

A feedwater TDS concentration was calculated by the model based on the inputted value of TSS, turbidity, organic TOC and feed water temperature. The designed TDS represented a design value of 269 658 mg/L of ions of SiO_2 and $B(OH)_3$, but does not include NH_3 and CO_2. The design TDS represented the feedwater quality along with the minimum requirements for the total designed head of the reverse osmosis feed pump. The TDS was based on the quality of the water at the project location which is site-specific dependent. The temperature of the feed flow was chosen in sync with the maximum documented temperature of 25 °C of the feed source. It may not be necessary to consider a design margin for both parameters, since the TDS and temperature both influence the requirements for the membrane supply pressure. This assessment is based on the site-specific water quality property. This model includes the designed feed flow and permeate flow of 450 m^3/h and 205.5 m^3/h respectively with a maximum system recovery of 70 %. This model adopts clean reverse osmosis membranes and includes a fouling factor of 1.00 in the membrane system computer model.

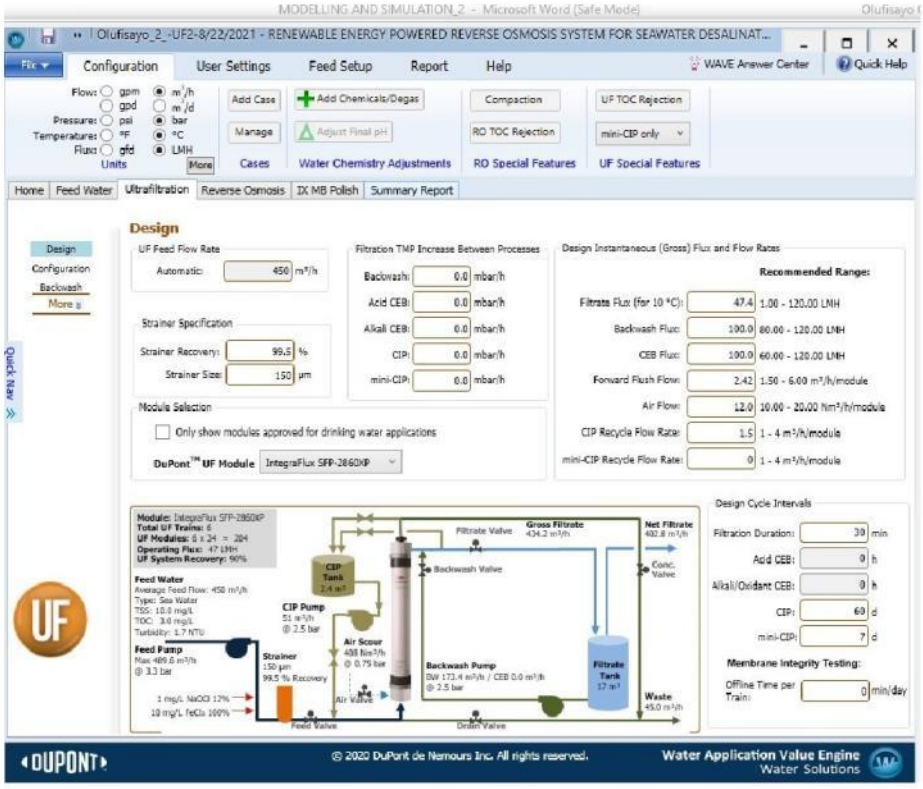

Figure 6: A screenshot from the UF Design tab of the WAVE program version 1.81.814

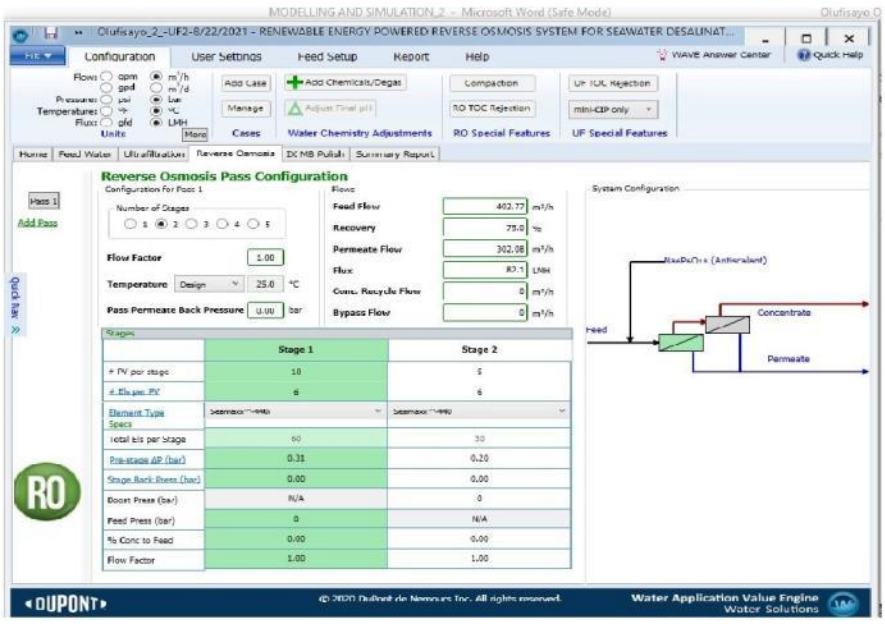

Figure 7: A screenshot from the RO Design tab of the WAVE program version 1.81.814

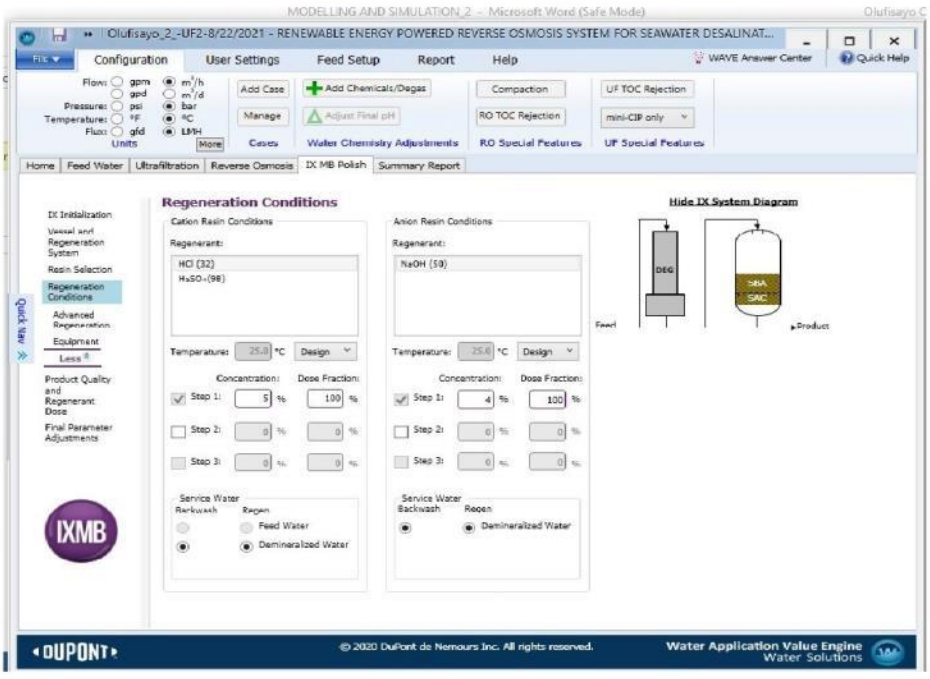

Figure 8: A screenshot from the IX Design tab of the WAVE program version 1.81.814

In addition to providing an interface for user input of system configuration data, the configuration tabs in Figure 6 to Figure 8 show the UF, RO an IX polishing which includes membrane filament configuration, as well as the membrane stages, the pump pressure between stages, the feed concentrate and permeate flow streams for the three designs. The screenshots shown in Figure 6 to Figure 8 are from WAVE water solution program version 1.81.814.

Two similar reverse osmosis membranes were modeled for this system. Table 8 contains a description of each membrane. As shown in Table 8, both model membrane elements provided a surface area of 3,679 m^2. The modeled membrane elements represent comparable low pressure, high productivity offerings from each listed membrane manufacturer.

Table 8: RO membrane modelled

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m^3/h)	Recirc Flow (m^3/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m^3/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m^3/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	Seamaxx™-440i	36	6	401.5	0.00	70.9	0.0	129.1	70.0	0.9	273.3	30.9	0.0	284.1
2	Seamaxx™-440	18	6	129.1	0.0	69.8	0.0	120.5	68.6	1.2	8.67	2.0	0.0	5,134

3.4 Model Output

The summary of the output data calculated by each of the design model ran is presented below.

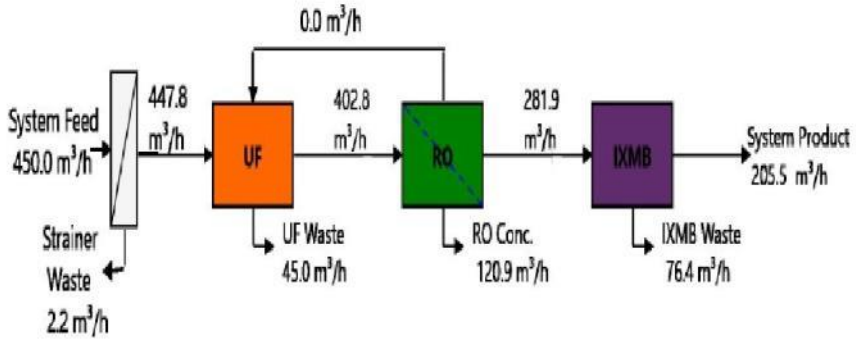

Figure 9: UF, RO, IX system flow diagram

Figure 9 shows the system flow of the desalination process model from the feed source to the system product. A designed system flow of 450 m^3/h is admitted into the system through a coarse and fine strainer. The strainer offers a little resistance to the flow by the filtration process which reduces the system flow to 447.8 m^3/h before entering the UF pretreatment process. The RO feed water from the UF has a flow rate of 402.8 m^3/h, and this is further reduced to 281.9 m^3/h after the RO membrane treatment before going into the post treatment process. The potable water at the end of the IX polishing process has a final flow rate of 205.5 m^3/h.

Table 9: UF, RO, IX model overview

		Strainer	Ultrafiltration	Reverse Osmosis	IX MB Polish
Feed	Flow Rate (m^3/h)	450.0	447.8	402.8	281.9
	TDS (mg/L)	29,658.0[b]	29,658.0[b]	29,646.0[a]	441.1[b]
	pH	7.0	7.0	7.0	5.9
	Pressure (bar)	1.2	1.2	71.2	2.1
	Temperature (°C)	25.0	25.0	25.0	25.0
Product	Flow Rate (m^3/h)	447.8	402.8	281.9	205.5
	TDS (mg/L)	29,658.0[b]	29,658.0[b]	433.2[a]	0.005[b]
	pH	7.0	7.0	5.7	7.2
	Recovery	99.5 %	89.95 %	70.0 %	72.9 %
	Operating Costs ($/h)	-	54.5	189.9	420.8
	Specific Energy (kWh/m^3)	-	0.06	3.50	0.990
	Operating Cost ($/m^3$)	-	0.135	0.674	2.048
System	Specific Energy (kWh/m^3)	5.91			
	Operating Cost ($/m^3$)	3.24			
	Feed Flow Rate (m^3/h)	450.0			
	Product Flow Rate (m^3/h)	205.5			
	Recovery	45.7 %			

Table 9 represents the summarized system configuration and output for the UF, RO and IX treatment process. It shows the inputted feed water and product water parameters developed by the model tool for each treatment process, as well as the overall system recovery for the design. It is important to note the final product water TDS and pH which are 0.04 mg/L and 7.1 respectively are both within acceptable standards for potable water.

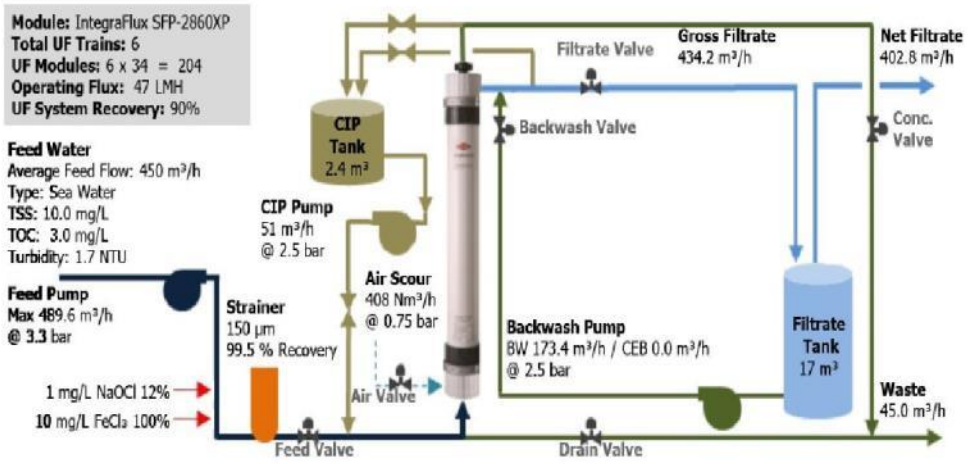

Figure 10: UF system flow diagram

Based on the information provided in the modeling tool, WAVE generated the UF process flow diagram as shown in Figure 10. Details of the UF system flow diagram are given in section 2 – Desalination System Configuration. The UF system flow diagram shows the flowrates (feed, product, backwash, CIP, air scour, chemicals), feed water composition (TSS, TOC, NTU, SDI), number of skids and modules, UF module type, UF system recovery and strainer recovery, tank sizes (backwash or backwash + filtrate), CIP. It also indicates different pressure regimes for the UF treatment process, starting from the feed pump with pressure of 3.3 bar. Sodium hypochlorite and ferric chloride are added in the percentages of 12 % and 100 % respectively immediately after the feed pump to prevent fouling of the UF membrane. The UF feed water is made to further pass through a fine strainer to trap any floating impurities in the water before the membrane. The backwash of the membrane is carried out with the filtrate from the UF process using a backwash pump at 2.5 bar. The UF recovery is 90 %.

Table 10: UF system overview

UF System Overview

Module Type		IntegraFlux SFP-2860XP			
# Trains		Online =	6	Standby =	0
				Redundant =	0
# Modules		Per Train =	34	Total =	204
System Flow Rate	(m³/h)	Gross Feed =	450.0	Net Product =	402.8
Train Flow Rate	(m³/h)	Gross Feed =	75.0	Net Product =	67.1
UF System Recovery	(%)	89.95			
TMP	(bar)	0.29 @ 10.0 °C		0.20 @ 25.0 °C	
Utility Water		Forward Flush:	Pretreated water	Backwash:	UF filtrate water
		CEB Water Source:	UF filtrate water	CIP Water Source:	RO permeate water

Six online trains were modelled for the system as shown in Table 10 with WAVE calculating the number of modules per train based on the flux and duration recommendations (Table 11) for each train having 34 modules. The module type adopted for this design was InegraFlux SFP - 2860XP. A total number of 204 modules were utilized in the 6 trains with individual train flow rate of 67.1 bar. A UF system recovery was calculated by the model to balance the hydraulics and provide

intake pressure for the RO system. RO permeate water was designed for the CIP water source. WAVE adopts three durations in developing CIP process which are:

- Chemical soaking duration – This is the time within which the UF module is soaked in each chemical during CIP.
- Duration of heating step: This is the time required daily to heat the CIP chemicals from the design temperature of the UF system to the CIP temperature in order to determine the system energy consumption.
- Duration of CIP recycling: This is the time during which the CIP solution is expected to move round through the UF Module circulates.

Table 11: UF operating conditions

UF Operating Conditions

	Duration	Interval	Flux/Flow
Filtration:	30.0 min	33.3 min	-
Instantaneous			
6 Online Trains			47 LMH
6 Total Trains			47 LMH
Average			42 LMH
Net			39 LMH
Backwash	3.3 min	33.3 min	100 LMH
mini-CIP	71.6 min	7 d	1.50 m^3/h
CIP	311.6 min	60 d	1.50 m^3/h

Table 12: UF designed system hydraulics

UF Flow Details

Stream		Maximum Flow[a]	Average Flow
Feed (Gross)	(m^3/h)	489.6	450.0
Feed Water Used for	(m^3/h)		
Pretreatment	(m^3/h)		2.3
Forward Flush & Process Streams	(m^3/h)		13.5
Feed (Net)	(m^3/h)	485.9	434.2
Filtrate (Gross)	(m^3/h)	485.9	434.2
Filtrate Used for Cleaning	(m^3/h)		31.5
Filtrate (Net)	(m^3/h)		402.8
RO Permeate for Cleaning	(m^3/h)		0.0
Air	($N\ m^3/h$)	408.0	24.4
Backwash (BW)	(m^3/h)	173.4	31.3
Forward Flush Flowrate	(m^3/h)	82.3	13.5
mini-CIP Recycle	(m^3/h)	51.0	0.1
CIP Recycle	(m^3/h)	51.0	0.0
Feed HCl (32%) Metering Pump	(L/h)	36.0	
Feed $FeCl_3$(100%) Metering Pump	(L/h)	1.7	
Feed NaOCl(12%) Metering Pump	(L/h)	1.8	
mini-CIP HCl (32%) Metering Pump	(L/h)	76.9	
mini-CIP Citric Acid(100%) Metering Pump	(L/h)	612.6	
mini-CIP NaOH (50%) Metering Pump	(L/h)	56.4	
mini-CIP NaOCl(12%) Metering Pump	(L/h)	748.0	
CIP HCl (32%) Metering Pump	(L/h)	50.2	
CIP Citric Acid(100%) Metering Pump	(L/h)	612.6	
CIP NaOH (50%) Metering Pump	(L/h)	35.5	
CIP NaOCl(12%) Metering Pump	(L/h)	748.0	

Footnotes:

[a] Maximum possible flow rate

Table 13: UF pressure ratings

UF Pressure Ratings

Process	T (°C)	TMP[a] (bar)	Fouling Max ΔP (bar)	Piping ΔP (bar)	Filtrate Pres. (bar)	Feed Pres.[b] (bar)	Pres. Rating (bar)	OK?[c]
Filtration								
Minimum Temp.	10.0	0.29	0.00	0.73	0.50	1.53	6.25	√
Design Temp.	25.0	0.20	0.00	0.50	0.50	1.20	6.00	√
Maximum Temp.	40.0	0.15	0.00	0.37	0.50	1.01	4.75	√
BW	25.0	0.43	0.00	0.50		0.93	6.00	√
mini-CIP	25.0			3.09		3.09	6.00	√
CIP	35.0			2.50		2.50	5.25	√

WAVE develops specifications for increase in pressure drop across the UF membrane known as transmembrane pressure (TMP) between successive backwash steps, acid / alkaline CEB, and CIP per hour as shown in Table 13 TMP, which helps in estimating the energy requirements for ultrafiltration taking into account the build-up of solids / fouling of the UF membrane during use.

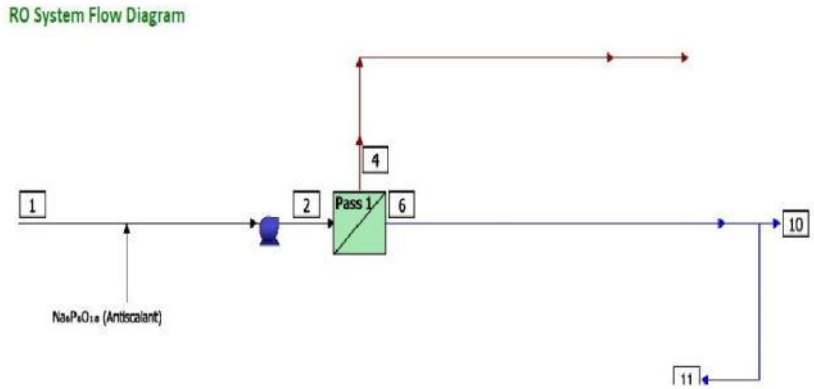

Figure 11: RO system flow diagram

WAVE generated the RO process flow diagram as shown in Figure 11 based on the information provided in the modeling tool. The flow diagram indicates the system components, and how they are arranged for an effective RO desalination system. Details of the RO system flow diagram and configuration have been given in section 2 – Desalination System Configuration. The RO system flow diagram shows the different systemic flow rates from the RO feed source (UF product water) through the high-pressure pump (HPP) to the concentration and product feed as represented in Table 14. It also indicates different pressure regimes for the RO treatment process, starting from the high-pressure pump to the RO concentrate. Different TDS at every stage are also shown in Figure 11 and the values given in Table 14.

Table 14: RO system overview

#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	402.8	29,646	0.0
2	Net Feed to Pass 1	401.5	29,739	71.2
4	Total Concentrate from Pass 1	120.5	98,094	68.6
6	Net Product from RO System	281.9	433.2	0.0
10	Net RO Product after UF Use	281.9	433.2	0.0
11	RO Permeate Used for UF	0.02	433.2	0.0

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	70.0 %
System Flow Rate	(m^3/h)	Net Feed =	402.8	Net Product =	281.9	(Permeate Used For UF)	

Pass		Pass 1
Stream Name		Stream 1
Water Type		Seawater With DuPont UF, SDI < 2.5
Number of Elements		324
Total Active Area	(m^2)	13244
Feed Flow per Pass	(m^3/h)	401.5
Feed TDS[a]	(mg/L)	29,739
Feed Pressure	(bar)	71.2
Flow Factor Per Stage		1.00, 1.00
Permeate Flow per Pass	(m^3/h)	281.9
Pass Average flux	(LMH)	21.3
Permeate TDS[a]	(mg/L)	433.2
Pass Recovery		70.2 %
Average NDP	(bar)	17.8
Specific Energy	(kWh/m^3)	3.50
Temperature	(°C)	25.0
pH		7.0 (After Adjustment)
Chemical Dose		3.0 mg/L $Na_6P_6O_{18}$(100%)
RO System Recovery		70.0 %
Permeate for UF	(m^3/h)	0.0
Net RO System Recovery		70.0%

Table 14 indicates the design parameters of the RO configuration. Only one pass with one online train was modelled for the RO system as shown in Table 14 with WAVE calculating the number of elements per train. The flow factor used in this model to account for the flow loss due to fouling was 1.00, since the model was for a new system.

Table 15: RO design warnings

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
$CaSO_4$ (% saturation) > 100	1
$BaSO_4$ (% saturation) > 100	1
CaF_2 (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

Table 16: RO chemical adjustment

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	8.4	7.6
Langelier Saturation Index	1.4	1.65
Stiff & Davis Stability Index	0.48	0.62
TDS[a] (mg/l)	29,630	98,094
Ionic Strength (molal)	0.60	2.15
HCO_3^- (mg/L)	128.3	476.5
CO_2 (mg/l)	0.28	13.69
CO_3^{-2} (mg/L)	35.37	16.71
$CaSO_4$ (% saturation)	25.1	116.9
$BaSO_4$ (% saturation)	134.6	549.4
$SrSO_4$ (% saturation)	12.9	82.8
CaF_2 (% saturation)	7.1	182.8
SiO_2 (% saturation)	0.00	0.00
$Mg(OH)_2$ (% saturation)	7.1	0.35

Table 16 presents a convenient way to calculate the risk of scaling in an RO system. The scaling risk from a chemical adaptation in the RO process is best calculated using the Langelier saturation index (LSI), the Stiff & Davis index (S&DI) and the saturation percentage for some salts such as $CaSO_4$, $BaSO_4$, SrSO4, CaF_2, Mg $(OH)_2$ and SiO_2. Table 16 above summarizes the scaling risk for the RO membrane process being modelled. In this table, WAVE flagged the percentage saturation of some/salts with values greater than 100 and also the LSI and S&DI values which aregreater than 0 by changing their colors to red to alert the designer. The interpretation of this model output is given in Section 4.5 – Results.

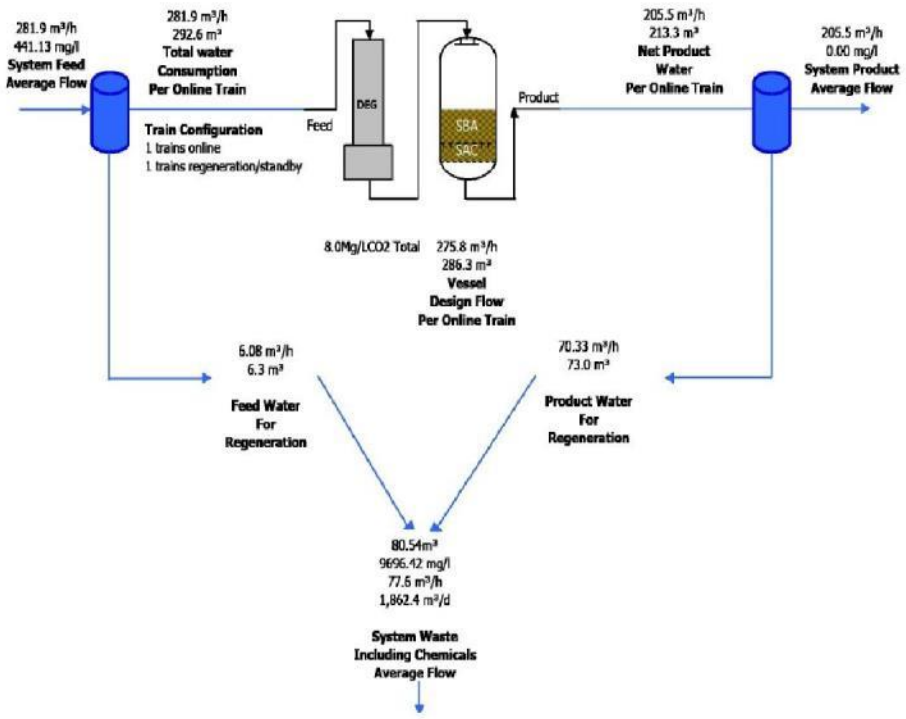

Figure 12: IX System Flow Diagram

The resin volume/operating cycle for this model was calculated based on the input specifications. The IX system configuration is shown in Figure 12 and analyzed in Table 17 with the WAVE calculated/designed system feed and system product flow rates set at 281.9 m^3/h and 205.5 m^3/h respectively. The system input flow was expected to be the same as the operating flow because a standby train was included for the model. The IX overall system recovery as shown in Figure 12 was 72.9 %. Specific velocity (BV/h) was selected, and used for the regeneration frequency, and as a result, the operating flow, the specific velocity value and the resin volume became fixed, while the length of operating cycles was calculated with the vessel size recommended by WAVE. WAVE also configured and developed the model parameters as shown in Table 17 based on the resin's arrangement/choice (*SAC, SBA*) and regeneration system *(MB: internal regeneration*) selected from the IX initialization window. The estimated run time for the IX process was 1.04 hours, while expected regeneration time based on the design model and calculations was 4.27 hours.

Table 17: IX polishing system overview

IX Process		RO Permeate Polishing			
Layout		[MB]			
#Trains		Online =	1	Regeneration =	1
System Average Flow Rate	(m^3/h)	Feed =	282	Product =	205
Net Product Flow Rate per Train	(m^3/h)				205
Throughput per Train per Cycle	(m^3)	Gross =	286	Net =	213
System Recovery	(%)		72.9		
Estimated Run Time	(h)		1.04		
Estimated Regeneration Time	(h)		4.27		

Flow Rates				
		System Average	Online Train per Cycle	
		Flow Rate	Flow Rate	Volume
System Feed	(m^3/h)	281.9		
Bypass	(m^3/h)	0.0		
Total Water Consumption	(m^3/h)	281.9	281.9	293 m^3
Total Regeneration Water	(m^3/h)	-76.4	-76.4	-79.306 m^3
Net Product Water	(m^3/h)	205.5	205.5	213 m^3
Bypass	(m^3/h)	0.0		
System Product	(m^3/h)	205.5		
IX Recovery		72.89 %		
System Overall Recovery (Including Bypass)		72.89 %		

Table 18: IX module configuration

Resin Type		SAC	SBA
Vessel Type		MB, Internal Regen	MB, Internal Regen
Design Flow Rate	(m^3/h)	276	276
Resin Name		AmberLite™ HPR1200 H	AmberLite™ HPR4200 Cl
Ionic Form (Delivered)		H	Cl
Resin Volume (Delivered Form)	(m^3)	2.95	5.15
Ionic Form (Reference)		Na	Cl
Resin Volume (Reference Form)	(m^3)	2.73	5.15
Total Bed Resin Volume	(m^3)	7.88	
Fraction of Bed	(%)	34.6	65.4
Potential Runtime	(h)	1.04	1.04
Potential Throughput	(m^3)	286	286
Operating Capacity	(eq/L)	0.81	0.44
Effective Operating Capacity	(eq/L)	0.77	0.42
Ionic Load	(eq)	2,103	2,140
Organic (TOC) Loading	(g/L TOC)		0.00
TSS Loading	(kg/m^2)	0.00	0.00
Regenerant		HCl	NaOH
Regeneration Dose	(g/L)	100.0	100.0
Regeneration Ratio	(%)	356	602
Excess Regenerant	(eq)	5,381	10,694
Vessel Outside Diameter	(mm)	2,500	2,500
Bed Depth (Delivered)	(mm)	613	1,072
Total Bed Depth	(mm)	1685	
Bed Depth (Reference)	(mm)	568	1,072
Total Bed Depth	(mm)	1640	
Freeboard	(mm)	1,900	1,900
Specific Velocity	(BV/h)	101	54
Total Bed Specific Velocity	(BV/h)	34.99	
Linear Velocity	(m/h)	57	57
Resin ΔP @ 25.0 °C	(bar)	0.35	0.58
Total Pressure Drop @ 25.0 °C	(bar)	0.94	
Capacity Safety Factor		0.949	0.950

Table 18 shows the design output for the resin adopted for this model using hydrochloric acid and sodium hydroxide as regenerants for the cation and anion resins respectively. The selected resin used for this model was Amberlite (SAC, SBA), loaded one on top of the other in MB: internal regeneration vessel.

Table 19: IX water quality

IX Water Quality

		Feed	Required Average	Required EndPoint	Estimated Average
pH @ 25.0 °C		5.88	-	-	7.18
Conductivity @ 25 °C	(µS/cm)	881	0.12	0.22	0.058
Na	(mg/L)	156.462	0.010	0.020	0.002
SiO_2	(mg/L)	0.000	0.010	0.020	< 0.001

3.5 Results

The data presented in the UF, RO, and IX model output are the expected operating conditions of the system. The information produced was for the sizing and selection of the system feed pumps, interstage boost pumps if any, and energy recovery equipment to fulfill the system operating requirements. The UF backwash was scheduled to be repeated severally, according to the fouling degree of the UF membrane modules. The frequency of the UF CIP is 1-3 months, adjusted according to the operating conditions, and the CIP operation is started with a backwash sequence and completed with a backwash sequence. Due to the relatively high frequency of mini-CIP (i.e. typically from 1 to 3 times per week), it is recommended to automate the process in order to reduce labor. The existing auxiliary system used for the standard CIP is employed to perform more frequent but shorter chemical cleanings or mini-CIP, so there is no need for additional installation or hardware. The total duration of the mini-CIP is typically 30 minutes and includes a regular backwash pre-cleaning, a heated chemical solution recirculation step with a soaking period in between (with intermittent air scour), and a final backwash post-cleaning. This step duration might be longer, up to or well over 12 hours if the fouling is severe. Note that the mini-CIP substitutes the CEB, not the standard intensive CIP program which still might be needed regularly. The water quality properties of the RO model showed that monovalent ions such as Na^+ and Cl^- were dominant (Table 2). Among the divalent ions, K^{2+} showed the highest concentration with 7.33 mg/L, while $Mg2^+$ and $SO4^{2-}$ had relatively lower concentrations with 3.45 mg/L and 4.66 mg/L, respectively. The consequential permeate concentration was 156.5 mg/L (Na +), while the other ions were not registered by the model, due to the lack or low concentration. The brine concentration (433.2 mg/L TDS) was acceptable for the RO recovery rate of 70 %, and this can also be further confirmed with the equation (R / (1 - R) = cb / cf), which adopts a rejection of the 100 %. [Yadala et al., 2018]. Output from the computer models of the RO membrane system generated warnings on the concentrations of calcium sulfate, barium sulfate, strontium sulfate, and calcium fluoride which had exceeded their respective solubility limits in the reverse osmosis concentrate flow stream. Antiscalant is required for this model to prevent a precipitation of these compounds in the feed / concentrate stream and the subsequent membrane scaling. The pH of the post-treatment water was 7.18, indicating that the water is safe for consumption.

4. CONCLUSION

The goal of this work was to develop a suitable/stable predictive model for the all-encompassing seawater reverse osmosis (SWRO) membrane desalination system. The optimal design of the SWRO process was carried out in this work with the Water Application Value Engine (WAVE) water solution modeling tool to model the UF pretreatment, RO membrane desalination and IX polishing posttreatment processes. Modeling the three processes has produced extensive results of the simulation, tied to operational variables and the system key performance. Profiles of feed pressure, feed concentration and feed velocity along UF membranes, RO membranes and resins were modelled for these operations together with the relationship between water recovery, temperature and feed pressure. All work on this model was aimed at gaining a better understanding the mechanism of the SWRO process, while at the same time showing the considerable potential for system optimization. The benefit of using the WAVE model and simulation tool is that it can facilitate the design of an efficient seawater desalination system that will optimize RO plant productivity as well as reduce the cost of potable water production from saline water sources.

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CHAPTER 5: LIFECYCLE COST (LCC) ANALYSIS AND EVALUATION OF THE ECONOMICS OF SEAWATER REVERSE OSMOSIS DESALINATION: CURRENT AND FUTURE CHALLENGES FOR BETTER WATER SUPPLY SUSTAINABILITY

This chapter presents a financial analysis of the CAPEX and operational expenditure (OPEX) of traditional seawater reverse osmosis (SWRO) desalination plant and discusses some important parameters to take into account when calculating the life cycle costs of a seawater desalination plant. Water Application Value Engine (WAVE) water solution modeling tool was used in simulating a 2 MGD SWRO plant and the design result was used to calculate the lifecycle cost of producing a unit (m^3/d) of potable water in Lagos, Nigeria deploying a curve fit approach and pertinent water economic analysis tools. The article was accepted for publication in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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LIFECYCLE COST (LCC) ANALYSIS AND EVALUATION OF THE ECONOMICS OF SEAWATER REVERSE OSMOSIS DESALINATION – CURRENT AND FUTURE CHALLENGES FOR BETTER WATER SUPPLY SUSTAINABILITY

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ABSTRACT

In the design of a reverse osmosis (RO) plant for the desalination of seawater, the cost of capital estimation (CAPEX) for such a large project is an important factor for potential investors and consulting engineers to bear in mind for pre-construction planning and proper evaluation. This paper presents financial analysis of the CAPEX and operational expenditure (OPEX) of a traditional seawater reverse osmosis (SWRO) desalination plant. It also lists and discusses important parameters to take into account when determining the life cycle costs of seawater desalination, namely, water quality characteristics, production or plant capacity, location, energy consumption, materials, maintenance, operation, RO module costs, chemicals, and award year. In this research study, a 2 MGD SWRO plant was designed using WAVE, and the design result was used to calculate the lifecycle cost of producing a unit (m^3/d) of potable water in Lagos, Nigeria, deploying a curve fit approach and pertinent water economic analysis tools. The aim of this study was to develop a reliable life cycle cost for RO systems with acceptable levels of accuracy, based on verifiable and practical parameters.

Key words: Desalination, Lifecycle cost, Seawater reverse osmosis (SWRO), CAPEX, OPEX, TWC.

1. INTRODUCTION

The high cost of desalination / treatment of water influences the decision-making process regarding the implementation of reverse osmosis (RO) technology. When developing an RO desalination business case, the designer must provide a cost estimate. The costs offered by different engineers typically vary widely depending on the system approach used. There are many ways to estimate the cost of capital, including:

- ✓ Empirical cost model – The empirical cost model is a model with capacity as the primary variable and is predicated upon meticulous historical data and arithmetical study to derive the estimate or result.
- ✓ Parametric cost model – The parametric model uses many variables to provide estimates. Usually, multifaceted empirical or hybrid empirical approaches are used to increase the specificity of different applications.
- ✓ Factor cost model – The factor cost model usually takes an estimate of the cost of capital of major equipment and adds a factor to explain the remaining cost of capital. It is widely used in the petroleum and water sectors, and involves project analysis, design and growth to be carried out, and usually entails vendor suggestions.

- ✓ Material settlement – Once a plant design is conceived and implemented, the estimator can start counting components and provide a material plan with a general cost or estimate for each item in the plan. This design is the most accurate, but it needs to be well developed (Huehmer et al., 2011).

A typical lifecycle cost (LCC) analysis involves part of or the overall asset cost through the lifecycle of the asset as the asset keeps up the performance demands. There are three different types of costs associated with desalination plants. These include cost of capital (CAPEX), cost of operation (OPEX), and total water cost (TWC). Each is explained below.

- ✓ Cost of Capital – This represents the main investment for the completion of a project during the construction phase. This includes the following cost factors: intake construction, brine treatment, intake pumps, pretreatment, desalination (including pumps, membrane racks, energy recovery, etc.), posttreatment, residue management pretreatment, water storage and pumping, asset procurement, rights of way, permits, engineering, escalation, contractor overhead, and profit and tax acquisition
- ✓ Operating costs – Operating costs are ordinary costs incurred on an annual basis. This includes the following cost factors: operation and maintenance, energy consumption, pretreatment chemicals, anti-scale agents, cleaning, maintenance parts, insurance, membrane replacement (usually on an annual basis), cartridge filter replacement, laboratory analysis and monitoring, and regulatory compliance (Huehmer et al., 2011).
- ✓ Total water cost – Total water cost or life cycle cost is the sum of capital and operating costs for the duration of the contract. Costs are calculated by dividing the sum of capital amortization (annual) costs and annual operation and maintenance costs by the average annual production of drinking water. In general, TWC excludes distribution costs.

OPEX are not only determined primarily by the energy costs used to operate the desalination plant, but also include the other costs mentioned above. On the other hand, CAPEX can be further subdivided into indirect costs and direct costs. Direct cost of capital includes land, major and ancillary facility costs, and construction costs. Indirect cost of capital includes freight and insurance, construction overheads, and contingent costs. Annual OPEX are incurred after the system is commissioned and during system operation.

A variety of funding and contract packages are available and have been successfully implemented in major projects in the past. Turnkey is one of the common financing models for large projects. Financing options under the turnkey schemes comprise build-own-operate (BOO) or build, own, operate transfer (BOOT). These agreements are predefined and have no initial government intervention or ownership, but the contracts are guaranteed. Most of the current seawater desalination schemes are privately funded projects under BOO / BOOT delivery finance schemes. When a BOO contract is signed, it is a long-term contract with the client and the services provided billed accordingly. For the BOOT program, the winner of the project bid offer performs the same function as BOO, but at the end of the contract period, the project is transferred to the client. The most significant parameter therefore, is the total water cost (TWC) which influences the BOO project award. All the above parameters are carefully considered, particularly the agreed energy prices, and additional regional eventualities are considered. BOOT bid valuation could be somewhat complicated because, at the end of the contract period, the project

sponsors need to evaluate the residual value of the system. Minor cost fluctuations, such as less than $ 0.01 per cubic meter, can result in hundreds of millions of dollars in investment costs for the private sector / bank for a project (Ghaffour et al., 2013). Another category of funding programs is engineering-procurement-construction (EPC). EPC contracts arise through direct contracts between clients and EPC contractors. EPC costs include all direct capital costs of the facility (excluding land costs) and contractor service costs. EPC services include detailed construction, contract, and project management costs. In return, EPC contractors need to offer projects with a fixed maximum contract amount and a fixed date to achieve the final performance of the system in terms of output and quality, efficiency and reliability (Loutatidou et al., 2014).

Government is the most prominent and common source of funding for major projects, but the private sector is also involved in this development. There are several commercial and / or non-exclusive desalination cost models developed to assess the capital and total cost of desalination. These seawater desalination cost programs allow you to estimate the cost of desalination of sea or brackish water using a variety of technologies. The most frequently used cost models are WT Cost© and cost curves. Others include global water intelligence desalination SWRO cost estimate, desalination economic assessment program (DEAP) AUDESSY, WRA model, and Kawamura model. Moreover. The unit price used to assess life cycle costs is USD per m^3 water production.

This study used a systematic approach to estimate the life cycle cost of desalination plants. This included a literature review in terms of global trends, real-world data from RO desalination plants, industry reports, and commercial products. The aim of this study was to present accurate and practical life cycle costs for RO plants operating on sustainable energy sources.

2. METHODOLOGY

Cost modeling based on numerous detailed designs lead to more accurate cost estimates. However, cost models based on unknown or undecided parameters will render the modeling tool unproductive. There are many parameters that can affect the CAPEX of a RO system, either technical or non-technical. Technical parameters include capacity, desired product water quality, raw water quality, pretreatment requirements, disposal of brine emissions, membrane options and more. Non-technical parameters can be of a social, ecological or geographical nature (Kizhisseri et al., 2020). These important parameters need to be considered when choosing the right desalination technique. The estimated cost of desalination plants for the various processes is site-specific and subject primarily to the parameters mentioned below:

- ✓ Electricity accessibility. If the facility is a stand-alone facility powered by distantly generated power, the RO plant will incur high electricity bills and raise the OPEX of the system.
- ✓ Desalting procedure setup, plant capacity and module design. The costs of investment on various profitable desalination technologies vary extensively between the membrane-based and terminal technologies. The capacity of the system is also imperative. The larger the system volume, the lower the total water cost and investment cost per cubic meter of the product.
- ✓ Geographic location and site-specific features. Desalination plants need to be constructed in the right places to avoid extra expenses such as high cost of water movement, or operation of the system.

- ✓ Fresh water quality, temperature, inlet location and required product water quality. If more advanced pretreatment is desired, the price can be greatly affected by the quality of the feed water, so the location of the plant should be carefully selected in terms of raw water quality, elevation, or current of the feed water, especially in terms of RO. The intake and pretreatment system are designed according to the quality and quantity of raw water and the geology of the location.
- ✓ Types of reject discharge and the product water storage capacity. New environmental regulations always require planners and plant design engineers to develop advanced processes for concentrated wastewater. The new regulations require that concentrates be diluted in a mixing zone, cooling water to be used to lower the brine temperature, and chemicals be removed (e.g. dechlorination) before being discharged to the sea.
- ✓ Post-treatment of generated water. The pH and hardness of desalinated water should be adjusted to be suitable for drinking water use. Generally, desalinated water is supplied to the distribution system after post-treatment.
- ✓ On the spot storing of the produced water. Depending on the dependability of the seawater treatment facility's infrastructure and power sources, and the need to store the water produced in an emergency, the storage capacity of the site can range from a few hours to about 5 days of system capacity.
- ✓ Product water recovery and energy prices. Energy prices are included as part of the total water cost of the contract for the service period. Nearly all contracts with BOO and BOOT designations include dost for energy modification provisions to cater for electricity cost fluctuations. Consequently, minimizing/reducing the general system energy consumption pattern will impact significantly on bringing down the water unit costs.
- ✓ Equipment, materials, chemicals and other consumables.
- ✓ Funding specifics and payback phase, and rate of inflation.
- ✓ Contracts, changes in rate of interest, and management costs.
- ✓ Operation and maintenance management, replacement of membrane and equipment (such as pumps and manifolds), requirements for training and cost of skilled labor. Recruiting the right personnel increases the rate of production and reduces downtime.
- ✓ Competitive offer, contract type, standard of service. Several BOO and BOOT contracts include minimum performance reliability standards.
- ✓ On the spot storage tank capacity of the produced water. (Ghaffour et al., 2013).

3. COST EQUATION

Huehmer et al. (2011) reported that many cost models have been developed over time as shown in Table 1, but the empirical cost model developed as part of funding from the U.S. Department of Pioneering and published by Watson et al. (2003), is the commonly used model. Later, several alternative empirical cost models were developed. These models use either polynomials, logarithmic logs, or semi-logarithmic models for regression analysis. Wittholz et al. (2008) performed an analysis on the dataset containing SWRO and BWRO, and the results indicate a linear regression as shown in the empirical correlation of Equation 1 below.

ln (Capital cost) = m x ln (Capacity) + constant ---------- Equation 1

Zhou and Tol (2005), using a similar regression analysis, evaluated the total water cost of the reverse osmosis desalination plant and derived a general model as shown in Equation 2.

F(Unit Cost) = G(Capacity, Year, Type) ---------- Equation 2

The model developed from both log-logs and semi-log regression analysis is shown in Equation 3.

ln(cost) = alpha x ln(capacity) + constant + dummies ---------- Equation 3

Table 1: Reverse osmosis empirical capital cost models (Huehmer et al., 2011)

	Zhou and Tol SWRO	Watson et. al SWRO	Wittholz et. al SWRO	Dore	Kawamura
Type	Log-Log	Power	Log-Log	ARIMA	Power
Year	2005	2003	2008	2005	2009
Equation	ln(cost) = mx ln(capacity) + constant + dummies	Cost = $M(capacity)^B$	ln(cost) = m x ln(capacity) + constant	$(1-B)Y_i$ = - 0.31149899 + v_i – 0.80700050 v_i - 1	Cost = $M(capacity)^3$
Units	m^3/d	m^3/d	m^3/d	m^3/d	MGD
N	1514	Not Reported	112	N.A.	
R^2		N.A.	0.907		
M		Not Reported	0.81		
Constant		Not Reported	4.07		
B		N.A.	-		

Linareset et. al developed a cost model by performing sensitivity analysis considering parameters such as pure water flow and module cost of RO membrane, and calculated the cost value (PV) represented in Equation 4.

$$PV(USD) = C\frac{1-(1+i)^{-n}}{i}$$ ---------- Equation 4

Where 'C' is the cost in US dollars, 'I' is the interest rate in percent, and 'n' is the duration of the project (year). PV calculates the value of the current amount compared to the same amount in the future, taking into account that the amount will increase over time based on interest rates. Other researchers have also developed cost equations to evaluate the cost of capital for a membrane desalination plant. These equations range from detailed cost equations to short-term cost estimation equations that represent either the total cost of capital or the unit cost of desalination. Some cost equations are shown in Table 2 below (Al Bazedi et al., 2016).

Table 2: Showing different cost equation from other researchers (Al Bazedi et al., 2016)

Item	Equation
	Capital Cost
Intake/Outfall and pretreatment Cost	$Cip = 1.47 * 996 * (Qf)^{0.8} = 1417 * (Qf)^{0.8}$
Pumping and Energy Recovery System	$C_p = 0.0141 * (\frac{Wref * (101.32\ P)}{Rf})$
Booster Pump	$BoosterPump(\$) = (665970 * (DesignFlow)^2 - 13682 * (DesignFlow) + 829.1) * 1.033$
Membrane Cost	$Cm = Cmem * (\frac{Am}{Amod})$
	Operating Cost
Membrane Replacement Cost	$Crep = P_m * Y_r * \frac{\lambda}{V_1}$
Chemical Treatment Cost	$C_c = 8000 * \left(\frac{24\ Wp}{Qm.\rho}\right) * 0.2 \quad \$/yr$
Electricity	$W_{pump} = \sum \Delta P * \frac{V_{pump}}{\eta K}$
M and Spare Parts	2% of direct capital cost
Labor Cost	0.048*capital cost
Pressure Pump Operating Cost	$C_{op} = Pf * \left(\frac{Qf}{\eta}\right) * D_{energy} * PlantloadFactor$

Loutatidou et al. (2014) uses the ordinary least squares (OLS) linear regression shown in Equation 5 as a modeling technique for calculating the EPC cost (target or dependent variable) using the variable capacity, salinity, year of award, etc. (training variable or regression variable):

$$Y = \beta_o + \beta_1 * X_1 + \beta_2 * X_2 + \beta_3 * X_3 + \ldots \beta_n * X_n \quad \text{----------} \quad \text{Equation 5}$$

Where Y is the target variable (in this case the EPC cost), X1 – Xn is the independent variable, and βo–βn is the regression coefficient.

4. RO DESALINATION SYSTEM CONFIGURATION

4.1 Designed Capacity

This study is based on production plant capacity of 2 MGD (9000 m^3/d) of potable water. The RO system train is configured with a two-stage PV configuration. The production capacity of the SWRO is 9000 m^3/d with a total recovery rate of 70 %. The proposed plant location is in Lagos, Nigeria.

4.2 System Configuration

The focal processes of the RO system are pretreatment, high-pressure pump, membrane treatment and post-treatment. The RO desalination process involves two stages of reverse osmosis. Brine from the first stage process is channeled into the second stage process by gravity, and the permeates from both stages are combined and fed into the post-treatment system before distribution as shown in Figure 1 below. The second stage brine is sent to an energy recovery device, which is an ERI (Energy Recovery Inc.) pressure exchange device.

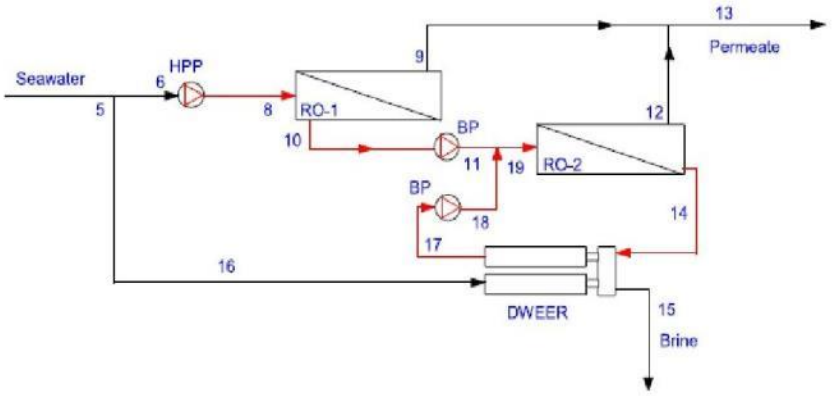

Figure 1: Line diagram of SWRO system showing ERD (Blanco-Marigorta et al., 2014)

Finally, the drinking water is pumped from the ground tanks of the seawater desalination plant to the overhead storage tanks. Four Nos transfer pumps (two duty, two standby) are used for this. From there the water is distributed to the water supply network (Blanco-Marigorta et al., 2014). This paper focuses on modeling of a RO desalination system using DuPont's water application value engine (WAVE) water solution software. The reverse osmosis desalination process involved in this model is made up of four different stages, as shown in Figure 2 below.

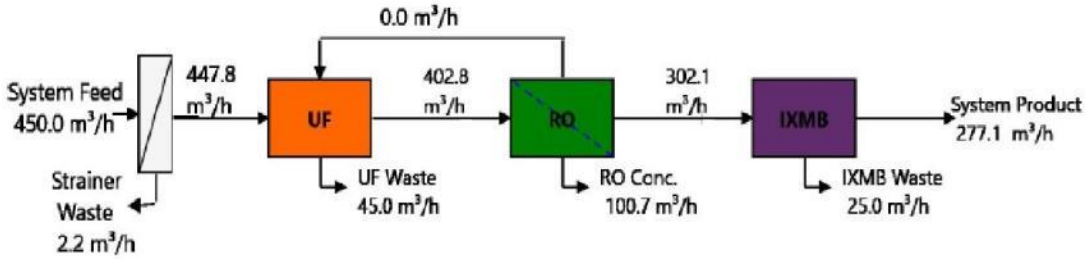

Figure 2: UF, RO, IX system configuration

The water from the system feed source is first passed through a strainer with fine and coarse screens to remove any floating particles in the feed stream before entering into the ultrafiltration (UF) pretreatment system. The ultrafiltration unit consisted of 6 online trains, with each of the trains consisting of 34 Integralflux SFP-2860 XP modules of 1.86 m in length (Table 3), which were interlocked and branched internally in parallel. The module occupied a total area of 51 m^2 with a

diameter of 0.225 m diameter configuration as shown in Tables 3 - 5. The module provided a total volume of 35 L. A CIP water source was provided from the RO permeate flux for the UF system.

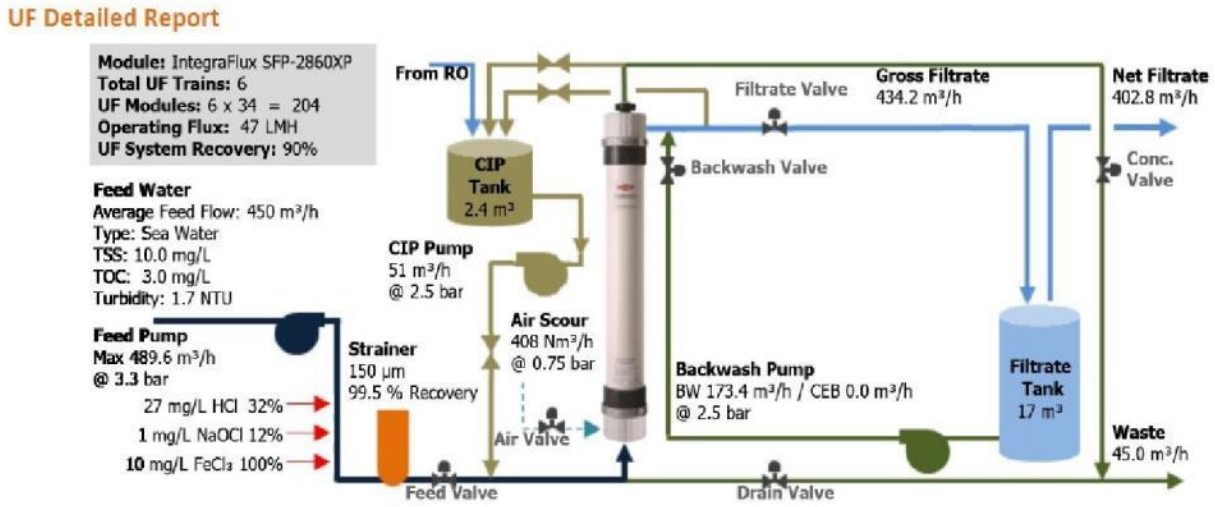

Figure 3: UF system configuration

Table 3: UF system overview

UF System Overview

Module Type		IntegraFlux SFP-2860XP			
# Trains		Online =	6	Standby =	0
				Redundant =	0
# Modules		Per Train =	34	Total =	204
System Flow Rate	(m³/h)	Gross Feed =	450.0	Net Product =	402.8
Train Flow Rate	(m³/h)	Gross Feed =	75.0	Net Product =	67.1
UF System Recovery	(%)	89.95			
TMP	(bar)	0.29 @ 10.0 °C		0.20 @ 25.0 °C	
Utility Water		Forward Flush:	Pretreated water	Backwash:	UF filtrate water
		CEB Water Source:	UF filtrate water	CIP Water Source:	RO permeate water

Table 4: System configuration options

UF Configuration Options

Standby Option:	Constant module flux, variable plant filtrate flow
Storage Tank Option:	Storage Tank sized to maintain constant net filtrate flow
Forward Flush Water Source:	Pretreated water
BW Water Source:	UF filtrate water
mini-CIP Water Source:	UF filtrate water
CIP Water Source:	RO permeate water

Table 5: UF system size and module details

UF System Size and Module Details

Trains		Module Details		
		Name: IntegraFlux SFP-2860XP		
Online Trains	6	Membrane Area	51 m^2	549 ft^2
Standby Trains	0	Length	1.860 m	73.2 in
Redundant Trains	0	Diameter	0.225 m	8.9 in
Total Trains	6	Weight (empty)	48 kg	106 lb
Max Offline Trains	1	Weight (water filled)	83 kg	183 lb
Modules/Train	34	Water Volume	35.0 L	9.2 gal
Total Modules	204			

The UF permeate was pumped at an elevated pressure with a high-pressure pump (HPP) as feed water to the RO desalination system, and the feed water flowed across a semi-permeable membrane barrier as shown in Figure 3. Solvent flows through a membrane faster than the dissolved solids; the difference in this flow rates results in separation of the solids from the solvent. The solvent, which in this case was pure water, passed through the membrane with a very low salt concentration. The concentrated water or brine left behind as waste was disposed of.

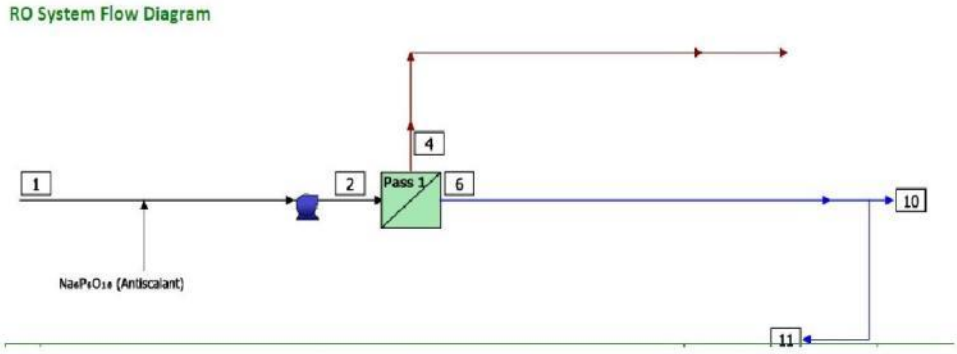

Figure 4: RO system configuration

A two-stage PV configuration was designed for the RO process train as shown in Table 6. The SWRO plant capacity was 9 000 m^3 per day with 75 % total rate of recovery. The UF process was configured for 99.5 % recovery rate while the IX polish (post-treatment) system was designed with a 91.73 % recovery rate. The pretreatment process UF permeate maintained an acceptable water quality condition of TSS $\leq$ 10 mg/L, turbidity $\leq$ 1.7 NTU and SDI $\leq$ 2.5 for the feed water into the RO process. The feed water was pressurized through the use of a HPP. The RO process was classified into two PV stages: the first and second stages comprising 10 and 5 PVs respectively, with a total of six seamaxx^{TM} - 440i elements installed in each PV. Specifically, it is important to note that the retentate from the first stage PV (i.e., the feed water to the second stage PV) in the RO process was not further pressurized by an interstage booster pump (IBP). This can be confirmed by the difference in the inlet feed pressures between the first and second stage PV. Such inlet pressure difference was measured at an average of 0.7 bar

(therefore, pressure drops within the first stage PV) during the study period of the RO operation. Sodium hypochlorite, hydrochloric and citric acids were used as chemical agents for the CIP to remove organic and inorganic foulants from the membranes.

Table 6: RO system overview

#	Description	Flow (m^3/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	402.8	29,646	0.0
2	Net Feed to Pass 1	400.1	29,838	144.7
4	Total Concentrate from Pass 1	100.1	118,928	129.1
6	Net Product from RO System	302.1	118.5	0.0
10	Net RO Product after UF Use	302.1	118.5	0.0
11	RO Permeate Used for UF	0.02	118.5	0.0

The configuration for the IX Post-treatment is shown in Figure 5 and Table 7 below.

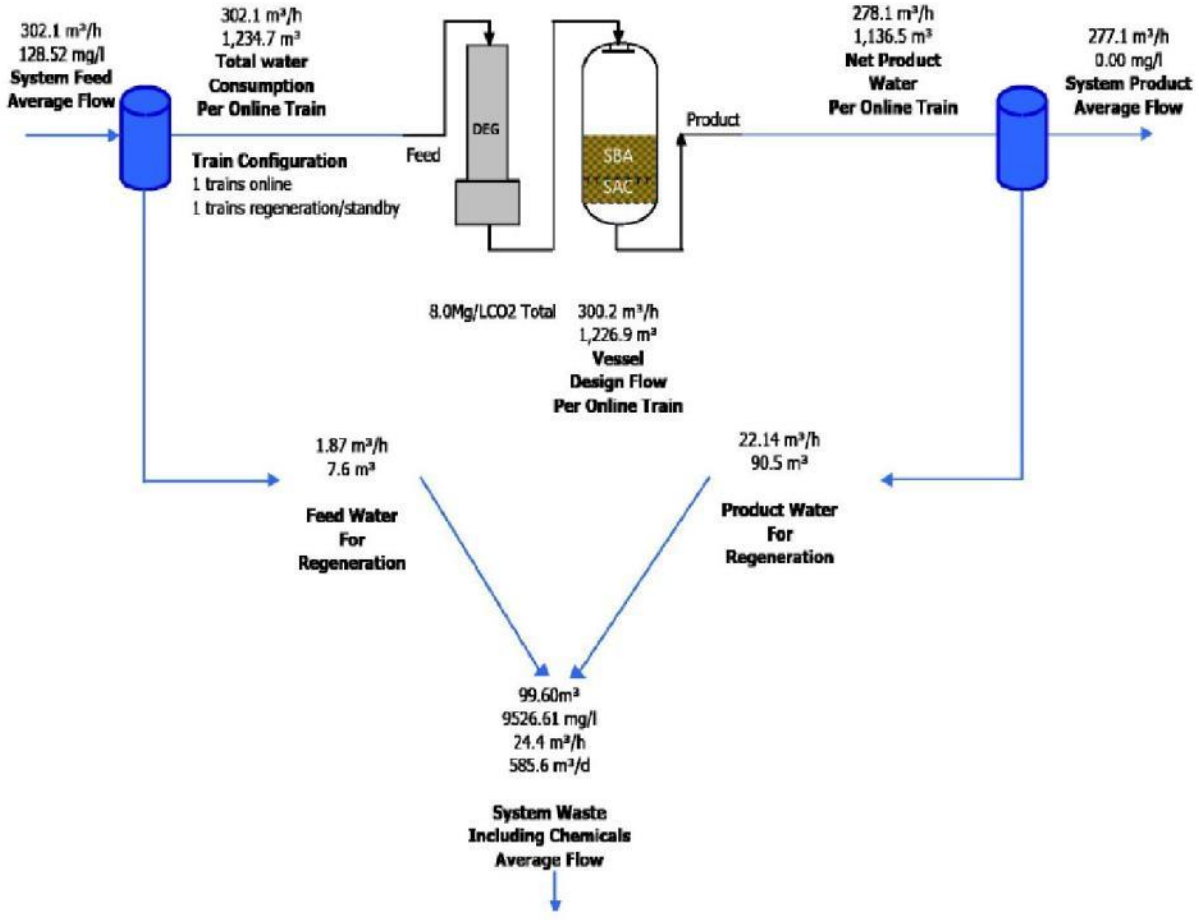

Figure 5: IXMB polishing system configuration

Table 7: IX system configuration

IX Process		RO Permeate Polishing			
Layout		[MB]			
#Trains		Online =	1	Regeneration =	1
System Average Flow Rate	(m^3/h)	Feed =	302	Product =	277
Net Product Flow Rate per Train	(m^3/h)				278
Throughput per Train per Cycle	(m^3)	Gross =	1,227	Net =	1,137
System Recovery	(%)		91.7		
Estimated Run Time	(h)		4.09		
Estimated Regeneration Time	(h)		4.47		

4.3 Plant Energy System

Desalination systems can be categorized into two groups: systems that use conventional sources of energy and those powered from renewable energy sources (RES) (wind, solar, etc.). The cost of water produced from desalination systems with a conventional source of energy (gas, oil, electricity) is much lower when compared to RES source at the construction stage, but the setup consumes enormous operational expenses (OPEX) during plant operation. On the other hand, desalination powered from a RES involves a massive capital investment (CAPEX) at the construction stage, but saves huge OPEX on power consumption during plant operation. This is also an attractive solution in terms of reduced environmental impact due to lower conventional energy consumption and lower gas emissions (Karagiannis and Soldatos, 2008). Tables 8 to 11 show the summary of energy consumption pattern of the plant, while Table 12 provides a summary of the power requirements.

Table 8: RO desalination plant power requirements

SWRO Treatment Plant							
Location		Facility	No.	Rating Each KW	Total Power Reqd KW	Power Reqd (Continuous) KW	
						Day	Night
I - Intake 1	i	Screens	1	0.75	0.75	0.75	
	ii	Conveyor	1	1.1	1.1		
	iii	Automatic Scrapper	1	1.5	1.5		
	iv	Low-lift Pump (2+2)	2	34	68	68	68
	v	Other small power	misc.	3.5	3.5	2.5	3.5
		Total Power Consumption for Intake			**75**	**71**	**72**
Recommended Solar Power for Intake & WTP	**72 kW-Hour**		**71,500 W-Hour**		**1,430,000**	**W-Hour/Day**	

Figure 9: UF process power requirements from WAVE

Electricity

Peak Power	(kW)	68.47
Energy	(kWh/d)	552.11
Electricity Unit Cost	($/kWh)	0.0515
Electricity Cost	($/d)	28.43
Specific Energy	(kWh/m³)	0.06

Table 10: RO process power requirements from WAVE

Pump	Flow Rate (m³/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	401.50	985.83	23,659.87	1,219.43
Pass 1 Total		985.83	23,659.87	1,219.43
System Total		985.83	23,659.87	1,219.43

Electricity

Peak Power	(kW)	985.8
Energy	(kWh/d)	23,660
Electricity Unit Cost	($/kWh)	0.0515
Electricity Cost	($/d)	1,219
Specific Energy	(kWh/m³)	3.50

Table 11: IXMB process power requirements from WAVE

Operation	Power (kW)	Energy (kW-h)		Hourly Cost ($/d)
		per Regen	per Day	
Feed Pump	22.7		545.5	28.11
Regeneration Protocol 1				
Backwash & Compaction Pump	0.0	0.0		
Regeneration Pump	0.1	0.2		
Fast Rinse Pump	0.0	0.0		
Heating	0.0	0.0		
Regeneration 1 Total	0.1	0.2	4.2	0.22
Regeneration Protocol 2				
Backwash & Compaction Pump	0.4	0.2		
Regeneration Pump	0.1	0.2		
Fast Rinse Pump	11.8	1.7		
Heating	0.0	0.0		
Regeneration 2 Total	11.8	2.1	48.8	2.51
Total Regeneration			53.0	2.73
Total System			598.5	30.85

Electricity

Peak Power	(kW)	34.64
Energy	(kWh/d)	4,863.18
Electricity Unit Cost	($/kWh)	0.0500
Electricity Cost	($/d)	250.7
Specific Energy	(kWh/m³)	0.990

Table 12: RO desalination plant power requirements summary

POWER REQUIREMENT SUMMARY		
Description	**KW-Hour/Day**	**Watt-Hour/Day**
Intake	1,430	1,430,000
UF Process	552	552,110
RO Process	23,660	23,660,000
IXMB Process	4,863	4,863,180
Total Power	**30,505**	**30,505,290**
AVG POWER AFTER ERD	**9,151.59**	**9,151,587**

4.3.1 Solar System and Variable Frequency Drive (VFD) Design

Table 12 evaluates the overall energy requirements for immediate implementation of the RO desalination system. To start an AC pump motor, 300 % to 600 % of the motor's total load current is required. This puts a heavy burden on the PV system. By using a variable frequency drive (VFD), these demand factors are not an issue and energy consumption is reduced as shown in Table 13.

4.3.1.1 Solar Design

Input Data for Solar Panel Design

Solar system voltage	-	240 Volts DC
Losses in wire, connection, battery	-	5 %
Plant operation hours	-	24 Hours
Daily sunshine hours in dry season	-	11 Hours
Daily sunshine hours in rainy season	-	9 Hours
Total solar power needed	-	9 151 587 Watt.Hr/Day

Solar panel watt	-	1000 watt,
Solar panel voltage	-	60 volts
Type of connection for solar panel	-	Series-parallel connection
Number of strings for solar panel	-	961 Nos

Solar Panel Design Calculation

Average daily sunshine hours	=	$\frac{\textit{(daily sunshine hours in dry season + daily sunshine hours in rainy season)}}{2}$
Total solar power after correction factor	=	*total solar power needed x (1 + Losses in wire, connection, battery)*
Solar array size after calculating sun hour	=	$\frac{\textit{total solar power after correction factor}}{\textit{average daily sunshine hours}}$
Total number of solar panel in each string	=	$\frac{\textit{solar system voltage (240 volts)}}{\textit{solar panel voltage (60 volts)}}$
Total watts of solar panel	=	number of strings for solar panel * solar panel watt * total No of solar panels in each string
Total number of solar panels	=	$\frac{\textit{total watts of solar panel}}{\textit{solar panel watt}}$

Input Data for Battery Bank Design

Battery bank's voltage	-	240 volts DC
Losses connection/wire loss factor	-	5 %
Battery efficiency	-	90 %
Battery aging	-	20 %
Depth of discharge:(DOD)	-	70 %
Battery operating temperature	-	25 °C
Battery discharge current	-	800 amp.hr
Total amp.hr of each string	-	800 amp.hr
Battery voltage	-	48 volts
Type of connection for batteries	-	Series-parallel connection
Number of strings for batteries	-	200 Nos

Solar Battery Bank Design Calculation

Reserve day = $\frac{\textit{total No. plant operation hours}}{\textit{total No. of hours without sun}}$

The battery bank required = *(total solar power needed / solar system voltage) / (battery efficiency) / depth of discharge:(DOD) x (1 + losses connection/wire loss factor) x reserve day x (1 + battery aging)*

Total No of batteries in each string	=	$\frac{\textit{battery bank's voltage}}{\textit{battery voltage}}$
Total battery bank amp.hr	=	*(Total amp.hr of each string) x (number of string for batteries)*
Total Nos of Batteries in Battery Bank	=	*(Total No of Battery in Each String) x (Number of String for Batteries)*
Total amp.hr	=	$\frac{\textit{total solar power needed}}{\textit{solar system voltage}}$

Average load = $\frac{\textit{total amp.hr}}{\textit{battery efficiency x (1 + losses connection/wire loss factor)}}$

Storage required = *(average load) x (reserve day)*

Depth of discharge = *the battery bank required*

Solar VFD (3 Phase) Design Calculation

Efficiency of solar VFD 3 phase - 95 %

Size of solar VFD = $\frac{\textit{(power requirement kW-h/day) x (100 + (100 - efficiency of solar VFD))}}{\textit{100}}$

Table 13: Solar system and VFD design

DESIGN OF SOLAR PANEL / BATTERY BANK / VFD				
SEAWATER REVERSE OSMOSIS TREATMENT PLANT				
Solar Panel Detail				
Solar System Voltage	240	Volts DC		
Losses in Wire,Connection,Battery	5	%		
Daily Sunshine Hours				
In Dry Season	11	Hrs.		
In Rainy Season	9	Hrs.		
Average Daily Sunshine Hours	10.0	Hrs.		
Total Solar Power need	9,151,587.00	Watt.Hr/Day		
Total Solar Power after Correction Factor	9,609,166.35	Watt.Hr/Day		
Solar Array Size after Calculating Sun Hou	960,916.64	Watt.Hr		
Select Size of Solar Panel	1000	watt	60	Volts
Solar Panel				
Type of Connection For Solar Panel		Series-Parallel Connection		
Number of String for Solar Panel	961	Nos	960.92	
Total Watt of Each Solar Panel String	1000	Watt		
Total No of Solar Panel in Each String	4	Nos		
Total Watts of Solar Panel	**3,844,000.00**	**Watt**		
Total Nos of Solar Panels	**3844**	**Nos**		
Battery Bank Details				
Battery Bank's Voltage	240	Volts DC		
Reserve Day:	0.416666667	Days	Remarks *For night operation from the batteries*	
Loose Connection/Wire Loss Factor:	5%	%		
Battery Efficiency	90%	%		
Battery Aging	20%	%		
Depth of Discharge:(DOD)	70%	%		
Battery Operating Temp:	25	C^{O}		
The Battery Bank Required:	31,776.34	Amp.Hr		
Enter Each Battery Rating	800	Amp.Hr @	48	volts
Batteries connection for Battery Bank				
Battery Bank				
Type of Connection For Batteries		Series-Parallel Connection		
Number of String for Battries	40	Nos	39.72	
Total Amp.Hr of Each String	800	Amp.Hr		
Total No of Battery in Each String	5	Nos		
Total Battery Bank Amp.Hr	**32000**	**Amp.Hr**		
Total Nos of Batteries in Battery Bank	**200**	**Nos**		
Calculations				
Total KW.Hr/Day	9,151,587.00	Watt.Hr/Day		
Total Amp.Hr	38,131.61	Amp.Hr		
Average Load	44,486.88	Amp.Hr		
Storage Required	18,536.20	Amp.Hr		
Depth of Discharge	31,776.34	Amp.Hr		
Day	24	hr		
Solar VFD (3 phase)				
Efficiency of Solar VFD 3 Phase	95	%		
Size of Solar VFD	2625.0	KW		

4.4 Energy Recovery

The energy components of RO systems have improved considerably in the last few years through deployment of energy recovery devices (ERDs). The RO system uses a high-pressure pump to overcome the osmotic pressure of raw water. The RO concentrate brine stream from this process contains pressure energy that can be recovered to reduce the overall energy

requirements of the RO system. Energy recovery technology reduces total energy consumption and therefore operating costs. Energy recovery is accomplished on the saline waste side of the system via either a turbo system such as turbochargers, Pelton turbines, reversible pumps, hydraulic boosters, or a volumetric measurement system such as ERD pressure exchanger, DWEER (dual work exchanger) or KSB (SalTec)-device.

5. RO DESALINATION COST COMPONENTS

This life cycle cost calculation is based on the following assumptions about the components of the seawater treatment plant as laid out in Table 14:

Table 14: RO desalination lifecycle cost assumption

S/N	Description	Assumption
1	Project location	Lagos, Nigeria
2	Plant capacity	2 MGD
3	Project lifetime	30 years
4	Electrical energy supply	One time investment in solar renewable energy source

All calculations are expressed in present value (PV) with a project duration of 30 years. Ghaffour et al. (2013) reported on the investment costs of a recently built large SWRO desalination plant with a capacity of \$900 per m^3 to \$1 200 per m^3 per day and a small plant with a capacity of \$2 500 per m^3 per day. The TWC ranged from \$0.5 /m^3 to \$1.20 / m^3, and energy and membrane replacement costs are the main components of the TWC. Depreciation of capital accounts for 35 % to 45 % and electricity accounts for 19 % to 40 % of TWC.

5.1 Capital Investment (CAPEX)

Tables 15 to 21 present the analysis of the total expected investment in the RO desalination plant. The TWC (Table 21) is calculated as the sum of the CAPEX and total OPEX throughout the life time of the project. Detailed calculations on the CAPEX and OPEX can be found in Tables 15 to 20. Powering the plant from renewable energy and the introduction of VFD and ERD lowered the OPEX considerably due to savings in the cost of energy, but increased the CAPEX due to the initial capital investments in renewable power systems.

Table 15: Capital investment (CAPEX)

CAPITAL INVESTMENT		
S/N	DESCRIPTION	AMOUNT (USD)
1	**Intake**	3,060,115.83
	Civil Works	77,761.65
	Pipeline	2,805,488.38
	Lowlift Pump - (2 duty, 2 standby)	126,182.80
	Screen	5,683.00
	Overhead Crane	25,000.00
	Automatic Scrapper	20,000.00
2	**RO Water Treatment Plant**	3,343,942.79
2.1	**Pre - Treatment**	963,997.31
	Raw Water Tank	39,024.29
	Feed Pump - (2 duty, 2 standby)	51,654.60
	Dosing Pump (11 duty, 4 standby)	146,239.50
	Strainer	5,683.00
	CIP Tank	10,227.50
	CIP Pump - (1 duty, 1 standby)	19,427.30
	Air Blower - (1 duty, 1 standby)	26,668.52
	UF Element	469,200.00
	Membrane Housing	102,000.00
	Train	18,720.00
	Filtrate Tank	23,498.00
	Backwash Pump - (2 duty, 2 standby)	51,654.60
2.2	**Reverse Osmosis Process**	1,845,148.07
	High Pressure RO Feed Pump Station	
	High Pressure Pump - (2 duty, 2 standby)	180,791.10
	Train	3,120.00
	Membrane Element	745,200.00
	Membrane Element Housing	162,000.00
	Dosing Pump - (1 duty, 1 standby)	19,498.00
	Stage 1 PV	450,000.00
	Stage 2 PV	225,000.00
	Sludge Tank	4,342.62
	Sludge Pump	23,129.50
	RO Permeate flux Tank	32,066.85
2.3	**Post - Treatment**	534,797.41
	Feed Pump - (2 duty, 2 standby)	51,654.60
	Feed water Regeneration Pump - (1 duty, 1 standby)	19,498.00
	Product Water Regenration Pump - (1 duty, 1 standby)	23,122.16
	Backwash & Compaction Pump - (1 duty, 1 standby)	19,498.00
	CO2 Dosing Pump - (2 duty, 2 standby)	51,652.00
	Fast Rinse Pump - (1 duty, 1 standby)	19,498.00
	Feed Water Regeneration Pump sump Tank	32,066.85
	Product Water Regeneration Pump Sump Tank	12,913.65
	Waste Disposal Tank	64,066.85
	Waste Disposal Pump - (1 duty, 1 standby)	25,827.30
	PV	12,500.00
	SBA Resin	73,750.00
	SAC Resin	128,750.00
3	**Others**	283,488.70
	Ground Tank	64,066.85
	High Lift Pump Station	
	Civil Works	3,210.00
	Electromechanical Works	69,938.32
	Elevated Water Tank	97,493.04
	Office and other civil works	48,780.49
4	**Solar Power / Electrical**	3,065,918.25
	Solar Panels, Accumulator and Inverter	2,622,600.00
	VFD	393,750.00
	Electrical system to incl. switch Control and Protection + lighting and small power	49,568.25
5	Energy Recovery	500,000.00
6	Land Acquisition / Right of way	4,797,423.40
	GRAND TOTAL	**15,050,888.97**

Table 16: CAPEX summary

	GRAND TOTAL(incl. Cont. and VAT)		**21,533,745.28**
	VAT	7.5%	**1,502,354.32**
	Plant Construction Cost		**20,031,390.96**
	(incl. cost escalation at 2.2% p.a(av. 2021))	6%	**841,507.52**
	Physical Contigencies 12.5%	13%	**1,881,361.12**
	Engineering and Design 5%	5%	**752,544.45**
	Construction Phasing		**Year 2023**
	Construction Periods (Years)		**3**
	Pre- Construction Provision + Preliminaries	10%	**1,505,088.90**

5.2 Operational Investment (OPEX)

Table 17: Operational expenditure (OPEX) on UF chemicals from WAVE

Chemicals

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
$FeCl_3$ (100%)	0.580		37.3	62.64
Feed		10		
Citric Acid (100%)	0.790		24.3	31.94
CIP		20000		
mini-CIP		20000		
HCl (32%)	0.046		796.3	42.50
Feed		27		
CIP		367		
mini-CIP		560		
NaOCl (12%)	0.176		69.2	13.85
Feed		1		
CIP		2000		
mini-CIP		2000		
NaOH (50%)	0.250		2.1	0.82
CIP		548		
mini-CIP		843		
Total Chemical Cost				151.75

Table 18: Operational expenditure (OPEX) on RO chemicals from WAVE

Chemical

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
$Na_6P_6O_{18}$(100%)(Pass 1)	1.250	3.0	11.7	36.25
Total Chemical Cost				36.3

Table 19: Operational expenditure (OPEX) on IXMB chemical from WAVE

IX Regeneration

IX Chemical Consumption			
Regeneration Protocol		1	2
Regenerant		HCl	NaOH
Bulk Concentration	(%)	32	50
Unit Cost	($/kg)	0.05	0.25
Regeneration Temperature	(°C)	25.0	25.0
Dose			
Weight Basis	(g/L)	100.0	100.0
Consumption			
per Regeneration			
@ Bulk Concentration	(kg)	853	1,031
@ 100 % Basis	(kg)	273	515
per Day			
@ Bulk Concentration	(kg/day)	19,712.9	23,829.6
@ 100 % Basis	(kg/day)	6,308.1	11,914.8
Daily Cost	($/day)	906.79	5,957.41

Total Chemical Cost	($/day)	6,864.20

Table 20: Operational expenditure (OPEX)

OPERATIONAL EXPENDITURE FOR 30 YEARS		
S/N	**DESCRIPTION**	**AMOUNT (USD)**
1	Maintenance	10,534,919.13
2	Landuse Charge	179,542.20
3	Membrane Replacement	1,214,400.00
4	Chemical	76,164,300.00
5	Manpower	1,599,998.40
TOTAL		**89,693,159.73**

Table 21: Total water cost (TWC)

TOTAL WATER COST		
SN	**DESCRIPTION**	**AMOUNT (USD)**
1	CAPEX	21,533,745.28
2	OPEX	89,693,159.73
TOTAL		**111,226,905.01**

The unit cost to produce *1 m^3/d of desalinated potable water is 1.11 USD.*

The introduction of RES and the geographical location of the treatment plant (Africa) increased the total production cost. In Nigeria, electricity from the national grid is inconsistent and many industries rely on self-generated power, such as a power generating set. Building a facility around a RES will initially overwhelm the CAPEX at construction, but will lessen or completely remove the OPEX on energy consumption and flatten the curve during operation. With the improvement of salt removal, the recovery rate is expected to increase significantly year by year. Figures 6 and 7 show the relationships between the components that make up the total amount of water. Since OPEX is calculated annually, total savings will increase, eventually reaching the break-even point within 20 years and shortening the time frame for capitalizing OPEX savings.

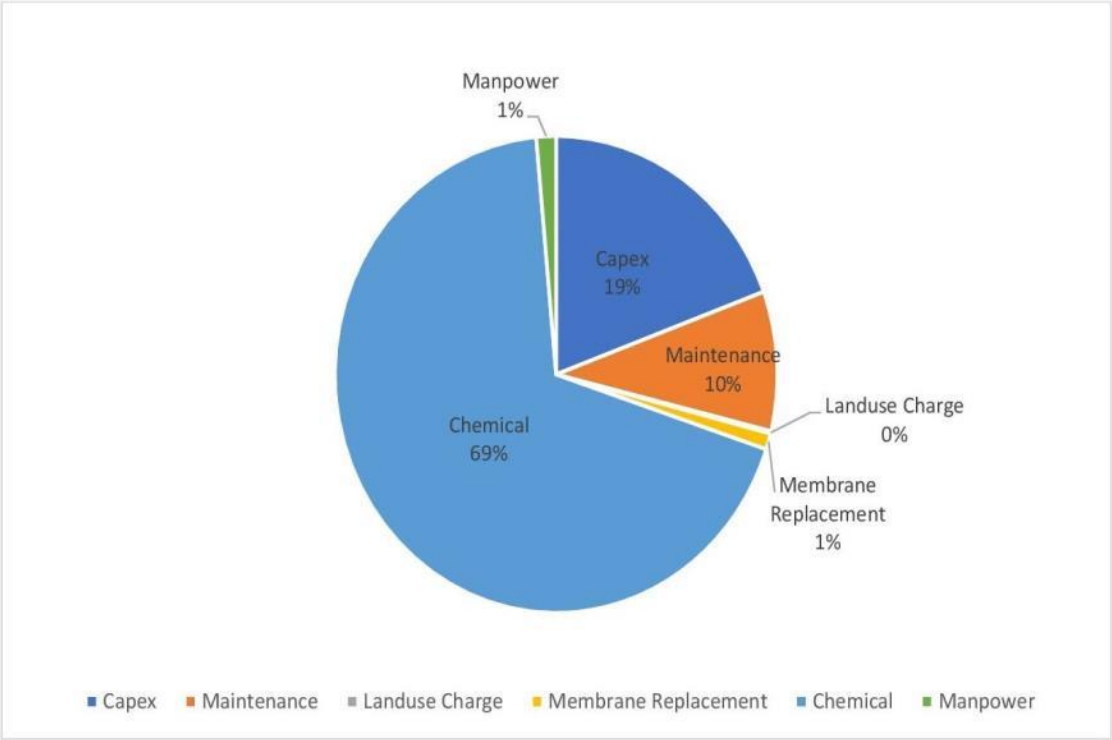

Figure 6: Pie chart showing the components of TWC

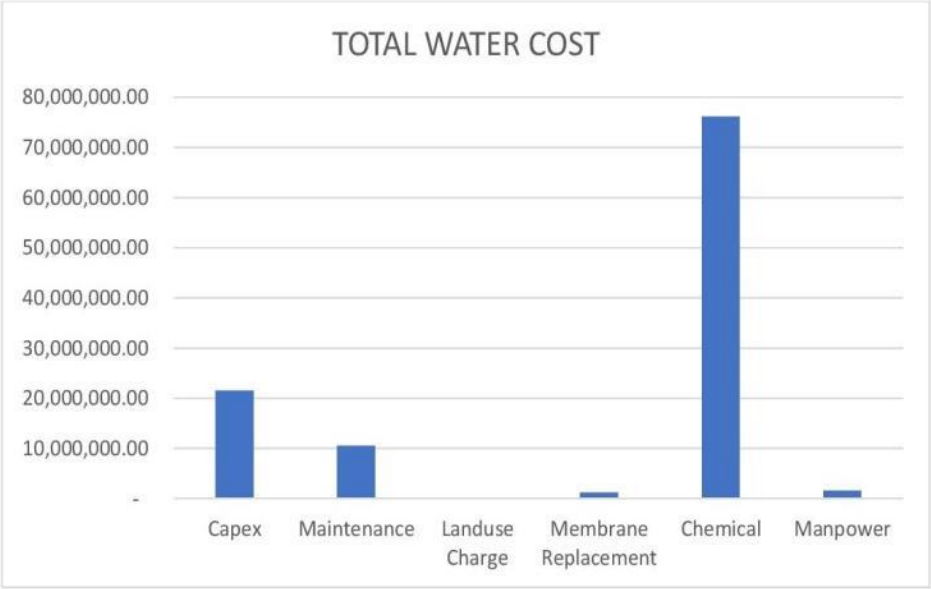

Figure 7: Bar chart showing the components of TWC

These results are based on specific assumptions about the overall nature of the project. As the actual events unfold and become clearer, the assumptions may change. Higher water tariffs, cost reductions, active government intervention, improved foreign exchange, import tariffs / tax exemptions and related factors will definitely continue to have a positive mpact on NPV.

Every effort has been made to generate a well-founded engineering output based on proven facts gained from decades of in-house knowledge (not just for the industry of interest, but also for the location / region). It has been complemented by further research data from consultants, renowned experts and organizations. Construction prices are based on past related construction prices because current construction and activities are unpredictable. In this way, you can easily adjust the cost of your project

6. CURRENT AND FUTURE CHALLENGE OF RO DESALINATION SYSTEM

Despite desalination technology being well developed, there are some challenges that prevent it from broad and effective implementation. Energy requirements related to salt and dissolved solute removal (pollutants) are much higher than the power required for freshwater treatment using traditional water treatment methods. Seawater desalination technology is also less generally recognized for the discharge of concentrated brine and chemical residues, and the disposal of used membranes (Zhou et al. 2014)

6.1 RO – future challenges and solutions

- ✓ Improvement in the pretreatment process. Most of the new plants use less chemicals. This is more environmentally friendly and significantly reduces the cost of consumable items.
- ✓ Robust pretreatment model is required at the intake to prevent red tide. The perfect solution for today's red tides is dissolved air flotation (DAF).
- ✓ Design enhancements and link process improvements through the use of different configurations.
- ✓ Advancement in design technology to produce membranes with high boron rejection that will in turn produce acceptable concentrations in permeates without the need for a second pass RO system.
- ✓ Chemical usage reduction, and improvement in membrane performance. Injection of acid and anti-scale agent can be reduced by membrane improvement. Additionally, the use of low-pressure membranes in SWRO pretreatment can be reduced and the use of coagulants avoided.
- ✓ Desalination systems can be combined or paired with other power plants in hybrid style to produce water at low cost.

The conclusion of this study is that the TWC in desalination plants will continue to increase due to unstable crude oil prices, fluctuations in currency and the ever-rising price of membrane elements. Another important topic is the steadily rising costs of energy (especially in Africa), transportation, raw materials, equipment, chemical prices, and stricter environmental regulations. A shortfall in experts/engineers specialized in the construction of plants and operation and maintenance experts can similarly add to the increased costs. Finally, currency fluctuations and inflation add to the high cost of SWRO construction (Ghaffour et al., 2013).

7. CONCLUSION

CAPEX and TWC play a significant role in the selection of an appropriate desalination method, as do other factors such as contract delivery type, capacity of the plant, energy consumption rate, and cost to mitigate the environmental impact. These are the most important parameters used by decision makers in project conception. However, the cost estimates are dependent on many factors, and the accuracy of these estimates depend on adoption of efficient, transparent and first-class evaluation tools. Any water desalination estimation methodology requires the development of a structured and transparent process for estimating the desalination cost of each plant by identifying and specifying all the parameters that contribute to the desalination cost. These cost evaluations are required for project development and project budgeting, and feasibility studies. This paper described the feasibility and reliability problems in estimating the cost of desalination, established the cost components for RO desalination projects powered from renewable energy sources using the factored cost model, and estimated/calculated the unit cost of producing potable water from seawater by RO desalination process in Nigeria. It also defines a model for investment analysis and cost estimation / evaluation of RO desalination plants based on renewable energy sources.

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CHAPTER 6: EXPERIMENTAL AND DATA ANALYTICAL STUDY OF A REVERSE OSMOSIS DESALINATION PLANT

This chapter investigates and evaluates the plant's performance parameters and how they are influenced by the variable operational parameters such as feedwater TDS, feedwater temperature, feedwater pH, and feedwater pressure. The effect of these variable parameters on RO membrane performance and system productivity were plotted into graphs and analyzed. The data used for this experimental study was extracted from the SW100-10 train of the V & A desalination plant and were statistically analyzed using Microsoft Excel. The article was accepted for publication in the International Journal of Mechanical and Production Engineering Research and Development (IJMPERD).

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EXPERIMENTAL AND DATA ANALYTICAL STUDY OF A REVERSE OSMOSIS DESALINATION PLANT

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ABSTRACT

Water is an important product used in every segment of human life, from household activities such as drinking, cooking and washing to countless industrial and agricultural purposes such as power generation. For this reason, many technologies for desalination have been established and further developed over the years to cover/meet the ever-increasing demand for freshwater around the world. The purpose of this work, therefore, is to quantify and investigate the effects of feed supply temperature, pressure, and pH parameters on the RO membrane elements. Raw data collected at the Victoria and Alfred (V & A) Waterfront Desalination Plant in Cape Town, South Africa were processed and analyzed for this purpose, and also to establish the working principle of SWRO, and at the same time develop a relationship model based on the identified system parameters for better understanding of SWRO operation.

Keywords: Desalination, Seawater reverse osmosis, Experimental Data.

1. INTRODUCTION

Today's increasing demand for freshwater by the world population cannot be met by the available fresh water in our ecosystem. This is why numerous technologies for seawater desalination have been established and advanced over the years to augment/satisfy the ever-increasing global demand for freshwater. Reverse osmosis is the fastest evolving desalination method due to its high productivity, high salt rejection (> 99. 7%), and moderately inexpensive membranes (Tan et al., 2012). In the design of a reverse osmosis system, the permeate is the desalinated water product produced by the RO membrane system, while the feedwater flow is the water in cubic meters per hour (m^3/h) supplied to the membrane element or system.

The working performance of a seawater RO system depends mainly on parameters such as; salinity (TDS), temperature, pH and pressure of the feedwater.

This experimental study was carried out in Victoria and Alfred (V&A) lakeside distillation plant in Cape Town, and in January 2019 during normal operation hours of the treatment facility. The production capacity (permeate flux) of the plant is 2 MLD / 2000 m^3/d of potable water produced from seawater treatment. The plant explores water from the Atlantic Ocean as source works, and is powered by the national electrical power network. The plant's main

system is made up of the following; the intake, low-pressure pump, pretreatment filtration component which are two types; media filter and casing strainer, high-pressure pump, pressure vessels housing RO membranes and energy recovery system.

2. METHODOLOGY

Feedwater was admitted into the plant trains at an average temperature of 16 °C, through the high-pressure pump at an average pressure of 55 bars. The plant's feedwater flow rate was precisely 4,446 m^3 /d representing a regular feed movement of 240 m^3 /h. The average permeates flow rate of the plant was 1,367 m^3 /d as related to the design capacity of 2 000 m^3 /d. The plant desalination recovery rate was 31 %. An energy recovery unit was deployed to improve the system feedwater pressure and also to recover energy sufficient for the plant. The plant was installed with an ERD pressure exchanger.

The following data were recorded during the everyday regular procedure of the RO plant at 2 hours intervals.

1. The system pressure before and after the high-pressure pump, filter, turbocharger and RO element.
2. Feedwater temperature and temperature before and after each RO element.
3. Feedwater thermal conductivity and permeate thermal conductivity before and after each RO element, and the salinity is calculated from the measured thermal conductivity.
4. The flow rates for the feedwater flow and permeate flow.
5. The energy consumption of the pumps.

This experimental study was conducted to determine the influence of the feedwater pH, feedwater TDS, feedwater temperature and feedwater pressure on the permeate TDS of the system, and also to know the effect of these parameters on the permeate flow and the system energy consumption. The working parameters for this experimental study were measured using the same equipment attached to the RO desalination plant.

Table 1: The Plant Data

S/N		QTY	UNIT
PLANT			
1	Number of units	3	Nos
2	Capacity of unit	2	MLD
3	500-3 Train	500,000	l/d
4	500-4 Train	500,000	l/d
5	1000-10 Train	1	MLD
UNIT			
1	Product water flow rate	1367	m3/day
2	Reject water flow rate	3079	m3/day
3	Total water feed flow rate	4446	m3/day
4	Recovery ratio	31	(%)
5	Temperature	16	(°C)
6	Feed TDS	32800	mg/l
7	Feed pH	7.2	
8	Feed Pressure	55	Bar
9	Permeate TDS	490	mg/l

3. EXPERIMENTAL SETUP

The V&A desalination plant in waterfront Cape town is a containerized desalination module producing 2 MLD of potable water from a saline water source supplied from the Atlantic Ocean. The salinity of the feed seawater is 328000 mg/l. The plant consists of three trains with the first train producing 500,000 liters per day, the second train producing 500,000 liters per day and the third train delivering 1 MLD making a total daily treatment capacity of 2 MLD. The three trains of the treatment plant are named 500-3 train, 500-4 train and 1000-10 train. The plant consists of the following main systems; the intake, the raw water pretreatment unit and cartridge filters, the high-pressure pump, the RO membrane unit, the energy recovery device, and the post-treatment system.

3.1 500-3 Train

500-3 module is made up of the low-pressure pump, pretreatment filtration unit which is two types; media filter and cartridge filter, high-pressure pump pressure vessels housing RO membranes and energy recovery system. The feedwater from the raw water tank is pumped by a low-pressure pump through the media and cartridge filters to remove any suspended solids in the feed flow before going into the membranes' compartments. The filtered feedwater flow is then pumped at an elevated pressure by the high-pressure pump through the pressure vessels housing the membranes for desalination to obtain a permeate flux. The 500-3 train comprises six independent pressure vessels connected in parallel, each of the pressure vessels houses seven membranes, thereby totaling forty-two membranes in the 500-3 train. The membranes are characteristically 8-inch LG-SW-440 SR casings, using a

total surface expanse of 41 m^2 440 ft^2. The permeate flux and the rejected brine are collected downstream of the pressure vessels. The rejected brine is utilized by the system in the brine energy recovery using a pressure exchanger (ERI PX55). The feed water flows mass balance at this period will equal the permeate flux even though it was not directly measured. The remaining feedwater flows from the filtration system compensating for the lost brine volume are channeled back into the feed flow at a point after the HPP through the pressure exchanger and booster pump as shown in Figure 1. The specification of the membrane is given in Table 1.

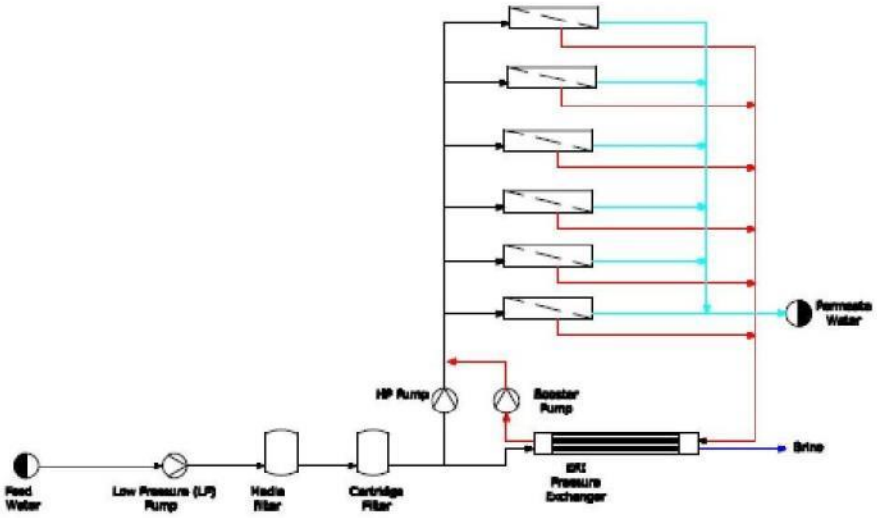

Figure 1: Schematic Drawing for 500-3 Train

Table 2: 500-3 (LG-440 SR) Membrane Data

500-3 (LG-440 SR) Membrane Data		
Description	**Data**	**Unit**
Number of Vessels	6	Nos
Number of Membrane in Vessels	7	Nos
Total Number of Membranes	42	Nos
Membrane Area	41	m^2
Membran Type	Spiral Wound	
Membrane Material	Thin film Nano composite Polyamide	
Maximum Operating Pressure	82.7	Bar
Maximum Operating Temperature	45	0C
ph Range	2 to 11	
Maximum Feed Flow	18	m^3/h
Rate of Salt Rejection	99.85	%

Table 3: 500-4 (SWC-5) Membrane Data

500-4 (SWC-5) Membrane Data		
Description	**Data**	**Unit**
Number of Vessels	7	Nos
Number of Membrane in Vessels	6	Nos
Total Number of Membranes	42	Nos
Membrane Area	41	m^2
Membran Type	Spiral Wound	
Membrane Material	Composite Polyamide	
Maximum Operating Pressure	82.7	Bar
Maximum Operating Temperature	45	0C
ph Range	2 to 11	
Maximum Feed Flow	17	m^3/h
Rate of Salt Rejection	99.8	%

3.3 1000-10 Train

1000-10 module is made up of a low-pressure pump, pretreatment filtration unit which are of two types; media filter and cartridge filter, high-pressure pump pressure vessels housing RO membranes and energy recovery system. The operation of the 1000-10 train is similar to 500-4, the feed water from the raw water tank is pumped at an approximate pressure of 3 bar by a low-pressure pump through the media and cartridge filters to remove any suspended solids in the feedwater flow before going into the membranes' compartments. The filtered feedwater flow is then pumped at an elevated pressure of 40 bar by the high-pressure multi-stage centrifugal pump through the pressure vessels housing the membranes for the desalination process to obtain a permeate flux. The 100-10 train comprises six independent pressure vessels connected in parallel, each of the pressure vessels houses seven membranes, thereby totaling forty-two membranes in the 1000-10 train. The 1000-10 pressure vessels membranes have an additional inside staged approach by which the prime membrane in all vessels on the feed axis is DOW SW30XLE-440i, while the rest six are DOW SW30-ULE-440i. The membranes are characteristically 8-inch hydraulic SWC-5 using an overall surface expanse of 41 m^2 440 ft^2. The permeate flux and the rejected brine are collected downstream of the pressure vessels. The rejected brine is deployed in the brine energy recovery using a turbo energy recovery system. The rejected brine flow is used to power the ERD turbine which in turn serves as a prime mover for the high-pressure pump elevating the pressure of the feedwater flow from 40 bar to the operating system pressure of 55 bar. The specific modular skid only has feedwater pressure with no pressure on the brine flow. The permeate flux pressure is assumed at 0.3 bar with negligible frictional loss as shown in Figure 3. The specification of the membrane is given in Table 3.

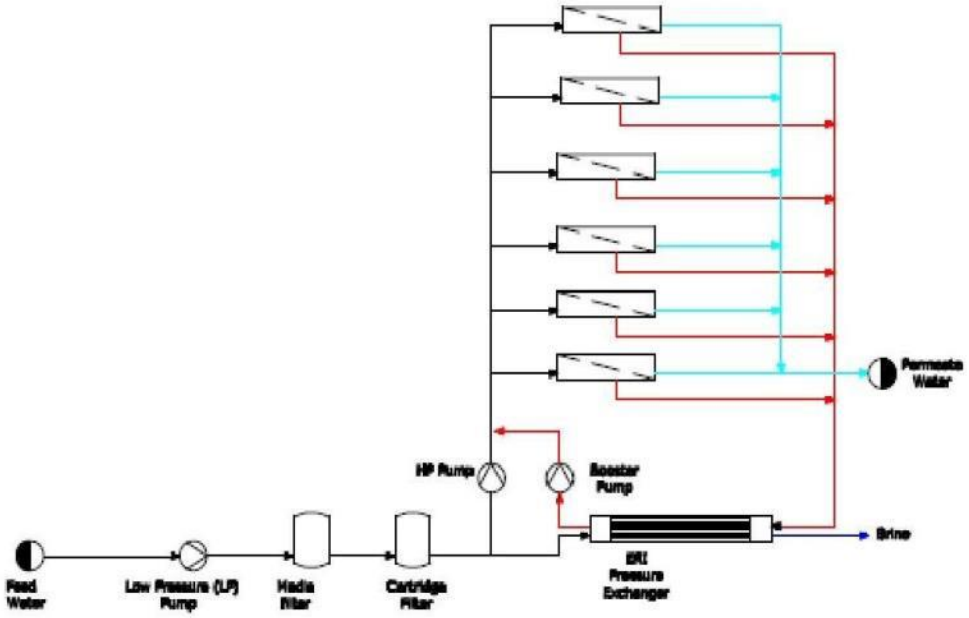

Figure 3: Schematic Drawing for 1000-10 Train

Table 4: 1000-10 Membrane Data

1000-10 Membrane Data			
	Data		
Description	**DOW SW30XLE-440I**	**DOW SW30-ULE-440I**	**Unit**
Number of Vessels	6	6	Nos
Number of Membrane in Vessels	1	6	Nos
Total Number of Membranes	6	36	Nos
Membrane Area	41	41	m^2
Membrane Material	Composite Polyamide		
Maximum Operating Pressure	83	83	Bar
Maximum Operating Temperature	45	45	0C
ph Range	2 to 11	2 to 11	
Maximum Feed Flow			m^3/h
Rate of Salt Rejection	99.8	99.7	%

4. RESULT AND DISCUSSION

RO systems performance is usually defined by some operational parameters such as permeate flow, permeate TDS and energy consumption, and these parameters are commonly impacted by variable parameters such as feedwater TDS, feedwater pH, feedwater temperature, and feedwater pressure. The core aim of this experimental study is to study the effect of these variable parameters on the RO system performance. The experimental daily average data for the treatment plant is presented in Table 5, while the relationship between key variable parameters is shown in Figures 16 to 19. The effects of the variable parameters on the RO performance are graphed and presented in Figures 4 to 15.

Table 5: Experimental Daily Average Data

1000-10 Train							
Date	Feed pH	Feed TDS	Feed Temp	Feed Press	Permeate TDS	Permeate Flow	Energy Consumption
15-Jan	7.78	55.23	16.78	51.95	795.15	39.62	120.69
16-Jan	7.84	54.89	16.08	52.2	796	38.63	120
19-Jan	7.89	54.12	16.29	51.17	843.33	39.73	120.22
20-Jan	7.02	54.76	14.66	51.61	727.83	39.29	120.08
21-Jan	7.61	53.8	15.37	51.98	712.08	39.39	120.33
22-Jan	7.29	54.55	15.4	51.52	740.46	38.91	121
23-Jan	7.76	55.03	15.64	51.17	739.23	38.22	120.31
24-Jan	8.46	59.98	15.92	51.96	815.73	38.88	120.55
25-Jan	7.7	55.1	14.83	51.07	692.33	37.33	120.45
26-Jan	7.47	54.16	14.42	52.67	694.09	38.85	120.5
27-Jan	7.71	54.44	16.41	52.73	658.84	36.72	120.38
29-Jan	7.69	54.72	13.81	52.61	620.92	38.22	120.08

4.1 Effect of Feedwater TDS

The feedwater TDS has a great impact on the permeate TDS. Figures 4 to 6 show the effect of feedwater TDS variation on permeate TDS, permeate flow and the system energy consumption. As can be seen in Figure 4, an increase in the feedwater TDS from 54.16 mg/l to 55.84 mg/l causes a linear increase in permeates TDS from 646 mg/l to 967 mg/l. A general increase in feedwater TDS causes fouling and scaling of the membrane surface, which will bring about a decrease in the effective area of the membrane, ultimately reducing the membrane permeate flow and increasing the permeate TDS and conductivity as observed in Figures 4 and 5 [Su X. et. al]. Similarly, Figure 5 shows that an increase in the feedwater TDS from 54.16 mg/l to 55.84 mg/l causes a decrease from 41.9 m^3/h to 36.8 m^3/h in permeate flow. The result shows that increasing the feedwater salinity reduces the permeate flow due to an increase in the salt rejection and increases the resistance of the membrane vapor permeation as observed in Figure 5 (Ncube et. al).

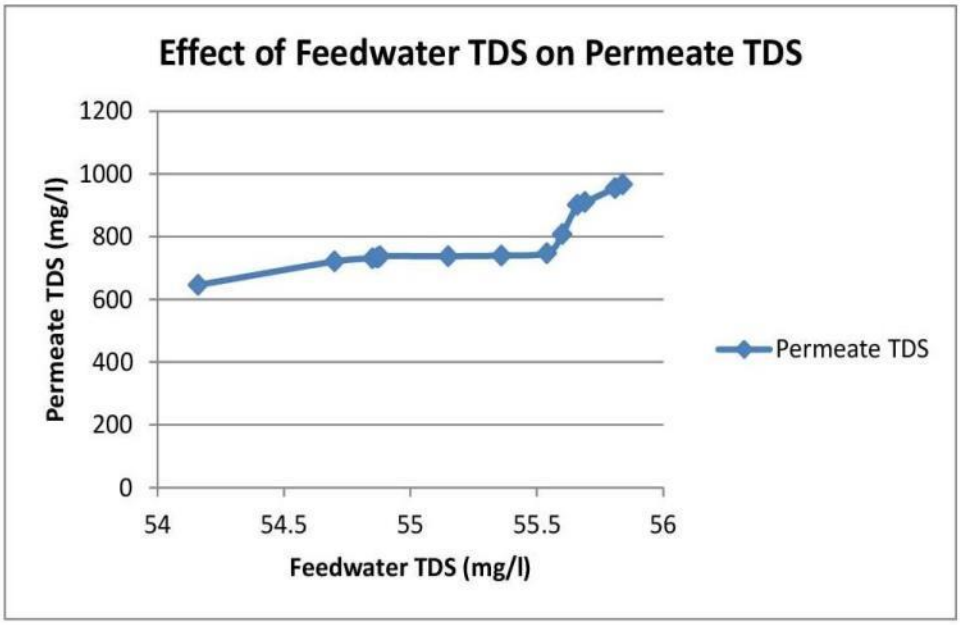

Figure 4: Effect of Feedwater TDS on Permeate TDS

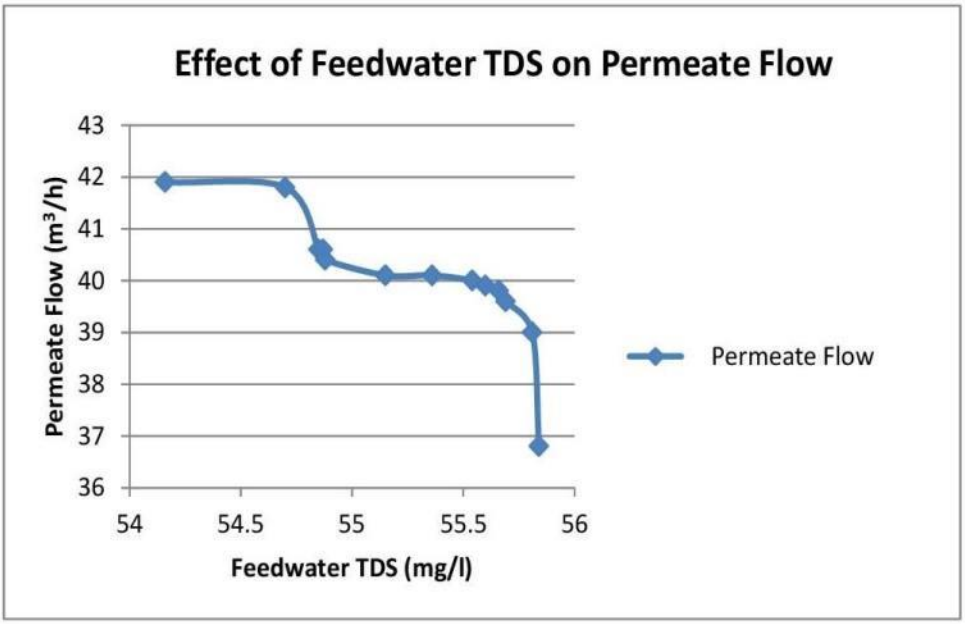

Figure 5: Effect of Feedwater TDS on Permeate Flow

Increased feedwater TDS increases the system osmotic pressure, thereby decreasing the net dynamic pressure and as a result, bringing the permeate flow rate to reduction as shown in Figure 5.

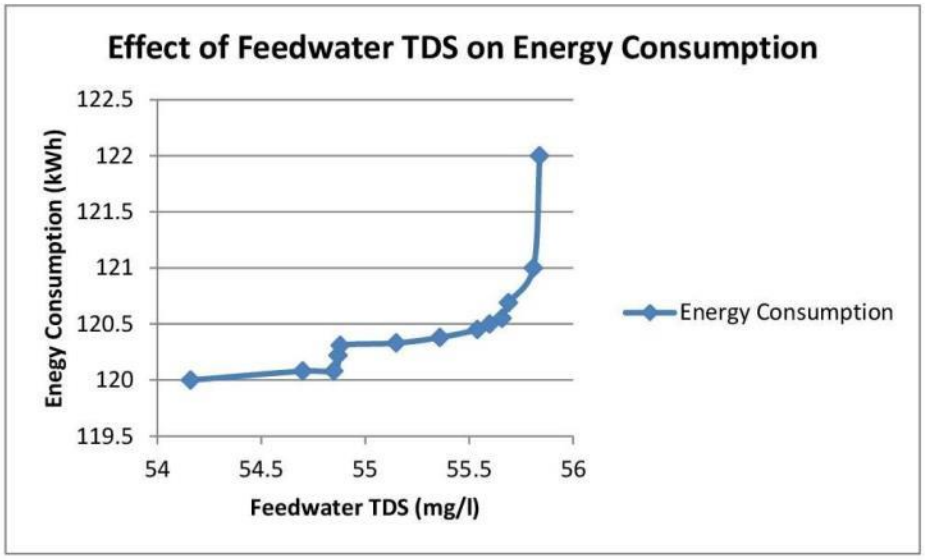

Figure 6: Effect of Feedwater TDS on Energy Consumption

Figure 6 shows that the same value range increase in feedwater TDS causes the energy consumption to increase from 120 kWh to 122 kWh. Increasing the feedwater TDS reduces the recovery rate and consequently raises the amount of energy used. As shown in Figure 6, increasing the feedwater TDS increases the system energy consumption due to high feed pumping pressure which is required in overcoming the high osmotic force. The increase in feedwater TDS which caused an increase in osmotic pressure will occasion the feedwater dynamic pressure to be equipoised [Ibrahim S. Mutaz et. al].

4.2 Effect of Feedwater pH

Figures 7 to 9 show the effect of feedwater pH on permeate TDS, permeate flow and energy consumption. As can be observed in Figure 7, this result shows that as the feedwater pH increases from 7.62 to 7.97, the permeate TDS increased from 646 mg/l to 967 mg/l. The feedwater pH demonstrates an insignificant influence on the permeate TDS when the pH is recorded to be overly basic or acidic. Studies have shown that the ionic rejection of the membrane increases with increasing pH [Sassi, K.et, al]. Figure 8 shows that permeate flow decreased from 41.8 m^3/h to 36.8 m^3/h with an increase in feedwater. This result shows that the feedwater pH interacts and influences the membrane separation performance by a direct effect on the membrane hydration and absorption ability to absorb solutions [Ibrahim Khaled El-Sayed Gabr]. Likewise, some recent experiments on SWRO pH have shown steady permeate flow and higher salt rejection at low pH, while the total permeate flow remains higher at high pH.

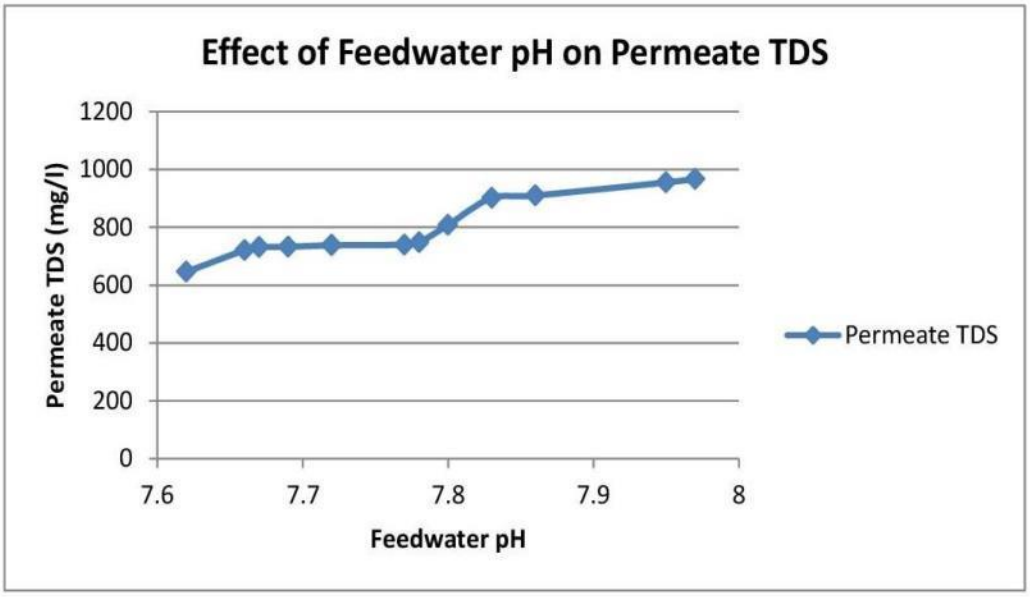

Figure 7: Effect of Feedwater pH on Permeate TDS

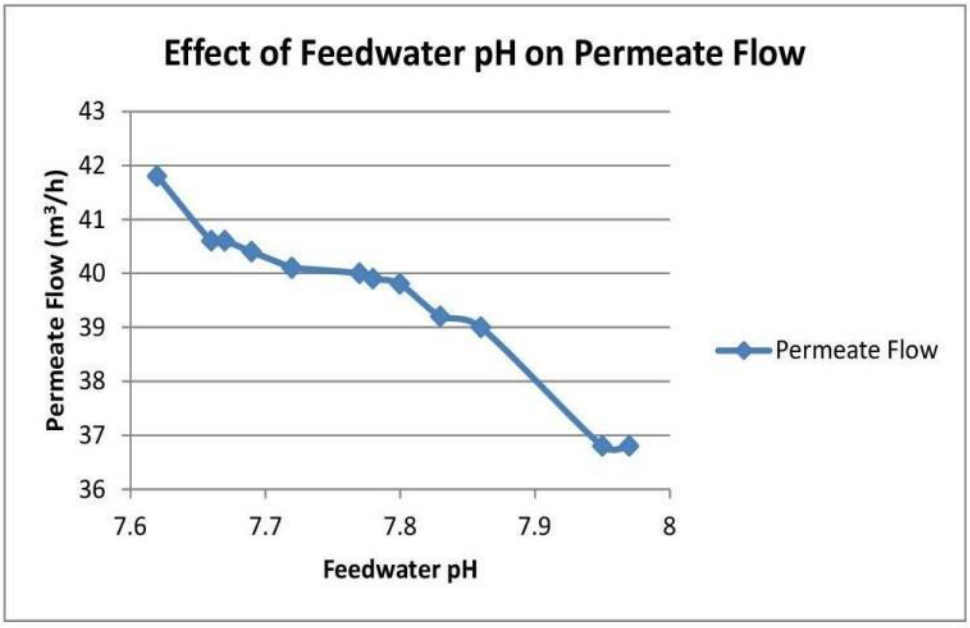

Figure 8: Effect of Feedwater pH on Permeate Flow

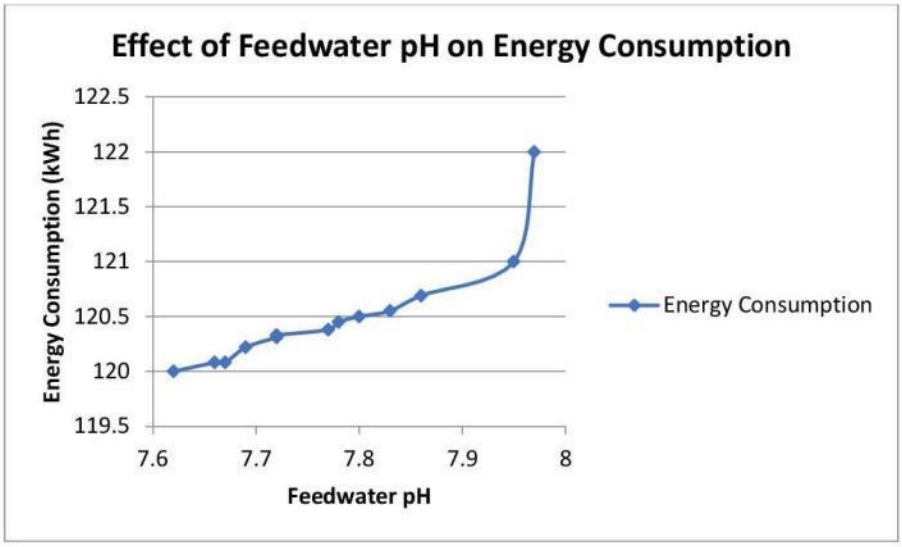

Figure 9: Effect of Feedwater pH on Energy Consumption

Figure 9 shows that an increase in feedwater pH increased the energy consumption from 120 kWh to 122kWh. An increase in feedwater pH causes a decrease in recovery ratio [Ibrahim Khaled El-Sayed Gabr] which leads to an increase in energy consumption [Alsarayreh, A.A.,],

4.3 Effect of Feed Water Temperature

Figures 10 to 12 show the impact of feedwater temperature on the permeate TDS, permeate flow and energy consumption of the system. Figure 10 shows the influence of feed water temperature on the permeate TDS. As the feedwater temperature increases from 15.95 ^{o}C to 17.42 ^{o}C, the permeate TDS shown an increase from 646 mg/l to 967 mg/l.

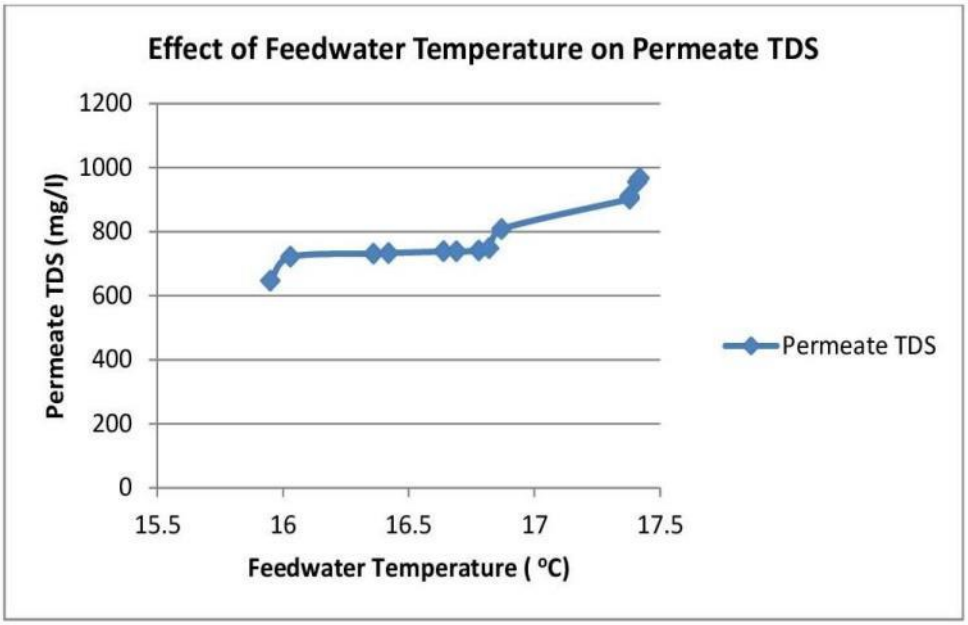

Figure 10: Effect of Feedwater Temperature on Permeate TDS

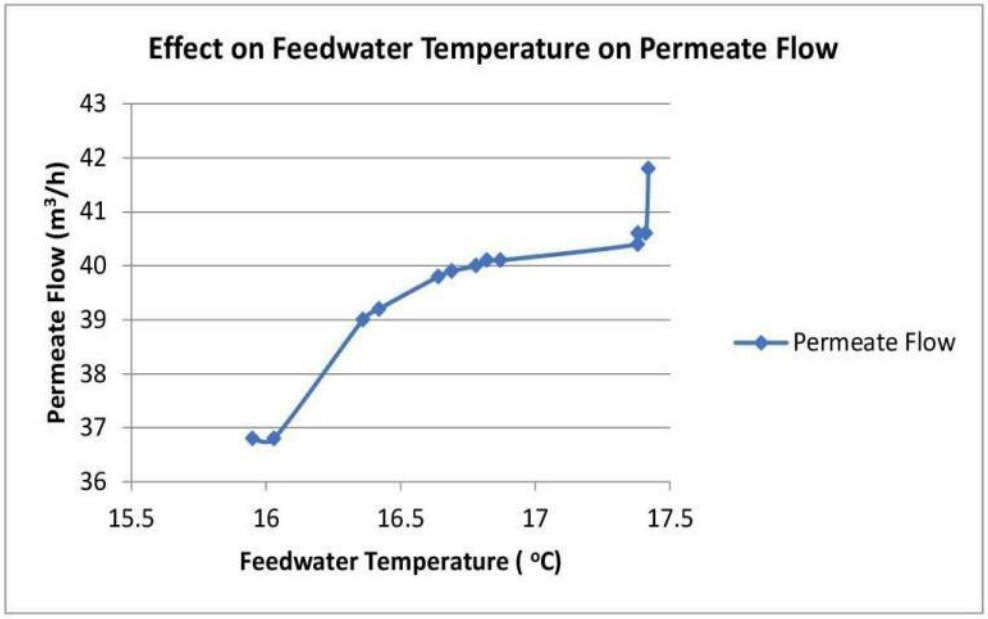

Figure 11: Effect of Feedwater Temperature on Permeate Flow

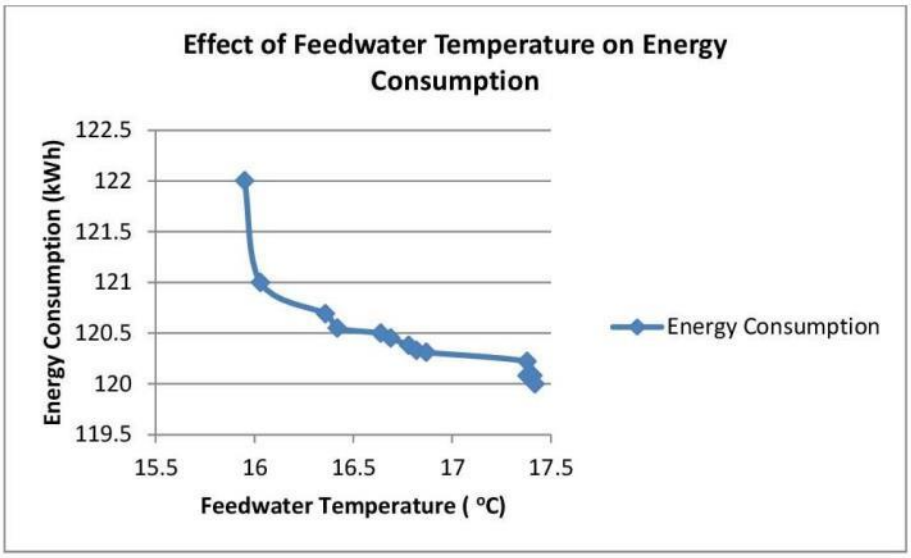

Figure 12: Effect of Feedwater Temperature on Energy Consumption

As shown in Figure 10, increases in feedwater temperature cause an increase in permeate TDS consistency with Cameron, I.B et.al submissions that an increase in the feedwater temperature will rise the membrane's permeability coefficient of salt and water which in turn will result in a reduction in viscosity of water, permeate flow escalation and membrane's permeability. Figure 11 shows that as the feedwater temperature increased from 15.95 ^{o}C to 17.42 ^{o}C, the permeate flow increased from 36.8 m^3/h to 41.8 m^3/h. This result shows that the permeate flow rises as the feedwater temperature increases. Recent research has shown that both the permeate salinity and flow rate increase by increasing feed water temperature, and so also is the recovery rate and the mechanical energy consumption which both increase, and at the same time reduces the efficiency of the high-pressure pump and energy recovery [Gule et. al]. Figure 12 shows that increasing the feedwater temperature from 15.95 ^{o}C to 17.42 ^{o}C decreased the energy consumption from 122 kWh to 120 kWh. The result shows that an increase in feedwater temperature leads to an upsurge in power usage/energy consumption in line with [Qasim et. al] report that an increase in temperature will lead to an increase in the system's rate of recovery, which in turn will lead to an upsurge in energy consumption. The productivity of an SWRO system can be strategically increased when located in a hot and dry area where the water temperature is high.

4.4 Effect of Feed Water Pressure

Figures 13 to 15 show the feedwater pressure plotted against the permeate TDS, permeate flow and energy consumption. Figure 13 shows a decrease in the permeate TDS as the feedwater pressure increases from 50.2 bar to 52.5 bar. The solvent dynamic force is escalated by pressure increase leading to a reduction in osmotic pressure and a high salt rejection rate when extra water is allowed to flow through the membrane. The mass transfer and surface

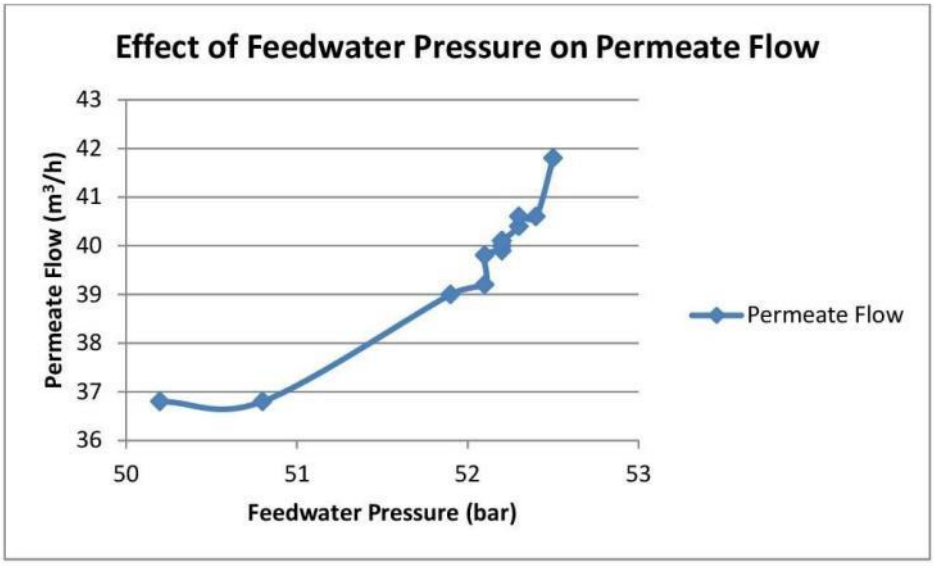

Figure 14: Effect of Feedwater Pressure on Permeate Flow

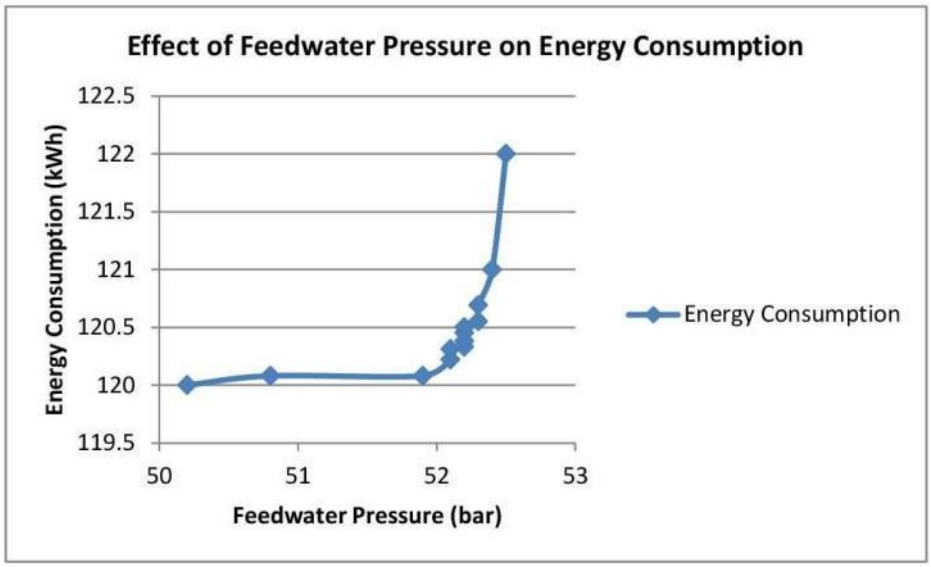

Figure 15: Effect of Feedwater Pressure on Energy Consumption

Figure 15 indicates an increase in feedwater pressure from 50.2 bar to 52.5 bar increased energy consumption from 122 kWh to 120.33 kWh. Increasing the feedwater pressure together with the feedwater TDS will also increase the energy consumption of SWRO. The above result also shows that when the feedwater pressure increases, it will increase the energy consumption and shortens the membrane life which tends to adversely affect the energy

consumption pattern of the system. Consequentially, this will have an undesirable impact on the system recovery, which drops as the feedwater pressure decreases. [Ncube et. al]. Effects of investigated variable parameters (feedwater TDS, feedwater temperature, feedwater pH and feedwater pressure) on the energy consumption are shown in Figures 6, 9, 12, and 15. Increasing the feedwater TDS, feedwater pH and feedwater pressure will directly increase the energy consumption.

4.5 Relationship between Average Daily Variable Parameters and System Performance Parameters

Figures 16 to 19 show the relationship between the experimental daily values for the variable parameters and key performance operational parameters during the study period from January 15th to January 29th, 2019. Feedwater TDS, feedwater pH, feedwater temperature and feedwater pressure were all recorded during this period using the integral measuring equipment mounted on the production line. The feedwater TDS and pH readings were taken daily before the pressurization of the plant, while the feedwater temperature and pressure were recorded immediately after starting the daily normal operational process. Figures 16 show the relationship between the feedwater TDS and permeate TDS which is linear as explained in section 4.1.

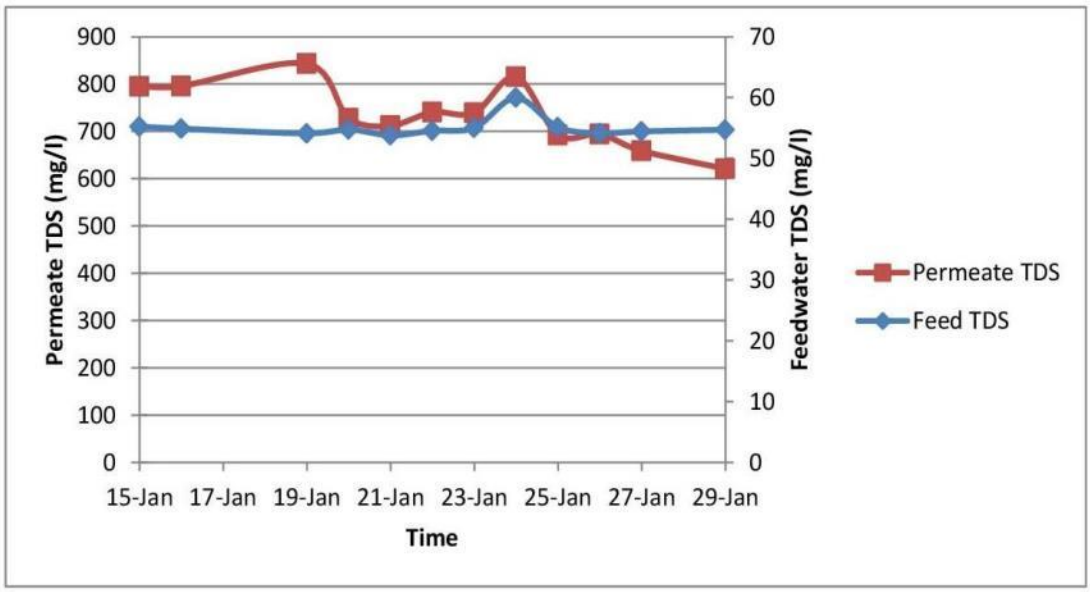

Figure 16: Relationship between Average Daily Values for Feedwater TDS and Permeate TDS

Figure 16 also illustrates the relationship between average experimental daily values of feedwater pH and permeate TDS. The result shows that an increase in feedwater pH reduces the permeate flow as explained in section 4.2.

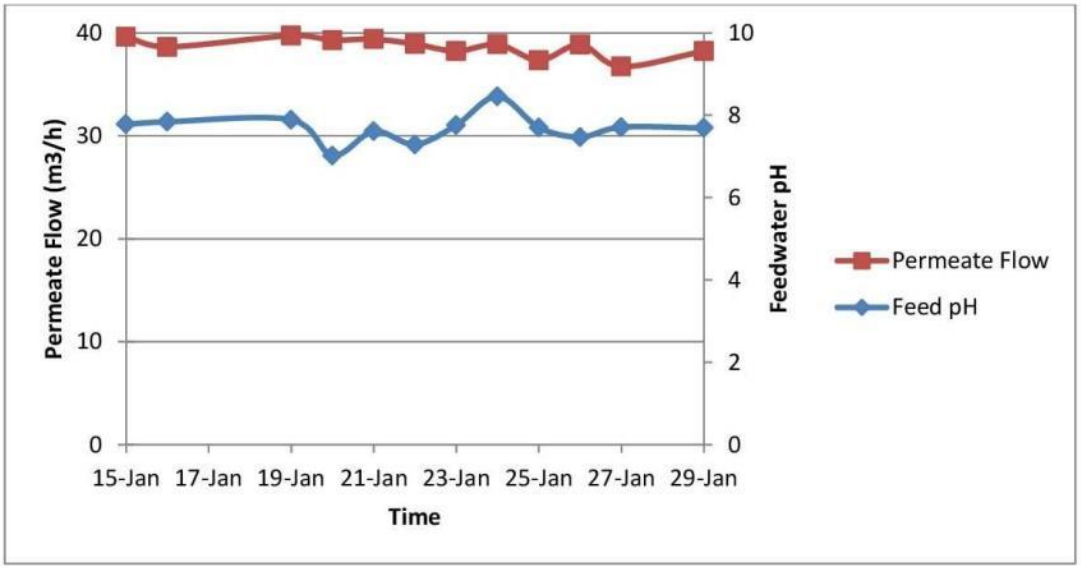

Figure 17: Relationship between Average Daily Values for Feedwater pH and Permeate flow

The relationship between the average daily values for feedwater temperature and the energy consumption is plotted in Figure 18, and it shows that an increase in feedwater temperature reduces the energy consumption but increases permeate TDS and permeate flow as explained in section 4.3.

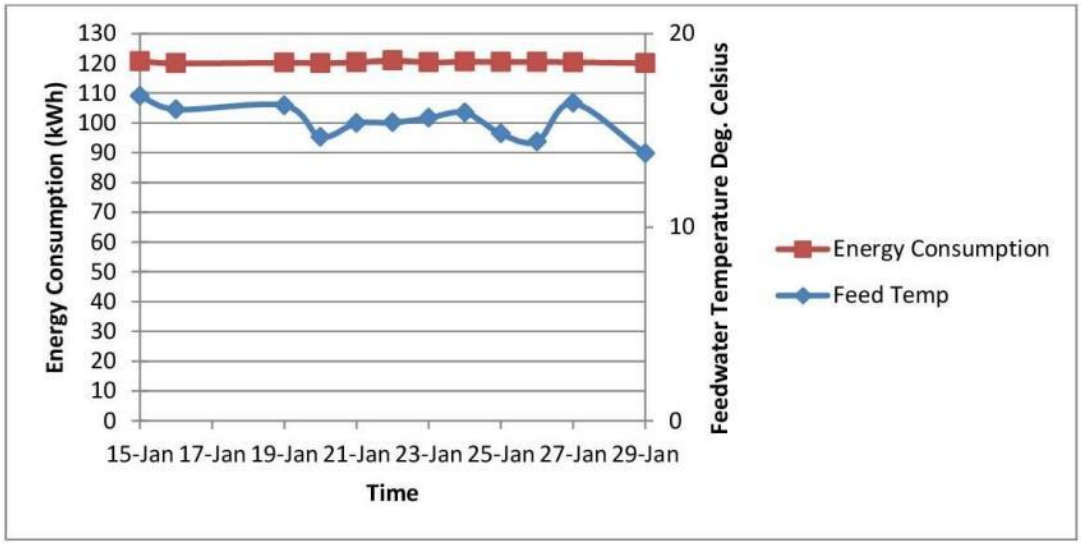

Figure 18: Relationship between Average Daily Values for Feedwater Temperature and Energy Consumption

The relationship between the average daily values for feedwater pressure and permeate flow is plotted in Figure 19 with an increase in feedwater pressure causing an increase in permeate flow as explained in section 4.4.

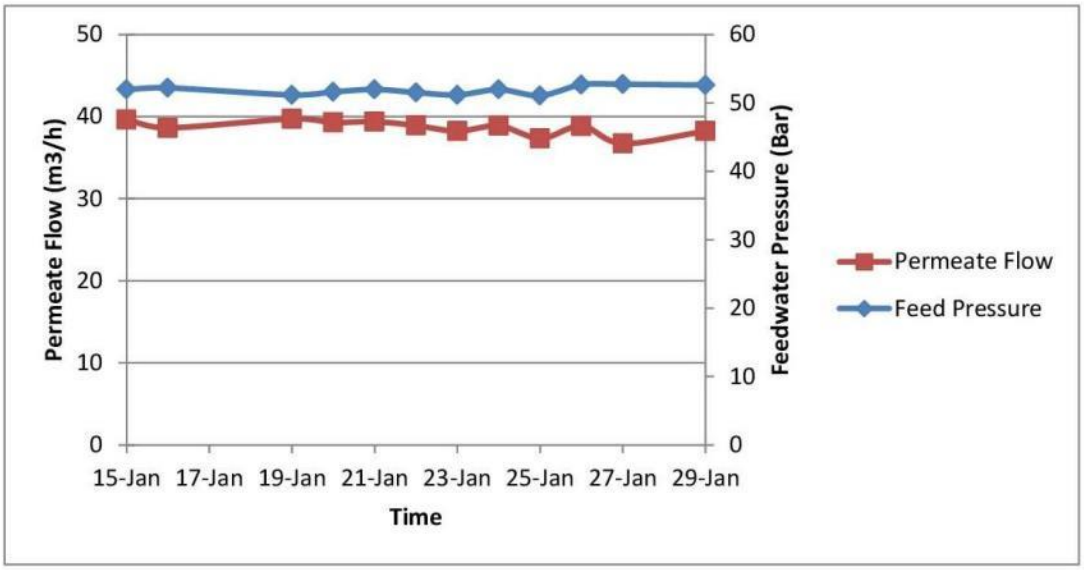

Figure 19: Relationship between Average Daily Values for Feedwater Pressure and Permeate flow

The above measurements are taken 24 hours a day at 2-hour intervals on the day of the month. Daily averages of measured data are calculated to test the performance of each component and detect changes in plant performance. The measurement data is recorded by the equipment connected to the system.

5. CONCLUSION

The effect of various operating parameters like feed water TDS, feedwater temperature, feedwater pH and feedwater pressure on RO membrane performance was studied at Victoria and Alfred (V&A) waterfront desalination plant, Cape town (2 MLD / 2000 m3/d). This experimental study was carried out to investigate and evaluate the plant's performance parameters and how they are influenced by the variable parameters.
The following remarks and conclusions can be drawn based on the study's results:

An increase in feedwater TDS causes a linear increase in permeates TDS and conductivity which causes fouling in membrane surface and scaling, and as a result reduces the effective area of the membrane, thereby ultimately reducing the membrane flux. Also, Increase in feedwater TDS causes a reduction in the permeate flow thereby resulting in a higher brine flow rate.

The increase of feedwater temperature results in increased permeate TDS and improves the membrane permeability which leads to escalation in the recovery rate and eventually leads to a decrease in energy consumption.

An increase in feedwater pH causes an increase in permeate TDS and energy consumption with a decrease in permeate flow rate.

An increase in feedwater pressure causes an increase in permeates flow which leads to an increase in the recovery rate. Generally, an increase in the feedwater pressure gradually escalates the energy consumed and ultimately reduces the membrane.

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CHAPTER 7: DISCUSSIONS

The study work on modeling and simulation was used to develop a stable predictive model for the all-encompassing seawater reverse osmosis (SWRO) membrane desalination system. The modeling and simulation exercise adopted the basic principles and equations of productive SWRO design, and the optimal design was carried out with the Water Application Value Engine (WAVE) water solution modeling tool to model the UF pretreatment, RO membrane desalination, and IX polishing post-treatment processes. Modeling the three processes produced extensive results in the simulation, tied to operational variables and the system key performance parameters. Profiles of feed pressure, feed concentration and feed velocity along with the UF membranes, RO membranes, and resins were modeled for these operations together with the relationship between recovery rate, pH, temperature, and feed pressure.

The experimental study in this research was carried out in Victoria and Alfred (V&A) lakeside desalination plant in Cape Town, in January 2019 during a normal operational hour of the treatment facility. The outcome of the experimental study confirmed the result of the modeling and simulation study on the relationship of key operational parameters to the productivity and membrane performance of the RO system. It also investigates and evaluates the plant's performance parameters and how they are influenced by the variable operational parameters such as feedwater TDS, feedwater temperature, feedwater pH, and feedwater pressure. The effect of these variable parameters on RO membrane performance and system productivity were plotted into graphs and analyzed. The data used for this experimental study was extracted from the SW100-10 train of the V & A desalination plant and was statistically analyzed using Microsoft Excel. The production capacity (permeate flux) of the plant was put at 2 MLD / 2000 m^3/d. The plant explores water from the Atlantic Ocean as source works and is powered by the national electrical power network. The plant's main system is made up of the following; the intake, low-pressure pump, pretreatment filtration component which are two types; media filter and casing strainer, high-pressure pump, pressure vessels housing RO membranes, and energy recovery system.

The average recorded operational specifications of the plant are presented below

Table 6: Recorded Average System Operational Specification

DESCRIPTION	RECORDED AVERAGE SYSTEM OPERATIONAL SPECIFICATION
Recovery Ratio	31%
Feedwater Pressure	55 bar
Feedwater Temperature	16^{o}C
Feedwater pH	7.2
Permeate TDS	490 mg/l
Permeate Flow	20 m^3/h

The feedwater TDS has a great impact on the permeate TDS. The graph of feedwater TDS against permeate TDS showed that an increase in the feedwater TDS causes a linear increase in permeate TDS. A general increase in feedwater TDS causes fouling and scaling of the membrane surface, which will bring about a decrease in the effective area of the membrane, ultimately reducing the membrane permeate flow and increasing the permeate TDS and conductivity. Similarly, increases in the feedwater TDS cause a decrease in permeate flow. The result of the study showed that increasing the feedwater salinity reduces the permeate flow due to an increase in the salt rejection and increase in the resistance of the membrane vapor permeation. Similarly, increased feedwater TDS increases the system osmotic pressure, thereby decreasing the net dynamic pressure and as a result, reducing the permeate flow rate. On the other hand, increasing the feedwater TDS reduces the recovery rate and consequently raises the amount of energy used. The graph also showed that increasing the feedwater TDS increases the system energy consumption due to high feed pumping pressure which is required in overcoming the high osmotic pressure developed in the system which causes the feedwater dynamic pressure to be equipoised. Plotted graph and analysis of the effect of feedwater pH on permeate TDS, permeate flow, and energy consumption showed that as the feedwater pH increases, the permeate TDS also increases. The feedwater pH demonstrates an

insignificant influence on the permeate TDS when the pH is recorded to be overly basic or acidic. The result also showed that permeate flow decreased with an increase in the feedwater indicating that the feedwater pH interacts and influences the membrane separation performance by a direct effect on the membrane hydration and absorption ability to absorb solutions, and demonstrated steady permeate flow and higher salt rejection at low pH, while the total permeates flow remains higher at high pH. An increase in feedwater pH increased the energy consumption and causes a decrease in recovery ratio which leads to an increase in energy consumption. The study also showed the impact of feedwater temperature on the permeate TDS, permeate flow, and energy consumption of the system. An increase in feedwater temperature increased the permeate TDS, permeate flow, and decrease energy consumption. The increase in the feedwater temperature increases the membrane's permeability coefficient of the salt and water which in turn results in a reduction in viscosity of water, permeate flow escalation, and membrane permeability. This result showed that as the feedwater temperature increases, the permeate salinity and flow rate increase, so also is the recovery rate and the mechanical energy consumption which brought about a reduction in the efficiency of the high-pressure pump and energy recovery. The result showed that an increase in feedwater temperature also leads to an upsurge in power usage/energy consumption and the system's rate of recovery. The feedwater pressure graph plotted against the permeate TDS, permeate flow, and energy consumption showed that increasing the feedwater pressure increases the permeate flow and energy consumption, but decreases the permeate TDS and brine flow rate. The solvent dynamic force escalated by pressure increase leading to a reduction in osmotic pressure and a high salt rejection rate when extra water was allowed to flow through the membrane, and the mass transfer and surface concentration formed on the membrane surface as a result of the salt rejection collection led to low permeate flow as a result of an increase in concentration polarization. Similarly, The permeate flow increased linearly with an increase in feedwater pressure as a result of the direct relationship between the membrane's water flow rate and the membrane's net dynamic pressure differential which causes the membrane's water permeability coefficient to diminish as the feedwater increased in a situation termed membrane compaction. The experimental result indicated an increase in feedwater pressure and increased energy consumption. Increasing the feedwater pressure together with the feedwater TDS also increased the energy consumption of SWRO. The above result implied that when the feedwater pressure increases, it will increase the energy consumption and shorten the membrane life which tends to

adversely affect the energy consumption pattern of the system. Consequentially, this will have an undesirable impact on the system recovery, which drops as the feedwater pressure decreases. Effects of investigated variable parameters (feedwater TDS, feedwater temperature, feedwater pH, and feedwater pressure) on the energy consumption showed that increasing the feedwater TDS, feedwater pH and feedwater pressure directly increased the energy consumption.

The study on lifecycle cost presented a financial analysis of the CAPEX and operational expenditure (OPEX) of a traditional seawater reverse osmosis (SWRO) desalination plant based on renewable energy sources. It also lists and discusses important parameters to take into account when determining the life cycle costs of seawater desalination, namely, water quality characteristics, production or plant capacity, location, energy consumption, materials, maintenance, operation, and RO module costs, chemicals, and award year. In this research study, a 2 MGD SWRO plant was designed using WAVE, and the design result was used to calculate the lifecycle cost of producing a unit (m^3/d) of potable water in Lagos, Nigeria, deploying a curve fit approach and pertinent water economic analysis tools.

The CAPEX, OPEX, and TWC play a significant role in the selection of an appropriate desalination method. The accuracy of the cost estimates derived from this study depended on the adoption of efficient, transparent, and first-class evaluation tools. This study used a systematic approach to estimate the life cycle cost of desalination plants. This included a literature review in terms of global trends, real-world data from RO desalination plants, industry reports, and commercial products to present accurate and practical life cycle costs for RO plants operating on sustainable energy sources. The production capacity of the SWRO is 9000 m^3/d with a total recovery rate of 70 %. The study analysis showed that the cost of water produced from desalination systems with a conventional source of energy (gas, oil, electricity) is much lower when compared to the RES source at the construction stage consumes enormous operational expenses (OPEX) during plant operation. On the other hand, desalination powered by a RES involves a massive capital investment (CAPEX) at the construction stage but saves huge OPEX on power consumption during plant operation. The study also showed that the introduction of RES and the geographical location of the treatment plant increased the total production cost, but building a facility around a RES will initially overwhelm the CAPEX at construction, but will lessen or completely remove the OPEX on energy consumption and flatten the curve during operation. The

TWC analysis showed that Chemical with 69% represented the highest cost center in the lifecycle cost RES powered desalination plant, followed by CAPEX – 19%, maintenance – 10%, manpower – 1.7%, membrane replacement at 1%, and lastly, the land use charge with 0.2% been the least. The plotted graph analyzing the relationship between elements of the total cost of water (TWC) confirmed that the total savings of a RES desalination system with the OPEX are calculated annually will increase, eventually reaching a break-even point within the little period and shortening the time frame for capitalizing OPEX savings.

Conclusively, the study estimated the **unit cost to produce *1 m^3/d of desalinated potable water as 1.11 USD.***

CHAPTER 8: CONCLUSION AND RECOMMENDATIONS

8.1 CONCLUSION

The main aim of this thesis was to extract data via literature review and used the extracted data to model and simulate an SWRO system, and then carry out an experimental study on an existing SWRO plant to establish the parameters that influence productivity for system optimization and determine the cost components in estimating the total cost of saline water desalination using a renewable energy source. The thesis result and conclusion have been discussed in chapter 7 above. The decision to build a seawater desalination facility involves many steps such as feasibility study, business plan, business case study, environmental impact, funding, and product market to mention a few, but of utmost importance is a business case study because it involves many of the other items. Lifecycle cost as discussed in this thesis presents a working tool and basic principle of a business case study for the construction and operation of a viable seawater desalination project. Similarly, to achieve a greater sustainable, cost-effective, improved performance and eco-friendly desalination process, the variable operational parameters such as feedwater flow, feed water pressure, and feedwater temperature must be prioritized and optimized as outlined in this thesis for the best result.

8.2 RECOMMENDATIONS

Improved productivity and membrane performance is the key objective of any SWRO system. Therefore, there is a need to implement the variations in the input operational variable parameters as outlined in the experimental result on a real plant for feasibility studies and system optimization. Similarly, a higher recovery rate saves seawater treatment production costs. Implementing the variations in the input operational variable parameters will reduce the membrane scaling and improve the recovery rate of the system. One of the biggest problems encountered in membrane desalination processes is the scaling of the membranes. Scale formation stems from the precipitation of poorly dissolved salts in the system.

The lifecycle cost aims to present accurate and practical life cycle costs for RO plants operating on sustainable energy sources. If the study result is implemented correctly, it will lead to optimum working conditions for all the system components and consequently reduce the corrective

maintenance practice, thereby improving the output while at the same time reducing the costs of operation. It will also be an attractive solution in terms of reduced environmental impact due to lower conventional energy consumption and lower gas emissions, and also lessen or completely remove the OPEX on energy consumption and flatten the curve during operation while increasing the total savings on TWC which will eventually reduce the break-even point and shortening the time frame for capitalizing OPEX savings

The calculated unit cost to produce 1 m^3/d of desalinated potable water is 1.11 USD, These cost evaluations are required most times for project development, project budgeting, and feasibility studies.

APPENDICES

APPENDIX 1

WATER APPLICATION VALUE ENGINE

WATER SOLUTIONS

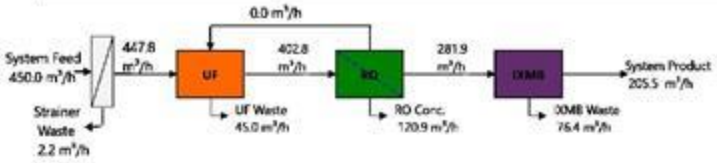
WAVE Program Version: 1.81.814

Calculation Engine Version: 01.11.19.00

Database Version: 23

UF RO IXMB

Project Name:	Olufisayo_2_-UF2-8/22/2021 - RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION_v2
Case Name:	Case 1
Customer:	
Prepared by:	Olufisayo Ojo
Company:	UKZN
Country:	South Africa
Date Created:	October 09, 2021
Project Notes:	
Case #:	1 of: 1
Case Notes:	Case 1
Keywords:	



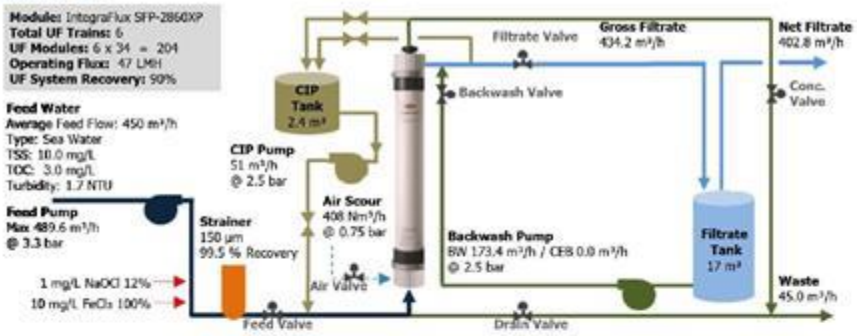
		Strainer	Ultrafiltration	Reverse Osmosis	IX MB Polish
Feed	Flow Rate (m³/h)	450.0	447.8	402.8	281.9
	TDS (mg/L)	29,658.0[b]	29,658.0[b]	29,646.0[a]	441.1[b]
	pH	7.0	7.0	7.0	5.9
	Pressure (bar)	1.2	1.2	71.2	2.1
	Temperature (°C)	25.0	25.0	25.0	25.0
Product	Flow Rate (m³/h)	447.8	402.8	281.9	205.5
	TDS (mg/L)	29,658.0[b]	29,658.0[b]	433.2[a]	0.005[b]
	pH	7.0	7.0	5.7	7.2
	Recovery	99.5 %	89.95 %	70.0 %	72.9 %
	Operating Costs ($/h)	-	54.5	189.9	420.8
	Specific Energy (kWh/m³)	-	0.06	3.50	0.990
	Operating Cost ($/m³)	-	0.135	0.674	2.048
System	Specific Energy (kWh/m³)	5.91			
	Operating Cost ($/m³)	3.24			
	Feed Flow Rate (m³/h)	450.0			
	Product Flow Rate (m³/h)	205.5			
	Recovery	45.7 %			

Footnotes:

[a]Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

[b]Total Dissolved Solutes includes ions, SiO_2 , $B(OH)_3$, NH_3 and CO_2 as H_2CO_3

UF Detailed Report



UF System Overview

Module Type		IntegraFlux SFP-2860XP			
# Trains		Online =	6	Standby =	0
				Redundant =	0
# Modules		Per Train =	34	Total =	204
System Flow Rate	(m³/h)	Gross Feed =	450.0	Net Product =	402.8
Train Flow Rate	(m³/h)	Gross Feed =	75.0	Net Product =	67.1
UF System Recovery	(%)	89.95			
TMP	(bar)	0.29 @ 10.0 °C		0.20 @ 25.0 °C	
Utility Water		Forward Flush:	Pretreated water	Backwash:	UF filtrate water
		CEB Water Source:	UF filtrate water	CIP Water Source:	RO permeate water

UF Operating Conditions

	Duration	Interval	Flux/Flow
Filtration:	30.0 min	33.3 min	-
Instantaneous			
6 Online Trains			47 LMH
6 Total Trains			47 LMH
Average			42 LMH
Net			39 LMH
Backwash	3.3 min	33.3 min	100 LMH
mini-CIP	71.6 min	7 d	1.50 m³/h
CIP	311.6 min	60 d	1.50 m³/h

UF Water Quality

Stream Name		Stream 1	
Water Type		Sea Water (10.0 - 40.0 °C)	
		Feed	**Expected UF Product Water Quality**
Temperature	(°C)	25.0	25.0
Turbidity	(NTU)	1.7	≤ 0.1
TSS	(mg/L)	10.0	-
Organics (TOC)	(mg/L TOC)	3.0	2.7
TDS	(mg/L)	29631	29658
pH		8.4	7.0

UF Configuration Options

Standby Option:	Constant module flux, variable plant filtrate flow
Storage Tank Option:	Storage Tank sized to maintain constant net filtrate flow
Forward Flush Water Source:	Pretreated water
BW Water Source:	UF filtrate water
mini-CIP Water Source:	UF filtrate water
CIP Water Source:	RO permeate water

UF System Size and Module Details

Trains		**Module Details**		
		Name: IntegraFlux SFP-2860XP		
Online Trains	6	Membrane Area	51 m²	549 ft²
Standby Trains	0	Length	1.860 m	73.2 in
Redundant Trains	0	Diameter	0.225 m	8.9 in
Total Trains	6	Weight (empty)	48 kg	106 lb
Max Offline Trains	1	Weight (water filled)	83 kg	183 lb
Modules/Train	34	Water Volume	35.0 L	9.2 gal
Total Modules	204			

UF Flow Details

Stream		Maximum Flow*	Average Flow
Feed (Gross)	(m^3/h)	489.6	450.0
Feed Water Used for	(m^3/h)		
Pretreatment	(m^3/h)		2.3
Forward Flush & Process Streams	(m^3/h)		13.5
Feed (Net)	(m^3/h)	485.9	434.2
Filtrate (Gross)	(m^3/h)	485.9	434.2
Filtrate Used for Cleaning	(m^3/h)		31.5
Filtrate (Net)	(m^3/h)		402.8
RO Permeate for Cleaning	(m^3/h)		0.0
Air	($N\ m^3/h$)	408.0	24.4
Backwash (BW)	(m^3/h)	173.4	31.3
Forward Flush Flowrate	(m^3/h)	82.3	13.5
mini-CIP Recycle	(m^3/h)	51.0	0.1
CIP Recycle	(m^3/h)	51.0	0.0
Feed HCl (32%) Metering Pump	(L/h)	36.0	
Feed $FeCl_3$(100%) Metering Pump	(L/h)	1.7	
Feed NaOCl(12%) Metering Pump	(L/h)	1.8	
mini-CIP HCl (32%) Metering Pump	(L/h)	76.9	
mini-CIP Citric Acid(100%) Metering Pump	(L/h)	612.6	
mini-CIP NaOH (50%) Metering Pump	(L/h)	56.4	
mini-CIP NaOCl(12%) Metering Pump	(L/h)	748.0	
CIP HCl (32%) Metering Pump	(L/h)	50.4	
CIP Citric Acid(100%) Metering Pump	(L/h)	612.6	
CIP NaOH (50%) Metering Pump	(L/h)	36.7	
CIP NaOCl(12%) Metering Pump	(L/h)	748.0	

Footnotes:

* Maximum possible flow rate

UF Pump Hydraulics and Electrical Cost

Pump	Peak Flowrate (m^3/h)	Average Pressure (bar)	Mechanical Power (kW)	Electrical Power (kW)	Energy (kWh/d)	Cost ($/d)
Feed	489.61	1.20	14.98	20.35	488.45	43.96
HCl (32%) Metering Pump	0.04		0.00	0.00	0.04	0.00
$FeCl_3$(100%) Metering Pump	0.00		0.00	0.00		
NaOCl(12%) Metering Pump	0.00		0.00	0.00		
Backwash	173.40	0.93	4.46	6.06	26.23	2.36
mini-CIP	51.00	3.09	4.38	5.95		
HCl (32%) Metering Pump	0.08		0.01	0.01		
Citric Acid(100%) Metering Pump	0.61		0.09	0.12		
NaOH (50%) Metering Pump	0.04		0.00	0.01		
NaOCl(12%) Metering Pump	0.75		0.07	0.10		
CIP	51.00	2.50	3.54	4.81	0.95	0.09
HCl (32%) Metering Pump	0.05		0.00	0.01		
Citric Acid(100%) Metering Pump	0.61		0.07	0.10		
NaOH (50%) Metering Pump	0.04		0.00	0.01		
NaOCl(12%) Metering Pump	0.75		0.06	0.08		
mini-CIP Solution Heating				0.00	0.00	0.00
CIP Solution Heating				27.55	5.46	0.49
Air Compressor	408.00	0.75	6.97	9.47	13.58	1.22
Electrical Valves				0.00	0.00	0.00
PLC and Instrumentation				0.60	14.40	1.30
Total Electrical Cost					552.11	49.69

UF Pressure Ratings

Process	T (°C)	TMP[a] (bar)	Fouling Max ΔP (bar)	Piping ΔP (bar)	Filtrate Pres. (bar)	Feed Pres.[b] (bar)	Pres. Rating (bar)	OK?[c]
Filtration								
Minimum Temp.	10.0	0.29	0.00	0.73	0.50	1.53	6.25	√
Design Temp.	25.0	0.20	0.00	0.50	0.50	1.20	6.00	√
Maximum Temp.	40.0	0.15	0.00	0.37	0.50	1.01	4.75	√
BW	25.0	0.43	0.00	0.50		0.93	6.00	√
mini-CIP	25.0			3.09		3.09	6.00	√
CIP	35.0			2.50		2.50	5.25	√

Footnotes:

[a] At actual, average flux

[b] Sum of TMP, fouling ΔP, piping ΔP and filtrate pressure. Does not include pressure drop at the strainer. Pressure drops are based on user inputs. Default values should not be used for pump sizing

[c] Comparison of Feed Pressure to Pressure Rating—a conservative comparison due to piping losses between the feed pump and module inlet.

UF Storage Tanks

Name	Bulk Conc. (%)	Minimum Recommended Volume (m^3)
Water[a]		16.7
CIP Tank		2.38
Chemical Storage[b]		
Ferric Chloride ($FeCl_3$)	100%	1.12
Citric Acid ($C_6H_8O_7$)	100%	0.73
Hydrochloric Acid (HCl)	32%	23.9
Sodium Hypochlorite (NaOCl)	12%	2.08
Sodium Hydroxide (NaOH)	50%	0.064

Footnotes:

[a] Storage tank sized to maintain constant net filtrate flow

[b] The mimimum recommended volume for chemical storage tanks is sized for 30 days of storage.

UF Design Warnings

None

Filtration Mode and Backwash Parameters

Normal Operation	Process Mode of Operation	Operation		Backwash (B/W)					Return to Operation[d]	Stop[e]
Operating Steps	Steps	1 Forward Flush at Start-up[b]	2 Filtration Mode	3 Air Inlet[c]	4 Drain	5 Backwash 1	6 Backwash 2	7 Forward Flush (FF)	2 Filtration Mode	- Stop
Pump and Valve Conditions	Feed Pump	o	o					o	o	
	Backwash Pump					o	o			
	Chem. Dosing Pump[a]									
	CEB Dosing Pump									
	CIP Recycle Pump									
	Feed Valve	o	o					o	o	
	Filtrate Valve		o						o	
	Conc. Valve	o		o	o	o		o		
	Backwash Inlet Valve					o	o			
	Drain Valve				o		o			
	Air Inlet Valve			o						
	Duration	~2.0-3.0 min.	30.0 min.	20 s	30 s	30 s	30 s	55 s	30.0 min.	
	Flow Rate	2.4 m³/h	47 LMH	12.0 N m³/h	By gravity	100 LMH	100 LMH	2.4 m³/h	47 LMH	
Remarks	1. The filtration mode follows Steps 2-3-4-5-6-7-8. Backwash can be repeated several times according to the fouling degree of UF membrane modules. 2. The valve opening and closing time for each process step should be considered when programming is designed. 3. "o" = valve or pump is opened or operating.									
Footnotes	[a] Use of chemical dosing pump during backwash is based on feed water source and quality. Refer to DuPont UF Design Guidelines. [b] Forward flush flow rate displayed on per-module basis. [c] Use of air scour and frequency is based on feed water source and quality. Air flow rate displayed on per-module basis. [d] May need to waste a portion of permeate to remove residual chemicals, depending on design and application. [e] If taken out of operation, add preservative and close all valves. Stop should occur only after backwash.									

CIP Parameters

CIP	CIP Mode of Operation	Operation	Backwash (B/W)[a]				CIP[b]				Backwash (B/W)[a]				Return to Operation[g]
	Steps	1 Filtration Mode	2 Air Inlet[a]	3 Drain	4 Backwash 1	5 Backwash 2	6 Drain	7 CIP Recycle[d]	8 Soak[e]	9 CIP Recycle[d]	10 Drain	11 Backwash 1	12 Backwash 2	13 Forward Flush (FF)[f]	1 Filtration Mode
Pump and Valve Conditions	Feed Pump	o												o	o
	Backwash Pump				o	o						o	o		
	Chem. Dosing Pump														
	CEB Dosing Pump														
	CIP Recycle Pump							o		o					
	Feed Valve	o												o	o
	Filtrate Valve	o													o
	Conc. Valve		o	o	o		o		o		o	o		o	
	Backwash Inlet Valve				o	o						o	o		
	Drain Valve			o		o	o				o		o		
	Air Inlet Valve		o												
	Duration	30.0 min.	20 s	30 s	30 s	30 s	30 s	30.0 min.	90.0 min.	30.0 min.	30 s	30 s	30 s	55 s	30.0 min.
	Flow Rate	47 LMH	12.0 N m^3/h	By gravity	100 LMH	100 LMH	By gravity	1.5 m^3/h	0.0 m^3/h	1.5 m^3/h	By gravity	100 LMH	100 LMH	2.4 m^3/h	47 LMH
Remarks	1. Frequency of CIP is 1-3 months, adjusted according to operating conditions. 2. Start CIP with backwash sequence; complete CIP with backwash sequence. 3. CIP is done manually. 4. "o" = valve or pump is opened or operating.														
Footnotes	[a] Air flow rate displayed on per-module basis. [b] This step should be repeated 2 times. [c] This step and duration is shown for a single chemical cleaning. If acid and base cleaning are both required, repeat Steps 6-13. [d] CIP recycle flow rate displayed on a per-module basis. [e] The duration of this step might be longer, up to overnight (12 hours), if the fouling is severe. [f] Forward flush flow rate displayed on per-module basis. [g] May need to waste a portion of permeate to remove residual chemicals, depending on design and application.														

Mini -CIP Parameters

Mini-CIP	Mini-CIP Mode of Operation	Operation	Backwash (B/W)[a]				Mini-CIP[c]				Backwash (B/W)[a]				Return to Operation[g]
	Steps	1 Filtration Mode	2 Air Inlet[a]	3 Drain	4 Backwash 1	5 Backwash 2	6 Drain	7 Mini-CIP Recycle[d]	8 Soak[e]	9 Mini-CIP Recycle[d]	10 Drain	11 Backwash 1	12 Backwash 2	13 Forward Flush (FF)[f]	1 Filtration Mode
Pump and Valve Conditions	Feed Pump	o												o	o
	Backwash Pump				o	o						o	o		
	Chem. Dosing Pump														
	CEB Dosing Pump														
	CIP Recycle Pump							o		o					
	Feed Valve	o												o	o
	Filtrate Valve	o													o
	Conc. Valve		o	o	o		o		o		o	o		o	
	Backwash Inlet Valve				o	o						o	o		
	Drain Valve			o		o	o				o		o		
	Air Inlet Valve		o												
	Duration	30.0 min.	20 s	30 s	30 s	30 s	30 s	10.0 min.	10.0 min.	10.0 min.	30 s	30 s	30 s	55 s	30.0 min.
	Flow Rate	47 LMH	12.0 N m^3/h	By gravity	100 LMH	100 LMH	By gravity	1.5 m^3/h	0.0 m^3/h	1.5 m^3/h	By gravity	100 LMH	100 LMH	2.4 m^3/h	47 LMH
Remarks	1. Due to relatively high frequency of mini-CIP (i.e. typically from 1 to 3 times per week), it is recommended to automate the process in order to reduce labor. 2. The existing auxiliary system used for the standard CIP is employed to perform more frequent but shorter chemical cleanings or mini-CIP, so there is no need of additional installation or hardware. 3. The total duration of the mini-CIP is typically 30 minutes and includes a regular Backwash pre-cleaning, a heated chemical solution recirculation step with a soaking period in between (with intermittend Air Scour), and a final Backwash post-cleaning. 4. Note that the mini-CIP substitutes the CEB, not the standard intensive CIP program which still might be needed regularly.														
Footnotes	[a] Air flow rate displayed on per-module basis. [b] This step should be repeated 2 times. [c] This step and duration is shown for a single chemical cleaning. If acid and base cleaning are both required, repeat Steps 6-13. [d] Mini-CIP recycle flow rate displayed on a per-module basis. [e] The duration of this step might be longer, up to overnight (12 hours), if the fouling is severe. [f] Forward flush flow rate displayed on per-module basis. [g] May need to waste a portion of permeate to remove residual chemicals, depending on design and application.														

UF Utility and Chemical Costs

Service Water

	Average Flowrate (m^3/h)	Unit Cost ($/m^3$)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water	45.00	0.1400	6.30	151.18
Waste Water Disposal	45.00	0.6900	31.05	745.12
Total Service Water Cost				896.30

Electricity

Peak Power	(kW)	68.47
Energy	(kWh/d)	552.11
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	49.69
Specific Energy	(kWh/m^3)	0.06

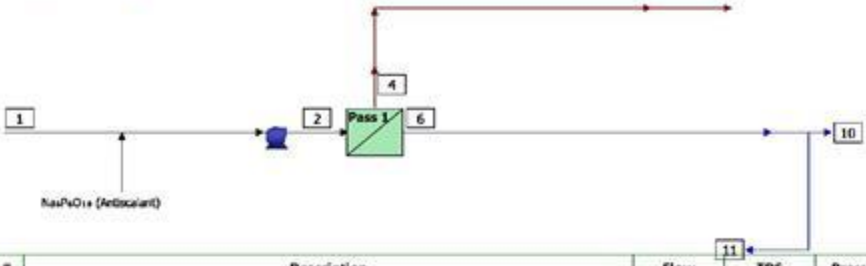
Chemicals

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
$FeCl_3$ (100%)	1.670		37.3	180.36
Feed		10		
Citric Acid (100%)	1.520		24.3	61.46
CIP		20000		
mini-CIP		20000		
HCl (32%)	0.100		796.3	92.40
Feed		27		
CIP		367		
mini-CIP		560		
NaOCl (12%)	0.330		69.2	25.97
Feed		1		
CIP		2000		
mini-CIP		2000		
NaOH (50%)	0.258		2.1	0.84
CIP		548		
mini-CIP		843		
Total Chemical Cost				361.03

Utility and Chemical Cost	($/d)	1,307.02
Specific Water Cost	($/m^3$)	0.135

RO Detailed Report

RO System Flow Diagram



#	Description	Flow (m³/h)	TDS (mg/L)	Pressure (bar)
1	Raw Feed to RO System	402.8	29,646	0.0
2	Net Feed to Pass 1	401.5	29,739	71.2
4	Total Concentrate from Pass 1	120.5	98,094	68.6
6	Net Product from RO System	281.9	433.2	0.0
10	Net RO Product after UF Use	281.9	433.2	0.0
11	RO Permeate Used for UF	0.02	433.2	0.0

RO System Overview

Total # of Trains	1	Online =	1	Standby =	0	RO Recovery	70.0 %
System Flow Rate	(m³/h)	Net Feed =	402.8	Net Product =	281.9	(Permeate Used For UF)	

Pass		Pass 1
Stream Name		Stream 1
Water Type		Seawater With DuPont UF, SDI < 2.5
Number of Elements		324
Total Active Area	(m²)	13244
Feed Flow per Pass	(m³/h)	401.5
Feed TDS*	(mg/L)	29,739
Feed Pressure	(bar)	71.2
Flow Factor Per Stage		1.00, 1.00
Permeate Flow per Pass	(m³/h)	281.9
Pass Average flux	(LMH)	21.3
Permeate TDS*	(mg/L)	433.2
Pass Recovery		70.2 %
Average NDP	(bar)	17.8
Specific Energy	(kWh/m³)	3.50
Temperature	(°C)	25.0
pH		7.0 (After Adjustment)
Chemical Dose		3.0 mg/L $Na_6P_6O_{18}$(100%)
RO System Recovery		70.0 %
Permeate for UF	(m³/h)	0.0
Net RO System Recovery		70.0%

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Flow Table (Stage Level) - Pass 1

Stage	Elements	#PV	#Els per PV	Feed				Concentrate			Permeate			
				Feed Flow (m³/h)	Recirc Flow (m³/h)	Feed Press (bar)	Boost Press (bar)	Conc Flow (m³/h)	Conc Press (bar)	Press Drop (bar)	Perm Flow (m³/h)	Avg Flux (LMH)	Perm Press (bar)	Perm TDS (mg/L)
1	Seamaxx™-440i	36	6	401.5	0.00	70.9	0.0	129.1	70.0	0.9	273.3	30.9	0.0	284.1
2	Seamaxx™-440	18	6	129.1	0.0	69.8	0.0	120.5	68.6	1.2	8.67	2.0	0.0	5,134

RO Solute Concentrations - Pass 1

Concentrations (mg/L as ion)						
	Feed	Concentrate		Permeate		
		Stage1	Stage2	Stage1	Stage2	Total
NH_4^+	0.11	0.34	0.36	0.00	0.03	0.00
K^+	355.0	1,098	1,170	4.75	88.65	7.33
Na^+	9,100	28,174	30,059	102.6	1,856	156.5
Mg^{+2}	990.0	3,084	3,302	2.29	39.95	3.45
Ca^{+2}	395.0	1,230	1,317	0.89	15.91	1.35
Sr^{+2}	5.70	17.76	19.01	0.01	0.23	0.02
Ba^{+2}	0.03	0.09	0.10	0.00	0.00	0.00
CO_3^{-2}	1.66	15.02	16.71	0.00	0.02	0.00
HCO_3^-	151.5	448.2	476.5	2.31	34.92	3.27
NO_3^-	0.01	0.03	0.03	0.00	0.01	0.00
F^-	0.86	2.66	2.83	0.01	0.22	0.02
Cl^-	15,727	48,712	51,986	166.3	3,013	253.9
Br^{-1}	90.00	276.9	294.5	1.83	31.48	2.74
SO_4^{-2}	2,830	8,822	9,451	3.12	53.39	4.66
PO_4^{-3}	0.00	0.00	0.00	0.00	0.00	0.00
SiO_2	0.00	0.00	0.00	0.00	0.00	0.00
Boron	0.00	0.00	0.00	0.00	0.00	0.00
CO_2	98.25	290.1	308.2	11.04	44.70	12.10
TDS*	29,646	91,881	98,094	284.1	5,134	433.2
Est. Cond. µS/cm	44,584	119,438	126,306	584	9,337	881
pH	7.0	7.5	7.6	5.5	6.4	5.7

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Design Warnings

Design Warning		Limit	Value	Pass	Stage	Element	Product
Permeate Flow Rate > Maximum Limit	(m³/h)	1.46	3.21	1	1	1	Seamaxx™-440i
Permeate Flow Rate > Maximum Limit	(m³/h)	1.46	2.09	1	1	2	Seamaxx™-440i
Element Recovery > Maximum Limit	(%)	15.0	28.8	1	1	1	Seamaxx™-440i
Element Recovery > Maximum Limit	(%)	15.0	26.3	1	1	2	Seamaxx™-440i
Element Recovery > Maximum Limit	(%)	15.0	20.3	1	1	3	Seamaxx™-440i

Special Comments

None

RO Flow Table (Element Level) - Pass 1

Stage	Element	Element Name	Recovery (%)	Feed Flow (m^3/h)	Feed Press (bar)	Feed TDS (mg/L)	Conc Flow (m^3/h)	Perm Flow (m^3/h)	Perm Flux (LMH)	Perm TDS (mg/L)
1	1	Seamaxx™-440i	28.8	11.2	70.9	29,737	7.95	3.21	78.5	80.28
1	2	Seamaxx™-440i	26.3	7.95	70.6	41,662	5.87	2.09	51.1	152.0
1	3	Seamaxx™-440i	20.3	5.87	70.4	56,378	4.68	1.19	29.1	305.8
1	4	Seamaxx™-440i	13.2	4.68	70.2	70,581	4.07	0.62	15.1	636.1
1	5	Seamaxx™-440i	7.7	4.07	70.1	81,169	3.76	0.31	7.7	1,301
1	6	Seamaxx™-440i	4.6	3.76	70.0	87,812	3.59	0.17	4.2	2,415
2	1	Seamaxx™-440	1.8	7.17	69.8	91,878	7.05	0.13	3.1	3,302
2	2	Seamaxx™-440	1.4	7.05	69.5	93,450	6.95	0.10	2.4	4,232
2	3	Seamaxx™-440	1.2	6.95	69.3	94,701	6.87	0.08	2.0	5,170
2	4	Seamaxx™-440	1.0	6.87	69.1	95,737	6.80	0.07	1.7	6,088
2	5	Seamaxx™-440	0.9	6.80	68.9	96,623	6.74	0.06	1.4	6,975
2	6	Seamaxx™-440	0.8	6.74	68.8	97,400	6.69	0.05	1.3	7,826

Footnotes:

*Total Dissolved Solids includes ions, SiO_2 and $B(OH)_3$. It does not include NH_3 and CO_2

RO Solubility Warnings

Warning	Pass No
Stiff & Davis Stability Index > 0	1
$CaSO_4$ (% saturation) > 100	1
$BaSO_4$ (% saturation) > 100	1
CaF_2 (% saturation) > 100	1
Anti-scalants may be required. Consult your anti-scalant manufacturer for dosing and maximum allowable system recovery.	1

RO Chemical Adjustments

	Pass 1 Feed	RO 1st Pass Conc
pH	8.4	7.6
Langelier Saturation Index	1.4	1.65
Stiff & Davis Stability Index	0.48	0.62
TDS* (mg/l)	29,630	98,094
Ionic Strength (molal)	0.60	2.15
HCO_3^- (mg/L)	128.3	476.5
CO_2 (mg/l)	0.28	13.69
CO_3^{-2} (mg/L)	35.37	16.71
$CaSO_4$ (% saturation)	25.1	116.9
$BaSO_4$ (% saturation)	134.6	549.4
$SrSO_4$ (% saturation)	12.9	82.8
CaF_2 (% saturation)	7.1	182.8
SiO_2 (% saturation)	0.00	0.00
$Mg(OH)_2$ (% saturation)	7.1	0.35

RO Utility and Chemical Costs

Service Water

	Flow Rate (m^3/h)	Unit Cost ($/m^3$)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water				
Pass 1	120.5	0.1400	16.86	404.71
Total Non-product Feed Water Cost	120.5		16.86	404.71
Waste Water Disposal				
Pass 1	120.5	0.6900	83.11	1994.63
Total Waste Water Disposal	120.5		83.11	1994.63
Total Service Water Cost				2399.34

Electricity

Peak Power	(kW)	985.8
Energy	(kWh/d)	23,660
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	2,129
Specific Energy	(kWh/m^3)	3.50

Pump	Flow Rate (m^3/h)	Power (kW)	Energy (kWh/d)	Cost ($/d)
Pass 1				
Feed	401.50	985.83	23,659.87	2,129.39
Pass 1 Total		985.83	23,659.87	2,129.39
System Total		985.83	23,659.87	2,129.39

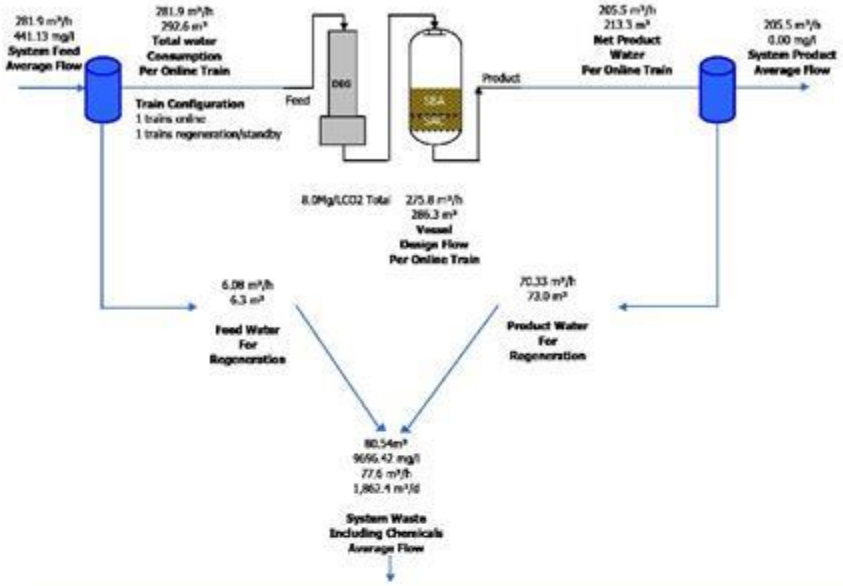
Chemical

Chemical	Unit Cost ($/kg)	Dose (mg/L)	Volume (L/d)	Cost ($/d)
$Na_6P_6O_{18}$(100%)(Pass 1)	1.000	3.0	11.7	29.00
Total Chemical Cost				29.0

Utility and Chemical Cost	($/d)	4,557
Specific Water Cost	($/m^3$)	0.674

IX Detailed Report

IX System Overview



IX Process		RO Permeate Polishing			
Layout		[MB]			
#Trains		Online =	1	Regeneration =	1
System Average Flow Rate	(m³/h)	Feed =	282	Product =	205
Net Product Flow Rate per Train	(m³/h)				205
Throughput per Train per Cycle	(m³)	Gross =	286	Net =	213
System Recovery	(%)		72.9		
Estimated Run Time	(h)		1.04		
Estimated Regeneration Time	(h)		4.27		

IX Resins and Vessels

Resin Type		SAC	SBA
Vessel Type		MB, Internal Regen	MB, Internal Regen
Design Flow Rate	(m^3/h)	276	276
Resin Name		AmberLite™ HPR1200 H	AmberLite™ HPR4200 Cl
Ionic Form (Delivered)		H	Cl
Resin Volume (Delivered Form)	(m^3)	2.95	5.15
Ionic Form (Reference)		Na	Cl
Resin Volume (Reference Form)	(m^3)	2.73	5.15
Total Bed Resin Volume	(m^3)	7.88	
Fraction of Bed	(%)	34.6	65.4
Potential Runtime	(h)	1.04	1.04
Potential Throughput	(m^3)	286	286
Operating Capacity	(eq/L)	0.81	0.44
Effective Operating Capacity	(eq/L)	0.77	0.42
Ionic Load	(eq)	2,103	2,140
Organic (TOC) Loading	(g/L TOC)		0.00
TSS Loading	(kg/m^3)	0.00	0.00
Regenerant		HCl	NaOH
Regeneration Dose	(g/L)	100.0	100.0
Regeneration Ratio	(%)	356	602
Excess Regenerant	(eq)	5,381	10,694
Vessel Outside Diameter	(mm)	2,500	2,500
Bed Depth (Delivered)	(mm)	613	1,072
Total Bed Depth	(mm)	1685	
Bed Depth (Reference)	(mm)	568	1,072
Total Bed Depth	(mm)	1640	
Freeboard	(mm)	1,900	1,900
Specific Velocity	(BV/h)	101	54
Total Bed Specific Velocity	(BV/h)	34.99	
Linear Velocity	(m/h)	57	57
Resin ΔP @ 25.0 °C	(bar)	0.35	0.58
Total Pressure Drop @ 25.0 °C	(bar)	0.94	
Capacity Safety Factor		0.949	0.950

Computation performed without adjustment.

*Combined resin pressure drop includes the pressure drop due to the inert resin.

IX Water Quality

		Feed	Required Average	Required EndPoint	Estimated Average
pH @ 25.0 °C		5.88	-	-	7.18
Conductivity @ 25 °C	(µS/cm)	881	0.12	0.22	0.058
Na	(mg/L)	156.462	0.010	0.020	0.002
SiO_2	(mg/L)	0.000	0.010	0.020	< 0.001

Additional Feed Water Information

IX Design Warnings

Design Warning		Limit	Estimate	Resin
Loading Time < Min	(h)	3.00	1.04	AmberLite™ HPR1200 H
Loading Time < Min	(h)	3.00	1.04	AmberLite™ HPR4200 Cl

Number of regeneration trains < Min	5	1	System

IX System Overview

Flow Rates				
		System Average	Online Train per Cycle	
		Flow Rate	Flow Rate	Volume
System Feed	(m^3/h)	281.9		
Bypass	(m^3/h)	0.0		
Total Water Consumption	(m^3/h)	281.9	281.9	293 m^3
Total Regeneration Water	(m^3/h)	-76.4	-76.4	-79.306 m^3
Net Product Water	(m^3/h)	205.5	205.5	213 m^3
Bypass	(m^3/h)	0.0		
System Product	(m^3/h)	205.5		
IX Recovery		72.89 %		
System Overall Recovery (Including Bypass)		72.89 %		

Cycle Times		
		Overall System
Regeneration Cycle	(h)	4.27
Loading Cycle	(h)	1.04
Complete Cycle	(h)	5.31
Cycles per Online Train per Day		23.12

IX Resins

IX Resin Type, Volume, Height, Capacity			
Resin #		1	2
Name		AmberLite™ HPR1200 H	AmberLite™ HPR4200 Cl
Ionic Form Delivered		H	Cl
Volume			
Delivered	(m^3)	2.95	5.15
Reference	(m^3)	2.73	5.15
Exhausted	(m^3)	2.81	5.89
Regenerated	(m^3)	2.95	6.19
Height			
Delivered	(mm)	613	1,072
Reference	(mm)	568	1,072
Exhausted	(mm)	584	1,225
Regenerated	(mm)	613	1,287
Capacity Summary			
Safety Factor		0.949	0.950
Operating Capacity	(eq/L)	0.81	0.44
Effective Operating Capacity	(eq/L)	0.77	0.42
Organic (TOC) Loading	(g/L TOC)		0.004

IX Vessels

IX Vessel Size, Hydraulics, and Pressure Drop		
Vessel #		1
Vessel Type		MB
Regeneration System		MB, Internal Regen
Diameter:		
Outside	(mm)	2,500
Inside	(mm)	2,474
Internal Area	(m^2)	4.807
Compartment 1		
Resin		AmberLite™ HPR1200 H
Resin Maximum Height	(mm)	613
Specific Velocity	(BV/h)	101
Linear Velocity	(m/h)	57
Resin ΔP: Loading	(bar)	0.35
Resin		AmberLite™ HPR4200 Cl
Resin Maximum Height	(mm)	1,287
Specific Velocity	(BV/h)	54
Linear Velocity	(m/h)	57
Resin ΔP: Loading	(bar)	0.58
Combined Resin		
Resin Volume (reference)	(m^3)	7.88
Resin Maximum Height	(mm)	1900
Specific Velocity	(BV/h)	34.99
Resin ΔP: Loading	(bar)	0.94
Compartment Wall Height	(mm)	3,799
Freeboard	(mm)	1,900
Vessel ΔP	(bar)	1.14
System ΔP	(bar)	1.14
Estimated Feed Pressure	(bar)	2.14

IX Regeneration

IX Chemical Consumption			
Regeneration Protocol		1	2
Regenerant		HCl	NaOH
Bulk Concentration	(%)	32	50
Unit Cost	($/kg)	0.10	0.26
Regeneration Temperature	(°C)	25.0	25.0
Dose			
Weight Basis	(g/L)	100.0	100.0
Consumption			
per Regeneration			
@ Bulk Concentration	(kg)	853	1,031
@ 100 % Basis	(kg)	273	515
per Day			
@ Bulk Concentration	(kg/day)	19,716.8	23,834.4
@ 100 % Basis	(kg/day)	6,309.4	11,917.2
Daily Cost	($/day)	1,971.68	6,149.29

Total Chemical Cost	($/day)	8,120.97

IX Service Water Consumption			
		Feed	Product
Volume per Regeneration	(m^3/ regen)	6.3	73.0
Volume per Day	(m^3/day	145.8	1,687.9

IX Regeneration Efficiency			
Individual Resin		1	2
Ionic Loading	(eq)	2,103	2,140
Regen. Requirements	(eq)	2,103	2,192
Total Regenerant	(eq)	7,484	12,886
Regeneration Ratio		356 %	602 %
Effective Regenearation Ratio		356 %	588 %

IX Regeneration Protocol								
	Conc	Flow Rate		Linear Velocity	Time	Volume		Water Source
	(%)	(m^3/h)	(BV/h)	(m/h)	(min)	(m^3)	(BV)	
Protocol 1								
SAC Resin								
Backwash		46.54	17.06	9.68	30.00	23.27	8.53	Demineralized Water
Settling					10.00			
Injection #1	5.00	9.55	3.50	1.99	33.56	5.34	1.96	Demineralized Water
Displacement Rinse		8.26	3.03	1.72	129.11	17.77	6.51	Demineralized Water
Drain					15.00			
Air Mix		472.96			15.00	118.24		Air
Settling					10.00			
Slow Refill		10.09			14.29	2.40		Feed Water
Fast Refill		275.84			0.85	3.90		Feed Water
Fast Rinse Recycle		275.84	101.09	57.38	8.57	39.40	14.44	Recycled water
Total					266.38	52.68		
Protocol 2								
SBA Resin								
Backwash		46.55	9.03	9.68	30.00	23.27	4.52	Demineralized Water
Settling					10.00			
Injection #1	4.00	10.51	2.04	2.19	70.70	12.38	2.40	Demineralized Water
Displacement Rinse		10.09	1.96	2.10	91.95	15.46	3.00	Demineralized Water
Drain					15.00			
Air Mix		472.96			15.00	118.24		Air
Settling					10.00			
Slow Refill		10.09			14.29	2.40		Feed Water
Fast Refill		275.84			0.85	3.90		Feed Water
Fast Rinse Recycle		275.84	53.52	57.38	8.57	39.40	7.64	Recycled water
Total					266.37	57.42		

Fast Rinse with full recycle

Operation	Power (kW)	Energy (kW-h)		Hourly Cost ($/d)
		per Regen	per Day	
Feed Pump	22.7		545.5	49.09
Regeneration Protocol 1				
Backwash & Compaction Pump	0.0	0.0		
Regeneration Pump	0.1	0.2		
Fast Rinse Pump	0.0	0.0		
Heating	0.0	0.0		
Regeneration 1 Total	0.1	0.2	4.2	0.38
Regeneration Protocol 2				
Backwash & Compaction Pump	0.4	0.2		
Regeneration Pump	0.1	0.2		
Fast Rinse Pump	11.8	1.7		
Heating	0.0	0.0		
Regeneration 2 Total	11.8	2.1	48.8	4.39
Total Regeneration			53.0	4.77
Total System			598.5	53.86

IX Water Composition

Ionic Concentration and Other Attributes				
Species		**IX Feed**	**IX Product (Effluent)**	**IX System Waste**
NH_3/NH_4^+ Total	(mg/L)	0.003	0.000	0
K^+	(mg/L)	7.329	0.000	27
Na^+	(mg/L)	156.462	0.002	4247
Mg^{2+}	(mg/L)	3.445	0.000	13
Ca^{2+}	(mg/L)	1.348	0.000	5
Sr^{2+}	(mg/L)	0.019	0.000	0
Ba^{2+}	(mg/L)	0.000	0.000	0
Total Exchangeable Cations	(meq/L)	7.34	0.00	187
CO_3^{2-}	(mg/L)	0.000	0.000	40
HCO_3^-	(mg/L)	3.220	0.000	0
CO_2	(mg/L)	5.681	0.000	0
NO_3^-	(mg/L)	0.000	0.000	0
F^-	(mg/L)	0.019	0.000	0
Cl^-	(mg/L)	253.868	0.000	4217
Br^-	(mg/L)	2.743	0.000	10
SO_4^{2-}	(mg/L)	4.662	0.000	17
$PO_4^{3-}/H_3PO_4/H_2PO_4^-/HPO_4^{2-}$ Total	(mg/L)	0.000	0.000	0
SiO_2 Total	(mg/L)	0.000	0.000	0
B Total	(mg/L)	0.000	0.000	0
Total Exchangeable Anions	(meq/L)	7.47	0.00	121
TDS	(mg/L)	441.1	0.005	9,696
pH @ 25.0 °C		5.88	7.18	12.58
Hardness	(meq/L)	0.35	0.00	1.28
Total Alkalinity	(meq/L)	0.05	0.00	1.32
Organics (TOC)	(mg/L TOC)	0.75	0.68	0.95
Total Suspended Solids (TSS)	(mg/L)	0.00	0.00	0.00
Conductivity @ 25 °C	(µS/cm)	881	0.058	26,383
Temperature	(°C)	25.0	25.0	25.0

IX Utility and Chemical Costs

Service Water

	Average Flowrate (m^3/h)	Unit Cost ($/m^3)	Hourly Cost ($/h)	Daily Cost ($/d)
Non-Product Feed Water	77.59	0.1400	10.70	256.72
Waste Water Disposal	77.59	0.6900	53.53	1,284.82
Total Service Water Cost			64.23	1541.55

Electricity

Peak Power	(kW)	34.64
Energy	(kWh/d)	4,864.03
Electricity Unit Cost	($/kWh)	0.0900
Electricity Cost	($/d)	437.8
Specific Energy	(kWh/m^3)	0.990

Utility and Chemical Cost	($/d)	10,100.28
Specific Water Cost	($/m^3$)	2.048

APPENDIX 2

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EDITING CERTIFICATE

Re: **Ojo E. Olufisayo**
Journal article: **A REVIEW OF SEAWATER MEMBRANE DESALINATION**

I confirm that I have edited this article and the references for clarity, language and layout. I returned the document to the author with track changes so correct implementation of the changes and clarifications requested in the text and references is the responsibility of the author. I am a freelance editor specialising in proofreading and editing academic documents. My original tertiary degree which I obtained at the University of Cape Town was a B.A. with English as a major and I went on to complete an H.D.E. (P.G.) Sec. with English as my teaching subject. I obtained a distinction for my M.Tech. dissertation in the Department of Homoeopathy at Technikon Natal in 1999 (now the Durban University of Technology). I was a part-time lecturer in the Department of Homoeopathy at the Durban University of Technology for 13 years and supervised many master's degree dissertations during that period.

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EDITING CERTIFICATE

Re: **Ojo E. Olufisayo**
Journal article: **A REVIEW OF RENEWABLE ENERGY POWERED REVERSE OSMOSIS SYSTEM FOR SEAWATER DESALINATION**

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Journal article: **MODELING AND SIMULATION FOR A SEAWATER REVERSE OSMOSIS SYSTEM**

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EDITING CERTIFICATE

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Journal article: **LIFECYCLE COST (LCC) ANALYSIS AND EVALUATION OF THE ECONOMICS OF SEAWATER REVERSE OSMOSIS DESALINATION - CURRENT AND FUTURE CHALLENGES FOR BETTER WATER SUPPLY SUSTAINABILITY**

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Dr Richard Steele
08 January 2022
per email

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